JOHANNES WIRGES

INFRASTRUCTURE

PLANNING THE CHARGING INFRASTRUCTURE FOR ELECTRIC VEHICLES IN CITIES AND REGIONS

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by

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Planning the Charging Infrastructure for Electric Vehicles in Cities and Regions

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Abstract

This thesis treats the planning of the charging infrastructure for electric vehicles (EVs) in cities and regions. The thesis incorporates a broad range of technological, economic, political, and behavioral aspects. Such an encompassing vision does not seem to have been presented in any previously published work. The document can be used as a scientifically founded handbook for German and international urban and infrastructure planners. It can also be used as a reference work for experts in specific domains of electric mobility who need information on aspects of the charging infrastructure for EVs lying outside their area of expertise. The thesis presents both original research as well as extensive evaluation of literature.

The report starts with a discussion of technologies for the charging of EVs, namely charging via cable, induction, and battery switching. The associated information and communication technologies for the operation and use of the infrastructure are also treated. The evaluation of advantages and disadvantages of different technological options indicates that charging via cable is and will be the most commonly used technology in the near future.

Then interactions of EV charging and the electricity system are discussed. Different phenomena occurring on the level of generation, storage, transmission, distribution, and local use of electricity are considered. Evaluating the order of scale of occurring effects shows these can be expected to be negligible on the national scale but significant on the local scale. Efforts should therefore concentrate on mitigating negative impacts on the local level of distribution networks and building installations.

The demand for public charging infrastructure is discussed from the EV drivers', infrastructure providers', and public service providers' perspective. A conflict can be seen between high demand for charging points currently stated by EV drivers and political organizations and low demand when considering a minimal necessary level utilization from the infrastructure providers' perspective. A formula is introduced that allows to calculate quotas of charging points per EVs, dependent on technical parameters, charging behavior, and a demanded minimal level of utilization.

The economic side of public charging infrastructure is then considered, notably by doing calculations for selected business models. The results show that it is difficult to operate public charging stations profitably. Possible solutions can be the display of advertisement at the charging stations or their cross financing by other services and products sold at the location. Also, the German state could pay subsidies for charging stations, for instance in the form of a subsidy paid per charged kWh.

Such an approach is warranted if the infrastructure creates enough benefits (positive externalities) for the society as a whole. Evaluating the positive externalities created by EVs and their charging infrastructure shows that many of them can only be realized under specific conditions. For instance, EVs need to be recharged with electricity from low polluting sources, such as renewable energies, for them to lead to lower CO_2 emissions than conventional vehicles.

Current EU regulation requires member states to set up policy frameworks that will lead to the provision of at least 1 publicly accessible charging point per every 10 EVs. It is discussed which regulations are in place on the EU level and nationally in Germany. It is then shown which regulations could be implemented by Germany to support the buildup of charging infrastructure. These are notably pushing policies which assign the responsibility of implementing charging stations to building owners or municipalities, or pulling policies which subsidize public charging stations provided by private companies.

For a future German regulatory framework, and any implementing of a charging infrastructure for EVs in a city or region, the cooperation between stakeholders plays an important role. Municipal utilities, municipalities, EV infrastructure companies, electricity providers, and distribution system operators are the stakeholders with the highest interest and power to contribute to a local infrastructure development. For stakeholders from the electricity sectors it is especially important to find partners that provide parking spaces for the installation of charging stations. It is shown how a stakeholder dialog can be initiated, how citizen participation can be implemented, and stakeholder cooperation can be formalized.

Planning a local charging infrastructure for EVs involves designating locations for the stations. The diversity of previously published location planning methods is shown. Then two method developed by the author are explained. The first is a method of decision support, for which a specific application to the Province of Liège in Belgium is presented. The method uses a questionnaire to develop infrastructure scenarios which are in line with the local policies in a region. A second location planning method is presented which prioritizes a given set of candidate locations for the installation of charging stations. An application is shown for supermarkets in the Austrian federal state of Styria.

Once locations for charging stations are determined on the regional level, the planning has to be refined for the street level. The diverse technical and urban planning aspects that a play a role are discussed. The different permits and contracts that need to be acquired are also treated. Then it is shown how criteria for street location planning and requirements of permitting procedures can be combined into operational planning procedures.

After charging stations have been implemented in a region, they need to be operated and maintained. It is discussed which activities this involves. Current reports of EV drivers are evaluated to show the shortcomings of current EV infrastructure operation.

A further step beyond operation and maintenance is the long-term development of charging infrastructure. A model is shown that simulates the time-spatial development of a charging infrastructure for EVs in the German region of Stuttgart in the years 2010–2020. The model takes the development of EV ownership as an input and calculates a corresponding charging infrastructure based on calculated quotas of charging points per EVs and inter-municipal commuter data.

The many aspects of EV charging infrastructure treated in this work can be integrated in two global visions shown in the introduction of the thesis. Different aspects can be considered as knowledge modules, which are linked by specific information. Alternatively a procedural view can be taken, in which the focus lies on which methods and background information is required in which stage of an EV infrastructure planning and implementation process.

Zusammenfassung

Diese Dissertation befasst sich mit der Planung der Ladeinfrastruktur für Elektrofahrzeuge (EF) in Städten und Regionen. Dabei behandelt die Dissertation ein weites Spektrum von technischen, ökonomischen, politischen und vehaltensbezogenen Aspekten. Eine dermaßen umfassende Sicht scheint in keinem bisher veröffentlichten Werk präsentiert worden zu sein. Das Dokument kann als wissenschaftlich fundiertes Handbuch von deutschen und internationalen Stadt- und Infrastrukturplanern vewendet werden. Darüber hinaus kann es als Referenzwerk für Experten in spezifischen Bereichen der Elektromobilität dienen, die Informationen zu Aspekten der Ladeinfrastruktur für EF benötigen, die außerhalb ihres Fachbereiches liegen. Diese Dissertation beinhaltet sowohl eigenständige Forschungsergebnisse, als auch eine ausführliche Auswertung der existierenden Literatur.

Das Dokument beginnt mit einer Diskussion der Technologien für die Ladung von EF, nämlich der Ladung über Kabel, induktiv und mittels Batterietausch. Die dazugehörigen Informations- und Kommunikationstechnologien für den Betrieb und die Nutzung der Infrastruktur werden ebenfalls behandelt. Die Auswertung der Vorteile und Nachteile der verschiedenen technischen Möglichkeiten zeigt auf, dass das Laden mittels Kabel momentan die meistverwendete technische Option ist, und auch in näherer Zukunft sein wird.

Anschließend werden die Interaktionen zwischen dem Laden von EF und dem Elektrizitätssystem diskutiert. Verschiedene Phänomene, die auf der Ebene von Erzeugung, Speicherung, Übertragung, Verteilung und lokaler Nutzung von Elektrizität auftreten, werden betrachtet. Eine Auswertung der Größenordnungen der auftretenden Effekte zeigt, dass diese erwartungsgemäß vernachlässigbar auf

nationaler Ebene, aber bedeutend auf lokaler Ebene sein werden. Die Bemühungen sollten sich deshalb darauf konzentrieren, negative Auswirkungen auf der lokalen Ebene von Verteilnetzen und Hausinstallationen einzudämmen.

Danach wird der Bedarf nach öffentlicher Ladeinfrastruktur aus der Sicht von EF-Fahrern, EF-Infrastrukturanbietern und Anbietern eines öffentlichen Dienstes diskutiert. Ein Konflikt wird sichtbar, zwischen dem hohen Bedarf an Ladepunkten, der momentan von EF-Fahrern und öffentlichen politischen Organisationen angegeben wird, und dem niedrigen Bedarf, der sich ergibt wenn eine notwendige Mindestauslastung der Infrastruktur aus der Sicht eines EF-Infrastrukturanbieters berücksichtigt wird. Eine Formel wird eingeführt, die es erlaubt Quoten von Ladepunkten pro EF zu berechnen, in Abhängigkeit von technischen Parametern, Ladeverhalten und einer geforderten Mindestauslastung.

Anschließend wird die ökonomische Seite öffentlicher Ladeinfrastruktur betrachtet, indem Berechnungen für ausgewählte Geschäftsmodelle durchgeführt werden. Die Ergebnisse zeigen, dass es schwierig ist, öffentliche Ladestationen profitabel zu betreiben. Mögliche Lösungen können die Anzeige von Werbung an den Ladestationen sein oder deren Querfinanzierung durch den Verkauf anderer Dienstleistungen oder Produkte am Standort. Darüber hinaus könnte der deutsche Staat Subventionen für Ladestationen zahlen, zum Beispiel in der Form einer Subvention, die pro geladener kWh gezahlt wird.

So ein Ansatz ist gerechtfertigt, wenn die Infrastruktur genügend Nutzen (positive Externalitäten) für die Gesellschaft als Ganzes erzeugt. Eine Auswertung der positiven Externalitäten, die durch EF und deren Ladeinfrastruktur erzeugt werden, zeigt, dass viele davon nur unter bestimmten Bedingungen realisiert werde können. Beispielsweise müssen EF mit Elektrizität aus Quellen mit niedriger Umweltverschmutzung, wie zum Beispiel erneuerbaren Energien geladen werden, damit sie zu niedrigeren CO_2 Emissionen als konventionelle Fahrzeuge führen.

Die aktuelle EU Gesetzgebung verpflichtet die Mitgliedsstaaten dazu, gesetzliche Rahmenbedingunen zu schaffen, die zur Bereitstellung von mindestens einem öffentlich zugänglichem Ladepunkt pro zehn EF führen werden. Es wird diskutiert, welche Gesetze aktuell auf EU Ebene und national in Deutschland in Kraft sind. Dann wird aufgezeigt, welche Gesetze von der Deutschen Regierung eingeführt werden könnten, um den Aufbau der Ladeinfrastruktur zu unterstützen. Dies sind insbesondere „schiebende“ (push) Strategien welche die Verantwortung zum Aubau von Ladestationen an Gebäudebesitzer oder Gemeinden übertragen, oder „ziehende“ (pull) Strategien, die öffentliche Ladestationen, die durch private Firmen betrieben werden, subventionieren.

Für einen zukünftigen deutschen gesetzlichen Rahmen und für jede Umsetzung einer Ladeinfrastruktur für EF in einer Stadt oder Region, spielt die Kooperation von Stakeholdern eine wichtige Rolle. Stadtwerke, Gemeinden, EF-Infrastrukturfirmen, Elektrizitätsversorger und Verteilnetzbetreiber sind die Stakeholder mit dem höchsten Interesse und der höchsten Macht, um zu einer lokalen Infrastrukturentwicklung beizutragen. Für Stakeholder aus dem Elektrizitätssektor ist es besonders wichtig Partner zu finden, die Parkplätze für den Aufbau von Ladestationen bereitstellen. Es wird gezeigt wie ein Stakeholderdialog angestoßen, wie Bürgerbeteiligung umgesetzt, und wie Stakeholder Kooperation formalisiert werden kann.

Die Planung einer lokalen Ladeinfrastruktur für EF beinhaltet die Bestimmung von Standorten für die Stationen. Die Diversität vorher veröffentlichter Planungsmethoden wird gezeigt. Dann werden zwei Methoden erklärt, die der Autor entwickelt hat. Die Erste ist eine Methodik zur Entscheidungsunterstützung, für die eine Anwendung auf die Provinz Lüttich (Liège) in Belgien präsentiert wird. Die Methode verwendet einen Fragebogen, um Infrastrukturszenarien zu entwickeln, die mit der lokalen Politik in einer Region in Einklang stehen. Eine zweite Standortplanungsmethode wird präsentiert, die eine gegebene Menge von Standort-Kandidaten für den Aufbau von Ladestationen priorisiert. Eine Anwendung auf Supermärkte im österereichischen Bundesstaat Steiermark wird gezeigt.

Sobald Standorte von Ladestationen auf der regionalen Ebene bestimmt sind, muss die Planung auf der Straßenebene verfeinert werden. Die diversen technischen und stadtplanerischen Aspekte, die eine Rolle spielen, werden diskutiert. Die verschiedenen Genehmigungen und Verträge, die erlangt werden müssen, werden ebenfalls behandelt. Dann wird gezeigt, wie die Kriterien für die Standortplanung auf Straßenebene und die Erfordernisse der Genehmigungsabläufe in operativen Planungsprozeduren vereint werden können.

Nachdem Ladestationen in einer Region aufgebaut wurden, müssen sie betrieben und gewartet werden. Es wird diskutiert, welche Tätigkeiten dies beinhaltet. Aktuelle Berichte von EF-Fahrern werden ausgewertet, um die Mängel des momentanen Betriebs der EF-Infrastruktur aufzuzeigen.

Ein weiterer Schritt nach Betrieb und Wartung ist die langfristige Entwicklung der Ladeinfrastruktur. Ein Modell wird vorgestellt, das die zeit-räumliche Entwicklung einer Ladeinfrastrukutr für EF in der Region Stuttgart in den Jahren 2010 – 2020 simuliert. Das Modell nimmt die Entwicklung des EF-Besitzes als Input und berechnet zugehörige Ladeinfrastrukturszenarien basierend auf berechneten Quoten von Ladepunkten pro EF und den Pendlerströmen zwischen Gemeinden.

Die vielen Aspekte einer Ladeinfrastruktur für EF, die in dieser Arbeit behandelt werden, können in zwei globale Sichtweisen integriert werden, die in der Einführung dieser Dissertation gezeigt werden. Verschiedene Aspekte können als Wissensmodule gesehen werden, die durch bestimmte Informationen verbunden sind. Als Alternative kann eine prozessorientierte Sichtweise eingenommen werden, in der die Betonung darauf liegt, welche Methoden und Hintergrundinformationen in welcher Stufe des Prozesses der Planung und des Aufbaus einer EF-Ladeinfrastruktur benötigt werden.

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Disclaimer

This document contains information on juristic and technical aspects concerning the planning, implementation, and operation of charging infrastructure. All information has been researched with utmost care, but no guarantees can be given for absolute correctness. The author cannot be held liable for damages resulting from the use of the information given in this document.

The given information is intended to be the most up-to-date available at the time of writing. But the domain of electric mobility is developing fast. Therefore it is recommended to check for subsequent developments (after mid 2015) in matters where details are important.

Specific products manufactured by specific companies are mentioned and shown in this document. This is done to root the discussion in the real world, referring to actually available products. The mention of these products in not meant as an endorsement. Most types of products shown here are also manufactured by other companies in similar forms.

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1. Introduction: towards a comprehensive view of the planning of EV charging infrastructure

In the year 2009 the German government has set up the target of having 1 million electric vehicles (EVs), on German roads by the year 2020 [1]. This target includes batttery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and range-extended electric vehicles (REEVs). The switch from gasoline- and diesel-powered vehicles to EVs is expected to bring environmental benefits, in particular a reduction of CO_2 emissions, lower the dependency on petroleum imports, and generate economic growth in the automobile and electricity sectors. Other industrial nations, namely the USA, China, Japan, the UK, and France, have also developed strategies to integrate large numbers of EVs into their national car fleets [2].

At the time of this writing, in mid 2015, it seems improbable that the ambitious target set by the German government will be met by 2020. In the beginning of 2015 there were 18 948 pure EVs [3] and 7 058 plug-in hybrid EVs (PHEVs) [4] registered in Germany. These EVs and those of the future require an electricity charging infrastructure, alike to the gasoline stations which refuel conventional vehicles today. In the end of 2014 there existed about 2 521 publicly accessible charging stations, providing 5 553 charging points, among them 102 DC charging points [4].

The planning of this charging infrastructure for EVs is a new task for urban planners, infrastructure planners, and civic engineers. To date no set of standard methods and procedures seem to exist yet for this new planning task. The initial motivation for this thesis therefore was to write an internationally readable handbook for Germany that contains all necessary background information, references to norms and legal documents, and a selection of pragmatic methods required for the planning task. This document was also meant to provide the most important information from other domains to the experts within one domain of electric mobility (urban planners, transport planners, electric engineers etc.). While being pragmatically oriented, the document was to follow scientific standards, meaning in particular that the origin and rationale behind statements and numbers was to be made as transparent as possible.

When doing research in the domain of electric mobility it is difficult to define a clear system boundary, separating the aspects that are being considered in detail from elements lying outside the system. There is a big risk of making unrealistic assumptions about aspects lying outside of the system which are not fully understood. In the years 2009–2015 when the author did research on EV infrastructure planning, the number of relevant aspects to consider steadily increased. This is best illustrated by recapitulating how different questions arose during the research of several years.

When the author of this thesis started doing research on the topic of charging infrastructure planning in May 2009, it started out as a *geographic location planning* task. The initial research question was where charging stations should be set up in three given cities. This involved geographic planning on a city-wide scale, as well as considering how charging stations could be inserted in the given surroundings on the street scale.

Within the same research project it already became clear that determining locations alone was not enough. The electric utility that wanted to implement such an infrastructure did not control parking spaces at attractive locations within the city. A *stakeholder analysis* was thus done, to see how different operators of parking spaces (city authorities, parking garage operators, supermarkets etc.) and other kinds of stakeholders such as distribution system operators, EV drivers, and local residents could be involved, and how conflicts could be avoided.

After having devised a plan for an initial infrastructure, the follow-up project then treated the *long-term geographic development* of the charging infrastructure. It was of interest how such an infrastructure should be developed in a longer term of ten years.

For determining the dimensions, i.e. the total number of charging points of such a long-term charging infrastructure, it was necessary to take a closer look at the *economics of charging point operation*, and the actual *demand for this infrastructure from the EV drivers' point of view.*

The author's research on the economics of charging point operation indicated, as had previously also been noted by others, that it would be difficult to operate charging points profitably because of high investment costs, and low revenues. The author proposed that the number of charging points be kept lower than the quotas of charging points per EV stated in official targets, so that supply would not exceed demand.

The difficulty of operating charging infrastructure in a self-sustaining way also became apparent in reality. Electric utilities which were setting up charging stations, supported by public funds within research projects, were slowing down their rollout of charging points and were calling for state subsidies for this infrastructure. From a researcher's perspective the arising question was: if the free market does not provide the required infrastructure, how could *public policy* be changed to change this? And which positive *externalities* (side effects) arise from such an infrastructure, that it is warranted to partially pay for it with taxpayers' money?

Thus, the pattern continued for several years: once one aspect was somewhat understood, the next question immediately arose. Over the years the author came to understand which main aspects are relevant when planning the charging infrastructure for EVs and how these aspects are related. The comprehensive vision on EV infrastructure planning was inspired by two books on general infrastructure planning, which treat a wide range of technical, economic, and political aspects: J. Parkin and D. Sharma: "Infrastructure Planning" [5] and A. S. Goodman and M. Hastak: "Infrastructure Planning Handbook: Planning, Engineering, and Economics" [6]. Inspiration also came from D. Shoup: "The High Cost of Free Parking" [7], an extensive work in which Shoup analyzes parking and parking requirements from diverse angles.

The aspects of EV charging infrastructure which are treated within this work correspond to the main chapters and one appendix which are:

- *Technologies for the charging of EVs (Chap. 2)*: EVs can be charged via three different technologies: conductive charging (via cable), inductive charging, or battery switching. The information and communication systems needed for the operation and use of charging facilities are also an important part of the infrastructure. The chapter shows different technical possibilities and discusses their advantages, disadvantages, and expected future uses.
- *Interactions of EV charging and the electricity system (Chap. 3)*: the charging of EVs has impacts on all parts of electricity systems, namely individual household installations, distribution networks, transport networks, electricity storage, and electricity generation. The phenomena occurring on these levels of electricity systems are discussed, and it is concluded which measures should be taken when implementing a local charging infrastructure for EVs. The process of electric installation of individual charging facilities is also treated in detail.
- *The demand for (public) charging infrastructure (Chap. 4)*: this demand is concretized by approaching it from three different perspectives: from the EV drivers' point of view, from the charging infrastructure provider's point of view, and when seen as a public service not underlying free market conditions.
- *Economic aspects of EV charging infrastructure (Chap. 5)*: different business models for the provision of charging stations are analyzed in detail. It is also shown how the economics of EV ownership and that of public charging station operation are interrelated.
- *Public policy and external effects (Chap. 6)*: the involvement of public authorities in the market for public charging infrastructure can be warranted, if the infrastructure provides enough positive externalities (side effects). The externalities created by EVs and their infrastructure are analyzed. Current and possible future policies of the European Union and of Germany are discussed.
- *Stakeholder cooperation for the development of an EV infrastructure (Chap. 7)*: the interests and actions of different stakeholder categories are discussed. Then the interaction of different stakeholders and possible conflicts are treated. Finally it is shown how a stakeholder dialog can be implemented and how stakeholder cooperation can be formalized.

- *Location planning of an EV charging infrastructure on the scale of cities and regions (Chap. 8)*: it is shown how the locations for charging stations can be planned on the regional scale. A method is presented for planning locations based on data given for zones of a region as well as for specific points. The method is parameterized to generate different scenarios of infrastructure implementation. A case study for the Province of Liège in Belgium is shown. A second method prioritizes given locations for the placement of charging stations. An application of this method to the prioritization of supermarkets in the federal state of Styria in Austria is presented.
- *Location planning of an EV charging infrastructure on the street scale (Chap. 9)*: the diverse aspects that have to be considered when planning charging stations on the street scale are treated. It is also discussed which permits need to be acquired from municipal departments and which contracts need to be set up with technical service providers. Then it is shown how the aspects to be considered and the requirements of the permitting procedures can be combined in operational planning methods.
- *Operation and maintenance of an EV charging infrastructure (App. A)*: it is discussed which tasks are part of the operation and maintenance of charging infrastructure. Then it is shown which problems are encountered by EV drivers at currently existing charging stations in Germany.
- *Long-term geographic planning and development of EV charging infrastructure (Chap. 10)*: different aspects of quantitative and qualitative development are discussed. A model is shown that simulates the time-spatial development of a charging infrastructure in the Region Stuttgart in Germany in the years from 2011 to 2020.

This work is not the first to approach the topic of EV charging infrastructure in a way that integrates multiple perspectives. When devising the outline of this thesis and during its writing several such works were already published. Tab. 1.1 shows a selection of such publications and their scope in relation to this thesis. The exact classifications can be a matter of debate. In any case, the overview shows that a work that treats the planning of EV charging infrastructure in such an encompassing way does not seem to have been published yet. Of the listed documents only the French green book on charging infrastructure (Negre et al. 2011 [8]) seems to have a similar wide scope. In hindsight it seems clear to the author why publications with such a wide scope are rare. The author underestimated the amount of background information that needed to be gathered to be able to make qualified statements within the different treated domains. The final document has about twice the length of that which was initially planned and several times the number of references initially deemed necessary.

This thesis contains chapters mainly consisting of own original research, and also chapters mostly consisting of literature research based on other authors' works. The nature of the different chapters concerning this aspect is also shown in Tab. 1.1 in the rightmost column. The information is shown for this thesis only, not for the previous publications.

Table 1.1.: Comparison of the scope of previous comprehensive publications on EV charging infrastructure and this thesis (last column) (✓: treatment of aspect, (✓): limited treatment, ∅: not treated), (Res.: mainly own research, Lit.: mainly literature survey, Res./Lit.: own research and literature survey)

	Morrow et al. 2008 [9]	TfL 2010 [10]	Negre et al. 2011 [8]	Kley 2011 [11]	Wilhelm et al. 2011 [12]	Boesche et al. 2013 [13]	Bluemel et al. 2014 [14]	Wirges 2015
Country	USA	UK	France	Germany	Germany	Germany	Germany	Germany
Context	Applied science	City politics	National politics	Science	Applied science, urbanism	Applied science, law	Applied science, urbanism	Applied science
Technology	✓	✓	✓	✓	(✓)	✓	✓	✓ Lit.
Electricity system	(✓)	(✓)	✓	✓	(✓)	✓	∅	✓ Lit.
Demand	✓	∅	✓	✓	(✓)	✓	✓	✓ Res./Lit.
Economics	✓	✓	✓	(✓)	∅	(✓)	∅	✓ Res.
Politics, externalities	∅	(✓)	✓	✓	(✓)	✓	∅	✓ Lit.
Stakeholders	∅	∅	(✓)	∅	(✓)	∅	∅	✓ Res./Lit.
Regional location planning	∅	∅	✓	∅	✓	∅	✓	✓ Res.
Street location planning	✓	✓	(✓)	∅	✓	(✓)	✓	✓ Res./Lit.
Operation	∅	✓	(✓)	∅	(✓)	(✓)	(✓)	(✓) Lit.
Geographic development	∅	∅	✓	∅	∅	∅	∅	✓ Res.

1.1. Integrated visions of EV charging infrastructure planning

Different views or metaphors can be used to integrate the many aspects that play a role in the planning of EV charging infrastructure into one global vision. In the following two such views will be presented. The first view shows the different aspects as modules of knowledge, which are connected by information. The second view is procedural and shows which aspects mainly play a role in which stages of a local EV infrastructure development process.

Fig. 1.1 shows the chapters of this thesis as knowledge modules, which are connected by specific information. Only the most important connections are shown in the figure. As can be seen, the connections are numerous, making it difficult to leave one of the treated aspects entirely out of consideration. The above recalled exploratory research process from region and street planning to stakeholder co-operation, to long term development, to economics and demand, to public policy can be traced in the figure. The figure shows in which chapter the connecting information is treated by the proximity of the label to the respective chapter. Many of these connections are explicitly named as cross-references within the text. Several points are mentioned several times in different chapters. It would be too lengthy to explain all these connections in detail. The reader is invited to reconsider the figure after having read the corresponding chapters.

An alternative view to structure the large amount of knowledge and methods presented in this thesis is process-oriented. Fig. 1.2 shows an idealized process of the planning and implementation of a local EV charging infrastructure, and how the need for different information and methods arises within this process.

According to the author's experience actual planning and implementation processes tend to be much more chaotic, parallelized, and iterative. The process is shown from the point of view of an organization or person that initiates and coordinates the project.

The idealized process begins with the clarification of the political frame conditions and the economic feasibility of the project. This serves to evaluate if the initiation of such a project is worthwhile from the organization's or person's point of view.

If the decision is taken to start such a project, meetings are held with other stakeholders to determine whether they are interested in collaborating in such a project. Involving stakeholders can also be done at a later stage, for instance after initially planning a technical solution and doing an initial regional planning, but should not be done too late, to avoid possible conflicts. Depending on the interest to cooperate from other stakeholders, the economic feasibility might have to be reevaluated. For instance it can make a big difference, whether the municipality provides public parking spaces free of charge or these have to be rented.

When an initial cooperation between stakeholders is established, it is decided which technologies will be used. This concerns the type of charging facilities and associated communication systems such as a central control center. It also concerns the possible use of controlled charging, and the use of electricity from renewable sources. The decisions taken at this point can again lead to a reevaluation of the costs of the implementation.

Once contributing organizations and the technologies to be used are known, the location planning of charging stations can be done. It is reasonable to do this on a regional level first, taking the overall estimated demand into account, and later perform the location planning on the street level. If public parking spaces are used for implementing the charging stations, detailed discussions have to be held with different municipality departments in order for the charging stations to comply with urban planning regulations and local standards. Contracts also have to be established with technical service providers such as the distribution network operator.

Once the charging station locations are determined, and permits and contracts have been established, ground and electric installation work can be done. In the following step these have to be operated and maintained. For the long-term development of the charging infrastructure further stakeholders can be involved, for instance further providers of parking spaces (supermarkets, cinemas etc.) or municipalities lying outside of the currently covered area.

Again, as in the previous knowledge-based global vision, all these points are not explained in full detail within this introduction. The reader should reconsider the figure after having read the respective chapters or the full document.

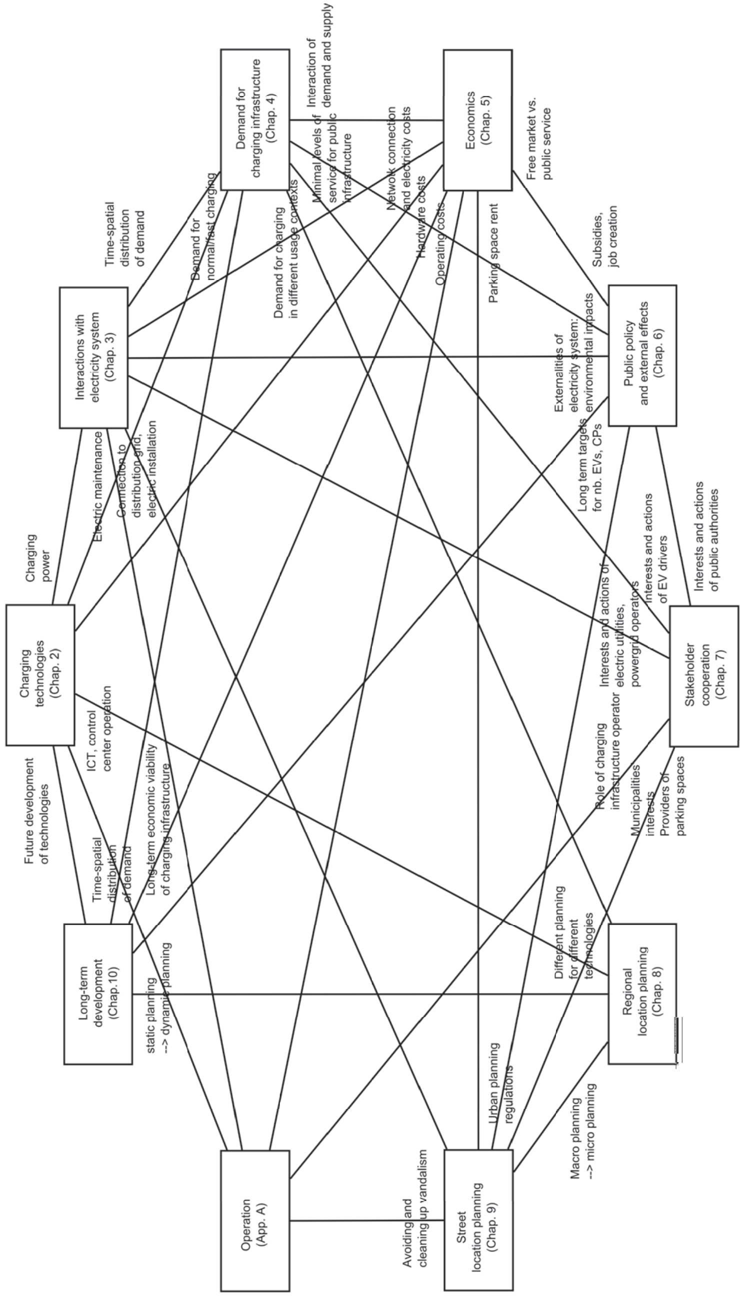

Figure 1.1.: Connections between different knowledge modules (= chapters) treated within this thesis

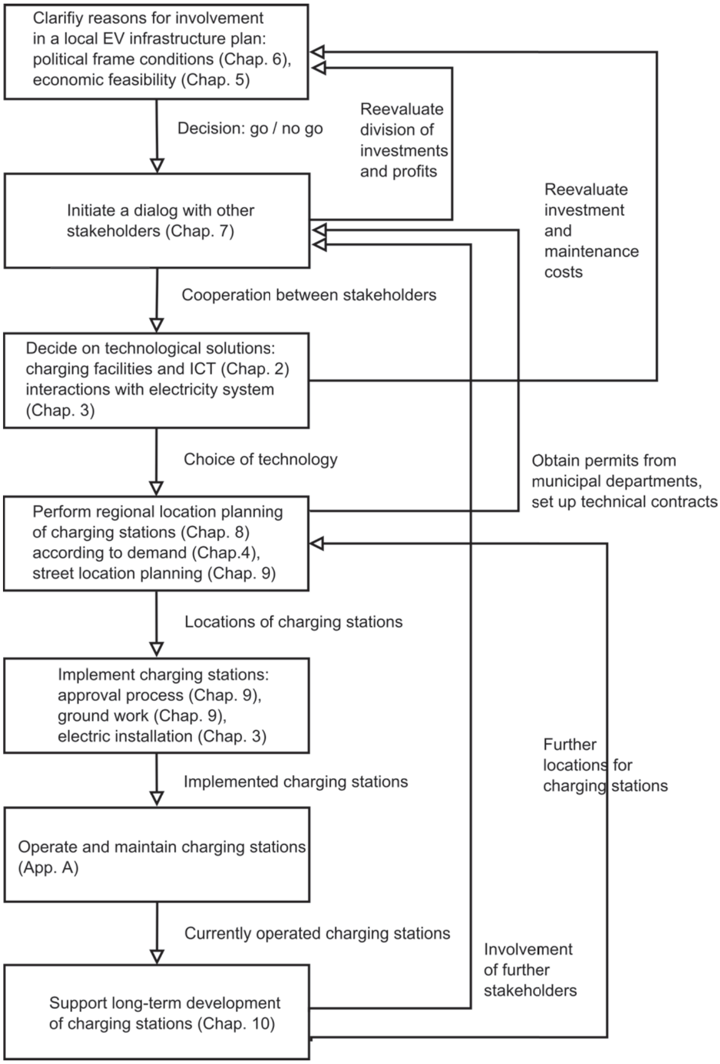

Figure 1.2.: The need for different knowledge and methods within an (idealized) EV infrastructure planning and implementation process

2. Technologies for the charging of EVs

A charging infrastructure for EVs consists of two main components: the electric charging facilities themselves and the information and communication technology (ICT) for using, operating, and controlling the infrastructure. Currently, three practical technological possibilities exist for charging EVs: conductive charging via cable, inductive charging, and battery switching. These technologies will be presented in the following sections. The current situation concerning standardization will be shown. In this document the standards will be named in the German and European versions DIN EN, the international ISO/IEC standards usually have the same number code. The advantages and drawbacks of these technologies will be discussed. Examples for the current application of these technologies will be given as well. Furthermore, the different kinds of ICT that form part of an EV charging infrastructure will be presented. It will be shown which ICT solutions exist for the operator of the infrastructure and for the users of the infrastructure respectively. Traditional means of conveying information, such as signs and printed maps, are also discussed in this context. Based on the discussion of standardization issues, advantages, drawbacks, and current applications, it will finally be concluded in which different domains these charging and information solutions can be expected to be applied within the next years.

Most publications treating the charging infrastructure for EVs also discuss different charging technologies. In-depth analyses do not exist in abundance, however. Good discussions of EV charging technology can be found in [15] and [11]. However, these discussions neglect ICT as an integral part of this infrastructure. The publication [14] gives a good overview of EV charging technology, also including an extensive analysis of ICT related aspects such as interoperability, roaming between different charging station networks, and payment modalities. A good overview of the use of ICT in the context of EV infrastructure is given in [16].

2.1. Electric facilities for the charging of EVs

For the charging of EVs with electric power, three practical technological solutions exist: charging the vehicle with a connector (conductive charging), via electromagnetic induction (inductive charging), or by taking the depleted battery out and replacing it by a charged battery (battery switching). Such charging facilities can be implemented as stand-alone facilities or integrated into other street furniture, such as street lighting or parking meters. As a special case, infrastructure dedicated to light electric vehicles (LEVs), such as electric bicycles or electric scooters will also be discussed. In the following sections it will be explained how these technological solutions work in principle and which norms and standards already exist for them. General advantages and drawbacks of these technologies will also be discussed. Additionally, some examples for the use of these kinds of charging facilities will be presented.

In this chapter only those technologies will be discussed in detail which charge EVs while they are parked. Recharging EVs while they are driving is also possible. The former can be referred to as *static charging* while the latter can be called *dynamic charging* [17]. An advantage of charging EVs while they are driving is that they can then be equipped with smaller batteries. One possibility of such dynamic charging is to supply EVs with electricity via sliding contacts. An example of this are trolley buses which are provided with electricity by overhead cables. Experiments are taking place to apply the same technology to freight transport via hybrid electric trucks [18]. EVs can also be charged inductively while moving. For this, induction coils need to be integrated into the road. This can be done at places where vehicles move slowly or stop, such as road crossings or at highly frequented long-distance motorways between cities [19]. Because these technologies of dynamic charging require profound and expensive interventions in the existing road infrastructure, it seems improbable that they will be implemented on a larger scale in the next years. Therefore they will not be discussed here in more detail.

2.1.1. Conductive charging

Conductive charging means that electric power is transferred to the vehicle by using an electric cable and a connector. The actual charging of the battery within the vehicle must take place via a direct electric current (DC). The alternating current (AC) from the electricity network can be directly passed into the electric vehicle, where it is rectified to DC for charging the batteries. This is referred to as *AC charging*, or *on-board charging* because the charger/rectifier is located inside the vehicle. Alternatively, the current can be rectified outside of the vehicle and DC fed into the vehicle. This is called *DC charging*, or *off-board charging* because the charger/rectifier is located outside the vehicle. In the following, first different forms of conductive charging facilities in general will be presented. Then the discussion will focus specifically on AC charging and DC charging respectively.

The duration of the charging process depends on the used electrical power level. Accordingly these different power levels are referred to as *slow, normal, fast* and *ultra-fast charging*. There is no generally accepted definition of these terms, however. Use of these terms varies and may be influenced by particular interests [20]. The approximate durations of charging given in the following assume a battery with 22 kWh capacity, no power losses, and constant charger power. The actual voltage levels used in Germany are 230 V for monophase and 400 V for triphase power. During fast and ultra-fast charging the battery is usually charged with high powers up to a state-of-charge of about 80 %, and with lower charging powers to 100 %. In this document, the following terminology is used:

- *Slow charging*: using powers up to 3.7 kW (16 A, 230V, monophase AC), which is the maximal power available from a household socket. An EV battery can then be fully recharged in about 6 hours.
- *Normal charging*: using powers above 3.7 up to 22.2 kW, which are power levels available from dedicated EV charging facilities, notably the power levels:
  - 7.4 kW (32A, 230V, monophase AC), providing a full charge in about 3 hours
  - 13.9 kW (20 A, 400V, triphase AC), providing a full charge in less than 1.5 hours
  - 22.2 kW (32A, 400V, triphase AC), providing a full charge in about 1 hour

- *Fast charging*: using powers over 22.2 kW, notably the power levels:
  - 43.6 kW (63A, 400V, triphase AC), providing a full charge in about 30 minutes
  - 50 kW (usual for CHAdeMO and CCS standards, DC), providing a full charge in about 26 minutes
- *Ultra-fast charging*: using powers over 50 kW. At the time of this writing in 2014 only the Tesla company implements a very high charging power of up to 120 kW, which is lowered towards the end of the charging process, in its Supercharger facilities [21]. Otherwise, such high power levels do not play a big role at the moment, but could become more important in the future.

When talking about connecting electric vehicles to an electricity supply, the terms *socket outlet*, *plug*, *cable*, *connector*, and *vehicle inlet* should be used as displayed in Fig. 2.1. This terminology is in accordance to the basic norms on conductive charging of EVs: DIN EN 61851-1 [22] and DIN 62196-1 [23].

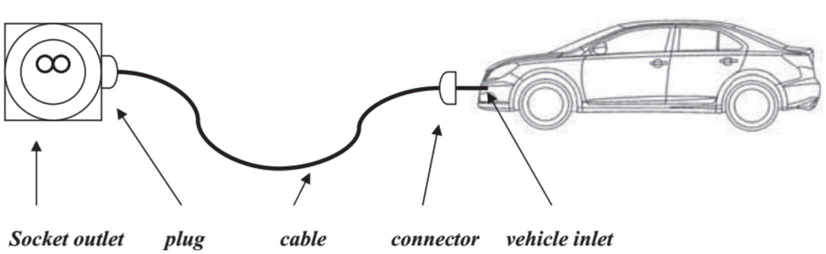

Figure 2.1.: Terminology for conductive charging of EVs [24]

Conductive charging facilities are built in diverse forms. Two basic forms can be identified. *Wallboxes* are mounted on walls or posts. This is a cost-efficient solution for private or public parking garages, or parking spaces next to buildings. Fig. 2.2 shows some examples of wallboxes. If charging facilities are to be installed at curbside parking spaces or in big open-air parking spaces, more expensive *charging posts* (also called *charging pillars*) must be used (see Fig. 2.3). Each charging facility can have several socket outlets or connectors. Wallboxes usually have 1 or 2, and charging pillars 1, 2, or 4 socket outlets or connectors [25] [26].

Figure 2.2.: Wallboxes: examples by Mennekes [27], Sedlbauer [28], and Schneider Electric [26]

Figure 2.3.: Charging posts: examples by Keba [29], Rittal [30] and Bauer [31]

Many manufacturers also provide charging facilities in a modular form with one master facility and several technically simpler slave facilities (or "satellites"), as can be seen in Fig. 2.4. Such an implementation is cheaper per charging point than using separate charging facilities, because the equipment for authentication and payment needs to be present only once in the master facility [32]. A further technical variant similar to the satellite system has been handed in for patenting in late 2013 [33]. It makes use of a "toggle unit". Here, several vehicles can be plugged into the charging facility at once. But internally only one charger is present, which charges these plugged-in vehicles successively. This reduces hardware costs as well as impacts on the electricity network.

If wallboxes or charging pillars are installed outdoors, the body housing needs to provide protection from weather and other environmental influences. These requirements are stated in the rule of application VDE-AR-N 4102 [34] and the norm DIN VDE 0100-722 [35]. For an installation outdoors, a protection level of at least IP44 has to be implemented [34] [35]. This IP (intrusion protection) level stands for protection from intrusion by small objects bigger than 1 mm (code “4” as first digit) and protection from splash water (code “4” as second digit) [36]. Charging facilities located next to roads have to be constructed in a way that they are protected from collisions [34]. Such a protection can also be installed in front of the charging facility, for instance in the form of a bollard. If the facility is installed in a special environments with, for instance, extreme temperatures, high humidity, or possible flooding, the type of the casing has to be agreed upon by the distribution network operator [34] .

Figure 2.4.: Satellite systems: examples with posts by Parken + Laden (with intergrated parking ticket machine) [37] and with wallboxes by Mennekes [27]

The fact that a group of parking spaces can be equipped with several charging pillars or wallboxes and that each of these can again contain several possibilities for connecting vehicles, simultaneously or not, leads to some confusion concerning terminology. Especially the terms “charging point” and “charging station” are used with differing meanings. In this report the author will use these terms as defined below. Fig. 2.5 shows an example for the use of these terms.

- *Charging facility* or *charging equipment* or *EV supply equipment (EVSE)*: an electric facility for charging EVs. A charging facility can have several socket outlets or, if the cables are fixed, several connectors.
- *Charging pillar* or *charging post*: a charging facility in the form of a pillar or post.
- *Wallbox*: a charging facility in the form of a box, to be mounted on a wall. If a wallbox is mounted on a post, then this forms a charging pillar.

- *Charging point*: an arrangement for charging one EV at a time. If a charging facility has two socket outlets and it is near two parking spaces, this arrangement forms two charging points. If a charging facility has two socket outlets, for instance supporting different plug standards, but only one vehicle can make use of these at once, this forms only one actually usable charging point.
- *Charging station*: a group of charging facilities with the associated parking places and further associated equipment such as ground markings and signs (in analogy to terms such as "gasoline station" or "train station").

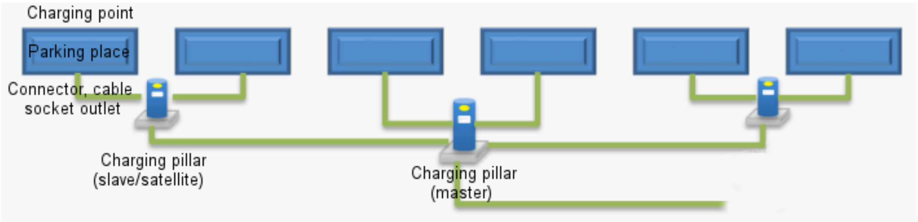

Figure 2.5.: Use of terminology: one charging station with three charging pillars (one master, two slaves), six charging connectors with six parking places, providing six charging points (adapted from [8])

Charging facilities of different manufactures make use of a wide range of technologies to implement means of user interaction, identification and authentication, payment, and communication with back-end systems. Manufacturers seem to be continuously adding new technologies to differentiate their products from those of competitors.

For the *user interface* colored light-emitting diodes (LEDs) and different kinds of displays, monochrome or in color, with or without touch screen are in use.

Identification and authentication can be done via key, personal identification number (PIN), transaction number (TAN), radio-frequency identification (RFID) card, or near-field communication (NFC) [38]. With the help of a smart phone further identification variants can be implemented via hotline, SMS, app, or website [39]. If communication according to ISO 15118 [40] is done over the charging cable, then a car can also directly identify itself at the charging station [41]. This way of identification via cable is also called *Plug & Charge* [42].

Payment modalities also exist in abundance: direct payment in cash, via Electronic Cash (EC) or credit card, via cell phone bill, via electricity bill, or via debit when the user is a registered customer at the charging station operator.

Connection of charging stations to a back-end system (also see Sec. 2.2.1) can also be achieved by different means. Internet communication protocols can be used via connection to a local area network (LAN) or wireless local area network (WLAN). Communicating over mobile phone networks via different protocols (GPRS, UMTS, LTE etc.) is also an option. A further possibility is to use communication technologies which make use of the power cable (Powerline Communcation (PLC)).

Depending on the functionalities of the charging facility, prices can vary from several hundred to several thousand euros. The required functionalities depend on the situation in which the charging station is located. A publicly accessible charging station might need means of user identification and authentication, payment, and back-end communication, but a private wallbox at home needs none of these.

The wide range of authentication and payment possibilities currently provided can raise difficulties for the users of public charging infrastructure, who have to cope with several non-compatible systems. When charging facilities support several possibilities of authentication and payment in parallel, this increases the cost of these charging facilities. The wide range of technically feasible solutions will hopefully narrow down to a small selection of de facto standard and interoperable solutions in the next years. Identification and authentication via charging cable communication (i.e. Plug & Charge) and payment via direct debit, through a roaming platform connecting different charging infrastructure operators, could become a commonly adapted solution in the future. The EU demands charging stations to also provide the possibility of ad hoc charging, without a contract between EV driver and charging point operator [43]. This can be realized via direct payment by card or in cash.

A problem that remained unsolved for several years was the lack of a standard for an electric connector for electric vehicles. Such a standardized connector is required for being able to connect vehicles of different manufacturers to charging facilities of different manufacturers, i.e. to assure interoperability. By 2014 the international standardization organizations have made some progress in this direction. The German and European norms DIN EN 61851-1 [22] and DIN EN 62196-1 [23] describe the general electrotechnical constellations admitted for the AC and DC charging of EVs. This involves the definition of three *cases* for cable connections between vehicle and charging facility and four *charge modes.* Based on this framework, the norm DIN EN 62196-2 [44] then defines three specific *types* of connectors.

The three possible *cases* for the cable connection according to DIN EN 62196-1 [23] and DIN EN 61851-1 [22] are:

- *Case A*: the cable is fixed permanently to the vehicle and plugged into the socket outlet on the charging facility (*case A1*: if it is a wallbox, *case A2* if it is a charging pillar). This case seems to be implemented very rarely.
- *Case B*: the cable is not fixed. It is plugged into the inlet of the vehicle and the socket outlet of the charging facility. This case is common for AC charging with lower powers. (*Case B1* refers to a connection to a wallbox, *case B2* to a connection to a charging pillar.)
- *Case C*: the cable is fixed permanently to the charging facility and plugged into the inlet on the vehicle. This case has to be used for mode 4 charging (see below).

The four different *charging modes* according to DIN EN 62196-1 [23] and DIN EN 61851-1 [22] are:

- *Mode 1:* charging is realized via a conventional household socket or mono- or triphase industrial plug socket according to DIN EN 60309 [45]. For this charging mode it should be assured that the used socket is equipped with a Residual Current protective Device (RCD). Such a device protects people from possible dangers due to the touching of electric contacts, by automatically disconnecting when an electric current leakage is detected.
- *Mode 2:* charging in this case is also realized via a conventional household or an industrial plug socket according to DIN EN 60309 [45], using mono- or triphase power. The charging cable includes an in-cable control box (also called In-Cable Control and Protection Device (IC-CPD)). The in-cable control box communicates via a pilot signal with the vehicle and includes a RCD.
- *Mode 3:* charging is realized via a dedicated socket for EV charging. The socket is embedded in a charging station or wallbox connected permanently to the electricity network. The vehicle and the charging facility communicate via a pilot signal. This constellation with dedicated equipment provides a high level of safety for persons, protection from overload and

thus fire protection, and the possibility to implement controlled charging schemes which take constraints from the electricity system into account.

- *Mode 4:* charging is realized via an external charging device (located outside of the vehicle), which is permanently connected to the electricity network. The vehicle and the charging facility communicate via a pilot signal. This mode corresponds to DC charging. In this mode the cable has to be fixed to the charging facility (case C).

For AC charging mode 3 with a dedicated socket and charging facility should be preferred. If no special charging facility is available, mode 2 can be used with a charging cable with an in-cable control and protection device. Due to lack of safety, AC charging in mode 1 should be avoided. For DC charging with high powers, only mode 4 provides an admissible and safe arrangement. AC charging in mode 3 and DC charging in mode 4 in is discussed in more detail in the following two subsections.

2.1.1.1. Conductive AC charging in mode 3

AC charging in mode 3 requires the use of a plug and socket outlet specifically designed for the charging of EVs. A problem that persisted for many years was that several such plug and connector types existed in parallel. The German and European norm DIN EN 62196-2:2012-11 [44] narrowed the alternatives down to three types of plugs and connectors, which are shown in Fig. 2.6 and 2.7.

- *Type 1*: this type of connector is favored by the Japanese and American industry. Because the connector format was developed by the Yazaki company, this type is also referred to as the *Yazaki connector*. It is specified in SAE J1772-2009 [46] from where it has been incorporated into the European norm [44]. The connector only supports monophase power. The maximally supported charging power is 8 kW (250V, 32A, monophase).

- *Type 2*: this type of connector is favored by the German industry. Because the connector was developed by the company Mennekes, it is also called the *Mennekes connector*. The connector support mono- as well as triphase power. This plug supports 250 V monophase at 13, 20, 32, 63, or 70 A, and 380 to 480V triphase at 13, 20, 32, and 63 A. Thus maximal charging powers of 17.5 kW for monophase and 52.4 kW for triphase power are possible. The plug allows bi-directional transfer of electricity, as well as the communication between vehicle and charging facility.

◦ *Type 3*: this type of connector is favored by the French and Italian industry. It also bears the name of the developing company as the *Scame connector*. This type of connector includes a shutter, which prevents people from touching the socket outlet. The use of such a shutter is compulsory in many European countries, among them Italy and France [47]. The standard DIN EN 62196-2:2012-11 [44] includes three versions of the plug with different geometries: Type 3a for maximally 250V, 16A monophase (4.0 kW), Type 3b for maximally 250 V, 32 A monophase (8.0 kW), and Type 3c for maximally 480V, 63 triphase (52.4 kW).

Figure 2.6.: Charging connectors and plugs of Type 1 (left) [48] and Type 2 (right) [49] according to DIN EN 62196-2

Figure 2.7.: Charging connectors and plugs of Type 3 [50] according to DIN EN 62196-2

While Type 1 will likely stay the standard connector in the USA and Japan, the Type 2 connector is on the way to become the single European standard. Already in 2011, the European Automobile Manufacturers Association (ACEA) recommended that a Type 2 plug and socket outlet be used for all public infrastructure from the year 2017 onwards. Type 2 was then declared as the single European standard by the European Commission in its "Clean fuel strategy" in 2013 [51].

However, many European countries, among them Italy, France, the UK, Spain, Portugal, and Denmark require the use of a shutter for normal household plugs in a domestic environment [47], a feature not included in Type 2 as defined by DIN EN 62196-2:2012-11 [44]. In mid 2013 Italian and German standardizing organizations have reached the compromise of using Type 2 plugs with an additional optional shutter [52].

In the 2014 "Directive 2014/94/EU on the deployment of alternative fuels infrastructure" the European Parliament and Commission state that charging points should be equipped with at least a Type 2 socket outlets or vehicle outlets, optionally with mechanical shutters [43]. However, for light electric vehicles (scooters, small three- and four-wheeled vehicles) the Type 3a connector will still be used [52] [20].

In autumn 2015 the German government published a draft of a charging pillar decree ("Ladesäulenverordnung") which implements technical parts of this EU directive in German law. The decree makes the provision of at least one Type 2 socket outlet/connector obligatory for AC normal and fast charging points, and the provision of at least one CCS connector for DC fast charging points (also see below) [53].

All three previously shown connector types support communication between the EV and the charging facility according to DIN EN 61851-1 [22]. This means that the proximity pilot pin signals that the cable is correctly plugged. The control pilot pin serves to control the charge via pulse-width-modulation (PWM). The charging facility communicates the maximally available ampere rating to the EV via the width of the square waves. The pulses are lead back to the charging station via the protective earth pin. The EV can request charging by setting different amounts of resistance on the pulse signal (charge, charge with ventilation).

More sophisticated forms of communication can be realized in the future with the emerging standard ISO 15118: Road vehicles – Vehicle to grid communication interface [40]. This communication protocol makes use of power line communication (PLC) over the control pilot pin. Wireless forms of communication are also being specified within this norm [54] [55]. Beyond functionalities such as automatic identification and billing, the protocol allows to implement smart charging solutions [41]. The EV communicates information such as the needed amount of energy, departure time, and minimal and maximal allowed current and nominal voltage to the charging facility. The charging facility communicates the available power over time, based on constraints from the electricity system, and possibly also prices for electricity back to the EV. The EV can then request an appropriate charge from the charging facility [41].

Conductive charging via cable is a straightforward solution. However, there are some drawbacks. Having to plug the cable in by hand can be cumbersome, especially in rainy or cold weather [56]. When charging stations are placed at curbsides, the cable might get in the way of pedestrians and cyclist. The openly accessible cable is also vulnerable to vandalism [56].

2.1.1.2. Conductive DC charging in mode 4

Apart from the conductive AC charging facilities presented above, *DC charging facilities* are also in use. In this case the rectifying of the AC current from the electricity network is done outside of the vehicle by the charging facility. Because there are fewer size and weight restrictions for a charger that is located outside the vehicle, DC off-board chargers can operate with higher charging powers [57]. Heat development is also less of a problem when the high power charger is located outside the vehicle.

In 2014 two concurrent standards are still in use for fast DC charging. The Japanese *CHAdeMO* standard, first implemented in 2009 [58], is supported mainly by Japanese and French car manufacturers. The German car manufacturers are mainly in favor of the more recently developed *Combined AC/DC Charging System (CCS)*.

The Japanese CHAdeMO association has developed a standardized connector for fast DC charging, shown in Fig. 2.8. The name is an abbreviation of "CHArge de MOve" standing for "charge for moving". It is a pun for the Japanese saying "O *cha demo* ikaga desuka", meaning "Let's have a tea while charging" [59]. The power level for the CHAdeMO connector is not fixed, but usually it is 50 kW. The standard also allows bi-directional flow of energy and is therefore ready for possible Vehicle-to-Grid (V2G) or Vehicle-to-Home (V2H) applications [58]. In late 2013 many cars already supported this standard: Nissan Leaf, Mitsubishi i-MiEV and Outlander PHEV, Peugeot iON and Partner, Citroen C-Zero and Berlingo, Toyota eQ, and others [58]. In mid 2014 about 3 700 CHAdeMO conform charging facilities existed worldwide, among them about 1 100 in Europe [60].

Figure 2.8.: The CHAdeMO connector [61]

The CHAdeMo standard has been integrated into international ISO/IEC norms. The connector will be included in the emerging norm DIN EN 62196-3 [62]. The AC charging facilities' specification will be part of DIN EN 61851-23 [63]. The CHAdeMO standard uses the Controller Area Network (CAN) protocol for the communication between the charging facility and the EV[58]. This is to be specified in the norm DIN EN 61851-24 [64] [58].

The Combined AC/DC Charging System (CCS) follows a different approach. Here a single vehicle inlet is used, which allows to plug in both the already standardized AC connectors as well as a new DC connector (see Fig. 2.9). The system is implemented in two versions compatible with a Type 2 AC connector in Europe (also called *Combo 2*), and compatible with a Type 1 AC connector in the USA (*Combo 1*) [65]. The advantage of this system is that it lowers the component costs on the vehicle side. The new vehicle inlet is also downward compatible to the already existing Type 2 charging facilities.

Like the CHAdeMo standard, the CCS is also being integrated into the corresponding norms. The DC connector is also to be specified in the emerging norm DIN EN 62196-3 [62] [66]. The DC charging system will also be part of DIN EN 61851-23 [63] [66]. One communication protocol is to be used for AC and DC charging, based on ISO 15118 [40] [65]. A preliminary specification of the communication protocol can be found in DIN SPEC 70121 [67].

In 2013 and 2014 the CCS standard is already supported by the BMW i3, the VW e-up! and Golf and the Chevrolet Spark [68]. As the CCS standard has been developed later than the CHAdeMO standard, fewer such charging stations exists. In May 2014 a first eight CCS fast charging stations have been inaugurated in Germany along the A9 highway between Munich and Leipzig [69].

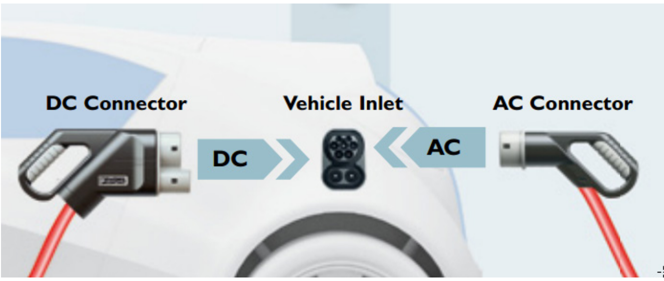

Figure 2.9.: The CCS DC connector, CCS vehicle inlet, and Type 2 AC connector [66]

It is probable that CCS Type 2 will become the one European standard for DC charging in the future. Already in 2011, the European Automobile Manufacturers Association (ACEA) has recommended that this standard be used [24]. In 2014 the European Commission and Parliament stated in the "Directive 2014/94/EU on the deployment of alternative fuels infrastructure" that fast DC charging stations provide at least one CCS Type 2 (also called "Combo 2") connector. The charging pillar decree ("Ladesäulenverordnung"), presented as a draft by the German government in autumn 2015, implements technical parts of this EU directive in German law. The decree makes the provision of at least one CCS connector for DC fast charging points obligatory [53].

However, in 2013 representatives from CHAdeMO, Nissan and Volkswagen argued that the best solution would be to set up multi-standard DC charging facilities within the next years. Fig. 2.10 shows an example of such a charging facility. These are said to cost only about 5 % more than a single-standard charging facility [70].

In September 2015 the German minister of traffic announced that the government will partially finance the implementation of fast charging stations at all approximately 400 highway service areas operated by the company Autobahn Tank & Rast until 2017. According to the first photos of charging facilties, these will also support the CHadeMO as well as the CCS standard, along with AC charging with high 43 kW power [71]. The charging stations installed by the food retailer Aldi Süd from 2015 on also support Type 2, CCS, and CHAdeMO recharging [72]. Thus, the competing fast DC charging standards CHAdeMO and CCS can still be expected to be widely used in parallel in the next years.

Figure 2.10.: Fast DC charging facility supporting both the CHAdeMO as well as the CSS standard [73]

For the customer it is convenient to have his vehicle recharged within a short time via DC fast charging. However, such charging facilities are costly. Even though prices have been decreasing in the last years, in 2013 a fast DC charging facility still cost about 15 000–20 000 € [74]. Another drawback is that the fast charging process can lead to faster aging of batteries [75] [76]. Charging electric vehicles with a high power of 50 kW also introduces a sudden demand peak into the power system, which might lead to overloading of local transformers and power lines (also see Chap. 3).

All in all, conductive AC and DC charging facilities have several advantages over inductive charging or battery swapping facilities, technologies which will be discussed in the following. Conductive charging is relatively inexpensive, technologically simple, and can be adapted to different circumstances. Conductive AC charging facilities with charging powers of 3.7 to 22 kW are mainly used today. These are widely used for recharging in private garages, work places and for public recharging. Fast DC charging stations are mainly being set up for public charging along highways and in city centers.

2.1.2. Inductive charging

Electric vehicles can also be charged via induction. In this case an electromagnetic field is created in a primary coil, which transfers energy to a secondary coil integrated in the vehicle (see Fig. 2.11).

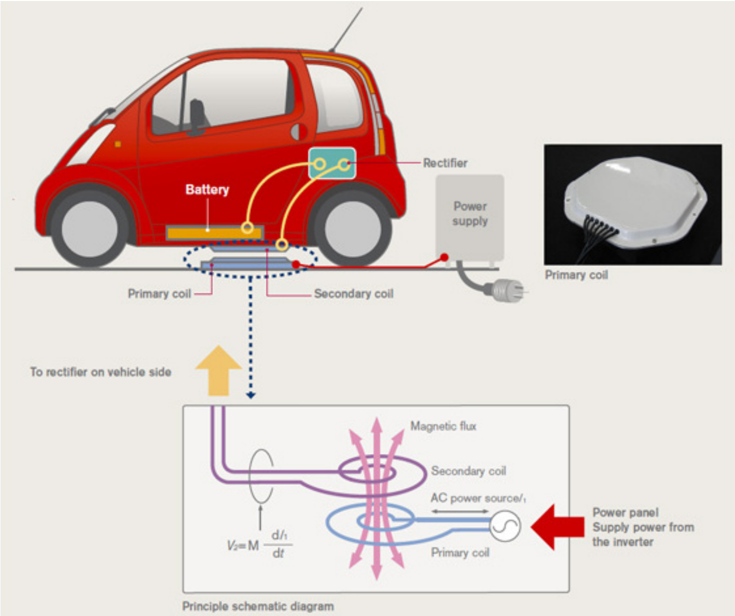

Figure 2.11.: Inductive charging facility by Nissan [77]

Inductive charging faces the obstacle that the development of a generally accepted standard is even more delayed than in the case for conductive charging. In Germany the general application guide VDE-AR-E 2122-4-2 [78] exists. General requirements for inductive charging of EVs are specified in the draft norm DIN EN 61980-1 [79]. More specific technical requirements are included in DIN IEC/IETS 61980-3 [80]. It is envisioned to define a complete norm by the end of 2019 [81]. Of course inductive charging equipment also has to conform with present laws concerning electromagnetic compatibility [82] [83].

What makes this technology so interesting, is that it allows to make the charging facilities and potentially even the charging process itself totally invisible to the user. The inductive coil can be integrated invisibly into the parking ground. The driver of the vehicle simply needs to park his vehicle on the equipped parking space to charge his vehicle. Authorization and start of the charging process can be automatized [84]. Thus, this seems to be a convenient solution. The fully automatized charging process also allows to recharge during very short parking times of a few minutes only. Additionally, this implementation is safe for users, as there are no open electric contacts.

There are, however, also drawbacks from a technical viewpoint. This technology requires an induction coil and further electrical components to be built into the vehicle. Also, the energy losses during inductive charging are generally higher than when charging via a plug [56]. If the driver parks carelessly and the two induction coils are not well aligned, the power transfer becomes even less efficient.

Inductive charging systems are already in use for small vehicles in logistic and production halls [15] and for low-speed short-range EVs in business compounds [85]. Inductive charging is also used for public electric buses in the city of Turin in Italy [86] and in Gumi in South Korea [87]. The technology seems interesting where vehicles are driving in closed compounds or circuits. Once the issue of standardization is resolved in the future, this technology also bears high potential for use in public charging.

2.1.3. Battery switching

The third relevant technological solution for the recharging of EVs is *battery switching* (or *battery swapping*). This means that the depleted battery is taken out of the vehicle and replaced by a charged battery.

The EV infrastructure company Better Place presented its specially designed battery switch station in May 2009 (see Fig. 2.12). The price for such a fully automatized station amounts to about 500 000 US$ [88]. A similar automatized battery exchange station has also been developed within a German research project [89] and by the car manufacturer Tesla [90].

To be able to switch batteries freely, they have to be of exactly the same format. For an application of battery switching in the large scale, manufacturers of EVs would therefore have to agree on a common standard or a selection of standards for batteries for EVs. This would limit their liberties in the design of vehicles, so it is unlikely that such standards will be developed [91] [92]. Nevertheless, the International Eletrotechnical Commission (IEC) is also working on standards for general requirements and safety for battery swap systems, which will have the code IEC 62840 [93].

Figure 2.12.: Battery switching station from Better Place [94]

An interesting approach which might combine switchable batteries with the flexibility of differently sized battery packs is to use smaller modular elements. Several projects are working on this topic. Modular batteries for different uses are being developed in form of the EnergyTube by Ropa [95] and the E-Motive Modular Multi-Use Battery System by the VDMA [96]. The idea of the project "Battery in motion" [97] is to specifically equip EVs with many small modular batteries instead of a single big one. An EV's battery pack can thus be adapted to the actual use of the EV, and unnecessary weight due to unnecessary batteries can be avoided. This concept might also lead to additional benefits of intelligent battery switching, by lowering the energy consumption of EVs by this weight reduction.

A battery switching facility is convenient from the user's point of view. Alike to refueling with gasoline today, the vehicle is recharged and ready to drive on within minutes. A battery switching station performs this task fully automatically, similar to a drive-through car wash, so that the driver himself does not have to take care of anything [88] [89]. A single facility can serve several hundreds of vehicles per day, and thus a few such facilities would be sufficient to cover the charging demand arising in an area. The surplus batteries that are stored at the switching station can potentially be used as a buffer between the electricity system and the suddenly arising demand for recharging from the users. The batteries can be charged slowly at night during times of overall low electricity demand, and they can even be used to feed electricity back into the grid [89].

In addition to the problem of a lack of standard battery formats, the high costs are one of the main drawbacks of this technology. The switching stations of Better Place cost about 500 000 US$ to build and 25 000 US$ to operate per month [98]. Additionally to the stations themselves, the system as a whole requires a surplus supply of batteries, which are today one of the most expensive components of electric vehicles [92]. The switching of batteries also makes issues surrounding the ownership of the batteries complicated. Only in a closed system, where all vehicles, batteries, and charging facilities belong to the same company is this not a problem. Better Place and Renault offered a service in which the customer leased the battery from Renault and could exchange it at Better Place switching stations [99].

Battery switching has already been tested for public charging in the larger scale. The company Better Place intended to implement large-scale networks of public battery switching stations, along with conventional conductive charging stations, in Israel, Denmark, and other countries [88]. However, in May 2013 the company had to announce its dissolution [100]. The company's revenues were not sufficient to cover the operating costs, and it was not able to raise additional investors' money. The company named the slow uptake of the service by the public and the lack of support by car manufacturers as the causes for their failure [100].

Nevertheless, in June 2013 the electric car manufacturer Tesla presented its own version of a battery swapping station [90]. In contrast to Better Place, the Tesla company does not aim at providing an actual public infrastructure but just an auxiliary service for the drivers of their Tesla S vehicles. The company sells vehicles to a wealthy target audience, therefore it may not be a problem that the price for one battery switch is intended to be 60 US$.

Battery switching is also being successfully applied in special cases with large fleets of identical vehicles. During the Olympic Games 2008 in China, a fully automatized battery switching system for electric buses was used [101]. Battery switching was also applied to Taxis in Tokyo [102]. It is also used for light EVs such as electric bicycles for tourists [103], electric motorcycles [104], and forklifts [15].

2.1.4. Combination of charging facilities with other equipment

Instead of having stand-alone charging facilities as those shown in the previous sections, it is also possible to integrate charging equipment into other street furniture. In the following section such combinations for the technologies of conductive and inductive charging will be shown. For battery switching facilities there is currently no known combination with other street furniture. Battery switching stations are implemented as technically complex facilities dedicated to this one purpose. It will also be shown how charging facilities are combined with facilities for electricity generation and storage, and how they are integrated into service vehicles.

Conductive charging facilities have already been combined with street lamps [105], parking ticket machines [106], billboards [107], bollards [25] and telephone booths [108] (see Fig. 2.13). Such combined facilities have to conform to the standards for charging equipment as discussed in the previous sections, as well as to those standards concerning their other functionalities

Figure 2.13.: Combinations of a charging facility with lamp post [105], parking ticket machine [106], billboard [107], and bollard [25]

Inductive charging facilities are integrated invisibly into the ground or implemented as ground plates, so there is usually little incentive to integrate them into other existing street furniture. Still, in a project in New York city inductive charging stations integrated into manhole covers are tested [109] (see Fig. 2.14).

An advantage of these varieties of charging facilities is the harmonic integration into the urban landscape and the avoidance of “visual clutter” which would be caused by adding charging facilities to the street furniture already in place. The use of such multi-purpose equipment can also be more economical than separate installations. The company Ebee Smart Technologies states that its charging points which can be integrated into street lamp posts will cost below 1 000 € [110]. Such integrated approaches can also make use of already existing electric lines and thus reduce the costs for the connection to the electricity network [111]. However, it has to be taken into account that charging facilities can require higher power connections than those for street furniture such as parking ticket machines or illuminated advertising. The downside of such an integrative approach is that such charging facilities might be harder to find from the users' point of view.

Figure 2.14.: Inductive charging facility integrated into a manhole cover [109]

Among the possibilities shown above, the combination of charging stations and street lights seems to be especially promising. The city of Berlin wants to test the integration of charging stations into lamp posts in the bigger scale starting by the end of 2013. Among the 270 000 street lamps in the city about 10 % fulfill the conditions for the additional installation of charging equipment. Attaching an additional electric consumer to street lamps can be done easily, because normally only 2 of the 3 available current phases are used by the lamps [110]. In France the Communauté du Pays d'Aix is also installing charging points at street lamps [111]. The German electric utility EnBW has also developed charging facilities integrated into lamp post. Additionally integrated modules can provide the technical services of wireless internet, emergency telephony, and environmental sensoring [112].

Charging facilities can also be integrated into service vehicles to provide an emergency recharging service for EVs that are stranded with empty batteries (see Fig. 2.15). Automobile clubs in the USA and Japan want to provide such a mobile emergency recharging service for electric cars in the next years [113] [114]. A mobile charging station has also been developed which allows to jump-start a stranded EV by transferring energy directly between two vehicles' batteries using CHAdeMO plugs [115]. Yet another technological approach for mobile charging is the use of a small external portable range extender, powered by conventional fuels [116]. A lesser form of mobility can be achieved by simply equipping charging facilities with wheels, instead of fixing them onto the groundwork [117].

Figure 2.15.: Mobile charging facility "Angel Car" [118]

Charging facilities can also be directly combined with equipment for electricity generation, such as solar panels or fuel cells, and electricity storage i.e. batteries. An example of a solar carport with integrated EV charging facilities can be seen in Fig. 2.16. The main advantage of such an installation is that it allows a partial decoupling of the charging facility from the electricity network and thus mitigates the impact of EV charging on the local power infrastructure. The article [119] proposes to charge EVs with electricity produced by hydrogen-powered fuel cells. This would locally decouple the charging of EVs from the electricity network altogether. The ChargeLounge project envisions to use batteries as buffers for their chargers. This allows the charging facilites to charge EVs with a higher power than the connection of the facility to the electricity network would allow [120].

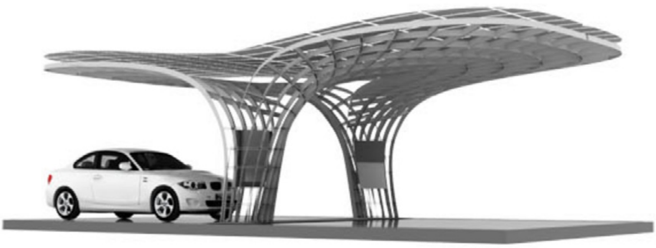

Figure 2.16.: Charging station with solar panels "Point.one" from Eight [121]

2.1.5. Charging infrastructure for light electric vehicles

For the charging of light electric vehicles (LEVs), such as electric bicycles and electric scooters, two possibilities exist: they can also use EV charging facilities for cars as those described above, if a household-type or smaller plug connection is provided. Alternatively they can use charging facilities dedicated to LEVs. As with bigger EVs the three technological solutions of conductive and inductive charging, and battery switching can be applied. Fig. 2.17 and Fig. 2.18 show examples of such charging facilities.

Figure 2.17.: Charging facilities for LEVs: conductive (author's photo) and inductive [122]

Figure 2.18.: Charging facilities for LEVs: battery switching [123]

For the conductive AC charging of LEVs, several manufacturers of electric bicycles, batteries, and charging infrastructure already use the *EnergyBus* plug standard [124] (see Fig. 2.19). This standard includes a specification of a plug system, with magnets for attachment, as well as a communication protocol. In

2014 work has started to transfer the EnergyBus system into an international IEC/ISO standard [125]. The standard will be included in the standards on light electric vehicles with the number 61851-3 [126]. The established standard can then be used for public LEV charging stations in the future. However, in parallel the type 3a connector (see Fig. 2.7) will probably be continued to be used for bigger LEVs such as scooters, and three- and four-wheeled LEV [52] [20].

Figure 2.19.: Standardized EnergyBus plug for the charging of LEVs [124]

With most LEV models the user can easily take the battery out and take it into his home or working place for recharging at a household socket. This possibility and the fact that LEV are mostly used for short-range trips [127] indicates that the demand for *public* LEV charging facilities will probably be low. But special applications are interesting, such as integration of conductive charging into electric bicycle rental stations [128]. The simplicity of battery handling of LEVs makes the installation of battery swapping stations for electric bicycles and electric scooters interesting for touristic regions [103] [129].

2.2. ICT as a part of EV charging infrastructure

In the previous sections the discussion focused on the electrotechnical components of a charging infrastructure. Now the information and communication technology (ICT) which is also part of such an infrastructure will be discussed. ICT is used by the operator to control the charging infrastructure. The EV drivers also need ICT services to find the available charging stations. First, information technology will be discussed from the operators' viewpoint, then from the users' viewpoint.

2.2.1. ICT for the operation and control of charging infrastructure

By networking separate charging stations to a control center, added value services can be implemented, which go beyond the mere charging of vehicles. Companies with different backgrounds are starting to provide ICT products for charging infrastructure. Manufacturers of charging stations provide the control software to go along with their charging facilities [25] [130]. Specialized EV infrastructure companies incorporate ICT as part of their services [131] [132]. Traditional ICT and electric infrastructure manufacturers also develop new products in this field [133] [134] [135]. Electric utilities are interested in using ICT to control the charging of EVs, as a first step to implementing smart grid applications in the long term [136].

Available ICT solutions vary in their functionalities. Fig. 2.20 shows a generic architecture compiled from several sources [137] [134] [138] [139] [140]. The general idea of such ICT systems is to set up a control center which serves as an information hub between several participants.

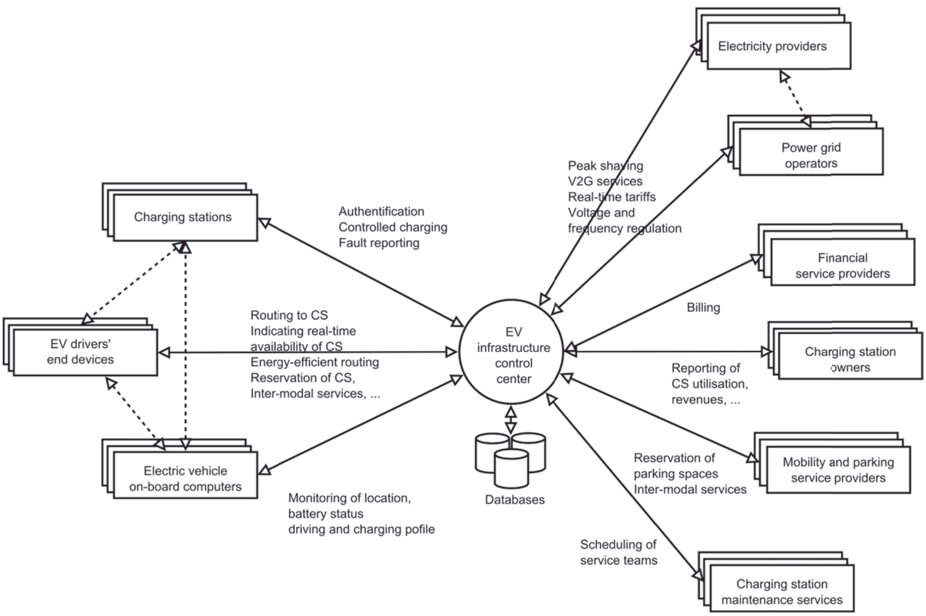

Figure 2.20.: A generic architecture for an EV infrastructure ICT system

The Open Charge Point Protocol (OCPP) provides a standard for the communication between charging facilities and a central control system [141]. Technically the protocol exchanges messages like a web service: SOAP/XML messages are transferred via HTTP [142]. The standard assures that charging equipment of different manufactures can be connected to the control systems of different providers. The development of this protocol started in the small scale in the Netherlands in 2009, and by september 2013 the OCPP consortium had more than 800 members from 35 countries [141], among them big German infrastructure companies like Bosch, Siemens, and Mennekes [143].

The most basic function that such a central system provides is remote authorization of customers and billing capabilities [133] [144]. In periods during which the communication between a charging station and the central system is not possible, the OCPP specification provides the possibility that charging points may authorize users using a locally cached ID list [142]. ICT systems can also include remote changing of configurations and update of firmware [142], as well as fault reporting and remote fault diagnostics and handling [133].

Several services can be provided to the users of the charging infrastructure via an end device such as a satnav, smartphone, or computer. The user can reserve a charging station in advance [133] [135]. The availability of charging stations can be shown in real time [133]. The driver can be routed to the next available charging station [135]. Special routing methods can be used which minimize the amount of energy consumed [138]. Functionalities for multi-modal travel might be implemented in such systems in the future, such as inter-modal route planning and multi-modal tickets [144].

The charging of EVs can be controlled remotely, to minimize impacts on the power system. Local load management can already be realized today. A group of charging stations can be controlled to assure that the maximal locally available power is not exceeded [133]. In the long term more sophisticated smart-grid services can be implemented, taking real-time information from electricity providers and electricity network operators into account. By timing the charging and feeding back of electricity, the electricity network can be stabilized (voltage and frequency regulation) [145], fluctuating renewable energy sources better integrated into the power system [144], demand peaks flattened ("peak shaving") [137], and real-time tariffs implemented [134]. Such applications are especially interesting for charging facilities at homes or work places, where vehicles remain parked for longer times, and thus allow for some flexibility in the timing of recharging. To make the most of such smart-grid applications, the current state of charge of the vehicles' batteries should be monitored, as well as their current locations [138]. Past data on charging and driving behavior then allows the operator of the infrastructure to forecast demand for charging [144]. The interactions between the charging of EVs and the electricity system on different levels is discussed in more detail in Chap. 3.

Reporting mechanisms of charging station utilization and revenues can be implemented. This is especially important in situations in which the owner of a charging station is different from the operator of the infrastructure [133] [132].

Most operators of EV charging infrastructure on the larger scale can be expected to implement a control center in a similar form as discussed above. To allow customers to *roam* between different infrastructure operators, it is envisioned to install a central clearing house. This clearing house would be connected to the control centers of participating infrastructure operators and allow for authentication and billing of customers among the charging infrastructure partners [146]. In Germany the initiative ladenetz.de (called e-clearing.net on the international scale [147]) allows EV drivers to roam between charging stations provided by different local municipal utilities [148]. In November 2013 there were already 31 utilities taking part in this initiative. The Hubject project (called Intercharge on the international scale [149]), which is a joint venture between RWE, EnBW, Bosch, Siemens, Daimler, and BMW, also works on providing roaming services between different charging infrastructure operators [150]. For the communication between the operators' control centers and a central clearing house, the Open Clearing House Protocol (OCHP) is being used [151]. Since autumn 2014 several big national charging service providers are collaborating to provide roaming on the European scale. Next to the two German providers named above, GIREVE from France, Enel from Italy, and MOBI.E from Portugal are participating in the initiative [152].

Since march 2014 the Bundesverband der Energie- und Wasserwirtschaft e.V. (BDEW) gives out unique identification numbers to simplify the roaming of EV users between different charging point providers [153]. Identifiers are issued for providers of electric mobility and for operators of charging stations. The BDEW does this this upon request from the German government [154].

2.2.2. ICT for the use of charging infrastructure

It is not sufficient to merely install charging infrastructure and implement a system to control and operate it. The availability of charging infrastructure also has to be communicated to the users. For this, a wide range of approaches with varying technical complexity exist. The approaches that will be discussed in the following are: paper maps, road signs, providing information at the charging facility itself, telephone hotlines, websites, and satnav and mobile applications.

The easiest way to show EV drivers where they can recharge their car is to provide them with a map of the currently installed infrastructure. This can be realized as a paper brochure and by providing a PDF document for download (see Fig. 2.21). The EV drivers can then keep the map in their wallets or in the glove compartments of their cars. This is a simple and effective approach. It needs to be assured that the map is updated and redistributed regularly, however, to account for newly added and removed charging stations.

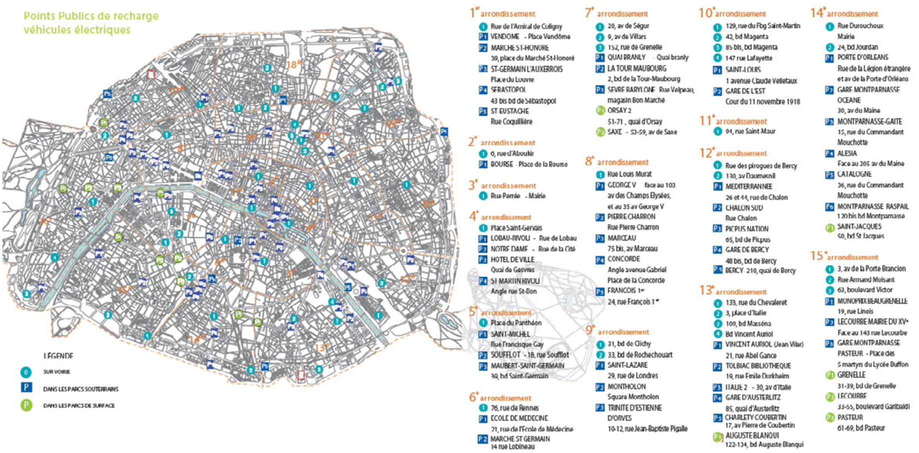

Figure 2.21.: Map of charging stations with address list for the city of Paris [155]

Another traditional approach is to install signs, either at the stations themselves or at a distance to lead EV drivers to charging stations. A negative side-effect of such signs is that they lead to further “visual clutter” in the streetscape. The German signs for the reservation of parking spaces for EVs can be seen in Fig. 2.23. They are combined with the standard parking space signs that are shown in Fig. 2.22. These signs for EVs were issued in 2011 and are in accordance with current German traffic regulations [156]. German law allows such special parking rules for specific types of vehicles [157] [158] [159].

The German electric mobility law, issued in June 2015, gives the federal ministry of traffic and the federal ministry for the environment the possibility to introduce decrees granting special rights to EVs. EVs may be allowed to park on public parking spaces, park for lower or no fee, and drive on streets not accessible to conventional vehicles [160]. The governments of the federal states may introduce special clauses for EVs in their regulations concerning the fees for parking on public parking spaces. The federal state governments may also authorize lower level instances to introduce such fee regulations.

Figure 2.22.: Signs 314 and 315 for parking spaces, and sign 286 for stopping restriction [156]

Figure 2.23.: Additional signs 1026-60, 1026-61, 1050-32, and 1050-33 for parking spaces for EVs [157]

A further sign for leading drivers to charging stations was officially issued in 2014 [161] (see Fig. 2.24). The sign is meant to be used along motorways to announce the availability of charging stations at service areas. In exceptional cases the sign can also be used with additional signs leading the drivers to a remotely located charging station (see Fig. 2.25).

Figure 2.24.: Sign 365-65 for leading EV drivers to a charging station [162]

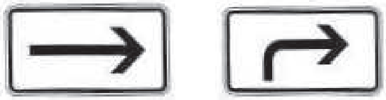

Figure 2.25.: Additional signs 1000-20 (pointing left: 1000-10) and 1000-21 (pointing left: 1000-11) which can be used to complement sign 365-65 [163]

The charging facilities themselves can also provide the user with information. The Sitraffic Epos charging pillars from Siemens can display city maps and further information on their large displays (see Fig. 2.26). This functionality could also be used at occupied charging stations to guide EV drivers to the nearest free station.

Figure 2.26.: City map on the screen of a Siemens Sitraffic Epos charging facility [164]

Many operators have set up telephone hotlines, the numbers of which are written on the charging facilities. This allows the EV drivers to directly contact customer support in case of a problem.

Several operators of charging infrastructure have implemented websites to provide their clients with information (see Fig. 2.27). Especially the website of ChargePoint [132] is worth mentioning, as it makes use of real-time data and provides the possibility of direct user interaction. The occupancy status of charging stations is displayed in real time. The users are also able to reserve charging stations via this web portal. The site additionally allows the users to propose new locations for charging facilities. Most companies provide only information on their own charging facilities. LEMnet [165], however, provides information on the charging facilities of all operators. Such operator-independent websites have multiplied in the last years. Other such websites for Germany and neighboring countries are PlugFinder [166], Smart Tanken [167], and GoingElectric [168].

These websites do not only provide information on locations of charging stations but also name the operator, number and type of sockets, price and opening hours.

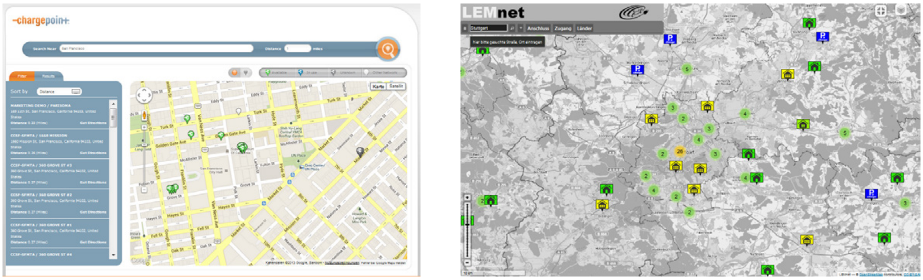

Figure 2.27.: Websites providing information on charging stations by ChargePoint [132] and LEMnet [165]

Websites have the drawback that it is difficult to consult them en route while driving an EV. Several companies have therefore integrated charging infrastructure maps and associated services into mobile devices such as satnavs and smartphones. Fig. 2.28 shows two examples. The PlugFinder website mentioned above is also available as an app [166]. Apps for specific EV models are able to give range information, control the charging process remotely, and initiate the preheating of the battery and vehicle some time before departing on a trip [169].

Figure 2.28.: Charging station maps in the satnav integrated in the Nissan Leaf [170] and the LEMNet app [171]

2.3. Conclusion: assessment of technologies and expected future applications

To conclude this chapter on the technologies for EV charging and associated ICT, the main aspects will now be summed up again. Based on the analyses of these technologies, an outlook for the expected application of these technologies in the near feature is then given. Table 2.1 gives an overview of the characteristics of the different charging technologies. Table 2.2 summarizes the characteristics of different kinds of ICT applications.

Charging EVs conductively via an electric cable and an AC current is a simple and economic solution. Standardization has well advanced, as the Type 2 connector with optional shutter will be the European standard soon. This technology can be expected to be the commonly used one, with different power levels, both for private charging at homes and work places, and public charging.

Fast DC charging is the other cable-bound charging method. The charging facilities are more expensive, however, and there are light negative side effects on battery lifetime and electricity network impacts. But this is outweighed by the convenience that comes with the faster charging process. The Combo 2 connector can be considered the European standard. The CHAdeMo standard can still be expected to be supported in parallel in the near future. Fast DC charging can be expected to be used for public charging in the bigger scale, especially along motorways.

Inductive charging of EVs is more convenient than cable-bound methods. There does not yet exist a standard for inductive charging of EVs. So this kind of charging plays no role in current EV infrastructure implementations. Once a standard is developed, this method might become interesting for use in small-scale local systems in public transport, car sharing, and in closed compounds. Because of its convenience, this charging technology might potentially be used for public charging in the longer term.

Battery switching is also convenient, but would require a standardization of battery formats. It is unlikely that EV manufacturers will agree on such a standard. This disqualifies the approach for large-scale public infrastructure. But the method is interesting for large fleets of identical vehicles with high daily mileages, such as public buses, taxis, or rented LEV. The introduction of standards for modular batteries might revive this idea in the long term.

Combining charging infrastructure with other street furniture can lead to a better integration into the urban landscape. The combination with facilities for electricity generation and storage can create positive synergy effects. But integrating charging facilities into existing street furniture retrospectively is difficult. New combined charging facilities can be expected to be used for public charging in special circumstances, such as in new urban developments or near historic monuments.

There seems to be little demand for a public charging infrastructure for LEVs. Concerning LEVs, standardization issues are well advanced. But the use of the EnergyBus and the type 3a connector in parallel seems inconsequent. LEVs are commonly used for short-range travel and can easily be charged at homes or at working places. For electric bicycles therefore, installing dedicated LEV charging infrastructure seems only reasonable for bicycle sharing projects, or projects for tourists. In countries where the use of scooters is common, installing charging facilities for them might be reasonable in city centers.

A charging infrastructure control center allows the operator to provide a wide range of added value services. Such ICT services will be expected by the users, so it is likely that many public charging infrastructure operators will provide these services. It seems very probable that roaming between operators in one country and later across European borders will be possible in the long term, enabled by a central clearing house.

Most operators of charging infrastructure can be expected to communicate the availability of stations to current and potential future clients by using several channels: by installing signs on the street, distributing paper maps, providing telephone hotlines and websites, and via applications on mobile devices. If charging stations are equipped with large displays, they can also be used to provide users with information. In Germany it can be expected that standardized EV charging station signs will be installed at almost all stations located in public space. Maps and applications on mobile devices can be used to find charging stations while en route, while website are better suited for general information and marketing purposes.

Table 2.1.: Comparison of different charging technologies

Technology	**Conductive AC charging**	**Conductive (fast) DC charging**	**Inductive charging**	**Battery switching**	**Combined charging facilities**	**Separate public LEV charging facilities**
Standardization	Advanced: Type 2 connector with optional shutter as EU standard, communication using ISO 15118	Advanced: CCS 2 as European standard, CHAdeMo still supported in parallel	Delayed: only general requirements standardized	Development of norm for battery formats between EV manufacturers unlikely	Standards for charging equipment as well as existing standards for other functionalities	Advanced: EnergyBus standard, Type 3a connector
Advantages	Simple solution, low costs, adaptable to different circumstances (private/public, different charging powers, ...)	Convenience of faster charging process	Charging facility can be made invisible, fully automatic process, can be used for short parking durations, no risk of electric shock	Fast and convenient for user, possibility of electricity system services by surplus batteries at the station	Better integration into streetscape, more economical than separate facilities, synergies with electricity generation and storage equipment	Allows long-range trips of LEVs
Disadvantages	Using plug and cable cumbersome, vulnerable to vandalism, cable can be tripping hazard	Higher cost of facilities, faster battery aging, demand peaks in power system, cable-bound (see left)	Further electric components in vehicle, higher energy losses	High cost of facility, surplus of batteries needed, ownership of batteries complicated	Charging facilities potentially harder to find	Demand for public charging is expected to be low, as LEVs are seldom used for long-range travel
Current applications	Charging at homes, work places, and in public	Public charging, especially along motorways	Small vehicles in logistic and production halls, business compounds, public transport: buses	Public infrastructure (failed), public transport: buses, taxis, rented LEV in touristic regions	Public charging	Tourism, bicycle sharing
Expected applications in the near future (next 10 years)	**Widespread common solution for charging at homes, at work, and in public**	**Widespread use for public charging, especially along motorways**	**Buses, taxis, carsharing, use in closed compounds, potential use as public charging in the long term**	**Fleets of identical vehicles with high mileage, potential revival of concept with modular batteries in the long term**	**Use for public charging in special circumstances: near historic monuments, in new urban developments**	**Integration in bicycle rental schemes, touristic projects**

Table 2.2.: Comparison of different ICT applications for an EV charging infrastructure

Technology	**Operator ICT: charging infrastructure control center**	**User ICT: paper maps**	**User ICT: signs**	**User ICT: websites**	**User ICT: mobile devices**	**User ICT: using charging station as information display**
Standardization	Advanced: communication protocols OCCP, OCHP, ID schemes	No specific standard needed	Advanced: official signs issued in Germany	No specific standard needed	No specific standard needed	No specific standard needed
Advantages	Added value services: routing, reservation of charging stations, controlled charging, ...	Simple, low costs	Facilitates finding of charging stations when in their proximity	Possibility to provide real-time information and direct user feedback	Provide real-time data, navigation, possibility of direct user feedback	Provide additional information services at the stations
Disadvantages	Higher costs for communication hardware and software, control center operation, ...	Need to be updated and exchanged regularly, map reading skills necessary	Leads to further visual clutter in the streetscape	Internet connection is needed, not suitable for consultation en route	Mobile device is needed	Requires big, more expensive display
Current applications	Local public charging infrastructure	Communicating availability of public charging infrastructure to users	Leading EV drivers to charging stations, reservation of parking spaces for EV	Communicating availability of public charging infrastructure to users	Leading EV drivers to charging stations	None known
Expected applications in the near future (next 10 years)	**Widespread use of control centers for local charging infrastructure, adoption of a common solution for roaming among operators and internationally**	**Use as flyers for marketing purposes**	**Standardized sign used for all public charging stations**	**Widespread use for information and marketing purposes**	**Widespread integration of EV charging infrastructure functionalities in satnavs and smartphones**	**Sporadic use at suitable charging stations**

3. Interactions of EV charging and the electricity system

In this chapter interactions between the charging of EVs and the electricity system will be discussed. First, the general structure of the German electricity system, its market structure, and its load curve will be shown. Then it will be discussed how uncontrolled charging, controlled charging, and controlled discharging can lead to different interactions with the electricity system. These interactions are afterwards described in more detail on five levels of the electricity system: the generation of electricity, the storage of electricity, transmission networks, distribution networks, and individual buildings. Specifics of the installation of electric facilities on site will also be discussed in this section. Based on this overview it will finally be concluded which of these effects should be taken into account in which way when planning a charging infrastructure for EVs in a city or region.

A large number of scientific publications treat specific effects that occur during the charging of one or many EVs on specific levels of the electricity system. But there do not seem to exist many publications showing the "bigger picture" and allowing the non-electric-engineer to understand the how and why of these effects. The final report on "Impacts and Opportunities of EV on Power Systems Operation" [172] and especially the associated presentation [173] of the European Grid for Vehicles (G4V) research project provide a good overview. Another extensive report treating interactions of EVs and the electricity system on all levels is the final report of the NET-ELAN project [174]. This is, however, a compilation of research reports by several authors and thus cannot provide an overall vision. A concise survey of impacts of EV charging on electricity systems can be found in [175]. This article only focuses on network impacts, however.

The specifics of the electrical installation of charging facilities will also be discussed within this chapter. This has already been explained in differing levels of detail in several handbooks. The German national platform on electric mobility has published a technical guide for EV infrastructure in 2013 [39]. The publication [32] discusses specifics of the electric installation in underground parkings in Germany. Such handbooks have also been published in the USA [176] [177] [178] [179]. The details of these publications from the USA might not be directly transferable to the situation in Germany. Still their pragmatic approach, using flowcharts to describe different process variants of electric installation, is worth noting.

3.1. The general structure of the German electricity system

Before going into detail about the different interactions between EV charging and the electricity system, the overall structure of the German electricity system will be considered in this section. The first subsection will shortly treat the different levels of the electricity system. Then the corresponding market structure is explained. Finally, the concept of the load curve is presented, and it will be explained why it plays such an important role for generation and network capacities.

3.1.1. Different levels of the electricity system: generation, transmission, distribution, consumption and storage

Electricity systems encompass the *generation*, *transmission*, *distribution*, *consumption*, and *storage* of electricity. The principal structure of the German electricity system is shown in Fig. 3.1. On the left side of the figure, it is displayed how power plants feed their produced electricity into the grid on different voltage levels. Big nuclear power plants, with a generation power in the scale of a gigawatt (GW), are connected to the extra high voltage networks. Medium-sized power plants, such as gas turbine plants, are connected to the high voltage network and smaller power plants to the medium voltage networks. Photovoltaic installations on house roofs only have a generation capacity of several kilowatt (kW). These and other small generators of electricity feed their produced electricity into the local low voltage network.

The generated electricity is transported to the consumers through long distance transmission networks and shorter distance distribution networks (see Fig. 3.1) in the middle). The transmission networks transport electricity over distances of up to several hundred kilometers. Operating at extra high voltage levels allows to transfer a given power with a lower electric current. This reduces the losses dissipated as heat during transmission [180]. Distribution networks distribute the electricity on the local level and connect the individual consumers and households to the network.

On the right side of Fig. 3.1 it can be seen that, mirroring the hierarchy of generation facilities, a hierarchy also exists for consumers and storages of electricity. On the higher level, pump power plants are connected to the extra high or high voltage networks. Pump power plants "store" electricity by pumping water up into a big water basin. The potential energy contained in the water mass is transformed back into electricity by letting the water flow downhill trough a turbine. The biggest pump storage stations in Germany can generate up to a gigawatt of power over several hours [181]. Big and medium sized consumers such as big manufacturing plants and businesses are connected to high and medium voltage networks. On the lowest level, private households are connected to low voltage networks.

3.1.2. The market structure of the German electricity system

In Germany the different levels of the electricity system are regulated to different degrees and controlled by different companies.

German electricity market regulations require that vertically integrated electricity companies and distribution network operators with more than 100 000 connected clients, and transport network operators in general, have to be unbundled [185]. The unbundling of companies in the German electricity sector entered into force in 2005 [186].

The generation of electricity takes place under free market conditions in Germany. In 2015 there are about 70 companies active as *electricity producers* with more than 100 MW generation capacity [4]. However, the market is still dominated by the four big companies RWE, E.ON, Vattenfall, and EnBW, which in 2013 controlled 59 % of the total power generation capacity (not considering renewable energies) [187]. With the phase-out of nuclear power and the introduction of additional small renewable energy plants, the market share of the big four electricity producers is decreasing [188].

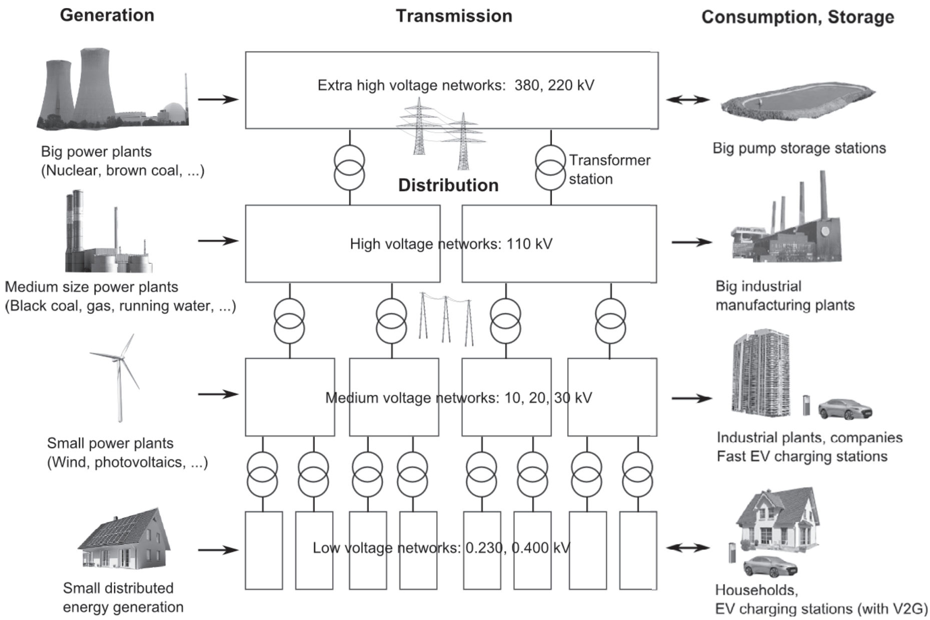

Figure 3.1.: General structure of the electricity system in Germany (based on [182] [183] [184]) and the integration of EV charging

The transmission and distribution networks are operated by regulated regional monopolists. They have to provide access to networks to producers and consumers of electricity for which they are financially compensated. There are only four *transmission system operators (TSOs)* in Germany: TenneT, 50Hertz Transmission, Amprion, and TransnetBW. They emerged during the unbundling process from the big four electric utilities. In 2014 there were 884 companies active as distribution system operators in Germany [187].

The market processes within the electricity system are partially uncoupled from the technical processes. A consumer of electricity has a contract with an *electricity provider*. In 2015 there were about 1 190 electricity providers in Germany [189]. These are often companies which also produce electricity or operate local distribution networks. The provider can buy additional electricity from electricity producers or traders which cover the demand of his consumers. Trading of electricity is for instance done on the European Energy Exchange (EEX) [190]. The electricity network operators (TSOs and DSOs) are then responsible for operating the network so that the transfer of electricity from the producers to the consumers can take place.

3.1.3. The load curve and its implications

A specific characteristic of the energy carrier electricity is that its generation must take place at the same time as its consumption. This is because storage of electricity on the large scale is not economically feasible (also see Sec. 3.3.2). The consumption and corresponding generation of electricity strongly vary over time. Fig. 3.2 shows the *load curve* for the entire German transmission network on a specific day. The typical *demand peaks* at early noon and in the evening, as well as the *demand valley* at night can clearly be seen. The shape of the load curve varies between different weekdays and seasons and can also be influenced by special occasions, such as holidays or sports events on television. Such load curves can also be analyzed for other levels of the electricity systems, such as the medium and low voltage networks in a city, the low voltage network in an urban district, or the house connection of a single building.

All elements of the electricity system have to be constructed in a way that they can support their respective *demand peaks*. This implies that for most of the time they are operating at levels below their installed capacities. Electricity networks on all levels are usually under-utilized for most of the time and approach their maximal capacities only at times of high demand.

The variation of power demand over the day has the interesting consequence that different types of power plants fulfill different roles [191]. The load curve can be divided into three levels. *Base load* refers to the energy demand that exists at all times. *Medium load* is the additional demand that is present during most of the day. *Peak load* is the demand that occurs during demand peaks. Different kinds of power plants are used to cover these demands due to technical and economic reasons. Base load power plants are types of power plants which are not able to change their power output at a short notice and thus run at uniform levels at all times. In contrast, peak load power plants can easily and quickly change their power output. Base load power plants have small fuel costs (variable costs) but high construction costs (fixed costs), while peak load power plants incur high fuel costs but are less expensive to build. Thus, for covering base load, nuclear, brown coal, and running-water power plants are used [192]. Medium load power plants are mainly black coal power plants [192]. Peak load is provided by gas and oil power plants, and pump storage plants [192]. The economics of power generation entails that electricity can be generated cheaper if the load curve is flatter, because then more base load power plants can be used. In the next section it will be shown how the charging of EVs might be used for smoothing of the load curve.

The introduction of high numbers of photovoltaic and wind power plants into the Germany electricity system in the last years has perturbed the traditional scheme described above. The German renewable energy law [193] states that electricity network operators *have to* take up the electricity generated from these renewable sources as long as no network bottlenecks occur. “Fuel costs” for these power plants is non-existent, therefore qualifying them as base load power plants. However, their power output is volatile over a day, due to changes in solar radiation (caused by the arc of the sun and by clouds) and changes in wind.

Fig. 3.3 and 3.4 show the electricity produced by solar and wind power respectively on the same day as the load curve already shown above in Fig. 3.2. Peak and medium load power plants therefore have to compensate for these fluctuations. The charging of EVs might also be used in a beneficial way to compensate for these fluctuations, as will be discussed in the following section.

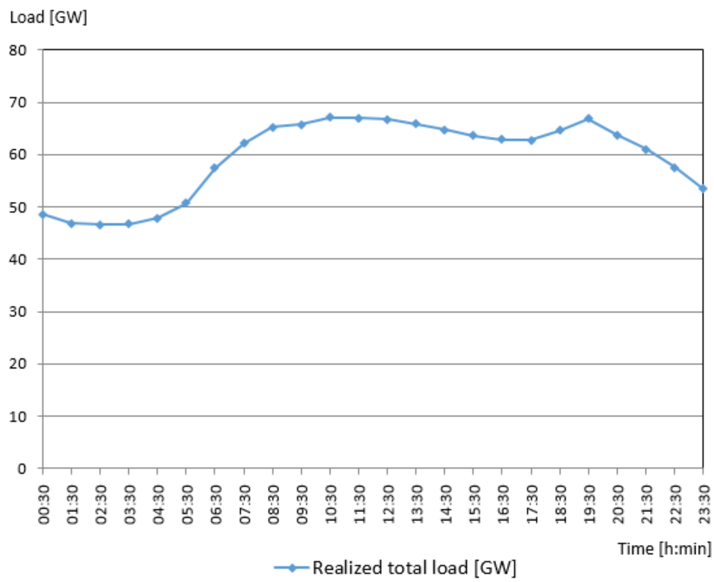

Figure 3.2.: Load curve of the entire German electricity transmission system (Wednesday, march 19th, 2014), data from [194])

To conclude this chapter on the basic structure of the German electricity system, the actual percentages of different kinds of power plants for the generation of electricity will now be considered. Fig. 3.5 shows the percentages of electricity (energy in TWh) produced from different sources in Germany in 2013. The dominant baseload sources are brown coal (25.6 %), black coal (19.6 %), and nuclear power (15.3 %). Peak power plants mainly generated energy from petroleum gas (10.5 %), petroleum (1.0 %), or hydro pump storage (1.0 %). Renewable energies make up 23.0 % of the generated electricity. Among these renewable sources wind with 8.4 %, bio mass with 6.7 %, and photovoltaics with 4.7 % dominate. Running water power plants play only a small role in Germany with 3.2 % of generated energy. The German government has enforced the phase-out of nuclear power in 2011 by law [195]. All German nuclear power plants will be shut down successively, with the last ones being shut down by the end of the year 2022.

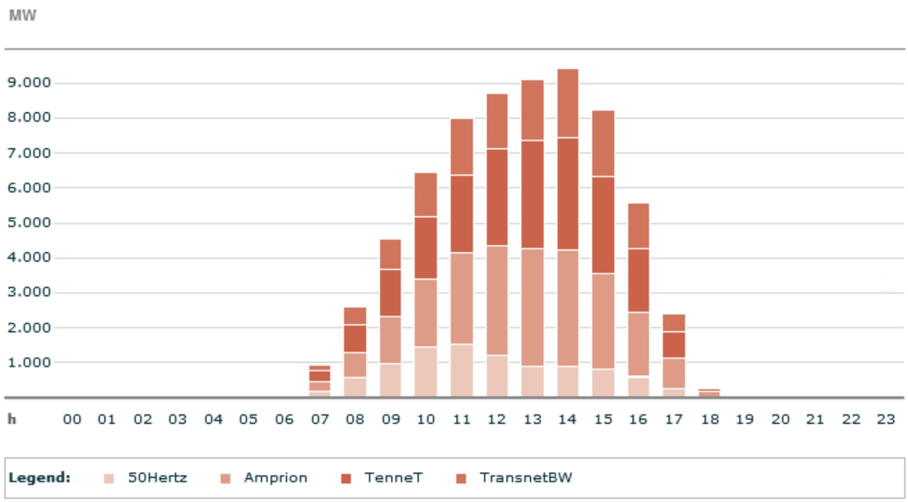

Figure 3.3.: Total electricity production by solar power in the four German transmission system control areas (Wednesday, March 19th, 2014) (translated from [196])

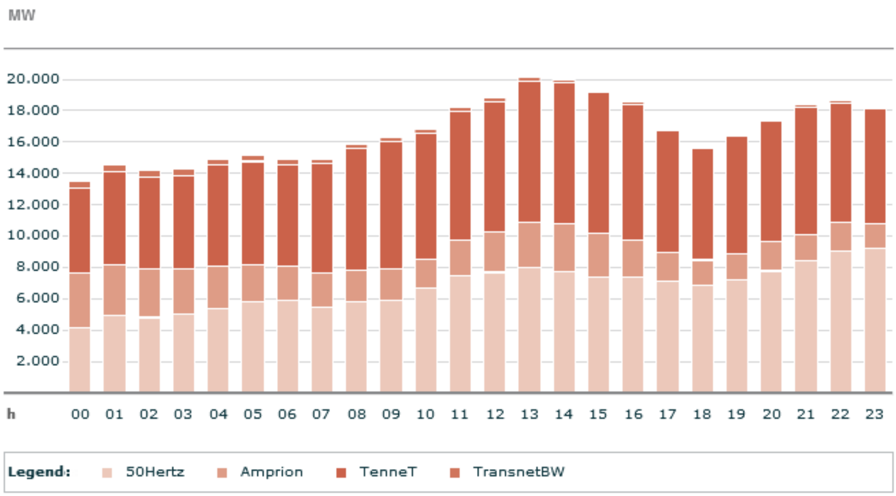

Figure 3.4.: Total electricity production by wind power in the four German transmission system control areas (Wednesday, March 19th, 2014) (translated from [196])

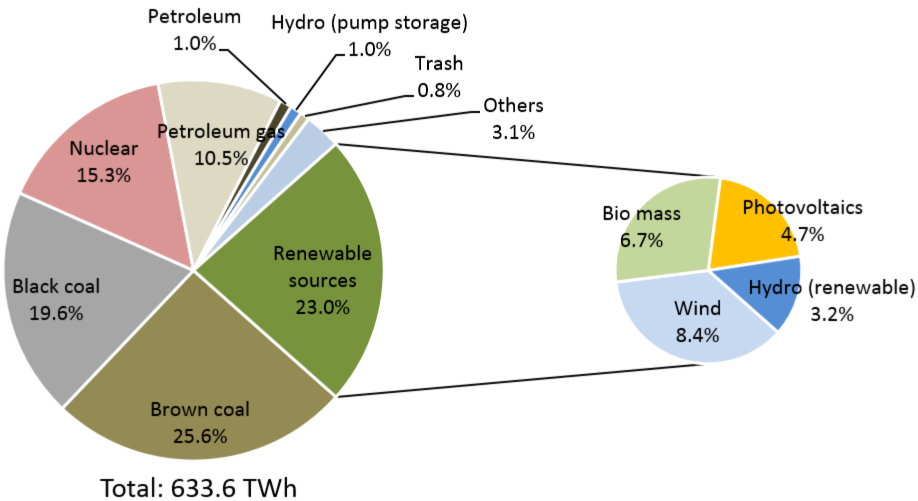

Figure 3.5.: Gross electricity production (energy in TWh) in Germany in 2013 by source (data from [197])

3.2. Charging EVs: uncontrolled, controlled, and with additional discharging

In the previous section, the general structure of the German electricity system was explained. The concept of the load curve was also presented. In this section it will be treated how the charging of EVs can influence the shape of the load curve. Three cases will be discussed: when the charging of EVs is not controlled at all, when it is controlled, and when discharging of electricity back into the network is implemented. The discussion will be generic here. Specific aspects for generation and storage, transmission networks, distribution networks, and for buildings are then discussed in more detail in the following Sec. 3.3.

3.2.1. Uncontrolled charging

Uncontrolled charging means that the EV driver connects his EV to a charging facility upon arrival at a destination. The EV then immediately starts to get charged with a more or less constant power until the battery is full or the EV is disconnected by the driver who drives off with his EV. With different nuances, this kind of charging is also referred to as *dumb charging*, *opportunity charging*, *charge anywhere/anytime* [198], and *eager charging* [199].

What is problematic about uncontrolled charging is that it leads to a high time-spatial concurrency of the charging operations of individual drivers. The distribution of the start times of trips per motive is shown in Fig. 3.6. In Fig. 3.7 the aggregated trips per mode is shown, with car trips being represented in red. A trip peak can clearly be seen in the morning when people drive to work and in the evening when they drive back home and to shopping and recreation activities. This concurrency also has a spatial aspect. In the morning many people drive into city centers to work, and in the evening they drive back into the surrounding residential areas or zones for shopping and recreation. If uncontrolled charging is used, a higher number of EVs start charging at arrival at their destination. These demand peaks can then overlap with the already present early noon and evening demand peaks in different levels of the electricity system (compare Fig. 3.2).

These additional demand peaks *may* lead to problems. They can lead to more electricity needing to be generated by peak power plants, which increases the overall costs for electricity production. The new demand peaks can exceed the capacities of transmission lines, distribution network lines, or building connections. It may require high investments to extend the presently installed capacities. Effects on different levels of the electricity system are treated in more detail in Sec. 3.3.

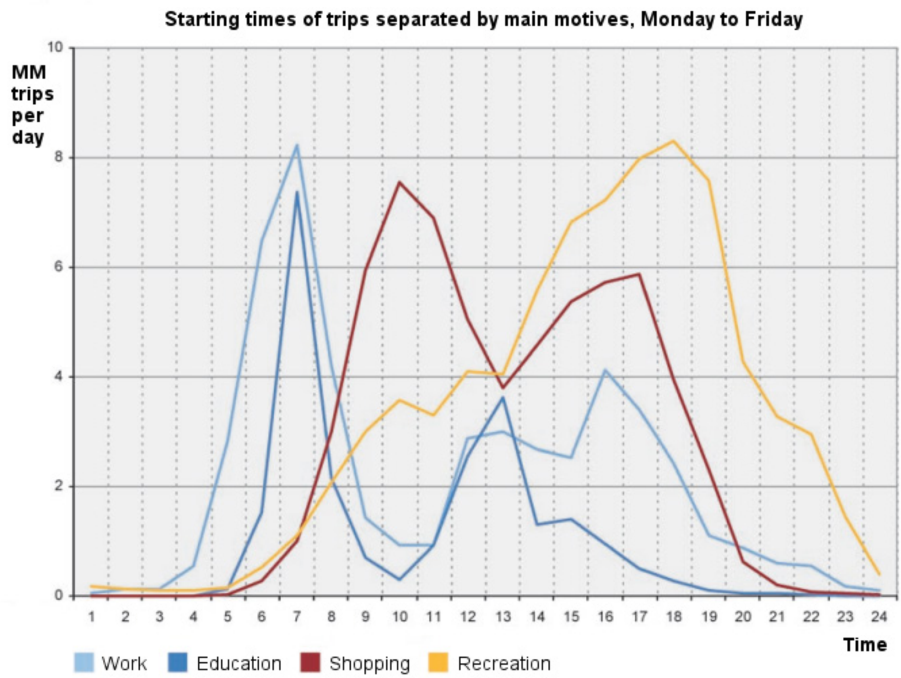

Figure 3.6.: Start time of trips separated by motives in absolute million trips per day in Germany, Monday to Friday (translated from [200])

3.2.2. Controlled charging

Controlled charging serves to break the previously discussed concurrency between the charging of EVs and demand by other consumers in the electricity system, and/or the concurrency between the charging operations of large number of EVs. It can also be referred to as *intelligent charging* or *smart charging*.

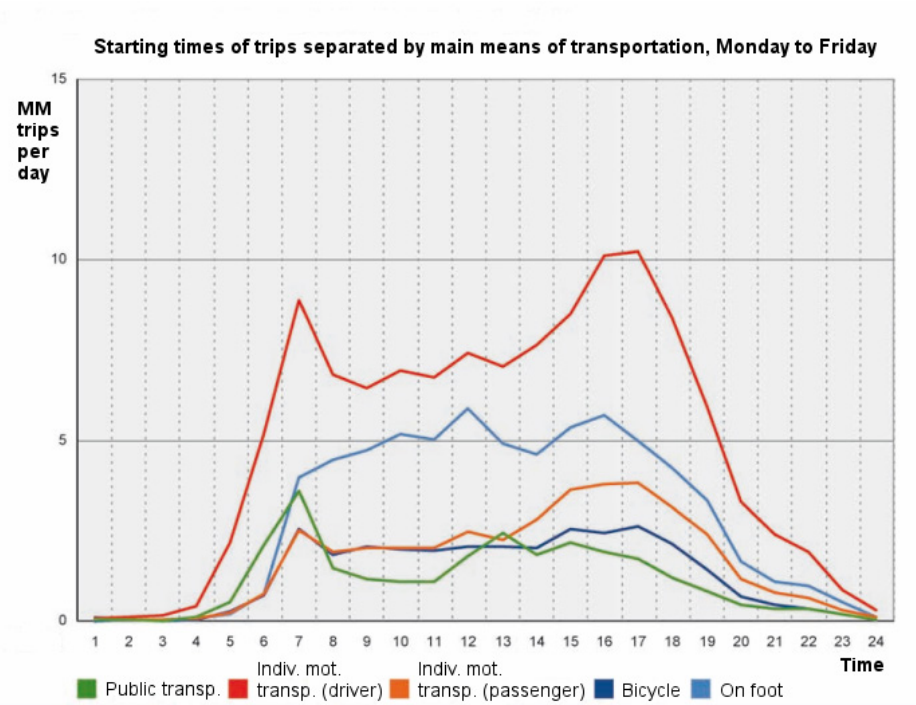

Figure 3.7.: Start time of trips separated means of transportation in absolute million trips per day in Germany, Monday to Friday (translated from [200])

The charging can be controlled with the:

- Power used for charging
- Timing of the charge

Controlling the charging process can be used to simply avoid the creation of new demand peaks. It can additionally be used to time the charging of EVs to especially occur during times of overall low demand, in the nighttime *demand valley*. This is also called *valley filling* (see Fig. 3.8). This principle can be applied on all levels of the electricity system in order to reach a better utilization of the installed capacities.

Instead of being scheduled when demand is low, charging can also be done when electricity production is (too) high. EV charging can be timed to catch generation peaks from wind and photovoltaics. This leads to a more uniform *residual load* [201] to be covered by conventional power plants. Additionally, this would avoid having to shut off wind power plants during times when the electricity network cannot take up their electricity. This is a situation which already occurs today in the German northern federal sate of Schleswig-Holstein today [201].

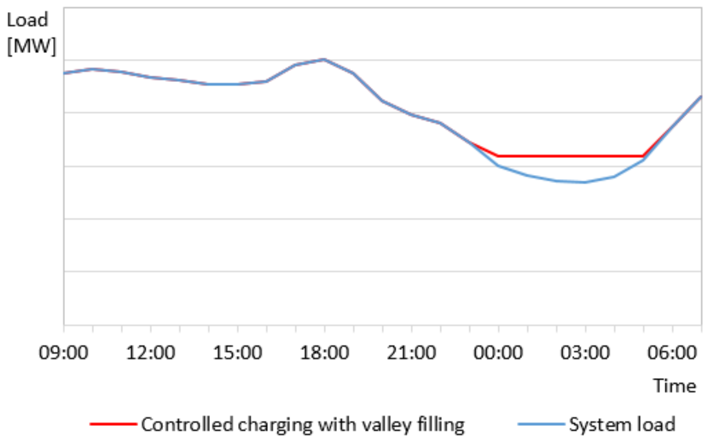

Figure 3.8.: Valley filling by controlled charging (visualization of principle, not to scale)

It makes sense to differ *charging with local control* from *charging with aggregated control* [202]. A few examples for these charging schemes will now be discussed.

Charging can be locally controlled by the charging station to profit from different time-of-use tariffs [175] [202]. In Germany such tariff models usually divide the hours of a day into two times of low and high tariff. Two different meters or a single meter switching between both tariffs are installed in the household. The electricity provider remotely switches between the two tariffs at certain times via ripple control. Because these signals are passed through the local distribution network, such tariffs are mainly available from local municipal utilities [203].

Another example of locally controlled charging is to coordinate a group of charging points of one charging station. The charging can be controlled so that the total power does not exceed power limits set by the connection of the charging station to the electricity network or the concerned building connection [204] [140]. The technical implementation of locally controlled charging does not seem to be a major challenge. The charging parameters can already be controlled locally by charging stations today, using the communication protocol in DIN EN 61851-1 [22] or using more sophisticated communication in the future with ISO 15118 [40].

To coordinate the charging of large numbers of locally dispersed vehicles, a central *aggregator* would be necessary [198]. The aggregator could control the charging of a large numbers of EVs and sell this as a service to network operators [198]. In the Danish Edison project such an aggregator architecture has been simulated [202]. The aggregator took distribution network constraints into account and provided a balancing service to the transmission grid, which in Denmark and on the studied island of Bornholm takes up a high amount of energy from wind power plants.

For the aggregated control of EV charging, it also seems that technical feasibility is not problematic [198]. Communication between individual charging stations and a control center can for instance be implemented with the Open Charge Point Protocol (OCPP) as explained in Sec. 2.2.1.

All in all, it seems there is much to gain from a transition from uncontrolled to controlled charging. Controlling the timing and the power of charging can be technically implemented relatively easily. Currently, local control can already be used, while aggregated control of large fleets of EVs will be possible in the long term.

3.2.3. Controlled charging and discharging

Beyond controlling the charge, it is also possible to discharge the energy stored in the battery back into the electricity network. This is commonly referred to as the *vehicle-to-grid (V2G)* concept. The idea seems to have been first published in the article [205], and the term seems to have been coined in the report [206]. In V2G, the batteries are used as intermittent energy storages which are charged at times when electricity can be generated cheaply during times of low demand and discharged at times of peak demand. This is generally referred to as *peak shaving* (see Fig. 3.9). Big hydro pump storage plants are already used in the same way in Germany [207]. The power stored in the EVs batteries could also be used to provide balancing power to transmission system operators [208] (see Sec. 3.3.3). As in the case of controlled charging, such services would only be feasible if a central aggregator controlled the charging and discharging of a large number of EVs or if distributed EV charging mechanisms followed an overall global aggregator's request. The communication needed to implement V2G is specified in the emerging norm ISO 15118 [40].

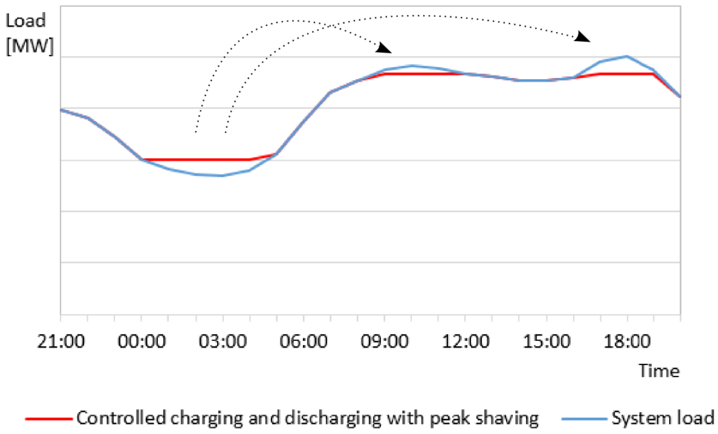

Figure 3.9.: Peak shaving by V2G (visualization of principle, not to scale)

On the smaller scale, the concept can also be implemented as *vehicle-to-home (V2H)*. Here, the EV's battery is integrated into an energy management system of a single building. The EV's battery can directly be charged by the house's photovoltaic panels to increase the auto-consumption of produced energy. At times of peak demand the energy stored in the EV battery can then be used by appliances in the house [209] [210]. This reduces the dependency on the electricity network and flattens the local load curve.

The concept of vehicle-to-grid has drawn a lot of attention by the media and the public [211], as it breaks with traditional paradigms of the consumption of energy by vehicles. But for a use on the bigger scale there still remain several unresolved issues.

The additional discharge cycles of the EV batteries lead to faster battery aging [174]. This means that the batteries' capacities deteriorate over time. The benefits produced by a V2G service would have to be higher than these and other incurred costs. Calculations done by the originators of the concept indicate that significant revenues can be generated by selling V2G power as different products in US electricity markets [208] [212]. But calculations done for the German electricity market of 2009, using the same formulas but different parameters and assumptions, indicate that V2G is not economically feasible in the German case [213].

Another problematic aspect is that today's electricity networks were constructed for a top-down distribution of electricity, from high to medium to low voltage networks. A *load flow reversal* occurs when more energy is locally introduced into the distribution grid, for instance by V2G or by solar panels, than is locally consumed. The flow of electricity is then reversed, from the low voltage network back to the medium voltage network. The voltage level in the local low voltage distribution network rises. This can cause damage in electric appliances and in the distribution network infrastructure [214].

The acceptance of V2G by users also seems to be low. In the survey [215] people were asked about their attitudes concerning different charging technologies with interactions with the electricity system. Many people see an importance in controlled charging, notably for profiting from temporarily lower electricity prices. It is also considered as important that EVs can be charged with the electricity generated by a house's solar panels or with renewable energies in general. However, many are skeptical about allowing V2G funtionalities for their cars. In the survey, only 45.9 % of respondents answered that they would be willing to allow V2G for a payment. Of those responding yes, 42.8 % demanded a payment of 101–200 € per year. 28.8 % demanded the payment to exceed 200 € per year. The survey [216] shows the same trend. Interest in participating in V2G was significantly lower than in a delayed charging scheme. Respondents who were not interested stated that they see little benefits in (apparently unremunerated) V2G (45 %), that they dislike the idea of utilities taking control (16 %), are worried about needing the car suddenly (13 %), and are uncertain about impacts on the battery (13 %). When a payment of 60 € was offered for participating in V2G, 27 % stated that they are more interested.

All in all, it is difficult to give a clear assessment of V2G today. It is an interesting theoretic concept with high potential. But many practical questions are still unresolved. In the report [217] different charging strategies were evaluated from an environmental and economic perspective. The authors come to the conclusion that "the additional gains due to battery discharging (V2G concept) are relatively small compared to unidirectional charging" [217].

3.3. Interactions of EV charging with the electricity system on different levels

In the following sections, effects of EV charging which occur on the levels of generation, storage, transmission networks, distribution networks, and buildings will be discussed. These system levels can also be interpreted as the main areas of responsibility of different stakeholders: producers/providers/traders of electricity (for storage and generation), transmission system operators, distribution system operators, and final electricity consumers such as building owners.

The analysis is done here with the aim of being able to tell which of the numerous occurring effects should be taken into account when planning a charging infrastructure in a city or region. For this, calculations are done to estimate the order of magnitude of some of these effects, and the results are compared to statistical data of the German electricity system. These estimates are done here in the spirit of solving a Fermi problem [218]. It is not the aim to determine exact quantitative values, but only to check if an effect could have a bigger impact or is negligible. Where such direct estimations are not possible, results from selected studies are cited. For the order of scale estimations the following reference values are used:

- *Total number of EVs in Germany in the future*: 1 million. This is the target stated by the German government in 2009 for the number of EVs in Germany by the year 2020 [1]. 1 million vehicles would correspond to less than 2 % (1.88 %) of the vehicle park of 53 million vehicles (of all classes) in Germany in 2014 [219].
- *Energy consumption of an EV*: 22 [kWh/100km] (compare [220])
- *Battery capacity of an EV*: 22 [kWh] (compare [221])
- *Distance driven by an EV per year*: 13 000 [km/a] (compare [222])
- *Charging power used*: 3.7 [kW]. This is the power level which can be expected to be widely used for charging EVs at homes and work places. Higher charging powers can be expected to be used only occasionally for public charging.
- *Simultaneity factor*: 1.0. For simplicity's sake it is assumed in the following that all EVs charge or discharge at once. This can be seen as the worst/ best case.

3.3.1. Interactions on the level of electricity generation

EV charging and discharging can have impacts on the generation of electricity if the form of the load curve is significantly altered. This is the case if new demand peaks are created by uncontrolled charging, if valley filling is implemented by controlled charging, or peak shaving with an application of V2G, or if EVs are charged at times when production from wind and solar power is high. Integrating an EV in a smart home (see Sec. 3.3.5) can partially make the building independent from large scale production of electricity. The most important interactions of EV charging and the generation of electricity have already been mentioned in previous sections in the discussion on uncontrolled charging, controlled charging and additional discharging (Sec. 3.2.1, 3.2.2 and 3.2.3). We will explain the main points again here.

EV charging inserts a new demand into the existing power system. For producers of electricity this is an opportunity to sell more of their product "electricity". How the electricity charged by EVs is produced depends on the timing of the charging. When uncontrolled EV charging creates new demand peaks, this demand has to be covered by peak load power plants. These plants are expensive to operate due to their high fuel costs for mainly gas or oil, and thus raise the overall average production costs of electricity. But if EV charging is scheduled to take place in the nighttime demand valley, this demand can be covered by economically producing base load power plants. The additional demand then leads to a better utilization of the existing base load production capacities. If peak shaving via V2G is implemented, the portion of electricity produced by base load power plants increases, and the portion produced by peak load power plants decreases. This again can lower the overall price of electricity production.

EV charging can be timed to occur especially when production from wind and solar power plants is high. This leads to a more uniform residual load to be covered by conventional power plants. Also, such timing can avoid having to decouple wind and solar power plants from the network at times when their production is so high that the network would otherwise not be able to take up the generated energy.

EVs can be integrated into smart homes. They can take up the energy generated by a solar panel on the roof and give it back at nighttime for use by appliances in the house. This would make the house partially independent from the industrial production of electricity, a case beneficial to the house owner, but probably not in the interest of large-scale electricity producers.

Now the order of magnitude of some interactions between EV charging and the generation of electricity is considered. If 1 million EVs were to drive on German roads, as envisioned by the German government for 2020 [1], they would consume electricity in scale of 1 000 000 [EV] * 13 000 [km/EV*a] * 0.22 [kWh/km] = 2.86 [TWh/a]. This is only 0.45 % of the electricity produced in Germany in the year 2013 [197] (compare Fig. 3.5). This demand could easily be covered by renewable sources only. It corresponds to 9.5 % of the electricity generated by solar power alone or 5.4 % of the electricity generated by wind power alone in 2013 [197].

If these 1 million EVs were to charge their batteries all at once, using a power of 3.7 kW, a rise in demand would be created in the order of magnitude of 1 000 000 [EV] * 3.7 [kW/EV] = 3.7 [GW]. In comparison to that, the minimal load within the German transmission system in the year 2013 was 32.473 GW, and the maximal load was 83.102 GW [223]. The total generation capacity of all power plants with more than 10 MW power in Germany in 2014 was 187.552 GW [224]. When all forms of renewable power plants as well as pumped water storage plants are excluded, the remaining conventional power plants still have a generation capacity of 95.913 GW. So, according to these figures 1 million EVs could be charged at a power of 3.7 kW at once, even during the highest demand peak of the year, even using only power from non-renewable sources.

Based on the estimates above, it seems that the additional electricity demand caused by EV charging in the near future will not be a major challenge for the generation of electricity, neither for the overall energy production nor for peak power. The phase-out of nuclear power in Germany until 2022 [195] and its replacements by other power sources will change some of the listed boundary values. Currently in Germany, nuclear power makes up about 15.4 % of generated energy (97.3 TWh in 2013 [154]) and about 6.4 % of the installed generation capacities (12.068 GW in 2014 [224]).

3.3.2. Interactions on the level of electricity storage

If EVs discharge a part of the energy contained in their batteries back into the electricity networks, they are actually being used as a temporary storage for electricity. In the following it will be discussed how using EV batteries for storage applications would compare to the currently existing electricity storage realized by pumped water storage plants. It will also be shown how old EV batteries, which have been taken out of service, could be used as stationary electricity storage.

Technically there are many possibilities for electricity storage, such as pumped water storage, compressed air energy storage (CAES), flywheels, batteries, capacitors, conversion to hydrogen, storage in the form of heat, and other possibilities [225]. Currently however, only pumped water storage is used in Germany on a bigger scale [226]. These kinds of storage plants store electricity by pumping water from a lower basin up into a basin on a higher level. The electricity is thus stored in the form of potential energy of the water mass. This potential energy is converted back into electricity by letting the water flow back down through a turbine. The electricity is stored in the nighttime demand valley when electricity can be generated cheaply by base load power plants and fed back into the electricity networks at times of peak demand. The overall efficiency (output energy/input energy) of pumped water storage plants in Germany lies in the range of 60 to 85 % [226].

Pumped water storage plants with a total generating power of 9.24 GW are connected to the German electricity network in 2014, among them also plants located in Luxembourg, Switzerland, and Austria [224]. That makes up about 5 % of the generation capacity of the German electricity system [224]. No reliable statistics seem to be available stating the total storage potential of all these plants. But an estimate can be made using the duration such plants can usually operate under full load, which is 4–8 hours [227]. The total storage capacity can than be estimated to lie in the order of magnitude of 9.24 [GW] * 6 [h] = 55.44 [GWh]. In the report [227] an estimate for the year 2009 of 40 GWh of total storage potential is stated, for a lower total generation power of all pumped water storage plants of 7 MW. Over the year 2013 these storage plants delivered more than 5.8 TWh of energy to the German electricity system (hydro power from non-renewable sources [197]), which is only about 1 % of all provided electricity.

In the future the batteries of EVs could also be used as electricity storage in the large scale if V2G is implemented. Using EV batteries as energy storage has the advantage that these storage capacities then serve a double use and do not have to be explicitly built. If available for a V2G service simultaneously, 1 million EVs could provide power in the order of magnitude of 1 000 000 [EV] * 3.7 [kW/EV] = 3.7 [GW], which is 40 % of the generation capacity provided by pumped water storage plants today. Higher powers could be produced with higher power connections of 11 or 22 kW. If a third of the capacity of each EV's battery were used as storage, 1 million EVs would provide a storage potential in the scale of 1 000 000 [EV] * 22 [kWh/EV] * 1/3 = 7.33 [GWh], which would provide about 13 % of the storage capacity of today's pumped water storage. If a third of each of these vehicles' battery capacity were fed back into the network each day this would yield a yearly energy in the order of magnitude of 1 000 000 [EV] * 22 * 1/3 [kWh/EV*d] * 365.25 [d/a] = 2.6785 [TWh/a], making up about 46 % of what pumped water storage provides today. In reality only a part of existing EVs would be available at one time. They would have to be parked, connected to a V2G capable charging station, and have enough battery capacity to allow a feeding back of electricity. Losses during the charging and discharging of the EVs also have to be taken into account. Still, the overall order of magnitude of this total storage capacity does make it an interesting application.

As already mentioned in the discussion of V2G above in Sec. 3.2.3, additional charging cycles due to a storage application lead to faster aging i. e. loss of capacity of the EV batteries. Thus some EV drivers might be reluctant to agree to participating in a V2G scheme. An alternative approach is to reuse old batteries which are no more fit for use in EVs. This is generally assumed to be the case when they have only 70–80 % of their nominal capacity left [228]. The *second(ary) use* [228] or *second life* [229] concept for EV batteries envisions that the batteries will be continued to be used for several years as a stationary storage, before finally being recycled. These stationary batteries can be used for any storage and V2G application discussed in this chapter, such as integration into smart home (see Sec. 3.3.5), provision of balancing power for the transmissions system (see Sec. 3.3.3), or peak shaving. A difficulty for a commercial use in the large scale is the precise determination of used EV batteries' residual capacity and their further expected lifetime as a stationary electricity storage [230].

3.3.3. Interactions on the level of transmission networks

The charging and discharging of EV batteries can have both negative and positive effects on the operation of transmission networks. EV charging can lead to *network congestion* i. e. approaching or exceeding the capacity limits of transmission lines. But EV charging and discharging can also be used beneficially to provide positive and negative balancing power to transmission system operators. These effects are discussed in the following.

Transmission networks have limits to the power they can transfer. If these limits are approached or exceeded, this is referred to as *network congestion*. This has the possible effect that the most economical power plant cannot be used, but instead a more costly one closer to the electricity demand. This raises the overall costs of electricity production. Network congestion can occur when the generation and consumption of electricity is geographically dispersed. Then high amounts of power need to pass through long-distance transmission networks. In Germany this is the case for offshore wind power which is generated in the north of Germany, whereas demand for electricity mostly occurs in the south. This is why large investments in the German transmission networks are planned for the future [231]. When high numbers of EVs are charged and possibly discharged, the overall stress on transmission networks might increase.

Simulations of the impacts of EV charging on the German transmission system are presented in the report [174]. A worst case for the year 2020 is simulated where no wind energy and pumped water storage is available at times of peak demand. Even under these conditions it would be possible to charge 2 million EVs at once with a power of 3.3 kW (assumption in this report) without exceeding the capacities of transmission lines. If electricity from pumped storage is fed into grid during times of peak demand, even 4 million EVs could be charged simultaneously without problems in the transmission system. Taking into account that existing EVs will not be charged all at once, it seems that constraints imposed by the transmission system will not play a role for EV charging in the near future according to this study.

This impression is reinforced when looking at the current network development plan of the four German TSOs. In Germany the TSOs are obliged by law (EnWG §12 [185]) to yearly develop scenarios for the development of the transmission network within the next 10 and 20 years. The scenarios in the network development plan of 2014 do not explicitly take additional strains on the transmission system caused by EVs into account [232] [233]. The report simply states that energy efficiency measures can lead to a lowering of electric consumption in the future, while the replacement of other primary energy carriers by electricity, for which electric mobility is named as an example, can lead to an increase in electricity demand. For the elaborated 10 and 20 year scenarios the overall energy consumption and peak load is assumed to be slightly lower than today.

The charging and discharging of EVs does not only pose a threat, but can also be beneficial for transmission network operation. In Germany the transmission network is divided into four *control zones* managed by the four TSOs. It is each

TSO's responsibility to keep the consumption and generation of electricity within its control zone in balance at all times, taking the exchanges of electricity with the neighboring control zones into account. This corresponds to maintaining the network frequency of 50 Hz within the network. The frequency deviates from this value if the amount of generated energy is not equal to the amount of consumed energy at a certain time. If more energy is generated than demanded, the generators start spinning faster under the lower load, leading to a higher network frequency. If less energy is generated than demanded, the generators spin slower under the higher load, leading to a lower network frequency [234].

Power plants are scheduled to produce the amount of power required at a certain time within the network. But, due to many factors, short-term imbalances between generation and consumption can occur. For instance, it is not possible to predict the consumption of energy by private households and industries with total precision, so small deviations can occur naturally. Fluctuations in generation also occur naturally for wind power and photovoltaics. And, according to German regulations [193], the electricity that these renewable power sources generate *has to be taken up in priority* by the electricity network operators if technically possible. Unpredicted fluctuations can also occur for conventional power generation, for instance if a fault occurs and a power plant has to be taken off the network.

In order to fulfill their duty of network frequency control, the transmission network operators need the services of small power plants (positive balancing power) and also of consumers (negative balancing power), who have to be ready to connect to the grid within seconds or minutes. The balancing powers are divided into three categories in Europe: primary control reserve (activated within 30 seconds), secondary control reserve (activated within seconds up to typically 15 minutes), and tertiary control reserve (activated to replace and supplement secondary control for longer durations) [235]. The four German TSOs publish their calls for tenders for these services on a shared website [236].

The charging and feeding back of electricity from EV batteries provides the opportunity to offer such services of negative and positive balancing power. For such a service to work, it would need the central control of an *aggregator* who controls the charge and discharge of a large number of EVs. The EV owner would receive a small fee for allowing the aggregator to control the charge and discharge of his vehicle's battery. As already explained above in Sec. 3.2.3, this fee would have to be higher than the costs incurred to the user by the aging of the battery due to the additional charge and discharge cycles.

In 2014 the German TSOs published call for tenders of 568 MW for primary control reserve (positive and negative), 2 042 MW for positive and 1 969 MW for negative secondary control reserve, and 2 473 MW for positive and 2 838 MW for negative tertiary control reserve [237]. The call for tenders have the lower limits of 1 MW for primary control reserve (positive *and* negative), 5 MW for secondary control reserve (positive or negative), and 5 MW over six timeslices of 4 h for tertiary control reserve (positive or negative) [236].

1 million EVs, using network connections of 3.7 kW, and if available all at once, could provide a positive or negative load in the order of magnitude of 1 000 000 [EV] * 3.7 [kW/EV] = 3 700 [MW]. This seems to be well in the same scale as the balancing capacities required. Entering the market with a low number of EVs also seems to be feasible. To provide a controllable load or power source of 1 MW, it would require an order of magnitude of 1 [MW]/3.7 [kW/EV] = 270 [EV]. To provide a load or power source of 5 MW it would require an order of magnitude of 5 [MW]/3.7 [kW/EV] = 1351 [EV]. If charging and discharging powers are higher than 3.7 kW an even lower number would be sufficient. Here it has to be taken into account that not all vehicles will be available at once, so a bigger pool of vehicles would have to be used. Still this seams to be feasible, if as already discussed above in Sec. 3.2.3, the prices paid for the service make it economically viable, which does not seem to be the case in Germany [213], and no technical constraints are imposed by load flow reversals.

3.3.4. Interactions on the level of distribution networks

EV charging, added to the present demand in a distribution system, can lead to an overload of the installed transformers and power lines. If too much power is fed back from the vehicles batteries into the distribution network, the installed capacities can likewise be overloaded. These aspects are now discussed in more detail.

When new demand peaks are created by the charging of EVs, the power limits of local transformer stations and distribution lines can be exceeded. High power causes the flow of high currents that can cause damage in the electric distribution infrastructure due to overheating. If the distribution network is operated closely to its power limits, this also shortens the operative lifespan of the installed transformers [175].

As already explained above, an overload can be avoided by scheduling the charging processes of the vehicles. At the distribution network level such a control can be implemented using ripple control by the DSO or by coordination by an aggregator which takes local distribution network constraints into account.

The problem of load flow reversal has also already been mentioned above. If V2G is implemented the discharging of large numbers of EV can lead to a flow of electricity from the local distribution network back into higher network levels. This entails a rise of the power level and puts stress on the network infrastructure and appliances [214]. However, if EV charging is scheduled to occur during times when production from local photovoltaic panels is high, this can effectively decouple the charging of EVs from the distribution network and avoid a load flow reversal induced by photovoltaic production [214]. Another way to partially decouple the charging of EVs from the distribution network is to use large stationary batteries as temporal buffers [120]. Secondary life EV batteries might also be used for this purpose (see Sec. 3.3.2 above).

It is difficult to generally make statements about the order of magnitude of EV charging impacts on local distribution systems. The structure of such systems strongly varies. For instance, in Germany medium to low voltage transformers can have capacities of less than 250 up to 1000 kVA, with 250 kVA, 400 kVA, and 630 kVA being the most often used [238]. Typical structures are also different from country to country. An overview of publications on the impact of EV charging on distribution networks from several countries is given in [239]. In the following a selection of studies applicable to the situation in Germany will be discussed.

The apparently often used CIGRE (Conseil International des Grands Reseaux Electriques) reference distribution network is used for the study [174] on the impacts of EV charging. It is assumed that 145 inhabitants with 60 cars live in the modeled area. In the simulations, power limits of distribution lines are already being reached with charging powers of 3.7 kW and only 3 % of households having EVs (i.e. two EVs in the modeled area). If higher charging powers are used, the limits are exceeded even earlier. If controlled charging is implemented the limits for 3.7 kW charging can be pushed up to 17 % EV penetration (i.e. 10 EVs in the modeled area). Then charging with higher powers is also possible. Limits for the discharging of EV batteries into the distribution network have also been modeled, here the limits lie higher with 20 % (i.e. 13 EVs) for 3.7 kW discharging in the worst case. The authors conclude that 1 million EVs in Germany by the year 2020, corresponding to a 3 % penetration rate, can already cause problems in the analyzed distribution network if their charging is uncontrolled. Higher charging powers can only be used if EVs do not charge simultaneously.

In the article [240] a medium voltage network with the underlying low voltage networks is modeled. The modeled network has a peak load of 14.3 MVA without EV charging. EVs are assumed to only charge using households sockets. With a penetration rate of 25 % of EVs and uncontrolled charging, one network branch exceeds the rated current. With 50 % of EVs and uncontrolled charging, several technical constraints are violated. Using intelligent charging allows to charge 25 and 50 % of EVs without problems to the analyzed distribution network.

The report [241] presents simulations performed with eight reference networks deduced from distribution networks in residential areas in Berlin. Charging powers of 3.7, 11, and 22 kW are assumed. Analyses are done for the transformers, cables, and for the voltage level. The transformers are found to be the most critical resource. With a base load of 70 % on transformers and using charging powers of 11 kW, it is possible to reach EV percentages of 30 to 80 % in the analyzed areas. If a lower charging power of 3.7 KW is used, more EVs can be charged. The authors conclude that 1 million EVs in Germany by 2020 will cause only few problems in distribution networks. However, they also advise to limit the charging power of EVs in residential buildings, using 3.7 kW in the majority of the cases and maximally 11 kW.

The article [242] analyzes a mixture of 200 low and medium voltage distribution networks from Germany and other European countries. The analyses show that about half of them can integrate 100 % of EVs with connection powers up to 11 kW. But a small number of 10 grids was found to already need reinforcements for EV penetration rates as low as 5 %. The results show that urban networks tend to be able to take up the additional load due to EV charging better than suburban or rural grids. The medium voltage grids were found to tolerate much less additional loads, with many of them not supporting any EV charging without additional grid reinforcements.

So, as already said, it seems difficult to make general statements about the impacts of EV charging on distribution systems. It appears that the low numbers of EVs in the next years will cause no problems in most distribution networks. However, problems can occur in some networks, especially if there are local clusters of EVs and/or higher charging powers are used. Such problems can be mitigated using low charging powers of 3.7 kW and/or controlled charging schemes.

3.3.5. Interactions on the building and power line level

On the scale of individual buildings and low voltage lines, EV charging can lead to a degradation of power quality due to introduction of current peaks and voltage harmonics. EV charging can also lead to voltage imbalances among the three phases in the electricity network or lead to an overload of the installed building connection. If EVs batteries are integrated into a smart house this has positive effects both for the building and the overlying distribution network. In the following these effects are discussed one by one in detail.

Electricity needs to fulfill certain normed characteristics in order to be best usable by electric appliances. Aspects which determine the *quality* of electricity in Germany include: a sinus-shaped voltage progression with stable amplitude (resulting in 230 V nominal voltage) and stable frequency (50 Hz with no additional harmonics) [243]. Large deviations from these normed attributes can cause disturbances and damage in sensitive electronic equipment. An effect which can easily be observed by the naked eye is the flickering of lights caused by voltage fluctuations. Such deterioration of the electricity quality in a network can be caused by effects both during the generation and consumption of electricity [191].

When EV charging facilities are connected to the electricity network, they can create *start-up current peaks* [244] The AC-DC converters (rectifiers) which are integrated in charging facilities can introduce *voltage harmonics* into the local electricity network [245]. Voltage harmonics are distortions of the sinus-shaped standardized voltage progression.

It is therefore necessary to thoroughly test charging facilities for their compliance to existing norms and regulations for electric appliances concerning electromagnetic compatibility [246] [82]. Such requirements are being or have already been integrated into the norms for AC and DC charging stations DIN EN 61851, part 21-1 [247], part 21-2 [248], part 22 [249], and part 23 [63]. The charging facilities also have to fulfill the requirements concerning impacts on power quality stated by the responsible distribution network operator [250] [251]. Different technical organizations already provide services to test charging stations for compliance to existing norms [252] [253].

When the monophase charging of many electric vehicles is unevenly distributed among the phases in a triphase distribution system, this can cause a *voltage imbalance* between the phases [254] [174]. The problem can be mitigated by the

DSO by prescribing to each client which phase his charging facility should be connected to, and thus distributing the load among the phases [241].

Problems might also occur on the level of individual buildings if the power of one or several EVs charging together with the electric load of other electric appliances exceeds the capacity of the installed building connection. The capacity of the building connection is determined by the distribution network operator according to DIN 18015-1 [255], based on the requirements of the house constructor when the building is first connected to the network. For a triphase connection of 230/400 V the norm states a minimal ampere rating of 63 A for 1 to 5 dwelling units without electric heating and water heating. This corresponds to an overall power capacity of 43.6 kW. For the peak demand of individual households, 8 to 30 kW, depending on the number and types of electric appliances used, can be typical [238]. So such minimal installed building connection capacities can be exceeded if EVs are charged at high powers (7.4, 13.9, or 22.2 kW) or if several EVs are charged at once. If the building connection needs to be upgraded or/and investments need to be made into the power lines and transformers of the distribution network, the distribution network operator can force the customer to pay a part of these expenses [250]. To avoid this, ICT companies provide software that schedules the charging of a large number of EVs in such a way that the total charging power never exceeds a given power limit [204] [133] [140].

The integration of charging facilities into a building's electricity system can go further in a *smart house* [256]. In such a house ICT coordinates the charging of the EV with the consumption of electricity by household appliances, such as the washing machine. The charging of the vehicle can also be coordinated with local electricity generation, for instance by photovoltaics. If the battery is used as an intermittent energy storage, the house can also draw energy from the battery during times of overall high demand. The feeding back of energy from the vehicle to the house is also referred to as *V2H (vehicle-to-home)*. A smart house is thus partially autonomous from the power system by locally controlling its own generation, storage, and consumption of electricity. This mitigates the impacts of both the high power demand of EV charging and household appliances, and the fluctuating energy generated by a photovoltaic installation on the higher-level power systems.

In Germany a household with 2, 3, or 4 members, living in a detached house without electric water heating, consumes in average 3 200, 4 000, and 4 400 kWh per year respectively [257]. In relation to that, the annual electricity consumption of one additional EV lies in the order of magnitude of 22 [kWh]/100 [km] *

13 000 [km]/[a] = 2 860 [kWh]/[a]. This means an enormous increase in the overall electricity consumption of the household of 90 to 65 %.

3.4. Electrical installation of charging facilities

After having looked at the impacts of EV charging on different levels of the electricity system in the previous sections, now the focus will be put on the very specific aspects of the installation of EV charging facilities on location. The electrical installation of charging facilities has to be done by a qualified electrician. There even exist specific professional trainings for electricians on this topic [258] [259]. Several publicly accessible handbooks have already been published on the topic in Germany [39] [32] and in the USA [176] [177] [178] [179] (and others). Some manufacturers of charging facilities also provide installation instructions for their products [260] [261].

The most important points to be considered will be presented in the following. This is not meant as a detailed installation manual, for this the documents listed above and the relevant standardization documents themselves, named below, should be consulted. The discussion here is only meant to provide the most important background information to EV infrastructure planners.

Generally, two cases for the electrical installation can occur: the charging facility is connected to a building's electrical installation behind the house connection box, or the charging facility is directly connected to the distribution network with its own service connection box. For the electrical installation of such facilities the requirements of the documents listed below have to be taken into account. The standard DIN 18015-1 only plays a role when installing charging facilities within existing buildings' electrical networks. The document VDE-AR-N 4102 is only relevant for public charging facilities located outdoors.

- The *Low voltage connection decree (Niederspannungsanschlussverordnung NAV)* [250] sets the general framework for connection of clients' facilities to the low voltage distribution network.
- The *Technical connection requirements for the connection to the low voltage network (Technische Anschlussbedingungen TAB für den Anschluss an das Niederspannungsnetz)* [251] extends the requirements for clients' facilities based on NAV §20, where it is stated that distribution system operators can issue further technical requirements. The document TAB

is such a document commonly used by all German DSOs, with possible comments and modifications by the local DSOs.

- The standard *DIN 18015-1* [255] treats basic principles for the planning of electric installations in residential buildings. In section 5.3.2 of this standard, the case of EV charging equipment is treated.
- The norm *DIN VDE 0100-722* [35] lists detailed requirements for the installation of conductive charging facilities in low voltage systems.
- The rule of application *VDE-AR-N 4102* [34] lists further requirements specifically for public charging stations which are located outdoors and which are directly connected to the low voltage distribution network. Many of these requirements play a role for the construction of the casing of the charging facility, but not for the final electrical installation.

The requirements for the installation of charging facilities for EVs are spread out among these documents, with several overlaps. The following list gives an overview of the most important requirements, sorted into three topics. These topics are the connection of the building/charging facility to the distribution network, the electric installation behind the house/service connection box, and the charging facility itself. For each aspect, the corresponding document is cited at the end of the paragraph. Additional explanations have been added by the author which are not part of these documents.

For the *connection of a building or a public charging facility to the distribution network* the following points have to be taken into account:

- A network connection contract is established between the client and the distribution network operator. The power of the network connection is stated in this contract. An example contract formula and an associated form of a German DSO can be seen here: [262] [263]. The DSO can demand a fee for the installation or change of the network connection. The DSO can also demand additional fees for the maintenance or upgrading of the overlying distribution network. An example of these fees from a distribution network operator can be seen here: [264]. Generally the fees are higher, the higher the required ampere capacity of the connection is, and the longer the length of the connection is (see for example [264]).
- The owner of the parcel of land on which the network connection is to be made has to agree in written form to the installation (example in form [263]). This is especially relevant when charging facilities are set

up on public or semi-public ground not directly controlled by the owner of the charging infrastructure. [250]

- The connecting cable of the facility to the distribution network is installed by and remains the property of the DSO. This connection runs from the branching point of the distribution network to the service connection box of the client. The responsibility for the facility behind the service connection box lies with the client. [250]
- The DSO determines the level of the overcurrent protection device for the network connection. [251]
- For buildings the network connection is in the form 230/400 V triphase, with minimally 63 A ampere rating. This allows a total power of about 43.6 kW. However, this minimal ampere rating remains valid for up to 5 dwelling units (if no electric heating and electric water heating is used). [255]
- When connecting a charging station directly to the distribution network, usually a triphase connection of 400 V is also chosen. A monophase connection (230 V) is only admissible for powers up to 4.6 kW. [34]

For the *electrical installation behind the service/house connection point* these points have to be considered:

- Electric main lines behind the service connection box have to be in the form of a radial distribution system (i.e. all main lines are directly connected to the service connection box, with no cross links among themselves). Every main connection line behind the service connection box with its own meter also needs to be protected by its own overcurrent protection device (i.e. circuit breaker), installed before the meter. [251].
- The power cable between the main distributor and the charging facility is to be triphased and have an ampere rating of 32 A (allowing a charging power of up to 22 kW). Additionally a duct for installing a communication network cable has to be installed. In the mains distributor additional space should be available to install an additional meter and further ICT components. [255]
- Every charging point has to be supplied via its own electric circuit. The concurrency factor of the circuit supplying the charging point has to be assumed as 1. This means that all other electric equipment attached to this circuit is assumed to be used at once. It is also assumed that all charging points are used with their nominal power at once. If a load management

system is implemented the concurrency factor of the overlying distribution circuit supplying several charging points can be assumed to be lower. [35]

- Every charging point has to be protected by its own residual current protective device (RCD) with a difference current rating of no more than 30 mA. These devices disrupt the electric circuit when they detect a current leakage, and thus protect persons from electric shock. The RCD has to be of at least type A. This type detects AC and pulsating DC current leakages [265]. If DC current leakages above 6 mA could occur (for instance at DC charging stations) a RCD of type B has to be used. This type detects AC, pulsating and also uniform DC current leakages [265]. [35]
- Every electric circuit supplying a charging point has to be protected by an overcurrent protective device (i.e. circuit breaker). Also, each electric circuit *should* be protected by an overvoltage protective device (i.e. surge protection device (SPD)) to protect the EV from possible damage due to lightning strikes into the distribution network. [35]
- If an emergency switching-off is necessary, the facilities have to be able to shut off the maximal charging current, and all active conductors and the neutral conductor. [35]

For the *charging facility* itself these requirements must be fulfilled:

- The client has to assure that no disturbances to the distribution network arise from the facility. This can be assumed to be the case when all relevant norms are fulfilled [250] [251]. The rule of application [34] explicitly names the standards DIN EN 61851-1 [22] and DIN EN 61851-22 [249] which specify requirements for electromagnetic compatibility. The rule of application also explicitly recommends to use a Type 2 plug according to DIN EN 62196-2 [44].
- The connection of electric facilities with a power demand of more than 12 kW needs the explicit permission of the DSO. The client provides the DSO with necessary information to allow it to determine the power requirements and judge the impacts on the network (an example form can be seen here: [266]). [251]
- Every socket outlet or connector is allowed to supply only one EV. [35]
- In charging modes 3 and 4 it has to be assured that no feeding of electricity into the local electric installation is done unintentionally. In charging modes 1 and 2 (see Sec. 2.1.1) a feeding in of electricity is not allowed. [35]

A visual overview of the important requirements listed above is shown in Fig. 3.10. Different constellations can fulfill these requirements. The scheme shown here is meant to represent a charging station providing two charging points in public space. A master charging pillar can contain the service connection box and meter with their associated overcurrent protection devices. Two satellite charging pillars can contain the required safety devices and the charging facilities themselves. Each satellite charging pillar has an own submeter for billing clients. If the charging service were billed according to charging time, and not charged energy, gauged electricity submeters would not be not required (see § 4 (2) MessEV [267] [268]). In the case of an installation within an existing building electrical network, the service connection box would be the existing house connection box. Further meters for dwelling units would be attached to the house connection box.

After the charging facility has been installed, it has to be checked for proper functioning for the first time. Checks of electric appliances are done according to DIN VDE 0100-600 [269]. Such a check consists of the three elements: inspection (visual and manual checking of parts), measurement (values of currents, voltages etc.), and testing (actual use of the equipment, especially of the installed safety measures). The charging facility has to be checked for proper functioning at regular intervals according to DIN VDE 0105-100 [270]. Compact service cases are available which allow to simulate the charging of an EV, and perform associated tests without the use of an EV [271]. The results of these checks have to be documented in a protocol (example at [272]).

3.5. Summary: interactions of EV charging and the electricity system

Figure 3.11 gives an overview of the effects that have been discussed within this chapter. The interactions are classified into threats (negative effects), countermeasures (possibilities to mitigate these negative effects), and opportunities (positive effects). This is an extension of a classification presented in [173].

All in all, it can be seen that uncontrolled charging poses a potential threat on almost all levels of the electricity system. But these threats can be mitigated with the implementation of controlled charging. Controlled charging could take into account different constraints on the different concerned levels of the electricity system.

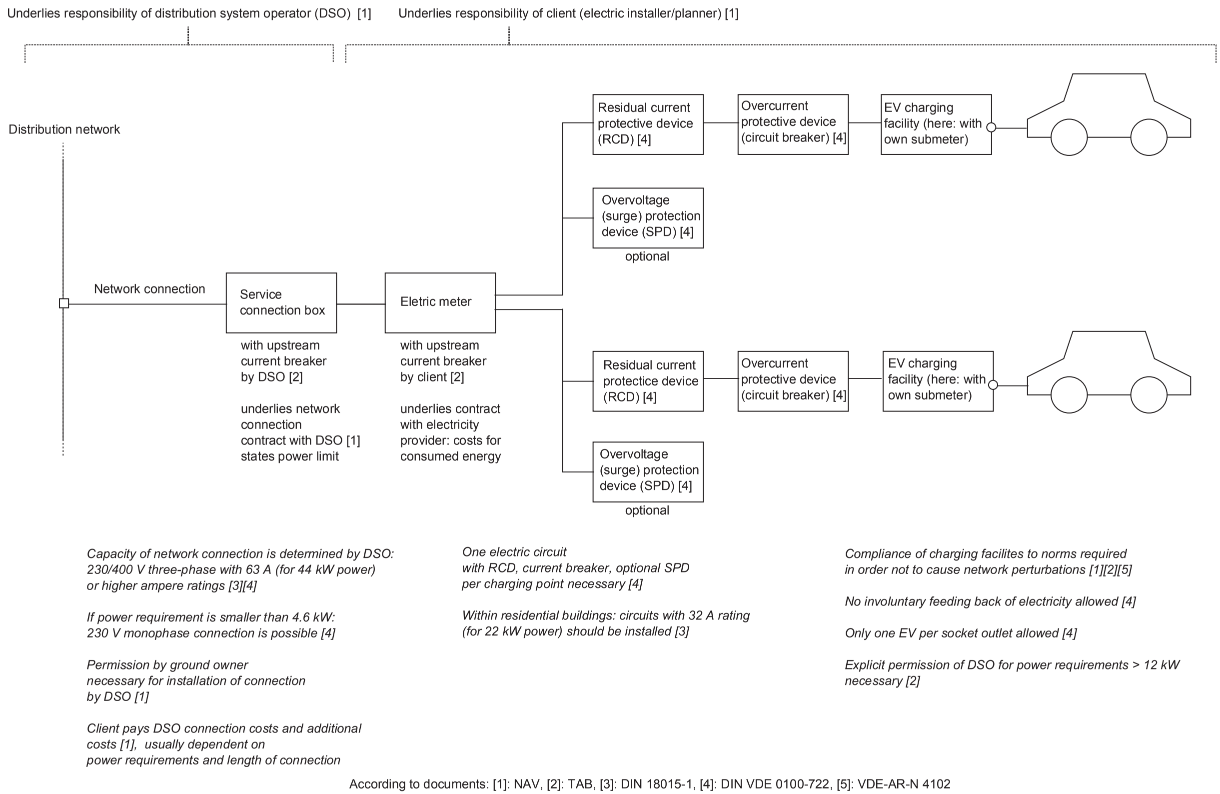

Figure 3.10.: Overview of the most important requirements for electric installation of charging facilities

At the moment it does not seem clear, however, how these different constraints should be weighted if they are opposing each other. If more sophisticated charging and discharging schemes are implemented, such as valley filling, peak shaving, or vehicle-to-home, EVs can even bring about positive effects for the operation of electricity systems on all levels.

In the detailed discussion of these effects in the sections above, attempts were also made to determine the order of magnitude of the different interactions. It seems that impacts are negligible on the large scale but can be significant on the small scale. As has been shown in Sec. 3.3.1, on the national level of Germany, 1 million EV would consume less than 1 % of the produced energy and be able to increase peak demand by only a few percent. EVs do not pose any problems for the German transmission system in the near future. Problems in the distribution network are rare, but can occur with only a handful of vehicles present, as has been shown in Sec. 3.3.4. Finally, as shown in Sec. 3.3.5 a single EV can increase the energy consumption of an individual household by 60–95 %.

This can also be interpreted as a stochastic effect which depends on the size of the sample. Considering all German households and businesses, 1 million EV would make up only about 2 % of all vehicles. As the number of concerned households and businesses gets smaller within transmission systems, distribution systems, and individual buildings, the possible spikes caused by small numbers of EVs become more and more significant. Having a household with 1 EV, means that in this sample 100 % of the vehicle park is electric. Of course the other 49 households with 0 % EVs would not have any problems. Supporting "0.02 EVs" would not be a problem on the household level either. This would be an electric appliance with a power of 0.02 * 3.7 [kW] = 74 [W], which corresponds to about the power of a single light bulb.

The electricity storage potential of EVs as shown in Sec. 3.3.2 is exempt from this effect. 1 million EVs used as storage could have a significant impact on the national level. This is because existing storage potential from pumped water plants is rather small, making up only about 1 % of all energy provided to the electricity system. Other forms of electricity storage are not economic enough for an implementation in the larger scale. Therefore the dual use of 1 million EVs for energy storage could already have a significant impact in this domain.

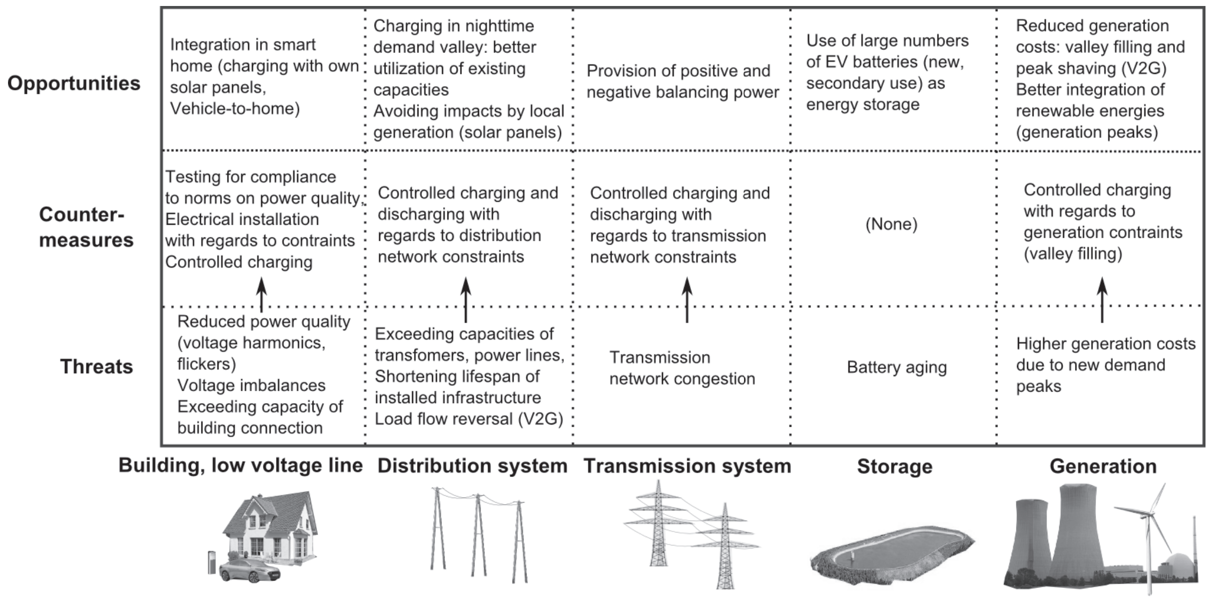

Figure 3.11.: Overview: interactions between EV charging and the electricity system on different levels

3.6. Implications for the planning of a local charging infrastructure

In this section the practical implications for the planning of a local charging infrastructure will be treated. As has been shown, the impacts of EV charging on the German generation capacities and the transmission system will be rather small. It is therefore advisable to focus on effects which occur on the level of distribution systems and individual buildings. Some further practical information relevant in this context will also be provided here.

Implications for the choice of the charging facility and implementation of controlled charging and discharging are the following:

- In order to not degrade power quality on the local scale, only such charging facilities should be installed that have been extensively tested for electromagnetic compatibility by independent organizations and received a corresponding certificate (see Sec. 3.3.5).
- The use of charging facilities can be expected to evolve from uncontrolled charging, to locally controlled charging, to centrally controlled charging, to possible V2G or V2H applications in the future. More sophisticated forms of communication between EVs and charging facilities than the presently used ones will arise once the norm ISO 15118 (see Sec. 2.1.1.1) is established. Charging facilities should therefore be bought from manufacturers who promise (or ideally guarantee) to retrofit and upgrade the charging facility models bought from them.
- Though the benefits of controlled charging and discharging have been listed above in detail, such applications make sense only for charging at homes or workplaces. There the vehicles remain parked for several hours allowing for enough flexibility in the timing of the charge and possible discharge. Public charging facilities, however, can be expected to be used only when EV drivers really need the recharge. They will want their vehicle to be charged by a significant amount within a short time and will not tolerate a deliberate delay of the charging operation. V2G applications also do not make sense for public charging facilities within the next years. These charging facilities should be available to EVs that require a recharge. But in a V2G application these facilities could be blocked by EVs which have already charged at home or the work place and are now feeding their stored electricity back into the electricity network. It seems that the only form

of controlled charging sensibly applicable to public charging stations is limiting the total power demand produced by a charging station at which several EVs can charge at once.

For the *connection of charging facilities to the distribution network* two cases can occur: the charging facility is connected to the electric cabling already existing in a building, or it is directly connected with its own cable to the distribution network. Implications for these two cases are:

- When charging facilities are installed at homes or workplaces, they are usually connected to the building network behind the building connection. The capacity of the connection of the concerned building represents the major possible bottleneck. Exceeding the installed capacity or requiring a more expensive connection supporting higher powers can be avoided by charging with low power (3.7 kW) and/or scheduling the charging of EVs to take place in the late nighttime when other high-power household appliances (laundry dryer, electric stove etc.) are not in use. If several EVs need to be charged at once, a local control system can be used which assures that the total power demand does not exceed a given limit (see Sec. 3.2.2).
- When public charging facilities are set up at curbside parking places, they require their own new connection to the distribution network. For the public charging facility it does not make a big difference if it is placed on the other side of the street or 20 m further down the road. This way, the length of the cable between distribution system lines and the new charging facilities might be decreased, which lowers costs for cabling and ground works. In Germany distribution cables are usually installed underground at both sides of the street. The presence of street lighting on a side of the street indicates the presence of distribution network cables [174]. By moving the location of a charging facility it might also be connected to another distribution line or transformer station which is much better suited to take up the additional load. Thus, to allow a cost efficient and impact-minimizing connection of charging facilities to the distribution network, network planners from the distribution network operator should be consulted when planning the locations of public charging facilities on the street scale.

4. The demand for (public) charging infrastructure

Despite the extent of research that has treated the planning of a charging infrastructure of electric vehicles in the last few years, the actual *demand* for such a public infrastructure is still not fully understood. Several publications deal with specific aspects of this demand, but few seem to treat the topic in an encompassing way.

An analysis from several angles is given in [273]. The article discusses demand from a mobility perspective, from a psychological perspective, based on simulation studies, and based on empirical findings from pilot projects. An analogy is seen in the demand for refueling stations for natural gas vehicles, where a lack of such infrastructure seems to hinder the large scale adoption of these cars. In this chapter a similar approach will be taken, by trying to understand the demand for charging infrastructure by looking at it from different angles.

The article [274] points to the conflict between the low measured utilization of public charging in pilot projects and the levels of utilization that would be necessary to operate the infrastructure economically. The authors also analyze demand from a mobility behavior perspective in another article [275].

The report [14] includes a chapter on the implementation of charging infrastructure in line with demand. The discussion combines the aspect of demand and the location planning of charging infrastructure. The report provides an overview of different methods which were used to determine demand for charging infrastructure from geographic data in the pilot regions. The demand for charging infrastructure is discussed within a framework of the following questions, which differentiate dimensions of demand: How many charging points? Where should they be located? Which technology should be used? Who are the users? When should the charging points be implemented? Within this thesis, spatial and temporal aspects of demand are treated in later Chap. 8 and Chap. 10.

Additionally to researchers trying to understand the demand for charging infrastructure in an objective way, political organizations such as the German national platform for electric mobility and the European Union put up targets for a future public charging infrastructure.

In 2014 the German national platform for electric mobility (NPE) published its updated point of view on the demand for charging infrastructure in the report [276]. For the case of 1.134 million EVs in 2020, the NPE sees a demand for 111 000 AC charging points in semi-public space and 70 000 in public space (see Fig. 4.1). The results originate from a commissioned unpublished study from the Federal Association of the German Energy and Water Industry (BDEW) and the consulting company A. T. Kearney. These values would correspond to about 1 semi-public charging point for every 10.2 EVs and 1 public charging point for every 16.2 EVs. Or together 1 semi-public or public charging point for every 6.3 vehicles. The NPE sees an additional demand of 300 fast charging points for the first 100 000 EVs. This corresponds to 1 fast charging point for 333.3 EVs.

The European Parliament and the Council have agreed on a directive on the deployment of alternative fuels infrastructure in 2014 [43]. The directive obliges EU member states to implement a minimal charging infrastructure for EVs. Such an infrastructure is described by:

> "Member States should ensure that recharging points accessible to the public are built up with adequate coverage, in order to enable electric vehicles to circulate at least in urban/suburban agglomerations and other densely populated areas, and, where appropriate, within networks determined by the Member States. The number of such recharging points should be established taking into account the number of electric vehicles estimated to be registered by the end of 2020 in each Member State. As an indication, *the appropriate average number of recharging points should be equivalent to at least one recharging point per 10 cars*, also taking into consideration the type of cars, charging technology and available private recharging points. An appropriate number of recharging points accessible to the public should be installed, in particular at public transport stations, such as port passenger terminals, airports or railway stations. Private owners of electric vehicles depend to a large extent on access to recharging points in collective parking lots, such as in apartment

> blocks and office and business locations. Public authorities should take measures to assist users of such vehicles by ensuring that the appropriate infrastructure with sufficient electric vehicle recharging points is provided by site developers and managers." [43] (emphasis added by author)

It is not explained how the lower limit of one charging point per 10 EVs was determined.

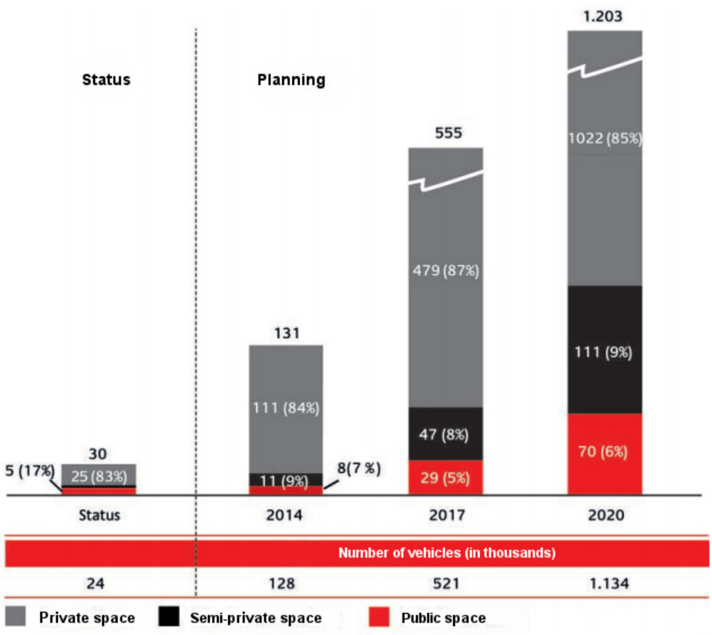

Figure 4.1.: Demand estimation for numbers of charging points (in thousands) by the German platform of electric mobility, "Status" is year 2013 [276] (translated)

Fig. 4.2 shows the actual development of the number of EVs and publicly accessible charging points in Germany from December 2011 to December 2014. By the end of 2014 there were 26 006 EVs (including PHEVs) registered in Germany. The number of publicly accessible charging points (including DC charging points) was 5 553 at that time. That makes 1 publicly accessible charging point for 4.68 EVs and 1 publicly accessible fast DC charging point for about 255 EVs.

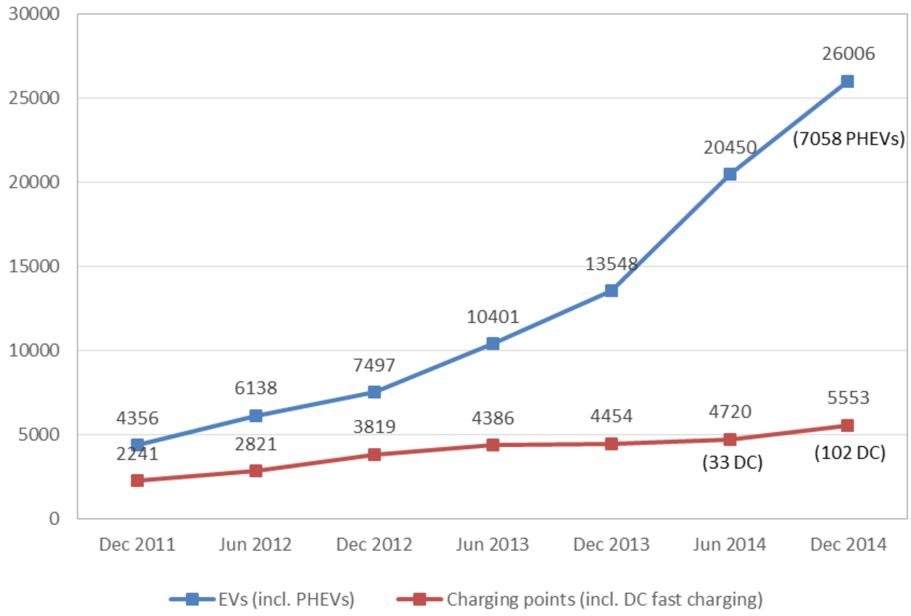

Figure 4.2.: Development of the numbers of publicly accessible charging points and EVs in Germany, December 2011 to December 2014 (data from [4])

It can be seen that, similar to the confusion between the terminology of "charging points" and "charging stations" (see Sec. 2.1.1), different terminologies are in use concerning the accessibility of charging stations (compare [11] [277] [14] [276]). The following terms will be used within this document:

- *Public charging station*: a charging station that is publicly accessible to EV drivers (not taking required membership at a specific service provider or similar limitations of use account). Within this document this term includes fully public charging station set up at public curb sides, but also semi-public charging stations (see next definition).
- *Semi-public charging station*: a charging station that is accessible only to parts of the public, for instance the clients of a business. Examples for semi-public charging stations are charging stations located in publicly accessible parking garages, at supermarkets, cinemas, and similar venues open to the public. Such charging stations may only be accessible during business hours.

- *Private charging station*: a charging station that is only accessible to selected private users (for instance the residents of an apartment house or the employees of a company).

The ownership of the ground on which the charging station is located (public ground or private ground) is *not* considered as a criterion in the above definitions. Accessibility to the charging station is seen as the key differentiating factor.

An interesting reference value to know is the number of gasoline stations in Germany (also see [278]). The number has been steadily decreasing in the last decades. In 2014 there were 14 622 public gasoline stations in Germany, 350 of them situated at rest areas of motorways [279]. It can be assumed that almost all of these had several fuel dispensers. At the same time there were 43 171 486 cars powered by gasoline and diesel (not including hybrid vehicles and trucks) in Germany [280]. That makes one gasoline station for 2 953 cars. This value might serve as an orientation for a required number of battery swapping stations or ultra-fast charging stations. But for public charging stations with slow and normal charging, where the cars remain parked for long durations, no direct inferences can be drawn. The use of these facilities is too different.

In the following sections the demand for public charging infrastructure will be analyzed by looking at it from different angles and incorporating results from different studies. First, the interaction of supply and demand in general are discussed. It is explained how demand and supply are defined in microeconomic theory. For the development of a charging infrastructure in the first years, the so-called chicken-and-egg dilemma will also be discussed. The demand for charging infrastructure will then be approached from three different perspectives: from the users' point of view, from the charging infrastructure operators' point of view, and when seen as a public service not underlying free market mechanisms. In the final section general conclusions will be drawn from this discussion for the planning of a charging infrastructure for EVs in a city or region.

4.1. Demand and supply

This section will treat the interdependence between the demand for charging points by users and the operators' willingness to supply a certain number of charging points. First demand and supply will be presented as they are understood in classic microeconomic theory. Then an analysis will be done of the chicken-and-egg dilemma supposedly occurring in the early stages of an EV infrastructure development.

4.1.1. Demand and supply in microeconomic theory

Microeconomics provides numerous models which help to understand specific aspects of markets. In the following it is discussed how supply and demand for a good are usually understood within this discipline [281] [282] [283] [284]. From the general microeconomic model several things can be learned about the supply and demand for charging points of EVs. At the end of the section it will also be discussed which relevant aspects are not included in the generic microeconomic model.

The interaction of demand and supply for a homogeneous good in a competitive market is visualized in Fig. 4.3. Demand for a good by consumers is modeled in form of a *demand curve*. The curve describes the quantity of a good that consumers are willing to buy, depending on the price of the good. If the price is low many customers want to buy the good. As the price for the good gets higher, consumers only want to buy the good in lower quantities. The willingness of producers to provide a certain amount of a good, dependent on the price, is modeled in form of the *supply curve*. If the price for a good is low, producers are willing to produce only low quantities of the good. But if prices rise, more of the good is put onto the market.

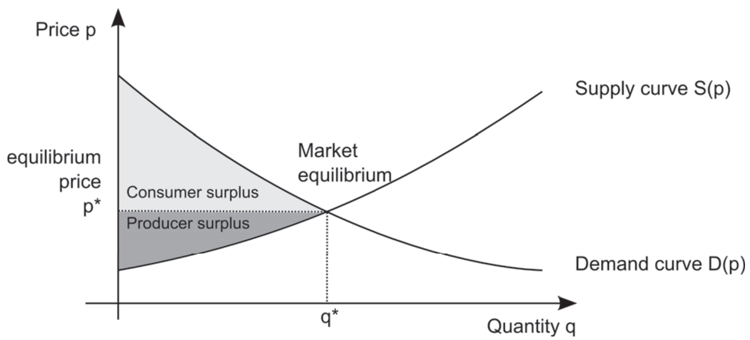

Figure 4.3.: Demand and supply for a homogeneous good in a competitive market as seen in classic microeconomic theory

The intersection of the demand and the supply curve is called the market equilibrium. At this point the quantity q* of the good is traded at the equilibrium price p*. The market equilibrium has the characteristic that the produced quantity corresponds to the consumed quantity of good (q* = S(p*) = D(p*)). In competitive markets the prices tend to adjust to reach the market equilibirium [282]. If the market price is lower than p*, demand is higher than supply. In this situation some producers will decide to produce more goods at higher prices than the market price, to satisfy the unmet demand. When more and more producers do this, the quantity of supplied goods and the market price rises. In a similar way, when the market price is higher than p*, demand is lower than supply. Producers which are not able to sell their goods will lower prices and/or produce lower quantities of the good. This pushes the market price and quantity of produced goods down towards the market equilibrium. The market equilibrium is an “equilibrium” in the sense that it is a situation in which no producer or consumer has an incentive to change his action [281].

The *consumer surplus* is the surface (the difference) between the realized price and the demand curve. It describes the total surplus that is created by consumers receiving the good at a price below that which they would be willing to pay for it. The *producer surplus* is the surface (the difference) between the supply curve and the realized price. It describes the surplus that is created by producers receiving a price for their goods which is above that for which they would have been willing to sell. In the market equilibrium the sum of consumer surplus and producers surplus is maximized. This is one argument why competitive markets, ideally resulting in market equilibria, are preferable to other market structures [284].

This basic microeconomic model can already help understand a few aspects of the demand for charging infrastructure. Applied to this domain the quantity of the good is the number of public charging points and/or the amount of energy charged at these points. The price is the price to be paid for the charge, for instance in the form of € per kWh. The consumers are the EV drivers, the producers the operators of charging infrastructure.

This basic model shows that it makes little sense to talk about the demand for charging infrastructure as a fixed quantity. Understanding demand involves taking into account at least the interactions between:

- The EV drivers’ (i.e. consumers’) economic interests
- The infrastructure operators’ (i.e. producers’) economic interests

- The quantity of charging points
- The price for the charging service

This is why three perspectives will be taken in the next sections: the users' perspective (Sec. 4.2), the operators' perspective (Sec. 4.3), and when seen as a public service not underlying free market mechanisms (Sec. 4.4).

If charging at public stations is free of charge, it makes economic sense for EV drivers to charge as much as possible there and use the private charging point at home less. So in such a situation the demand for public charging is high. But if the price for charging at a public station is significantly higher than that paid for electricity when charging at home, EV drivers will be much more selective about public charging, and the demand for public charging sinks.

Another visible aspect is what can happen if numbers of charging point are set up as targets without considering market mechanisms. If a desired quantity of charging points is stated, which lies above the market equilibrium quantity q^*, a gap exists between the price that EV drivers are willing to pay, and the price that the operators expect for the service. Rationally acting suppliers in a competitive market simply will not supply such a high number of charging points.

However, if the produced supply is a fixed number, independent of the price for the good, the situation can also be analyzed using demand and supply curves [281]. Examples of this are fixed ratios for charging points such as: 1 charging point per 10 EVs in the region or 1 charging point for every 50 parking spaces. In this case the supply curve is a vertical line in the graph at the fixed quantity q^* (see Fig. 4.4). The equilibirum price p^* is solely dependent on the demand curve. In the market equilibrium the price is set at a level where supply exactly meets demand. When the price is set higher, the demand is lower than supply. The installed charging points would be underutilized. When the price is set too low, too many EV drivers want to charge which leads to an over-utilization of the available charging points. An analogy exists here to the pricing for public parking spaces. A good pricing policy can lead to a more efficient use of the available parking spaces. A sufficient amount of them is kept free for those car drivers who need them urgently enough that they are willing to pay a certain amount for them [285].

It is also worthwhile to note the effects occurring with the supply and demand for charging points that the above basic microeconomic framework fails to reproduce. A *competitive market* requires that each EV driver can charge at each infrastructure provider's charging points. In Germany operators are working on providing roaming solutions between different providers, allowing a client of one operator to also charge at other operators' facilities (see Sec. 2.2). In 2014 this is not fully realized yet, however.

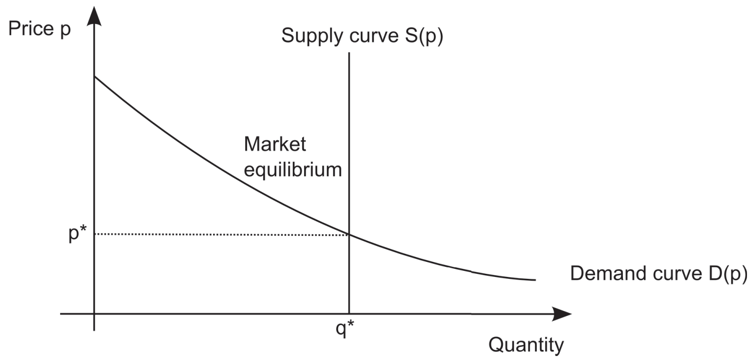

Figure 4.4.: Demand and fixed supply which does not depend on price

In the basic case a *homogeneous good* is assumed, which is a good that consumers can not differentiate for instance by the quality of the good. Electricity is such a homogeneous good. But it makes sense to differentiate different possibilities of charging this electricity. Fast charging points can be expected to be used differently from slow and normal charging points. The location of the charging point can also play a big role for its use, whether it is at a shopping mall, on the street near the city center, or at a motorway service station.

It also makes sense to consider differences in demand from drivers of different EV types. Plug-in hybrid EVs (PHEVs) and range-extended EVs (REEVs) can run on gasoline or on electricity. In the terminology of economics these two are then *substitutable goods*. If the electricity from public charging stations is cheaper per km than the equivalent for gasoline, it makes sense to charge the battery publicly. Because PHEVs and REEVs usually have smaller batteries than pure EVs, these types of vehicle might even use public charging points more often, and have a higher willingness to pay for such a service.

On the supply side, it can be expected that some operators will not care about the willingness to pay of EV drivers and will provide charging for free. Restaurants, hotels, cinemas, and similar venues emphasizing customer satisfaction and retention can provide free charging as an additional service to their clients. For them the charging service does not need to be profitable because they generate their revenues from other products and services (also see Sec. 5.4).

4.1.2. The chicken-and-egg problem

The interdependency between the availability of public charging infrastructure and the uptake of EVs by customers is often referred to as an *chicken-and-egg problem* [286]. The term is derived from the philosophical question "Which came first, the chicken or the egg?", which poses a dilemma due to its circular dependency. The problem is seen not only for electricity, but for all kinds of alternative fuels including hydrogen, compressed natural gas (CNG), and liquefied petroleum gas (LPG). The Council of the European Union describes the problem for alternative fuels infrastructure like this: "In this vicious circle refueling stations are not being built because there are not enough vehicles. Vehicles are not sold at competitive prices because there is not enough demand. Consumers do not buy vehicles because they are expensive and the stations are not there." [287].

The fact that the availability of fueling infrastructure is important for the choice of alternative fuel vehicles has been shown in several surveys [288] [289] [290] [291] (also see Sec. 4.2.5 below). The stated preference survey [288] shows that the availability of a recharging infrastructure plays a bigger role in the purchase decisions for electric cars than for cars with other fuels. This seems to be due to the shorter range of today's EVs in comparison to other types of vehicles.

The survey [288] also shows that with an expanding refueling network, customers are willing to pay more for a corresponding vehicle. The marginal willingness to pay for further expansions decreases with higher levels of infrastructure provision. So the availability of a basic charging infrastructure is considered to be as important, while further expansions are seen as continuously less relevant. The same effect is visible in the survey [291].

For the case of electricity as an alternative fuel, certain characteristics have to be taken into account that differentiate it from other fuels. On the one hand EVs, with a driving range of 100–150 km with a full battery, have to be recharged more often than other types of vehicles. On the other hand, a basic electric supply network is already available almost everywhere. Without any dedicated charging infrastructure available, EVs can already be charged using household sockets at homes or work places.

The mutual dependency of EV diffusion and infrastructure availability can be and has been broken by several factors in the last years. The *dependency of EVs on public charging infrastructure* has been lowered due to the following factors:

- EVs can be used by a large group of people who do not require a public charging infrastructure and charge only at home (see Sec. 4.2.3 below). If an EV is used as a private second car, it can be used only for those trips where its range is sufficient. EVs can also be used in business fleets, where the distance of planned trips is predictable. For longer trips employees take conventional vehicles available in the fleet. It has to be noted, however, that no significant need for public charging as an impetus for the development of this market arises from these users of EVs either.
- Plug-in hybrid electric vehicles (PHEVs) and range-extended electric vehicles (REEVs) also do not depend on a public charging infrastructure. But, as has already been argued above, it makes economic sense for them to use public charging points, if the price of electricity provided there is cheaper than the equivalent per km for gasoline. Because they are equipped with smaller batteries than pure EVs, their pure electric range is also smaller [221].
- A further possibility of lowering EVs dependency on public infrastructure would be to manufacture them with bigger batteries. This way they could be used for longer trips even without public charging infrastructure. Because of the high prices of batteries, few manufacturers currently equip their cars with big batteries. The Tesla company is an exception. The Model S is available with a battery of 85 kWh, which is 3–5 times the capacity of other available EVs batteries'. However, with a price of 81 750 € the car is also 2–4 times as expensive as other available EVs [221]. In the report [9] it has been argued that it is overall more economic to provide more charging points for EVs than building EVs with bigger batteries.

The inverse *dependency of EV infrastructure on use by EVs* has been lowered by these factors:

- Within the framework of the German electric mobility model regions, the state had subsidized the installation of large numbers of charging points [274]. These charging points have been installed at a time when there were small numbers of EVs and thus little need for them (also see Fig. 4.2). Currently German charging infrastructure operators are hesitating to install more charging points [292] [293]. Further explicit subsidies for the installation of charging points could lead to more of them being provided. But currently the German state does not provide direct subsidies [294].

- Charging infrastructure can be set up by operators who do not see it as a business model that depends on a high level of utilization. Municipal utilities can provide public charging points as a public service. Shopping centers, restaurants hotels, and similar facilities can install charging points as an additional service to their clients.

All in all, it can be noted that large groups of users could use EVs, even without a single public charging point being available. Regional public charging infrastructure has already been implemented within the German model regions. So that it can be said, that the lack of public charging infrastructure is not an impediment in specific regions. But the already existing potential user base does not seem to be fully tapped, mainly because of the high prices and perceived limited range of EVs (also see Sec. 4.2.5 below). The unattractiveness of current EVs in comparison to conventional cars seems to be the main impediment to the diffusion of EVs, while the chicken-and-egg problem does not seem to play such a big role, when looking at it closely as has been done above.

4.2. Demand from the users' perspective

This section treats the demand for charging points from the users' point of view. Many different theories and results obtained using varying scientific methods allow to understand this demand better. First, the ranges of current EVs will be analyzed. Then it will be shown how many people in Germany would be able to charge an EV at home and at their working place. The ranges of current EVs are then set in relation to the mobility behavior of car drivers today, to see how many conventional cars could be replaced by EVs. The psychological phenomenon of range anxiety will afterwards be discussed. Then the preferences and willingness to pay that (potential) EV users state in surveys is analyzed. Finally the actual utilization of charging points as it was observed in different pilot projects is shown.

4.2.1. Driving ranges of current EVs

Gasoline-powered cars can drive distances of about 450–1 200 km, and diesel-powered cars distances of about 600–1 700 km with a full fuel tank [295]. Because current batteries have lower energy densities than gasoline or diesel and are expensive to manufacture in big sizes, current EVs have much smaller driving ranges with a full battery. The driving ranges of EVs available in Germany in 2014 is shown in Fig. 4.5.

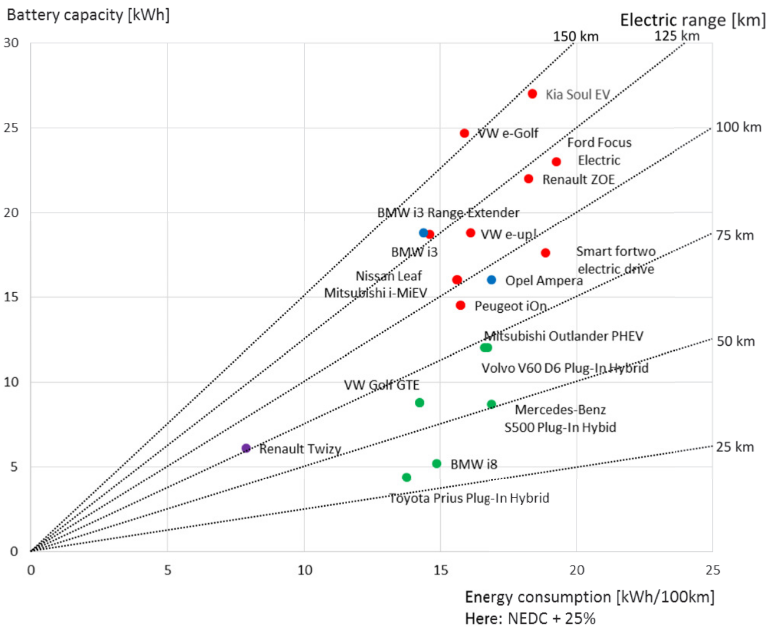

Figure 4.5.: Electric driving ranges of EVs (red), PHEVs (green), and REEVs (blue) available in 2014 (data from [221])

The diagram assumes the full utilization of the battery's capacity and an average energy consumption based on the specification using the New European Drive Cycle (NEDC) given in [221], plus an additional 25 % (the rationale for this is explained below). For plug-in hybrid electric vehicles and range-extended electric vehicles the range for *electric* driving is displayed. The driving range of each vehicle is determined by dividing the battery capacity in kWh (assuming a 100 % utilization here) by the average consumption in kWh/100 km. Selected ratios of battery capacity to energy consumption, i.e. driving ranges, are shown as lines in the diagram.

It can be seen that the average energy consumption of EVs is about 15–20 kWh/100 km. However, there is a large variance concerning the size of the battery. The Toyota Prius Plug-in Hybrid has a small battery with only 4.4 kWh, while the Kia Soul EV has a battery with 27.0 kWh capacity. In Fig. 4.5 it can be seen that EVs typically have a range of about 100–150 km. Range-extended EVs can be expected to have slightly smaller batteries and smaller electric ranges, as seen for the Opel Ampera. PHEVs have significantly smaller electric ranges of 25–75 km.

The Renault Twizy, displayed in the diagram on the far left, is a light four wheeled vehicle and not a full electric car. The vehicle can have a maximal speed of 45 or 80 km/h, depending on the model. It is included in the diagram because it shows that reasonable ranges can be reached with small batteries if the average energy consumption is also low.

A well-known EV not included in the diagram is the Tesla Model S. With a battery capacity of 85.0 kWh and an energy consumption of 22.125 kWh/100 km (NEDC + 25 %) it has a range of about 384 km. With these specifications the vehicle lies far outside the ranges displayed for others EVs in the diagram. However, it also has to be noted that the Tesla Model S has a very high purchasing price of 81 750 € [221].

The discussed diagram Fig. 4.5 shows the approximate driving ranges of current EVs, based on average consumption values. Making reliable statements about consumption values is difficult, however, as these can strongly vary under different circumstances. Currently, manufacturers of EVs specify the average energy consumption of the vehicle per km and its range based on the New European Drive Cycle (NEDC) [296]. The acceleration and deceleration behavior specified in this cycle is rather stylized. The NEDC is defined for a flat road without slopes. Moderate temperatures from 5 to 32 °C are used for the tests. Lights, heating, and air conditioning are shut off. It is known that manufacturers of vehicles exploit tolerances in the NEDC by using additional techniques such as using special tires with low rolling resistance or taping off gaps in the car body to achieve even lower values in the consumption tests [297].

An extensive study has been done to compare the specified NEDC and real-world consumption values of gasoline- and diesel-powered vehicles in [298]. The study shows how discrepancies between NEDC specifications and real world consumption have been steadily increasing since the year 2000. By the year 2012 the average real world fuel consumption lay about 25 % above the specified NEDC values. The orientation value "NEDC + 25 %" has therefore been used to display more realistic consumption values and driving ranges in Fig. 4.5.

Because the problems with the official NEDC specifications of vehicles are widely known, a more realistic testing procedure called the World-Harmonized Light-Duty Vehicles Test Procedure (WLTP) is being developed. Beyond a more realistic drive cycle, the procedure also includes more strict rules about the way the tests are performed [299]. The European Union intends to replace the NEDC by the WLTP by the year 2017. This is opposed by the automobile manufacturers who fear that they will not be able to meet CO_2 emissions targets if emissions values are determined under the new test procedure [300].

The energy consumption of EVs can vary strongly in different weather conditions. In a gasoline or diesel powered vehicle, excess heat generated by the motor is also used for heating the passenger cabin. But electric motors generate almost no excess heat, therefore the energy for electric heating has to be taken from the battery. Electric radiators work with high powers of several kW, thus their energy consumption is quite high. In very cold weather the situation is further aggravated because the usable capacity of the battery is lower than in warm temperatures [301]. The independent organisation TÜV Süd has tested the ranges of EVs in temperatures of -7 °C. Their tests have shown that the range of EVs can then decrease to almost half of that at moderate temperatures of 23 °C [301]. This is why some EV manufacturers provide their cars with optional heaters which use conventional fuels [301]. In high summer temperatures, the use of air conditioning can also lead to a higher energy consumption of the vehicle. Because air conditioning usually works with lower powers, the impact is not as severe. The source [302] states a resulting range decrease of up to 30 %.

In the context of energy consumption of EVs it has to be noted that there is also a dissipation of energy while an EV is connected to a charging station. A part of the energy is lost during the charging process. The efficiency of the charging process differs between different charging methods (inductive/conductive, AC/DC) and also between different chargers. Three conductive AC chargers tested in [220] had charging efficiencies of 75, 76, and 95 %. The article [303] states an AC charger efficiency of about 90 %.

Energy can also be consumed by the *preconditioning* functionality of some EVs. This means that the radiator or air conditioning of the car are turned on automatically to reach a comfortable temperature while the vehicle is still parked and connected to the charging station [304]. The electricity for this preconditioning is taken from the charging station and not from the vehicles battery. The idea behind this functionality is to increase the vehicle range by decreasing the energy that is needed by the radiator and air conditioning during the trip.

Both the losses during charging and the energy used for preconditioning do not have a negative impact on the range of an EV. However, they have to be considered when quantifying the actual energy consumption of EVs.

4.2.2. Availability of private parking places for private charging

The most convenient location to charge EVs is at home or at work, where they remain parked at dedicated parking spaces for longer durations. However, not all people have a private parking place at home or at work, and sometimes there is no electricity connection at this place. The availability of parking spaces with electricity outlets at homes has been analyzed for the USA in [305]. The report [8] includes an analysis of the parking situation and implications for charging infrastructure in the French city of Rouen. The methodological approach taken is to identify the "primary" parking and charging places for cars, in private space at homes or companies, in public car parks, or on the street. Additionally a low demand for "secondary" parking and charging places is estimated. In the following, the parking situation in Germany will be considered.

Fig. 4.6 shows the usual parking space for cars in Germany at homes, according to the size of the municipality. In very small municipalities 90.9 % of the cars are parked on the owner's estate. This percentage declines with the size of the municipality. In very big municipalities only 40.1 % are able to park on their own estate, while 50.7 % park in the close proximity. Overall, 69.9 % of cars are parked on the own estate at homes in Germany.

The above data from one of the biggest German mobility surveys does not differentiate between parking in a private garage and parking in the private driveway, a difference which is important in the context of private charging. More detailed data in this direction has been collected in the survey [215]. Fig. 4.7 shows the availability of garages or carports in municipalities of different sizes. The same clear tendency can be seen as before, namely that more people have a private parking space in smaller municipalities. It can additionally be seen that the large majority of the private parking places are in garages.

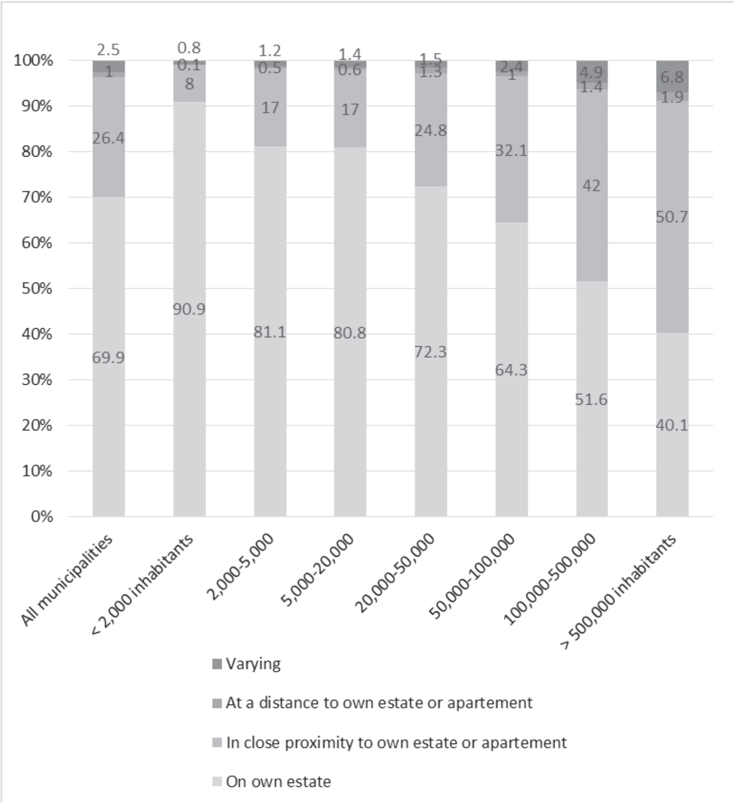

Figure 4.6.: Usual parking space for cars at homes in municipalities of different sizes (data from [306])

In the survey [215] people who responded that they have a private parking place at their homes were then asked about the availability of an electricity connection at this parking place. People living in single family houses had an electricity connection available 84.6 % of the time, in semi-detached or serial houses it was 72.8 %, and in multiple-dwelling units it was 49.8 %.

In the survey people were also asked about the parking situation at their workplaces. 54 % state that they have no dedicated parking place at work. 35.5 %

have a dedicated parking place outdoors, and only 10.5 % have a dedicated parking place in a roofed car park.

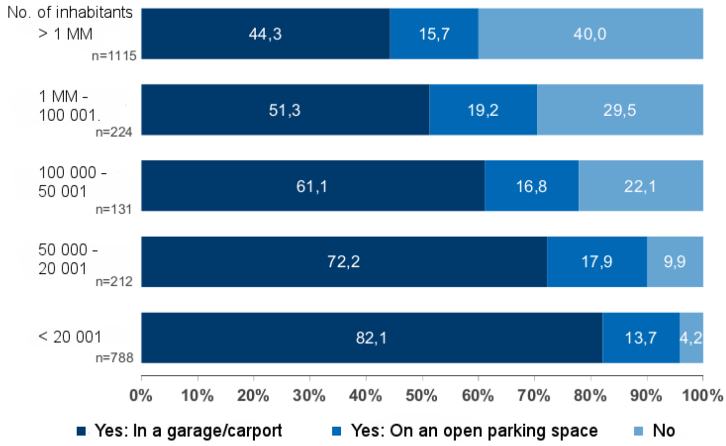

Figure 4.7.: Availability of private parking spaces at respondents' homes in municipalities of different sizes [215] (translated)

It is a matter of debate whether people who park their cars on the street near their homes should be provided with public charging possibilities. The large majority of people in Germany seem to see the possibility of charging an EV at home as a prerequisite to buying an EV [307]. In the US city of Seattle, a survey was conducted with people who had no possibility of charging an EV at home [308]. The survey shows that the availability of public charging possibilities would make this group more inclined to buy an EV or PHEV. However, problems are seen if charging stations are too far away from home and people have to carry things or the weather is bad. Also, some fear to leave the car at a public charging stations overnight where it is vulnerable to vandalism. People also worry that these public charging stations could be occupied. The report comes to the conclusion that the installation of public charging stations for this group is not worthwhile in the next years.

The city of Amsterdam, on the other hand, strongly supports the buildup of charging infrastructure for the group of people who park their EV on the street. Inhabitants who buy an EV can apply for a public charging station near their home [309]. Another possible approach is to set up public *fast* charging stations which can be used on demand by people without private charging possibilities [310].

4.2.3. Evaluation of mobility data

In the previous two sections the driving range of EVs has been discussed from a technical viewpoint, and it has been analyzed how many potential drivers of EVs have a dedicated parking space with electricity at their home and workplace. To understand the demand for public charging infrastructure, these two elements have to be set in relation to the mobility behavior of potential EV users.

The article [311] presents results of simulations based on one-week travel patterns from German mobility surveys. It is analyzed what percentage of privately used cars could be replaced by EVs without a change of mobility habits while assuming different battery capacity and infrastructure availability. The results are shown in Fig. 4.8.

It can be seen that with a battery capacity of 24 kWh and the possibility to charge only at home using a regular household outlet, already about 60 % of the vehicles could be replaced by EVs. If additional charging possibilities are provided at work, the percentage rises to over 65 %. If charging points are provided at (all) public places, the percentage rises to almost 80 %. It can additionally be seen that different charging powers make almost no difference for charging at home and at work, where vehicles remain parked for long durations. A bigger difference can, however, be seen for public locations, where shorter parking durations are common, and fast charging can thus be more suitable.

An additional analysis also presented in [311] takes the restriction into account that home charging requires a private parking place. As has already been shown above, in Sec. 4.2.2, in Germany about 70 % of cars are parked on the owners' estate. As Fig. 4.9 shows, the percentages are thus reduced but still remain quite high. With a 24 kWh battery, about 50 % of vehicles could be replaced by EVs, with additional charging at work it is about 55 %, and with additional public charging over 60 %.

The authors of the study [311] come to the conclusion that efforts should concentrate on providing technologically simple home charging stations in the next years. A study summarized in [312] comes to a similar overall result. In the study simulations were done based on mobility data from the city of Cologne. The researchers come to the conclusion that the limited range of EVs is not a problem for urban mobility. They also conclude that charging via household sockets at home and at work is largely sufficient.

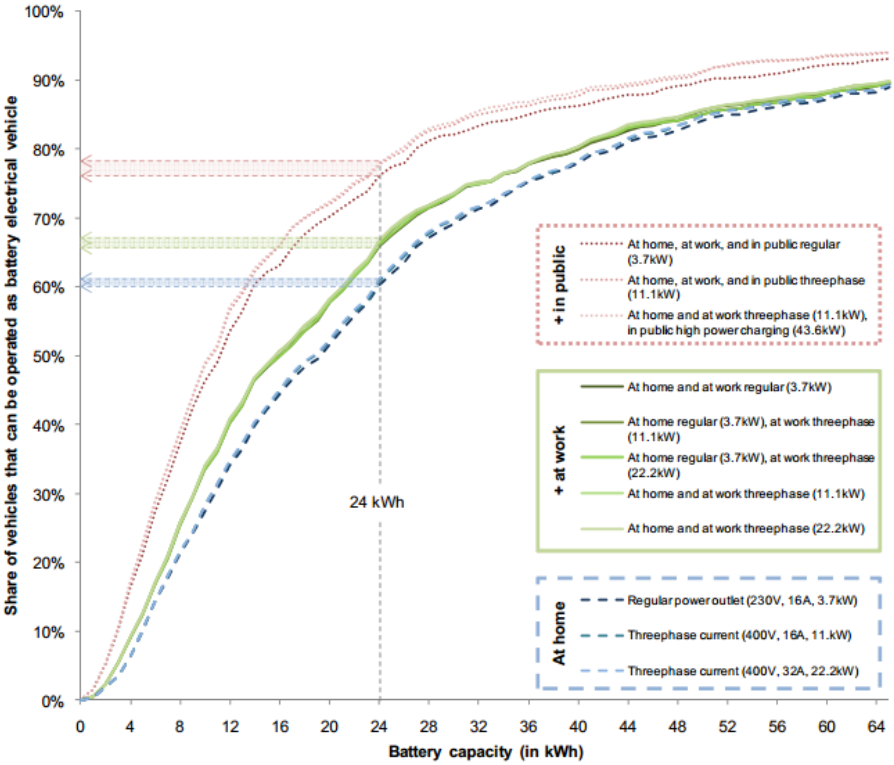

Figure 4.8.: Percentage of personal cars that could be replaced by EVs under different battery capacities and infrastructure availability [311]

Other studies also assess what percentage of the vehicle fleet could be electric if an EV is only recharged once a day, for instance at home during the night. The study [313] analyzes travel data of one week and vehicle mileage data of 8 weeks of 1 000 German households. A quite strict constraint of maximally 70 km traveled per day is applied. Additionally, constraints are applied which verify the surveyed data's representativity for the mobility behavior of the entire year. The results hows that about 7.5 % of vehicles meet these demands. Furthermore, it is found that almost half of the identified car's drivers are retired persons. Also, many of these cars are used as second cars in the associated households.

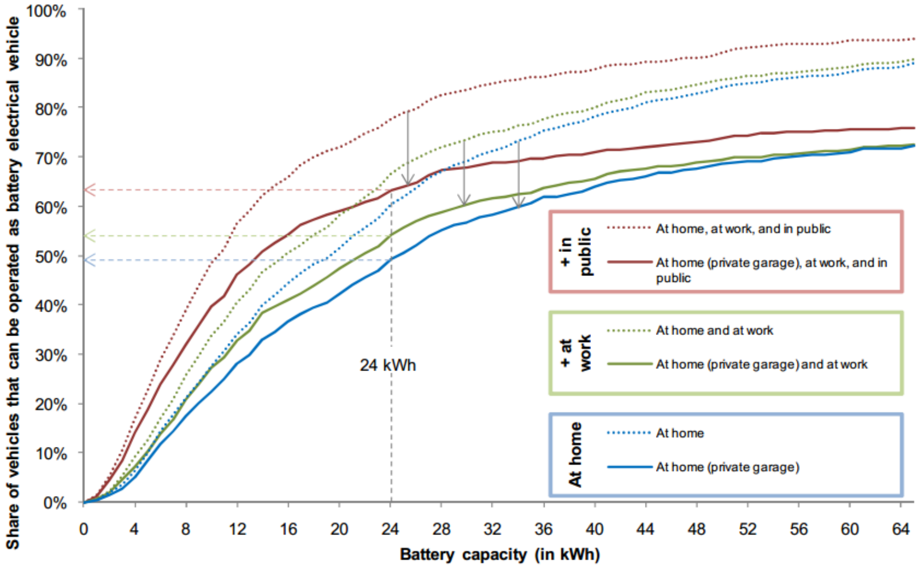

Figure 4.9.: Percentage of personal cars that could be replaced by EVs when taking the availability of private home parking into account [311]

The report [222] points out that the use of data from one-day or one-week travel surveys leads to an overestimation of the percentage of cars that could be replaced by EVs. The longer the considered time frame is, the more long-distance trips occur. Fig. 4.10 visualizes this phenomenon. About 90 % of cars maximally drive 100 km on a given day, but only about 10 % of the cars maximally drive 100 km per day within a year. Because no empirically collected one-year travel data exists, the authors constructed such a database from several travel surveys of different time spans. Further results are presented in the article [314]. One year is taken as the time frame, and it is assumed that EVs are only recharged at home in the evening. Then 13.1 % of privately used cars in Germany could be replaced by EVs without a change in behavior, and 15.5 % of privately used cars could be replaced if the owners used a different means of transport (public transport, conventional car) on 1 to 4 days a year. The study finds that cars that could be replaced by EVs are mostly small or middle class cars, owned by households with lower incomes. The authors point out that this conflicts with the fact that EVs are expensive to purchase and need to be driven high yearly distances in order to be more economically attractive than conventional vehicles.

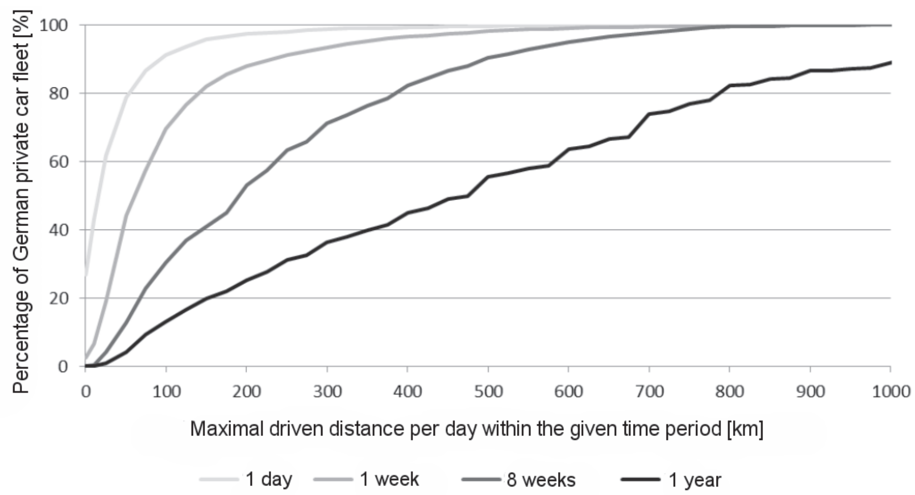

Figure 4.10.: Maximal driven distance per day for different time frames (translated from [222])

The availability of charging infrastructure influences the percentage of total driving distance that PHEVs can drive in electric mode. The article [315] presents simulations done with logged data from 229 vehicles on one day in Austin, Texas, USA. The vehicles are assumed to be fully recharged when leaving home. The charger network coverage stands for the probability that a charging point will be found at a destination. It is assumed that public charging points operate with 6 kW of power. In Fig. 4.11 it can be seen that more electricity and less gasoline is used when more public charging infrastructure is available. Thus, the availability of charging infrastructure can have a large impact on energy consumption and fuel costs for PHEVs. The article [275] also shows that the share of electric driving of PHEVs is significantly increased when charging stations are available at all destinations.

4.2.4. The phenomenon of range anxiety

Range anxiety is the concern of not being to able to reach a destination when driving longer distances with an EV which possesses a limited driving range (see [316] for an overview of different definitions). The report [317] clarifies that the phenomenon “cannot be described as an anxiety as such. Rather it manifests as an awareness of the current range, to which the driver adapts via coping strategies”.

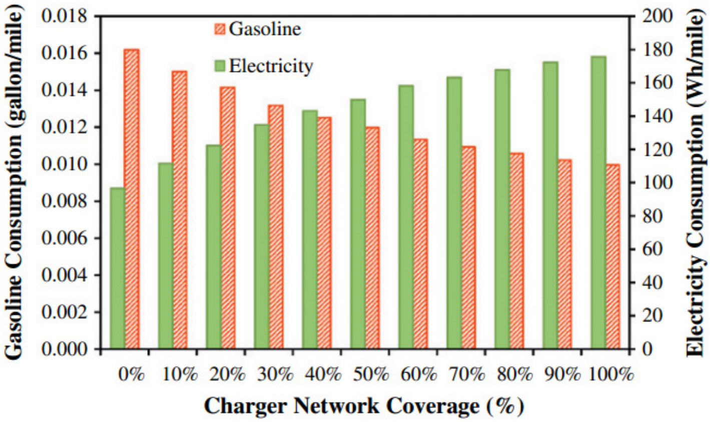

Figure 4.11.: Simulated gasoline and electricity consumption of a PHEV with a 20 mile (32 km) driving range and different levels of infrastructure coverage [315]

It seems to be a partially irrational phenomenon. Several studies (see Sec. 4.2.3) and trials (see Sec. 4.2.6) have demonstrated that the ranges of current EVs are sufficient to cover the daily mobility needs of many users. However, the ranges that users would prefer EVs to have lie significantly above these values [318]. Thus, the effect has also been called the *EV range paradox* [318].

EV drivers do not feel range anxiety when driving to routine locations, for instance when commuting between home and work [317]. Also, the feeling seems to be reduced over time as drivers become accustomed to their electric car [319] [320]. The adaption of users to the range of their EV seems to take about 3 months [321]. However, some EV drivers have also reported that their range anxiety has *increased* with experience. This is because they realized that the display of the state-of-charge of the vehicle is not entirely reliable [319]. This effect may strongly depend on the model of vehicle used.

The phenomenon of range anxiety has practical consequences for the demand for a public infrastructure for EVs. In addition to the factual "rational" demand, there exists a psychological component to the demand [322] [323]. EV drivers seem to perceive a public charging infrastructure as a safety net and fallback option, which they require in order to take advantage of the full range of their EV. This psychological demand for a public charging infrastructure is hard to quantify.

The psychological impact of a public charging infrastructure has been nicely observed in a field trial by the Tokyo Electric Power Company (TEPCO) in Japan in 2007 [323] [324]. For their business trips, employees could chose EVs or gasoline-powered cars from the company's fleet. Originally, a fast charging station was only installed at the company's headquarter. In this constellation the EVs typically returned from their trips with very high states-of-charge of the batteries, often making use of less than half of the available range. When a second fast charging was installed 6 months later in the center of the service area, it could be observed that the EVs were used much more often and for much longer trips. However, the second charging station remained largely unused, with only 2–3 charging operations per month. It seems that the *mere possibility* of intermediate charging made the EV drivers much more willing to drive further out.

Acknowledging the psychological importance of public charging infrastructure, it is not only important to provide the infrastructure, but also to communicate its availability. For this, charging stations can be set up at well visible locations. Their availability can be communicated to EV drivers via satnav and smartphone applications (compare [316]) (also see Sec. 2.2.2).

Range anxiety can lead to an overemphasis of the importance of public charging infrastructure. On the other hand, it can also lead to a higher use of charging infrastructure. EV drivers tend to leave an unused safety buffer in their batteries [316] [317] [325]. It seems that EV drivers only feel comfortable using 75–80 % of their available range [325]. Thus, it has been observed that EV drivers charge their vehicles more often than necessary, when high-levels of state of charge (SOC) still remain (see Sec. 4.2.6 below). Some EV users want their EV to be fully charged as a safety precaution or to have flexibility in their planning [317].

A phenomenon related to range anxiety is *charge anxiety*. This is the worry that the EV which has been plugged in is not charging correctly [319]. Another term recently coined in this domain is that of *charge rage* [326] [327]. This expression is used for the conflicts that result when EV drivers want to use a charging station that is already occupied. In such cases EV drivers have been observed to unplug other EVs before their charge had been completed. Drivers are also calling or messaging each other to ask to remove a fully charged car.

4.2.5. Results of surveys: stated preferences about charging infrastructure

In this section results of surveys that show the demand for charging infrastructure from the potential users' point of view will be discussed. When looking at the results of surveys the difference between *stated preference* and *revealed preference* has to be kept in mind. Stated preference is what people answer when they are asked to make hypothetical choices. Revealed preferences are the choices that are observed in reality. It is often the case that what people say they prefer and what they actually do is not the same thing [328]. Also, it has to be kept in mind that the phenomenon of range anxiety, i.e. the *perceived* range limitation of EVs, can insert a bias into survey answers.

Five aspects will be discussed below: the perception of the general importance of public charging infrastructure, the preferred locations for charging, the link between charging and parking duration, the stated willingness to pay for public (fast) charging, and the preference of electricity from renewable sources for EV charging.

A majority of people considers the availability of a home charging possibility a prerequisite for buying an EV. In [307] 95% of the respondents saw this as a precondition (also compare [329]). The lack of public charging infrastructure is one of the main concerns of potential private buyers as well as test users of EVs. Other important factors are the high purchasing price, the limited range and the long duration for charging. The relative ranking of these concerns by respondents varies between studies (most important issues listed first):

- [330]: 1. public infrastructure, 2. range, 3. purchasing price
- [307]: 1. availability of home charging, 2. public infrastructure, 3. range, 4. charging duration
- [331]: 1. range, 2. purchasing price, 3. charging duration
- [332]: 1. range, 2. purchasing price, 3.public infrastructure
- [333]: 1. range, 2. public infrastructure, 3. purchasing price
- [334]: 1. purchasing price, 2. range, 3. public infrastructure

There seems to be no clear ranking between the lack of public charging infrastructure, the high purchasing price, and the low range of EVs. This makes sense because these three issues are closely interconnected. The need for public charging is seen because the range of EVs is limited. If buyers have to pay high prices for an EV, they expect a high range and a good supporting charging infrastructure. They would probably be less demanding if the purchasing prices of EVs were significantly lower than that of conventional vehicles. The duration of the charge seems to be a subordinate issue. However, some users worry about needing the car suddenly in an emergency situation [329].

Among those that use EVs in business fleets, public charging infrastructure is seen as much less important. This is because EVs used in fleets usually follow predetermined trips. EV fleet users in [335] named range and purchasing price as the main barriers to using EVs, well before the lack of public charging infrastructure. The same trend is found in [333]. In [334] the majority of EV business fleet users stated that the availability of public charging would not increase their daily distances driven.

As the lack of charging infrastructure is seen as problematic, the *availability* of a public *fast* charging infrastructure has a strong positive impact on the intention to buy an (PH)EV as has been shown in [329]. In [336] 41 % of survey respondents stated that they were extremely interested or very interested in using public charging locations.

The perceived dependence on public infrastructure seems to be reduced as drivers gain more experience with their EV. In the survey [337] 89 % of respondents agreed before an EV trial that “having a supportive public charging infrastructure is essential for people with EVs”. After three months trial, agreement had sunk to 73 %. Similarly, before the trial 76 % stated that they could complete their daily trips without public charging infrastructure, while after three months agreement had risen to 85 %. After three months 61 % stated they would buy an EV if their only possibility to charge would be at home.

Potential buyers of PHEVs in the USA were asked about their preferences concerning the location of charging in [329]. The preferred locations can be seen in Fig. 4.12. The two most important locations are at home and at work. The planned use of public charging locations is displayed in Fig. 4.13. Retail stores and gasoline stations are seen as the preferred public locations.

Similar tendencies concerning the preferred locations of charging stations can be seen in other surveys with potential users of EVs. The German survey [330] showed an order of preference of: 1. at home, 2. at work, 3. at a gasoline station, 4. at a public charging station. The survey [215], also from Germany, resulted in an order of preference of: 1. at home, 2. fast charging at a gasoline station, 3. at work, 4. in public parking garages and public parking spaces, 5. at charging stations along roads. The study additionally showed that people living in multiple dwelling units assigned higher importance to charging locations away from home. People with high daily driving distances (for instance commuters) assigned higher importance to being able to charge the EV at their place of work. The prominence of gasoline stations as location in these three surveys is surprising. This might be due to the fact that the survey participants were not fully aware of the longer durations of EV charging in comparison to the refueling of gasoline vehicles today.

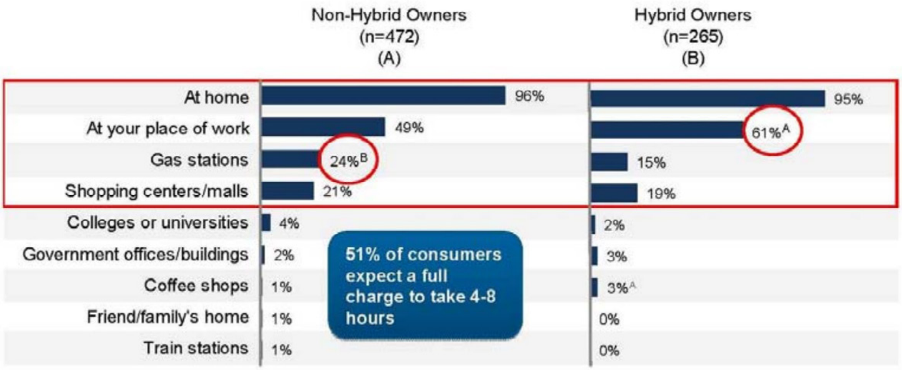

Figure 4.12.: Preferred charging locations for PHEVs stated by non-hybrid owners and hybrid owners [329]

Experienced EV users were asked about their wishes for further charging stations in the Austrian survey [334]. They see it as most important to install further fast charging stations at motorway rest areas. Similarly, according to the survey [338], experienced EV drivers in Norway also see the implementation of public charging stations between cities as the most important.

People consider the charging of EVs only worthwhile during longer parking durations. In the survey among potential German EV users [339], the majority of respondents considered charging only worthwhile for parking durations over 1 h. In the survey [340] among Austrian EV business fleet users, the majority of respondents also stated that they would only charge outside the business compound for parking durations of 1–2 h (53%) or more than 2 h (22 %).

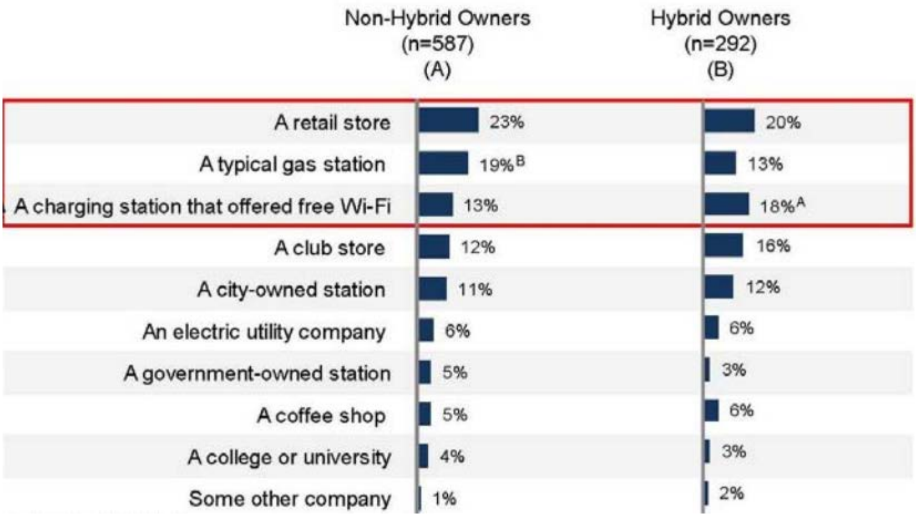

Figure 4.13.: Planned usage of public charging locations for PHEVs stated by non-hybrid owners and hybrid owners [329]

Several surveys have also treated the prices that people are willing to pay for public charging. In [336] people were asked about the willingness to pay for a charge of 15 minutes, providing a range of 6–7 miles (9.7–11.3 km). 23 % responded that they would only use it for free. 29 % would only pay less than 1 US$. 29 % would pay 1–2 US$ and 18 % would pay more than 2 US$.

Customers seem to be willing to pay more for *fast* charging than normal charging. In the German study [215] among potential EV users 56.6 % answered they would be willing to for pay 5 € for a fast charge, if a normal charge would cost 2–3 €. In the study [329] from the USA about 75 % of respondents agreed to pay under 1 US$ for a fast charge when a corresponding home charge cost 0.75 US$. The percentage dropped to 50 % for more than 1 US$ (see Fig. 4.14). In the survey [338] the majority of experienced EV users from Norway said that a price of 2.5 to 6 € for a 15 min quick charge is acceptable. Many respondents answered they would be willing to pay double the price of what charging at home costs per kWh. In the survey [340] among Austrian EV business fleet users 44 % stated they would not be willing to pay more for a fast charge, but 33 % said they would pay an additional 1–5 €, 18 % an additional 5–10 €.

It seems that there is a basic willingness to pay more for public charging and especially public fast charging. But the comparison to the prices paid for charging at home limit the prices perceived as acceptable. This makes sense, as the lower fuel costs of EVs are seen as one of their main tangible advantages [307] [331].

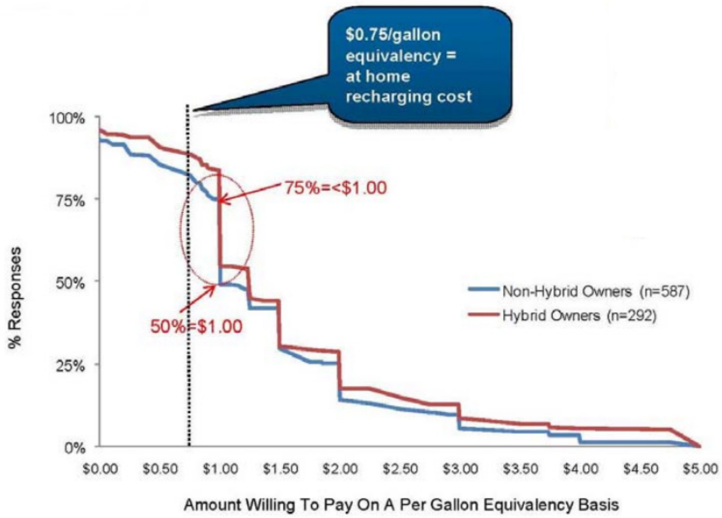

Figure 4.14.: Stated willingness to pay for fast charging at a public station [329]

Potential EV drivers also care about the source of the electricity used for charging. In the survey [215] 72.9 % of respondents agreed to the statement that EVs are only environmentally friendly when they are charged with energy from renewable sources. The same trend is seen in the interview study [341] where test drivers of EVs said their vehicles should be charged by electricity generated from solar, wind and hydro power. The respondents mainly opposed (71 %) that electricity generated from coal be used for EV charging.

4.2.6. Results of pilot trials: use of existing charging infrastructure

The demand for public charging infrastructure can also be better understood by looking at the data collected during pilot trials and first public charging infrastructure implementations. It has to be considered, however, that these experiences are often not fully representative of possible future EVs, EV drivers, or public charging infrastructure. Often prototypes or small series of EVs are used.

The test drivers are often people employed by specific companies participating in a trial. Some vehicles are not used as private vehicles, but as business fleet vehicles. An overall low number of public stations available can also influence results. Additionally, the charging at public charging stations is often provided free of cost. Also, in some pilot regions the public charging infrastructure is also used for charging electric car sharing vehicles. These factors and others can lead to biased results, which should therefore be interpreted with caution. In the following it will be attempted to provide the basic contextual information of the trial results.

The mobility and parking behavior when using an EV does not seem to differ significantly from that when using a conventional vehicle, as has been observed in the Berlin, Germany, field trial [342]. However, several subtle changes in mobility behavior have been observed in pilot tests in Los Angeles and New York, USA [341]. Many pilot users used a second conventional car for doing long trips. They also chained trips and eliminated individual trips. Additionally, they used several techniques to adapt to the lower range of the EV, such as more carefully planning trips and lowering energy consumption by driving slower and turning off air conditioning or electric heating. Drivers in different trials report that they make *more trips* with their EV than they had with their conventional car before [341] [333]. In part, this seems to be caused by the novelty of using an EV. The phenomenon can also be interpreted as a *rebound effect*: with less environmental impact and lower fuel costs of EVs, users are incited to use the vehicle more often.

EV drivers show different behaviors of charging their EVs. In [337] the three schemes *charging whenever there is a chance*, *charging when the state-of charge is below a certain level*, and *charging at a regular interval* reached about equal levels of agreement among UK test drivers. The same tendency is seen in the German survey among potential EV users [339]. Drivers seem to to follow one predominant charging behavior, which they adapt under different circumstances [337]. The charging behavior is dependent on the way the vehicle is used, for instance drivers who always plug their vehicle in tend to use it more often over the course of a day. The survey results of [343] indicate that for EVs used in business fleets, plugging into the charging station after each trip, after returning to the business compound, seems to be the most natural routine.

Many private EV users do not recharge their EV every day. In the MINI E trial in Berlin EV drivers were found to charge their vehicles an average of 3 times a week [344]. In the Lisbon trial [333] many EV drivers also stated that they did not charge their vehicle every day.

EV users tend to recharge their vehicle when there is still a medium state of charge remaining. This effect could again be observed in different trials (see Fig. 4.15 and Fig. 4.16) (also observed in [345]). Once a charge is initiated, it is usually continued until the battery is full or almost full [334] [346].

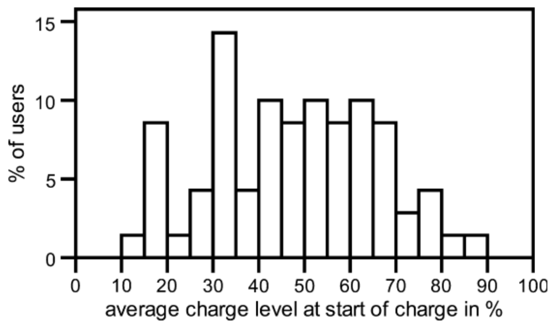

Figure 4.15.: Distribution of state of charge at the beginning of charging operations registered for BMW MINI E vehicles in Berlin [344]

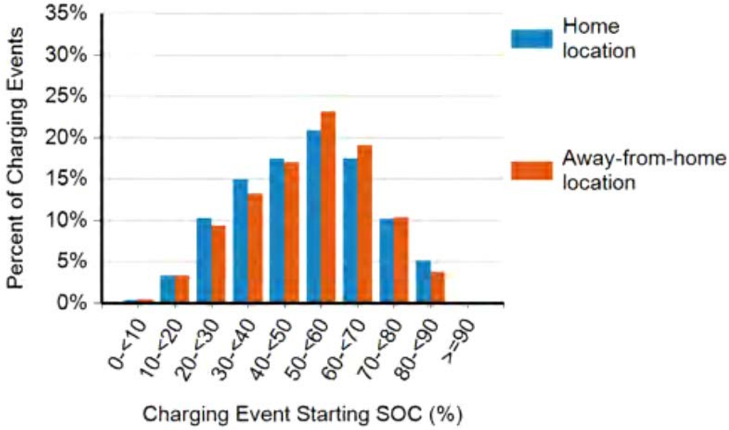

Figure 4.16.: Distribution of state of charge at the beginning of charging operations registered for Nissan Leaf vehicles in the USA [346]

Pilot projects all over the world have consistently shown that the use of public charging stations is low in comparison to that of charging stations at homes and workplaces. This is in line with the stated preferences about the locations for charging seen in different surveys (see Sec. 4.2.5 above). In the MINI E trial in Berlin, Germany, it was seen that only 3 % of the charged energy was taken from public charging stations. The test drivers used their wallboxes at home for the great majority of charging. 46 % of the users never used a public charging station [342]. In the UK project Plugged in Places the majority of charging was also done at home and workplaces, with 42 % and 23 % of energy respectively [347]. The remaining 35 % of energy was drawn from semi-public and public locations, such as public and commercial places, and on-street charging points (see Fig. 4.17). The public and semi-public charging points made up 37 % of the installed charging points.

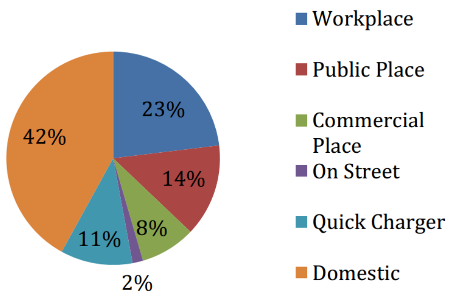

Figure 4.17.: Distribution of charging energy delivered at different kinds of locations in the North England Plugged in Places project in the UK [347]

In the EV project in the USA 9 % of the energy was drawn from public AC and 5 % from public DC fast charging stations [346] (see Fig. 4.18). These made up 29 % and 1 % of all installed charging points respectively. In the German survey among more than 3 000 EV drivers [345] these also stated they mainly charged at home or work. Only 4 % said they would charge "(almost) daily" in public space within the city. 14 % said they would do so 1–3 times per week.

Fig. 4.19 lists the measured use of AC charging stations at different kinds of locations in the EV Project in the USA. It can be seen that among locations with public access, the highest average charging events were seen for arts and entertainment locations, such as a theaters, cinemas or museums. Business offices which set up charging possibilities for their visitors and employees also registered high utilization. Shopping locations are also high up on the list. Restaurant and parks are, however, lower on the list than could be expected.

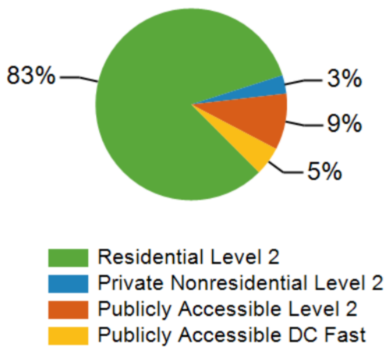

Figure 4.18.: Distribution of charging energy delivered at different kinds of locations in the EV Project in the USA [346]

Venue	Number of Sites	Lowest Events per Week	Highest Events per Week	Average of Events/ Week
Arts & Entertainment	42	0.02	189.25	7.10
Business Office	54	0.01	130.45	6.41
Retail, Big Box, National Accounts	61	0.20	63.04	4.60
Malls	18	0.03	32.40	4.43
Utilities	35	0.05	65.97	4.26
Parking lots & Garages	147	0.03	63.96	3.88
Healthcare/Medical	39	0.04	11.27	3.02
Retail, Small Business, Local	122	0.01	36.02	2.85
Educational Services	74	0.05	15.83	2.63
Hospitality/Travel	114	0.04	66.65	2.36
Govt/Public Admin	92	0.04	36.15	2.33
Non-profit	19	0.10	14.06	2.17
Automotive	20	0.06	12.50	2.04
Professional & Technical Services	19	0.08	6.09	1.94
Restaurants	82	0.01	38.14	1.83
Multi-family	19	0.08	11.52	1.74
Parks & Recreation	11	0.16	3.65	0.87
Military	1	0.12	0.12	0.12
Total Sites	1048			
Fleet	35	0.02	138.44	6.89
Workplace	44	0.03	74.09	8.03

Figure 4.19.: Use of public charging stations at different locations measured in the EV Project in the USA [348]

The use of public AC charging points over the hours of a day is shown for 2 674 public AC charging points in the USA in Fig. 4.20. Most people seem to use these stations in the early noon, possibly when they are arriving for work at a nearby location. The use of these charging stations is significantly lower on the weekend.

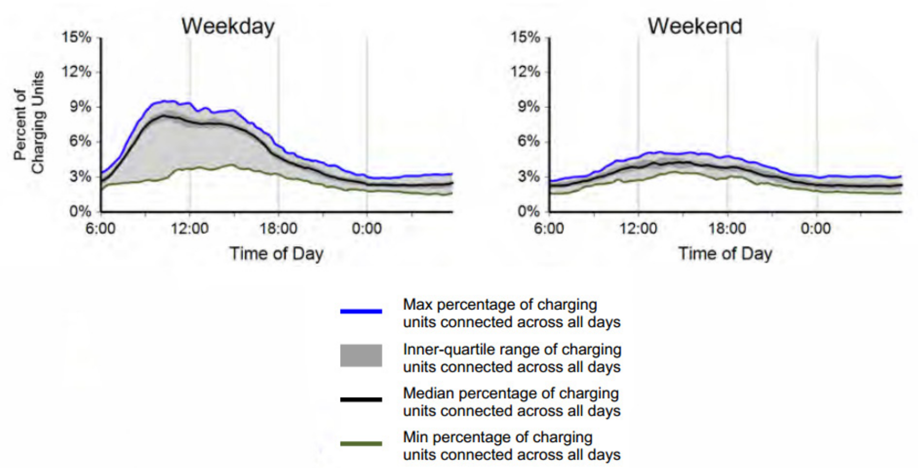

Figure 4.20.: Temporal use of public AC charging facilities measured in the EV Project in the USA [346]

In several projects it has been observed that some EV drivers misuse charging stations as free and reserved parking places. Some EV drivers deliberately use parking spaces reserved for EVs at charging stations even though they have no need to charge at all [349] [350]. EVs often remain parked at public charging stations long after the battery has been fully charged. In Amsterdam residents who buy an EV can apply for a public charging station near their home. It has been observed that the public stations have a high occupany level of 30–70 %. However, only 12–18 % of the time that EVs were connected to a charging station were actually used for charging. All in all, public charging stations are only used 4–5 % of the time of the day for the charging service they are meant to provide [309]. This often large difference between parking time and charging time has also been reported from other projects [351] [346].

The use of public DC fast charging stations has been high in many pilot projects. In the USA free DC fast charging stations within the EV project have been used an average of 16 times per week [352]. Even though they made up only 3 % of the publicly installed charging points, they supplied 34 % of the publicly charged energy [346]. From Norway it is reported that three fast chargers in Oslo and Bergen that provide charging free of costs, are each used an average of 9 times a day [338]. In the UK Plugged in Places project it has been found that DC fast charging points provided 11 % of all charged energy, even though they made up only 1 % of all installed charging points, including homes and work places [347].

The problem that EVs remain parked for long durations at the charging stations does not seem to exist for DC fast charging. Rather, drivers stop at the station for short durations only and then immediately drive on [353] [352].

In the EV project in the USA data collected from 87 charging facilities shows how they are used over the hours of a day (see Fig. 4.21). Their use is distributed over the day with the highest level being reached in the early evening. Their use is only slightly lower on the weekends, while the use of public AC charging is strongly reduced on weekends (see Fig. 4.20).

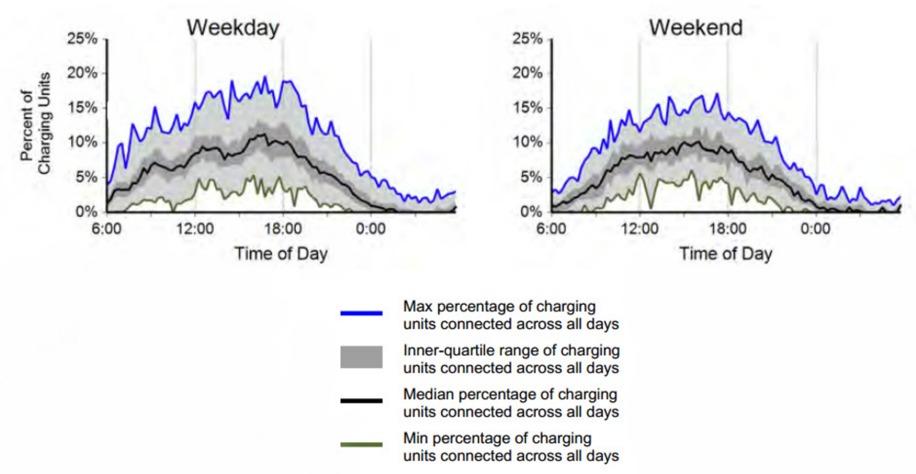

Figure 4.21.: Temporal use of public DC fast charging facilities measured in the EV Project in the USA [346]

Some disappointing facts about fast charging have also been registered in tests. In the test [310] EV drivers had to learn that the fast charging station model used only charged the EV to 80 %. Also, the charging process was much slower in cold weather (45 vs. 25 min in moderate temperatures). When fast charging the Nissan Leaf it was found that the vehicles battery management system very seldom accepts the maximal charging power of 50 kW. In 60 % of the time the charging power was found to be between 20 and 35 kW [352].

Specific data has also been collected about the mobility and charging of PHEVs and REEVs within experiments. Trials of the Toyota Prius Plug-in Hybrid in Japan, France, and the USA have shown that a higher daily charging frequency leads to a lower gasoline consumption [354]. This vehicle model has an electric range of about 21.7 km under the NEDC, allowing a large part of short trips to be made in EV mode. A gasoline consumption reduction in relation to a conventional vehicle of about 50 % has been found. The authors of the article [354] argue that charging at home and work is the most important, but public charging stations can lead to additional charging operations and thus to a lower overall gasoline consumption of PHEVs.

In the EV project in the USA large amounts of data have been collected about the use of the Chevrolet Volt, an REEV, and the Nissan Leaf, an EV [346]. This allows a direct comparison of the use of the two vehicle types. REEVs were used by people with significantly higher average trip distances and daily distances driven (41.0 vs. 29.5 miles per day). REEVs were recharged more often (1.5 vs. 1.1 times per day), however, less often at locations away from home (14 vs. 20 %). The REEVS were more often recharged with very low state of charge remaining in the battery. The battery had less than 10 % of energy remaining for more than 25 % of charging operations at home, a case which occurred very rarely for the EVs. This effect was also observed in the Austrian study [334] for REEVs and PHEVs. This behavior makes sense. The drivers of REEVs do not have to worry about being stranded with an empty battery, therefore they can use its full capacity.

When EVs from an electric car sharing system also use the public charging infrastructure, its utilization can be strongly increased. In Amsterdam, Netherlands, the EVs of the Car2Go system made up 66 % of all registered charge sessions. They were charged averagely 258 times a year at 77 different locations, while EVs from private users (including external visitors) were only recharged an average of 19 times a year at 4 different locations [309]. Similarly, in San Diego, USA, the fleet of 333 Car2Go EVs were responsible for 35 % of all electricity drawn from public AC charging stations [346].

4.3. Demand from the infrastructure operator's perspective (i.e. supply): demanding sufficient utilization

In the previous sections the demand for charging infrastructure has been extensively analyzed from the users' perspective. The different aspects of range of EVs, private parking space availability, mobility behavior, the phenomenon of range anxiety, stated preferences, and measured use of charging infrastructure altogether help to understand the users' perspective. But, as has been argued in Sec. 4.1.1 on demand and supply in microeconomic theory, looking at the infrastructure operators', i.e. suppliers', side is equally important.

An infrastructure operator within a free market system will try to adjust the number of provided public charging points and the price for the service to maximize his profits. Economic aspects of charging infrastructure provision will be looked at closer in Sec. 5.2. Within this chapter an approach will be taken to quantify the number of public charging points in relation to the number of EVs in a region, based on a minimum level of utilization. The following formula was developed by the author in 2011 and published within the article [355]. The almost same approach to quantifying the number of charging points for selected countries had already been published earlier by other authors in the report [322].

The amount of energy that is recharged at public charging points (CPs) in a region can be described as:

$$i = 1, 2: \quad V \cdot e \cdot d \cdot R_i = C_i \cdot p_i \cdot 24[h] \cdot U_i$$

With the variables:

- i: $= 1, 2$ different types of public CPs: normal and fast charging
- V: number of EVs in the region
- $e\,[\frac{kWh}{km}]$: average energy consumption of an EV (including losses during recharging)
- $d\,[km]$: average daily driven distance of an EV
- $R_i\,[\%]$: percentage of energy charged at public CPs of type i

C_i: number of public CPs of type i in the region

p_i $[kW]$: charging power of public CPs of type i

U_i $[\%]$: level of utilization of public CPs of type i

The left side of the formula describes the total amount of energy that EVs charge at public charging points of type i. The right side of the formula describes the energy that is drawn from charging points of type i. The formula thus states the obvious: the energy that the EVs charge is equal to the energy taken from charging points. The formula can be transformed in order to obtain direct quotas of charging points per EVs, given the other variables:

$$i = 1, 2: \quad \frac{C_i}{V} = \frac{e \cdot d}{p_i \cdot 24[h]} \cdot \frac{R_i}{U_i}$$

The technical variables e, d, and p_i can easily be estimated. Higher levels of uncertainty exist for the amount of energy recharged publicly R_i and the demanded level of utilization of public charging points U_i.

Fig. 4.22 and Fig. 4.23 show a sensitivity analysis for public charging stations with powers of 22 and 50 kW with different values of R_i and U_i. For these calculations the energy consumption of EVs e is set at 0.228 kWh/km (based on [220]). The daily driven distance d is set at 36.1 km (based on [356]). The charging powers p_i are 22 and 50 kW respectively. The percentage of energy recharged at the type of public charging point R_i is varied from 1 to 15 %. For 22 kW the level of utilization is varied from 1.04 to 25 % which corresponds to a use an average use of 0:15 to 6:00 h per day. For 50 kW the level of utilization is varied from 2.08 to 25 % which corresponds to an average use of 0:30 to 6:00 h per day.

In practice, the percentage of energy recharged publicly can be assumed to be quite low (compare Sec. 4.2.6). EV infrastructure operators can be expected to try to implement charging infrastructure that does not depend on very high levels of utilization. Realistic quotas of charging stations per EV thus lie in the farther corner of the diagrams shown in Fig. 4.22 and Fig. 4.23. These quotas around 0.0149 and 0.0032 lie considerably below the quota in the order of magnitude of 0.1 public charging points per EV proposed by the EU [357] and the German national platform on electric mobility [278].

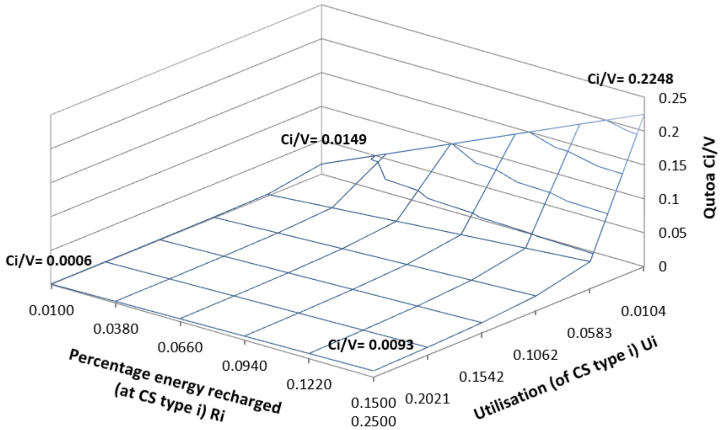

Figure 4.22.: Quotas of charging points per EV for 22 kW charging power and different levels of utilization U_i and percentage of energy charged publicly R_i

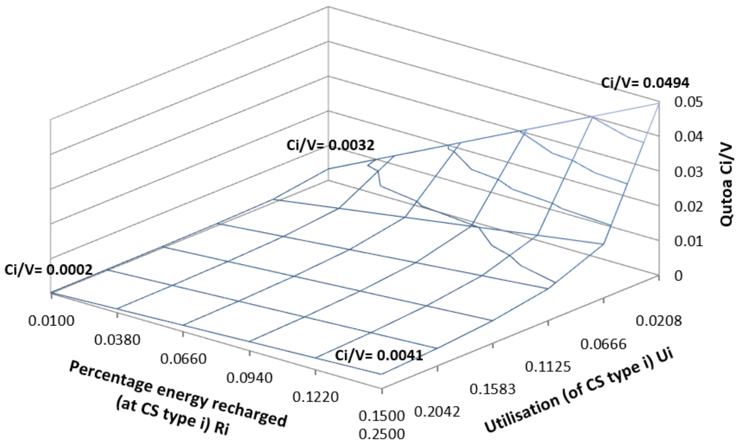

Figure 4.23.: Quotas of charging points per EV for 50 kW charging power and different levels of utilization U_i and percentage of energy charged publicly R_i

The formula can also be used to perform an inverse calculation. If a quota of 0.1 CPs/EV for public 22 kW charging points is accepted, and it is assumed that about 5 % of the energy is charged at these public points, these can be expected to be in use only 0.77 % of the time. This corresponds to an average daily use of only 11 minutes. This level of utilization is hardly satisfactory from an infrastructure operator's perspective. The role of the average daily utilization in the economics of charging infrastructure provision is treated in more detail in the calculations in Sec. 5.2.3.

The formula thus shows that when it is taken into account that EVs can only recharge a limited amount of energy publicly, and it is only worthwhile to set up public charging points when they achieve a certain level of utilization, the numbers of public charging points per EV should be lower than commonly assumed. If much more public charging points are set up they are bound to be underutilized.

4.4. Demand when seen as a public service: defining minimal levels of service

In the previous sections the demand for charging infrastructure has been extensively analyzed from the users' point of view. Additionally, it has been shown that an infrastructure supplier that demands a certain level of utilization of his public charging points will tend to implement much lower numbers than the 0.1 public charging points per EV proposed by the EU and similar targets by the German national platform on electric mobility. In this section a third perspective beyond economic supply and demand mechanisms will be taken. Public charging of EVs can be seen as a public service, similar to services such as public transport, water supply, garbage collection, and others. For such public services, *minimal levels of service* can be defined which guarantee the availability of a service to all citizens, independent of the actual level of utilization and profitability of the service. The targets stated by the EU and the German platform on electric mobility can be interpreted as such minimal levels of service, centrally determined without consideration for local economic demand and supply mechanisms.

Service levels can be defined for the quantity, but also for different aspects of the quality and reliability of a service [358]. In the following, several definitions of minimal levels of service for public charging infrastructure are proposed. These can be adapted to a specific local situation. An important point is that these goals need to be stated in a measurable quantitative way, so that it can be verified that they are met. Because these service levels are defined along different dimensions, they can be combined. For instance requirements can include a sufficient overall quantity as well as a good areal coverage, and low repair times. When a municipality commissions a charging infrastructure provider, a detailed service level agreement can be set up as a binding contract (see [10]).

- *Quantity of charging points for an area*: there are at least 0.1 (or 0.05, 0.025) public charging points available for every registered EV in the area.
- *Quantity of charging points for individual parking facilities*: every publicly accessibly parking facility with more than 50 parking places provides at least 1 and every parking facility with more than 100 at least 2 charging points for EVs.
- *Areal covering*: within the central city area, all locations lie within a 5 (or 10) min walking distance to a public charging point. For a walking speed of 4 km/h this corresponds to a maximal distance of about 330 (or 660) m to a charging point. Such a requirement can also be stated in the form of charging points per square kilometer. Covering an area so that the distance to the next charging point is never bigger than 330 m would require at least 1 charging point per $\pi \cdot (0.33\,km)^2 = 0.34\,km^2$, corresponding to about 3 charging points per km^2.
- *Temporal availability*: between the time of 9:00 and 18:00 h on weekdays, an arriving EV driver has an average chance of at least 70 (or 80) % of finding a free public charging point (i.e. in that time the average occupancy of a charging point is below 30 (or 20) %). If average availability is lower, further charging points need to be installed in the area and/or policies put in place that require EV drivers to move their vehicles, once the charging operation is completed.
- *Fast repair / low down times*: if a charging point is reported to be broken, a service technician arrives at the site within 24 (or 48) hours, and the charging point is repaired within 48 (or 72) hours.
- *Distribution of fast charging stations along traffic corridors*: along a traffic corridor connecting two big cities, fast DC charging stations are available every 50 (or 75, 100) km, from both sides of the motorway.

A lower bound for the number of public charging stations required to achieve an areal covering of all of Germany's cities and villages can easily be estimated in the spirit of solving a Fermi problem [218]. Germany has a total surface of 357 169 km^2. This surface is covered to 52.3 % by agricultural areas, 30.2 % by forests, 2.4 % by water, and only 13.5 % by settlement and traffic areas. This built area has a total surface of 48 225 km^2 [359]. Above it has been shown that always having a charging station available within 330 m corresponds to about 3 charging points per km^2. Thus, a total covering of Germany's cities and villages would require *at least* 48 225 km^2 * 3 CP/km^2 = 144 675 charging points. In reality, a much higher number would be necessary because the settlement area is spatially dispersed, and charging points therefore cannot be placed to achieve maximal spatial covering.

The second point listed above, linking the number of charging points to a number of provided parking spaces, seems especially promising from a policy perspective. In Germany, as in other countries, regulations are already in place that require a certain number of parking spaces to be constructed along with a building depending on its use. For instance in the German federal state of Baden-Württemberg, the construction code requires that for big shops without public transport accessibility one parking space is built for every 10–30 m^2 of shop surface, or for buildings with a high number of visiting clients (doctor's office etc.) one parking place is constructed for every 30–40 m^2 of office space [360] (also compare [361]). The use of such parking requirements in the USA has been criticized in [362], as these requirements seem to be based on little factual information and can lead to high construction costs and high land occupation by unnecessary free parking spaces.

In any case, such construction regulations can be extended to also include charging points for EVs. The government can thus require private companies such as parking garage operators, malls, supermarkets, and big cinemas to provide semi-public charging infrastructure. Semi-public infrastructure means that the charging points are accessible to clients of these establishments, potentially only during opening hours.

The French government has already taken steps in this direction in 2011. The issued regulation [363] requires that buildings with residential and tertiary use being built from 2012 on need to be equipped with the necessary cabling to allow 10 % of the associated parking spaces to be equipped with charging points. From 2015 on office buildings also need to be equipped with cabling as well as the charging points at 10 % of the associated parking places.

4.5. Summary and conclusions: the demand for public charging infrastructure

This section will recapitulate the main points concerning the demand for charging infrastructure which have been discussed in the previous sections. The overview also allows to point out contradictions between the different aspects of demand.

Classic microeconomic theory provides a framework to think about demand and supply of a good. The framework shows that demand within a free market should not be thought of as a fixed quantity, rather the demand that will be met in a free market system is an interaction of the quantity of a good, the price of a good, the consumers' interests, and the suppliers' interests. This was the motivation to take a look at demand from three perspectives in the sections of this chapter: the consumers' (EV drivers') point of view, the suppliers' (i.e. infrastructure operators') point of view, and when seen as a public service, neglecting free market mechanisms.

For charging infrastructure for EVs the interaction between demand and supply is more complicated than usual because there seems to be a causal loop between the two. People seem to be reluctant to buy EVs as long as there is little public charging infrastructure available. Infrastructure providers seem to be reluctant to implement charging infrastructure as long as there still is only a small numbers of EVs. However, when looking closer at this "chicken-and-egg problem", it becomes apparent that in Germany this seem to have been partially resolved in the last years. Within the German model regions large numbers of public charging points have been set up subsidized by the state, at a time when there was little actual need for them. Large numbers of drivers would not need any public charging infrastructure at all and just charge their EV at home. Also, several PHEV and REEV models have been put onto the market which do not require public infrastructure.

Many different aspects help to understand the demand for charging infrastructure from the EV drivers perspective. The discussion in this chapter has treated the ranges of EVs, the possibility of charging EVs at home, the mobility behavior of car drivers today, the preferences stated about charging infrastructure, and the actual use seen in pilot projects. The most important points will now be recalled shortly.

The ranges of EVs available today are limited. Taking into account that real world energy consumption is usually significantly higher than that specified by the manufacturers, current EV usually have a driving range of about 100–150 km with a full battery.

The majority of people in Germany would be able to charge their EV at home. Overall about 70 % of people park their car on their own estate, of which the great majority uses a garage or carport. About 85 % of the people living in a detached or semi-detached houses and having a private parking place also have an electricity supply available at this place. Although it is a matter of debate, currently is does not seem worthwhile to install public charging points for people who park their vehicle on the street, as this group will not be among the early adopters of EVs.

Setting the ranges of current EVs in relation to the mobility behavior of today's car drivers shows that large numbers of people could already use EVs with just the possibility to charge at home. The identified percentages vary between studies from 13.1 % [314] up to 50 % [311] in Germany. If EV drivers use conventional cars or public transport on a few days a year this percentage rises. The study [311] has shown that the percentage rises only slightly when additional charging possibilities at work places and when additional public charging infrastructure is put up. Another study [313] shows that especially second cars and cars used by retired persons could be replaced by EVs.

The phenomenon of range anxiety leads people to demand higher ranges of their EVs than they actually need, and it leads to overestimating the demand for public charging infrastructure. There seems to be a psychological need for public charging infrastructure as a safety net, which EV drivers require to feel confident about making longer trips with their EVs, but which they actually use seldomly. Usually range anxiety seems to be decreasing as people gain more experience with their EV.

When asked about their preferences about charging infrastructure, many people say that they see the availability of public charging infrastructure as a prerequisite for buying an EV. However, the high prices and limited driving ranges of EVs are seen as equally important barriers to adoption. Potential EV drivers say that they would prefer to recharge their vehicle at home and work. Experienced EV drivers mainly see a need for more fast charging stations between cities. The willingness to pay for a public charging service seems to be limited. There seems to be a general willingness to pay more for fast charging.

Pilot trials have shown that EV drivers follow different charging strategies. Charging at each possibility, when the state of charge is below a certain level, and at regular intervals all seem to be equally common behaviors. Usually drivers charge their EV every few days only and when the state of charge is still medium high. Pilot trials have shown that the amount of energy charged at public charging stations is quite low, compared to the amount of energy charged at homes and workplaces. The use of public DC fast charging stations has been high in pilot projects. Often a small number of fast charging stations has supplied more energy in total than a much larger number of normal charging stations set up within the same region. It has also been confirmed within tests that PHEVs can reduce their gasoline consumption by charging often. Drivers of REEVs, however, have been found to often drive their car until the battery is empty instead of recharging on time.

The demand for public charging infrastructure has also been discussed from the suppliers', i.e. infrastructure operators', perspective. The introduced formula allows to take into account that the energy demand from EVs in a region is limited, only a part of that energy is drawn from public charging stations, and the operator will demand a minimal level of utilization of the existing infrastructure, before putting up more charging points. The calculated quotas of charging stations per EV are considerable lower than those currently proposed by political organizations.

Finally, the demand for charging infrastructure was treated as the demand for a public service. When market mechanisms are not taken into consideration, different possibilities exist to define minimal levels of service based on the quantity of charging points, areal coverage, temporal availability, and other aspects.

All in all, the analysis in this chapter has shown that the demand for public charging infrastructure seems to be overstated both by EV drivers and by political organizations. Potential buyers of EVs see the availability of a public charging infrastructure as a prerequisite for buying an EV. However, the existing public charging points are rarely used, and EV drivers are not willing to pay much for occasionally using such a service. Political organizations put up targets in the spirit of minimal levels of service for a public service, but rationally acting infrastructure suppliers in a free market would not install such high numbers of charging points, as they would be underutilized.

5. Economic aspects of EV charging infrastructure

Early on during the electric mobility hype in Germany in the years 2010–2011, experts and scientists already warned that there did not seem to be a feasible business case for public charging infrastructure. Early EV enthusiasts had already gained experiences with the Park & Charge network, a non-profit oriented charging infrastructure for EVs which has been in operation in Austria, Germany, Switzerland, and Italy since the 1990s. The energy drawn from these charging stations was only about 0.5–1 kWh per day [364]. In 2010 the presentation [364] noted that the expensive high-tech public charging pillars being set up by electric utilities in the German model regions could hardly amortize themselves from user fees alone. A more detailed calculation was presented by another author from the early EV community in 2011 [277]. He also concluded that there is no feasible business model for public commercial AC charging and that the infrastructure should be provided publicly by local municipalities.

Scientist were also noting early that public charging infrastructure was economically questionable. The scientific article [311] showed in 2010 that public charging stations with their additional authentication and billing capabilities would incur much higher costs for EV owners than private charging stations. But these charging stations could be expected to be rarely used, as it is sufficient for many EV users to only recharge their EV at home. The authors therefore concluded that efforts should concentrate on providing technologically simple and cheap private charging stations.

The author of this thesis also did economic analyses for public charging infrastructure from a scientific point of view in 2011, which were published in 2012 in the article [355] and elements of which can be found in Sec. 4.3 of this thesis.

These analyses showed that public charging points would need a sufficiently high level of utilization for their amortization. To allow high levels of utilization, the number of charging points in an area would have to be kept low, much lower than the high number of public charging points envisioned by political strategies.

It is not clear at which time electric utilities in Germany began to doubt the economic viability of public charging infrastructure. In 2011 a manager of the big German electric utility RWE told a newspaper: "Public charging infrastructure cannot be operated in a cost-covering way until 2020" (author's translation) [365]. In 2013 the company had installed less public charging points than initially planned because the number of EVs in Germany was only increasing slowly. The company had apparently also overestimated the importance of public charging infrastructure to EV drivers [293]. In late 2011 the Federal Association of the Energy and Water Industry (BDEW) stated that public charging infrastructure would not be self-sustaining in the near future and should therefore be supported by the state [366].

Later, in 2013, several EV infrastructure providers began to pull out of the market entirely or even ended up bankrupt. The prominent EV infrastructure provider Better Place was dissolved in May 2013. It had been operating EV infrastructure, namely battery swapping stations, in Israel, Denmark, and other countries. It went bankrupt as it was not able to raise additional funds, and revenues were still not sufficient to cover operating cost. The company named the low public uptake of the service and lack of support from car producers as reasons for its failure [367]. The failure of Better Place seems to be partially due to the fact that it mainly followed the approach of battery swapping. The battery swapping facilities built by the company each cost 0.5 million US$ to build and 25 000 US$ to operate per month [98].

The big infrastructure company Siemens announced in September 2013 that it would pull out of the market for EV charging infrastructure. The segment had been making losses. Additional stated reasons were the slow development and size of the market and little possibilities to differentiate their products from those of competitors [368].

Also in September 2013 the U.S. charging infrastructure manufacturer and operator Ecotality went bankrupt. In 1999 it had received a grant of 99.8 million US$ from the U.S. Department of Energy to build up public charging infrastructure in the USA [369]. After the bankruptcy the company was sold for only 4.3 million US$. It was bought by the CarCharging Group, a company active in the same domain, which had already bought competitors such as 350 Green before [370].

In June 2015 the Federal Association of the Energy and Water Industry (BDEW) repeated and concretized its demand for public subsidies for charging stations. The association demanded a public subsidy of 7 000–5 000 € each for 10 000 charging pillars until 2017. This was supposed to cover 40 % of their total costs [371].

The above historical overview strongly indicates that today public charging infrastructure cannot be operated in an economically self-sustaining way. Within this chapter this hypothesis will be checked and possible solutions to the problem will be tested. Because EV drivers should also pay the costs for public charging infrastructure, the economics of EV ownership will be discussed first. Then the economics of EV infrastructure will be analyzed. First, frame conditions for the provision of such infrastructure in Germany will be explained, next possible business model variants will be discussed. Economic calculations will then be done for selected business model variants. The economics of EV ownership will afterwards be reconsidered, this time also taking additional costs due to public charging into account. Finally, it will be discussed which lessons can be learned from today's business model for gasoline station for a public charging infrastructure. In the last section within this chapter the main findings will be summed up.

Within this chapter the economic analyses will only take explicit exchange of money into account. Benefits and cost incurred by external effects, such as lower CO_2 and noise emission by the use of EVs, will not be considered. Such external effects will be analyzed in more detail in Sec. 6.1.

5.1. The economics of EV ownership

Before the economics of EV charging infrastructure is analyzed in more detail in the following sections, the economics of EV ownership will be shortly considered here. The cost for building and operating a public charging infrastructure should be paid for by EV drivers through usage fees. These fees can be thought of as additional operating costs or fuel costs for the vehicle. In this section the economics of EV ownership will be investigated without considering additional costs incurred by infrastructure, which will be taken into account later in Sec. 5.3. Exemplary calculations are done for a specific vehicle available in 2014, the

Smart Fortwo. The vehicle is available as an EV, with the option of renting the battery, and as a gasoline vehicle. This allows a direct and realistic comparison of these three options.

The total cost of ownership (TCO) approach is taken here. This means that the purchasing costs and the operating costs are summed up over the entire time of ownerhip of the vehicle. This approach has already been taken in many studies to compare EVs with conventional vehicles ([372] [373] [374] [375] [376]).

In general it can be said that EVs are more expensive to purchase but cheaper to operate, due to lower electricity costs and lower maintenance costs, and thus have the potential to reach lower TCOs than conventional vehicles in the long term.

In Germany there are no state subsidies for the purchase of EVs in place in 2014. EVs are, however, exempt from paying car taxes for a duration of 10 years [377]. If employees receive an EV as a company car, they have to pay taxes for this monetary benefit which are set at above 12 % of the value of the car per year (depending on the distance from home to work). Regulations in Germany reduce these taxes by calculatory reducing the value of the EV, depending on the size of the battery [378].

The following TCO model assumes that the vehicle is bought by a private user via a down payment, i.e. without taking up a loan. Operating costs occurring in later years are discounted to the present value at the time of purchase (compare [375] [376]). The ownership of the vehicle is modeled as one continued lifeline. It is assumed that if the vehicle changes owner, he receives an appropriate price taking the value of the vehicle as well as future operating savings into account (compare [375]). No explicit assumption for the lifetime of the vehicle and its battery is made. Residual value or disposal costs are considered to be zero. The TCO is plotted for a lifetime up to 15 years in the figures below.

The *total cost of ownership for a vehicle after year n has ended, depending on yearly driven distance d*, can be calculated by:

$$TCO(n,d) = p + ((d \cdot f) + b + m + s + i + t) \cdot \frac{1}{1+r} \cdot \frac{1 - (\frac{1}{1+r})^n}{1 - \frac{1}{1+r}} \tag{5.1}$$

With the variables:

$n\,[a]$: year of ownership which has just ended.

$d\,[\frac{km}{a}]$: distance driven per year.

p [€]: purchasing price of the vehicle: the Smart Fortwo EV costs 23 680 € with the battery and 18 910 € if the battery is leased [379]. The gasoline powered equivalent costs (depending on configuration) about 12 435 € [380].

f [$\frac{€}{km}$]: fuel costs per km: an electricity price of 0.2913 €/kWh is assumed [381] and a gasoline price of 1.5595 €/l [382]. A fuel consumption 25 % above the NEDC specifications [379] [380], and EV charging losses of 5 % are assumed. The fuel (electricity) cost for the EV in this case is: 0.151 kWh/km * 1.25 * 1.05 * 0.2813 €/kWh = 0.0557 €/km. The fuel (gasoline) costs for the conventional vehicle are: 0.043 l/km * 1.25 * 1.5595 €/l = 0.0838 €/km.

b [$\frac{€}{a}$]: battery rent per year (if applicable): the Smart Fortwo EV is offered with the option of renting the battery for 65 € per month [379], which corresponds to 780 € per year.

m [$\frac{€}{a}$]: maintenance costs per year: the service contract provided for the gasoline vehicle costs 228 € per year [380]. It is assumed that the maintenance of the EV is 20 % cheaper (compare [383]) and thus would cost 182.40 € per year.

s [$\frac{€}{a}$]: technical inspection costs per year: in Germany a new car has to be technically inspected after 3 years and afterwards every 2 years. A technical inspection costs about 53.50 €. Conventional vehicles also need an inspection of their exhaust fumes at a cost of 41.00 € [384]. These costs are recalculated as annual costs for a duration of 15 years. Technical inspection costs for an EV are then 7/15 * 53.50 = 24.97 €/a and 7/15 * (53.50 + 41.00) = 44.10 €/a for a conventional vehicle.

i [$\frac{€}{a}$]: insurance costs per year: for both cars an equal insurance for 348 € per year is offered [379] [380].

t [$\frac{€}{a}$]: car taxes per year: EVs are exempt from paying car taxes in Germany for the first 10 years. For simplicity's sake, this is extended to the entire lifetime in this calculation. The conventional vehicle underlies a car tax of 26 € per year [377].

r [%]: discount rate: a moderate discount rate of 2 % is used here. The last term in the formula models the present value (at the time of purchase) of the money paid in later years for variable costs of the vehicle. With a higher discount rate the situation becomes more favorable for the gasoline vehicle, as costs occur not so much at the time of purchase but in later years.

The above TCO model does not take into account additional costs for an EV induced by the purchase and installation of a wallbox at home. It is assumed that the EV is charged using a normal household socket. Costs for tire replacement are also not part of the model. These can be expected to be the same for the two types of vehicles and thus would not change the difference in TCO. Costs for road tolls and parking fees are also not included. These only change the results if exemptions for EVs are in place for either of the two.

Fig. 5.1 shows the result of a calculation with a driven distance of 13 000 km per year. This driven distance is slightly larger than the average value for German vehicles according to [222]. The calculation shows that the battery renting option is only favorable in the first years in comparison to buying the EV with the battery. The annual battery rent of 780 € even pushes the operating costs of the vehicle to 2 085 €/a, far above those of the EV with battery at 1 306 €/a and the gasoline version at 1 736 €/a. Even after 15 years and a total of 195 000 km traveled, the gasoline vehicle has a significantly lower TCO than the EV, of more than 5 000 €. The TCO difference to the EV with battery renting option even increases to more than 10 000 €.

The situation becomes more favorable for the EV when the distance traveled per year is higher. Fig. 5.2 shows the results of a calculation for 30 000 km traveled per year. It can be seen that with the higher distance driven per year, the EV with the bought battery and gasoline vehicle have almost equal TCO after 15 years and 450 000 kilometers traveled. However, it is uncertain whether the battery of an EV, making up a big part of an EVs value today, has such a long lifetime. The study [374] assumes battery lifetimes of 144 000–192 000 km. The presentation [372] assumes battery lifetimes of 161 000–315 000 km. The article [383], however, assumes a battery lifetime of 489 000 km. Battery aging is not a problem in the battery renting option, as the battery is replaced by the rental company when its capacity diminishes. But with the high battery rent it still remains unattractive in the long term in this case.

The above calculation has been done for one specific EV available in 2014. The difference in purchase price of more than 10 000 € between the gasoline and electric version with battery seems large. However, the same can be found for small vehicles from other manufactures. The VW up! is available as a gasoline vehicle for about 10 375 € (depending on configuration [385]), while the electric version e-up! costs 26 900 € [386]. The Citroën C1 gasoline vehicle costs about 11 250 € (depending on configuration [387]), while the similar C-Zero EV costs 23 393 € [388]. The battery renting option offered for the analyzed Smart Fortwo EV lowers the purchasing price by 4 770 €. But the high battery rent of 720 € per year leads to an overall even higher TCO in the long run.

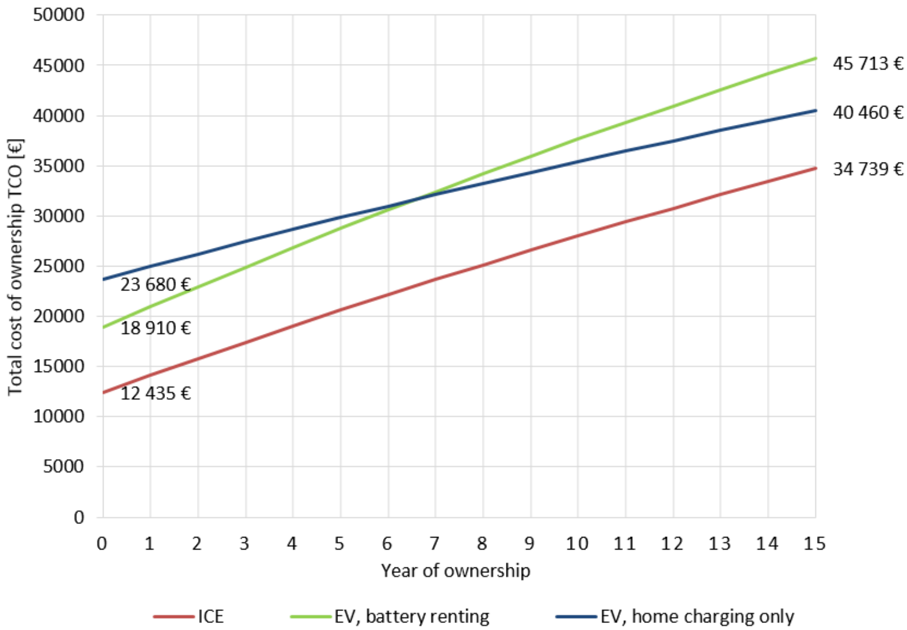

Figure 5.1.: TCO comparison of a Smart Fortwo EV with and without battery renting option, and gasoline vehicle for 13 000 km driven per year

More extensive studies have also come to the conclusion that current EVs are usually not economically attractive without subsidies [373] [376]. Some studies point out that EVs do not have to be as economic as gasoline vehicles, because the first buyers of EVs are willing to pay more due to the novelty of the technology [389] [374].

Several studies assume, however, that EVs will become competitive as their purchase prices decline with lower battery prices in the future and the oil price rises [373] [374]. In the long term the use of EV batteries in secondary uses (see

Sec. 3.3.2) might lead to higher residual values of end of life batteries, slightly reducing the TCO for EVs [228].

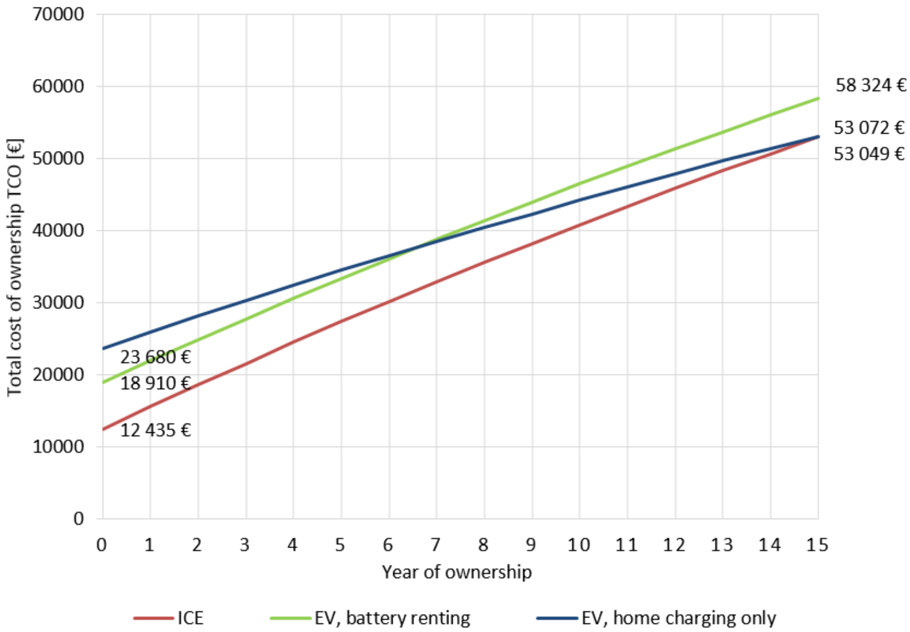

Figure 5.2.: TCO comparison of a Smart Fortwo EV with and without battery renting option, and gasoline vehicle for 30 000 km driven per year

In this section it was demonstrated how the economics of EVs works in principle. These types of vehicles have significantly higher purchasing costs but lower operating costs than comparable gasoline vehicles. With higher distances traveled the operating costs play a bigger role and lead to more favorable TCOs for EVs. However, for the analyzed vehicle the TCO of the EV never became significantly lower than that of the comparable gasoline vehicle.

In Sec. 5.3 the economics of EV ownership will be revisited, also taking the cost for public charging infrastructure into account that EV drivers should pay for. Such costs can be thought of as additional operating costs or fuel costs for an EV.

5.2. The economics of EV infrastructure

After having investigated the economics of EV ownership, now the economics of EV infrastructure will be considered. First, the general frame conditions and possible business models will be discussed, then calculations will be done for a selection of specific business models.

5.2.1. Frame conditions for the economics of EV infrastructure

Before business models for public EV infrastructure are discussed, the frame conditions for such a business in Germany must be understood. In the following it will be analyzed whether such an infrastructure is a public good in the economic sense and thus should be provided by the state. It will then be analyzed whether a natural monopoly for such a charging infrastructure exists, indicating that the infrastructure should be provided by a regulated monopolist. It will also be discussed whether the market for public charging is a contestable market, which allows companies to enter and exit the market freely. Then the general regulative framework will be discussed within which such a business takes place in Germany.

5.2.1.1. EV infrastructure as a private or common good

Infrastructure systems can have properties which differentiate them from conventional private goods. In economic theory goods are differentiated by whether they are rivalrous in consumption and whether they are excludable. *Rivalrous* in consumption means that the consumption of the good by a person reduces the amount of the good available to others. *Excludable* means that people can be excluded from the use of the good. According to these criteria goods can be categorized as *private goods*, *club goods*, *common goods*, and *public goods* [283] (see Tab. 5.1).

Classic infrastructure systems such as public roads, public parks, and street lighting are public goods. Other infrastructure systems, such as free public parking spaces which are accessible by anyone but can only be used by one person at a time, are common goods. The aspect of non-rivalry of the use of infrastructure can be a matter of debate. For instance, to a certain degree the use of a road by a person does not limit its use to other persons. But if too many people use a road negative impacts occur in the form of congestion.

An EV charging infrastructure that allows anyone to freely charge would be a common good. However, most EV infrastructure systems require authentication and payment. This makes such an infrastructure a very conventional private good: only one person can use a charging point at a time, and only those are allowed to access them that pay for the service. This indicates that such a service should not be provided by the state but by private companies alike to gasoline stations today.

Table 5.1.: Different types of goods: examples of infrastructure systems

	Excludable	**Non-excludable**
Rivalrous	**Private goods**: charging infra-structure with authentication, metered parking, gasoline refueling	**Common goods**: free charging infrastructure, free parking
Non-rivalrous	**Club goods**: toll roads, private parks, telecommunication	**Public goods**: public roads, public parks, street lighting, public radio and television

5.2.1.2. EV infrastructure and natural monopoly

Another concept of economic theory that plays a role for infrastructure systems is that of *natural monopoly*. A natural monopoly for a good or service exists, if one big supplier can provide the service at lower costs than several small suppliers (for a formal discussion see [283]).

Electricity, water, and rail networks are examples of natural monopolies. Natural monopolies are usually strongly regulated by the state to hinder the concerned companies from taking advantage of their market power.

A charging infrastructure for EVs does *not* seem to be a natural monopoly. An infrastructure provider mainly has to invest in charging facilities and their installation. There are little economies of scale in setting up this infrastructure. This means that when more charging points are set up, this does not significantly reduce the average cost per charging point. Only the cost of implementing and operating an infrastructure control center, providing a customer hotline and other services, is independent of the number of charging points and can thus be supplied more cost-efficient per charging point for a large number of charging points. If EV drivers can freely use infrastructure provided by different operators (i.e. roam between different networks), it makes little difference whether the infrastructure is provided by a monopolist or by several companies. Thus, there seems to be no incentive to install a regulated monopolist to operate a public charging infrastructure network.

5.2.1.3. EV infrastructure and contestable markets

A contestable market is a market that can easily be entered and left by companies [390]. The possibility of new companies entering the market for short time spans forces the established companies to provide the produced service or product at a competitive price. This is especially relevant in the case of a (natural) monopoly, where the single provider can dictate the price.

The market for the public infrastructure for EVs does *not* seem to be contestable in the above sense. Every owner of a parking space can in principle set up a public charging station at his location. However, the most attractive inner city locations are managed by cities, car parks, and retail stores. These will tend to make a contract with a single charging station operator, posing a barrier to market entry for all later competitors.

Also, a charging infrastructure operator cannot easily leave the market, because then high sunk costs occur. The high installation costs for stations cannot be recuperated, and public charging stations cannot easily be put to other uses [391].

This aspect indicates that if a city does decide to install a regional monopolistic operator of charging infrastructure, it is unlikely that this monopoly will be contested by other companies.

5.2.1.4. The regulatory framework for public charging infrastructure in Germany

A charging infrastructure for EVs operates within the market for electricity. This is a domain which is strongly regulated in Germany. The *Energiewirtschaftsgesetz* (energy market law) [185] sets the general conditions. Accordingly, the distribution and transmission networks are operated by regulated regional monopolists, while the generation of electricity takes place under free market conditions (also see Sec. 3.1.2).

In which way a charging infrastructure for EVs is integrated into the existing electricity market system determines how it is operated and financed, and which regulations apply. The report [392] and article [393] name several possible organization forms for public charging infrastructure, three of which will shortly be discussed here: EV infrastructure as part of the distribution network, as a new regulated infrastructure, and within a free market. The last case applies for Germany today.

If charging points are considered as *part of the distribution network*, they are being installed by the local distribution system operator(s) (DSOs). Their installation is paid for by network charges. An EV owner has a contract with an electricity provider, and can draw electricity from his provider at any public charging point. This organization form is implemented by the national distribution system operator ESB in Ireland [394].

Charging infrastructure can be seen as a *new regulated infrastructure* if a city grants a concession for the buildup and operation of charging infrastructure to one company. Within the concession contract the city can state its requirements, thus regulating the regional monopolist. The charging infrastructure operator has the guarantee that the concession will not be granted to further companies. This is the way that public transport is organized in many cities today. The buildup and operation of the infrastructure is then financed by user fees as well as public funds by the city. These organizations forms exist for charging infrastructure in the cities of London in the UK and Amsterdam in the Netherlands [393].

In Germany charging infrastructure is currently being set up *under free market conditions*, mainly by big electricity providers and local municipal utilities. In principle the infrastructure has to refinance itself by user fees alone, though the installation of many charging points has been subsidized by the state within the German model regions for electric mobility [274].

In the directive on clean fuels infrastructure of 2014, the EU states that "the establishment and operation of recharging points for electric vehicles should be developed as a competitive market with open access to all parties interested in rolling out or operating recharging infrastructures" [43]. The EU explicitly sees the possibility for member states to pay public subsidies for the charging infrastructure.

Different possibilities exist for how EV drivers can access the public charging stations [395]. In a *distribution model* EV drivers can access any charging point with their EV. The money is paid to the provider he has a contract with. This is the case if the distribution system operator manages the public charging infrastructure as has been discussed above. In a *roaming model* the station is accessible to clients of the operator. But clients of other operators can also charge for a slightly higher fee. In a *provider model* only the clients of the charging station operator can access the station. A further possibility is *unrestricted access*, for instance when the charging is entirely free of costs or it is paid in cash. Public charging infrastructure in Germany is currently evolving from the provider model to the roaming model. The EU demands that unrestricted access be possible at all charging stations in the future [43].

The article [396] arguments that the operation of a charging infrastructure for EVs already fits within the electricity market regulations in place in Germany today. Public charging stations can be seen as vending machines for electricity [396] or seen like any other household socket for electricity [397]. They should not be seen as part of the public electricity distribution grid (also compare [398]). Therefore neither can EV drivers demand that all public charging stations are accessible to them, nor can electricity providers demand to be able to sell their electricity over all such public charging points [396]. Charging infrastructure operators can make contracts with electricity providers like any other company and freely devise contracts with EV drivers and other charging infrastructure operators. Though they are not obliged to do so, charging infrastructure operators in Germany are currently implementing roaming solutions that allow EV drivers registered at one operator to also charge their vehicles at the charging stations provided by other operators. Ladenetz [148] and Hubject [150] are such roaming networks in Germany.

Electricity used for charging EVs is loaded with the usual taxes and fees for electricity. In 2014 there are no exemptions nor additional taxes for this use. In Germany the average price for electricity of 29.13 ct€/kWh for private households in 2014 consisted of [381]:

- 25.1 %: *Electricity generation and marketing*: electric utilities can increase their profit margin by increasing this share
- 22.5 %: *Electricity transmission, distribution and metering*: used for maintaining the electricity networks, these fees are regulated
- 52.4 %: Total taxes, fees and contributions:
  - 21.4 %: *Renewable energies contribution*: used for subsidizing generation of electricity from renewable sources
  - 16.0 %: *Value added tax*: state tax
  - 7.0 %: *Electricity tax*: state tax
  - 6.1 %: *Concession fee*: paid to the municipalities because electricity distribution networks make use of public road space
  - 0.9 %: *Offshore liability contribution*: used to cover liabilities which can occur for transmission system operators when they cannot connect offshore wind parks on time
  - 0.6 %: *Cogeneration of heat and power surcharge*: used for subsidizing this technology
  - 0.3 %: *Energy intensive industries contribution*: these industries are exempt from paying network fees, private households compensate for the omitted fees
  - 0.03 %: *Sheddable load contribution*: used to pay these loads which are used by transmission network operators to maintain the balance of the network

It can be seen that taxes, fees and contributions make up about 52.4 % of the electricity price. Charging station operators can obtain electricity from renewable sources from electricity providers and declare this to their customers (§42 Energiewirtschaftsgesetz [185] and §78–79 EEG Gesetz [193]).

For gasoline a mineral oil tax of 65.4 ct€/l is imposed. In 2014 this tax made up about 42 % of the price paid for gasoline by the consumer [382]. The income from this tax is intended to be used by the state to maintain public roads and compensate for negative externalities (pollution, noise) of motorized traffic. If EVs are used in larger numbers in the long term, it is possible that a similar tax might also be imposed on electricity used for charging of EVs.

If charging infrastructure operators set up charging points at public parking places, they are using public road space to pursue their own private business. They therefore have to pay a special use fee (Sondernutzungsgebühr) to the city (for the situation in Baden-Württemberg see [399]). The city can refrain from raising such fees if the special use is "predominantly in the public interest" [399]. Possible conflicts can occur if a charging station operator displays advertisements at his charging stations and this is not allowed by the city's guidelines for urban infrastructure or regulations for the protection of historical monuments [400].

5.2.2. Business models for public EV infrastructure

In this section variants of business models for a public EV charging infrastructure will be discussed. Variants of how the user pays and how the amount of service consumed is measured will be shown. Then some business models will be discussed that combine the service of EV charging with other services.

The user can pay according to different modalities (compare [401] [402] [403]):

- *No fee*: the public charging service is provided for free. This invites EV drivers to charge their vehicles as often as possible, which can lead to a blocking of charging stations for those that really need them. It is also possible to provide the service for free to customers (of a store, restaurant, cinema etc.) and have external visitors pay.
- *Pay per use*: the client pays only when he uses a charging station. This can also be implemented in form of a prepaid card.
- *Basic costs and additional payment per use*: the client pays a basic subscription fee and additional fees for his use. This is a modality which is for instance also common for cell phone contracts.
- *Flatrate*: the client pays a fixed amount per month/year not depending on actual use. This also incites EV drivers to charge as much publicly as possible, blocking the available charging station to those that require them.

Effectively, the user pays to have his EV recharged. But the method of measuring the "amount of service" that a user consumes can vary (compare [401]):

- *Paying for charged energy*: the user pays for the actual charged energy [kWh] measured by a gauged meter in the charging station.

- *Paying fixed price per charge*: the user pays a fixed fee for a limited (according to charged energy or time) or unlimited charge.
- *Paying for charging time*: the fee is calculated solely according to charging time. This can for instance be implemented like a parking meter. The user throws some coins into the charging station, after which he can use it for a certain amount of time. This approach has the advantage that the charging point then does not require a gauged electricity meter (see §4 (2) MessEV [267] [268]). However, if an EV only supports lower charging powers than the charging point would allow, the overall price paid for the charging service can be too high [404].
- *Paying for parking time*: the fee is calculated according to the parking time at the charging station, not dependent on the charged energy. This incites EV drivers to remove their vehicle from the charging station once the charging process is completed. In this variant it is also possible that conventional cars use the parking space of the charging station if other parking spaces in the proximity are occupied and they are willing to pay the higher price [401].

The operator of a charging infrastructure can combine the charging service with other services which provide additional revenues (compare [405] [402]):

- *Advertising on the charging station*: this is an option already supported by some charging station manufacturers (see Sec. 2.1.4). However, it might not be in the interest of the municipality to have additional advertisement placed in public space. This option for generating additional revenues is considered in more detail in Sec. 5.2.3.5.
- *Revenues from additional products/services consumed by the EV driver*: if an EV driver stops at a store or restaurant to charge his EV, he also buys and eats something there. These revenues might be high enough so that the charging service can be partially of fully cross-financed. Gasoline stations currently operate in a similar fashion, as is shown in Sec. 5.4.
- *Bundling of services*: many possibilities exist here, for instance, the access to public charging infrastructure can be combined with a wallbox at home, a household electricity contract, and possibly even the leasing of an EV.
- *EV car sharing stations are also made accessible to private EV users*: if charging stations are set up to charge the EVs of a local car sharing scheme, these existing charging stations can also be made available to private users

of EVs. In this case the infrastructure is mainly financed by the car sharing schemes, while additional revenues come from private EV drivers.

- *Provision of auxiliary services to the electricity system (controlled charging, V2G)*: additional revenues are generated by using connected EVs, with the approval of their owners, to provide balancing power to transmission system operators or peak power to electric providers. Though very interesting in theory, it seems unlikely that such services will be realized for public charging stations in the near future (also see Sec. 3.6).

5.2.3. Evaluating the profitability of selected EV charging infrastructure business models

Based on the above discussion of possible business models of public EV charging infrastructure, profitability calculations for selected business models will be performed in the following. Several publications have already treated the cost of public charging stations. The publications [311] [277] [373] [406] [32] [407] analyze cost component of the installation and operation of charging infrastructure. These publications do not consider possible revenues however. The publication [408] presents a method for a profitability analysis of charging stations, also taking into account indirect benefits such as marketing and customer attraction. Costs and revenues of fast charging stations are treated in [409].

In the following analysis, installation and operating costs, as well as revenues are considered in order to obtain an overall picture of the economic viability of public charging infrastructure. Specific costs can vary from case to case, which has lead several authors to state ranges for costs components [311] [277] [373] [407]. The methodological approach taken in the analysis in the following is to take specific values for the costs components, while varying parameters which determine the revenues. Several different cases, partially based on different constellations considered in [277], are analyzed.

In all considered cases the charging service is provided directly to EV drivers and not, for instance, as a public service paid for by the municipality. It is assumed that EV drivers specifically pay for the amount of energy recharged at a charging stations in kWh, i.e. flat rate schemes or other payment variants as discussed above are not analyzed here.

5.2.3.1. The basic business case

This basic case treats the installation and operation of a charging station on the public curbside. The charging station considered here provides one charging point of 22.2 kW (32 A, 400 V, triphase) with a Type 2 socket. Identification is done with an RFID card. The charging station communicates with a back-end system. The formulas and values introduced here are used with alterations in the other cases in the following subsection. Because few economies of scale occur for the installation and operation of public charging stations, it is admissible to model a single charging station, instead of a modeling the entire charging infrastructure in a city.

Capital expenditure ($Capex$) and operational expenditure ($Opex$) are calculated without value added tax (VAT) in these formulas, while these taxes are included in the revenue ($Revenue$). In Germany the final customer pays the VAT of an additional 19 % on the value of a product, making up 19/(100+19) = 15.97 % of the final purchase price. Companies deduce the value added taxes they have already paid to other companies from the value added taxes they have to cede to the state. This transfer of money is modeled in a simplified way here by using cost components without VAT and deducing the full VAT of 19 % from the final revenues from selling electricity to customers.

The *capital expenditure (Capex)* (without value added taxes) for installing a charging station is calculated by:

$$Capex\ [€] = c + n + w + s + a \tag{5.2}$$

With the variables:

c [€]: cost for the charging station without value added tax. The charging station should be equipped with one Type 2 socket for 22.2 kW charging, with RFID identification, and possibility to connect to a back-end system. The author made an inquiry among several German manufacturers of public AC charging stations to determine this value [410]. Named prices varied from 4 400 to 7 500 €. The lowest price of *4 400 €* is taken.

n [€]: network connection and reinforcement costs. For these costs the values are taken from a German distribution system operator in Baden-Württemberg [264]. The basic fee for a network connection is 1 120 €, plus an additional 77 € per meter of cable, without VAT. It is assumed that the charging station is installed on the curbside, at a distance of 3 m to the underground distribution cable. Total network connection costs are then: 1 120 + 3 * 77 = *1 351* €. The charging station is assumed to have one charging point of 22.2 kW power. For this connection power no additional network reinforcement costs have to be paid to the DSO [264].

w [€]: further installation and ground work costs including parts. Ground work and installation work of six hours is assumed at 50 €/h making up 300 €. Parts are assumed to cost 50 €. Making *350* € in total.

s [€]: signage and ground markings, including labor costs. Costs for the sign and post are assumed to be 80 € and for the ground markings of the parking space 100 €, making *180* € in total (compare [32]).

a [€]: administrative costs for the acquisition of permits from the municipality and the distribution grid operator. These costs are assumed to be *200* € (compare [277]). Costs for planning and administrative work can be much higher in some cases (see [32] [407]).

The *operational expenditure (Opex)* (without value added taxes) for a charging station is calculated by:

$$Opex\ [\tfrac{€}{a}] = r + m + t + c + (u \cdot 24\ [\tfrac{h}{d}] \cdot 365.25\ [\tfrac{d}{a}] \cdot p \cdot e) \tag{5.3}$$

With the variables:

r [$\frac{€}{a}$]: parking space rent, or special use fee per year. Parking garages in the centers of Karlsruhe and Stuttgart offer monthly subscriptions for 40–115€ per month [411]. The lowest parking fee of 40 € is taken, which corresponds to costs of 480 €/a, or 480 * 0.8403 = *403.34 €/a* without VAT.

m [$\frac{€}{a}$]: maintenance and repair costs per year. These costs are assumed to be 5 % of the cost of the charging station per year (based on [11]) which is then *220 €/a*.

$t\,[\frac{€}{a}]$: telecommunication fees per year. A fee of 10 € per month is assumed based on currently available mobile phone contracts [412]. This corresponds to a cost of 120 € per year, or 120 * 0.8403 = *100.84 €/a* without VAT.

$c\,[\frac{€}{a}]$: control center operation costs per year The installation and operation of a control center costs a fixed sum, not dependent on the number of charging stations which are operated. As already argued in Sec. 5.2.1.2 this might be one of the few aspects where economies of scale occur: it becomes less expensive per charging point, the more charging points are operated. It can be assumed that only operators with a large number of charging points will install a control center. If annual costs of 100 000 € are assumed to operate 1 000 charging stations, this would correspond to *100 €/a* per charging station. This estimated value is taken.

$e\,[\frac{€}{kWh}]$: electricity costs per kWh for the charging station operator without value added taxes. These are assumed to be the normal household prices for electricity [381]. It is assumed that a charging infrastructure operator, drawing small amounts of electricity via hundreds or thousand of different meters does not qualify for electricity prices at the industrial level. The normal household price is taken here minus the value added tax of 19 %. Therefore the price without these taxes is 0.2913 €/kWh * 0.8403 = *0.2448 €/kWh*.

$p\,[kW]$: power of the charging station. A charging station with a power of *22.2 kW* (32A, 400 V, three phase) is modeled here.

$u\,[\%]$: utilization rate of the charging station. As has been discussed in section 4.2.6, the actual use of public charging stations seems to be quite low, because EV owners mainly charge their vehicles at home. The utilization rate is varied from 0.25 h/24 h = *1.04 %* to 1.25 h/24 h = *5.21 %*. The utilization time only includes the time for charging, not the entire time spent parking at a station.

The *revenue* (including value added taxes) from selling electricity to EV drivers is calculated by:

$$Revenue\,[\tfrac{€}{a}] = (u \cdot 24\,[\tfrac{h}{d}] \cdot 365.25\,[\tfrac{d}{a}] \cdot p) \cdot (e + m) \tag{5.4}$$

With the variables:

$u\,[\%]$: utilization rate of the charging station (see above).

$p\,[kW]$: charging power of the station (see above).

$e\,[\frac{€}{kWh}]$: electricity costs per kWh for the charging station operator (see above).

$m\,[\frac{€}{kWh}]$: markup on electricity per kWh including value added taxes of 19 %. It can be argued that the price for charging publicly should maximally correspond to the equivalent price for gasoline. The Toyota Prius plug-in hybrid is taken as an efficient reference vehicle. Driving with a depleted battery, the car consumes 3.7 l/100 km [221], adding 25 % to this NEDC value results in 4.625 l/100 km. With a gasoline price of 1.5595 €/l [413], this corresponds to a cost of 7.2127 €/100 km. When driving in electric mode, the same vehicle consumes 11.0 kWh/100 km, or adding 25 % and assuming 5 % charging losses 14.437 kWh/100 km. According to this rationale the maximal cost of public charging should thus be 7.2127 €/14.437 kWh = 0.4995 €/kWh. Taking an average electricity price of 0.2448 €/kWh (without VAT) [381] for the charging station operator, his markup should thus not exceed 0.4995−0.2448 = 0.2547 €/kWh. For the calculation markups of *0.1252, 0.1552, 0.1852, 0.2152 and 0.2452 €/kWh* are taken which result in round values for the price of charging at the station of 0.37, 0.40, 0.43, 0.46 and 0.49 €/kWh.

Using the above definitions of *Capex* (Eq. 5.2), *Opex* (Eq. 5.3), and *Revenue* (Eq. 5.4), the *accumulated costs and revenues after year n, taking taxes into account, as well as an interest rate on the capital investment*, is calculated by (adapted from [414]):

$$
\begin{aligned}
K_n = &-Capex \\
&+ \left(\frac{1}{1+t_v} \cdot Revenue - Opex - t_g \cdot MAX\{0, Revenue - Opex - d\}\right) \\
&\cdot \frac{1}{1+i/(1-t_g)} \cdot \frac{1-\left(\frac{1}{1+i/(1-t_g)}\right)^n}{1-\left(\frac{1}{1+i/(1-t_g)}\right)} \qquad (5.5)
\end{aligned}
$$

With the variables:

t_g [%]: taxes on profits. The operator of the charging station has to pay taxes on his profits. Profits are net revenues minus operational costs and minus depreciation allowances in this context. The tax rate depends on the organization form of the operator. If a small business is organized in the form of a private company (Personengesellschaft) it has to pay municipal company taxes (Gewerbesteuer). Calculation of the Gewerbesteuer depends on many factors (see [415]). A simplified calculation is done here by multiplying the Steuermesszahl (basic tax rate) of 3.5 % by the Hebesatz (collection rate) determined by the municipality in which the company is seated (based on [414]). The Hebesatz in Karlsruhe was 349 % in 2013 [416]. This leads to an overall tax rate for the Gewerbesteuer of 3.5 % * 349 % = *12.215 %.* A big company organized in the form of a stock company would have to pay an additional Körperschaftsteuer (corporation tax) of 15 % plus the Solidaritätszuschlag (solidarity tax) of 5.5 %. Assuming a small private company, the latter two taxes are not included here. Private income tax that would have to be paid by a company owner is also not considered here.

t_v [%]: value-added tax. As already explained above, the tax is paid by the final consumer of the product, and is ceded to the state by seller of the product. This tax rate is *19 %* in Germany.

i [%]: interest rate of the investor after taxes. Interest rates of *5 to 10 %* are considered here. In the formula this interest rate is increased to account for the taxes to be paid on profits by a multiplication with $1/1 - t_g$, effectively modeling the payment of profit on taxes via an higher overall interest (based on [414]).

$d\,[\frac{€}{a}]$: Depreciation allowance per year. German regulations foresee usage times of 19 years for charging stations ("Ladeaggregate") [417]. A linear depreciation is applied here resulting in a yearly depreciation of $1/19 = 0.0526$ %/a of the initial hardware and installation costs Capex (see above).

In Eq. 5.5 the expression $\frac{1}{1+t_v} \cdot Revenue$ models the part of the revenue that remains after the value-added tax t_g, paid by the customer, is ceded to the state. The multiplication with $\frac{1}{1+t_v}$ takes into account that the value added tax t_v is *added* to the final value of the service, and *does not make up the percentage within the final price paid by the customer* as one could think.

The expression $-t_g \cdot MAX\{0, Revenue - Opex - d\}$ models the taxes that the charging station operator has to pay on profits. The profits are defined as revenues minus operating costs minus the depreciation allowance. The depreciation allowance allows the operator to include the wearout of charging facilities as part of his annual operating costs. If profits are zero or negative, the operator does not have to pay any taxes on profits.

The three expression inside the round parentheses (revenues after value added tax, minus operating costs, minus taxes on profits) model the net profits per year.

The last complicated term in Eq. 5.5 models the interest rate of the investor. The generic finance mathematical term $\frac{1}{1+r} \cdot \frac{1-(\frac{1}{1+r})^n}{1-\frac{1}{1+r}}$ models the discounting of future money (also compare Eq. 5.1), effectively modeling an interest rate on investments in this context. The term is used here with $r = i/(1-t_g) = i \cdot 1/(1-t_g)$. The multiplication of the interest rate *after* taxes on profits i with $1/(1-t_g)$ models an effective interest rate *before* the ceding of taxes on profits (based on [414]).

The result of the calculation can be seen in Fig. 5.3. Here and in all following diagrams accumulated costs are shown for a duration of 19 years. This is the life duration of a charging station according to German depreciation regulations [417]. The value seems to be optimistic, shorter life durations of 7.5 [277], 10 [408], or 10–15 [409] years are assumed in previous publications.

Fig. 5.3 shows the calculation result for the basic case. A payback is achieved in the year when the accumulated costs and revenues rise above 0 €. Because the interest rate of the investor is integrated in the model, the investor has already earned his demanded profits at this point. The scenarios modeled here combine values of utilization, electricity price for the customer, and interest rate of the investor in distinct cases ranging from the most optimistic to the most pessimistic. This is done here to demonstrate sensitivity to these values, while allowing to show only a single characterizing diagram for each business case considered in the following. More extensive sensitivity analyses spread over several diagrams would make it more difficult to compare different business cases, which is the main intention here.

Fig. 5.3 supports the hypothesis that the business case for public charging is problematic under current conditions. Only in the most optimistic case modeled here, with the maximal price for charging of 0.49 €/kWh, which comes close to the equivalent price for gasoline, and a high utilization of 1:15 h per day, can a payback be achieved within the considered time horizon. For the slightly more pessimistic case of 1:00 h per day utilization and a price of 0.46 €/kWh payback already seems impossible. In the more pessimistic cases, revenues are not even sufficient to cover operating costs.

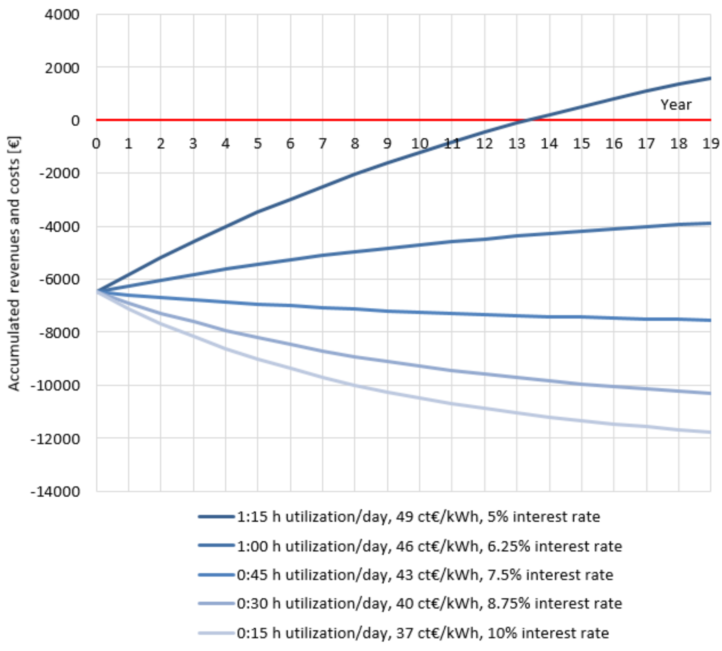

Figure 5.3.: Accumulated revenues and costs for a 22.2 kW AC charging station in the basic case

The strong divergence of the lines in the diagram indicates why reliable profitability analyses of public charging infrastructure are so difficult. It is easily possible to define input parameters which make it a “great” business model and just as easy to define input parameters which make the business model “catastrophic”.

The achieved revenue is roughly the cost per kWh multiplied by the utilization. Thus the utilization rate is the most important variable varied, ranging from 0:15 h to 1:15 h, which is a factor of 1 : 7, while electricity costs are only varied from 0.37 to 0.49 €, which is only a factor of 1 : 1.32. The interest rate from 5 to 10 % determines the curvature of the line. With a higher interest rate future costs and revenues are more strongly discounted, they make less of a difference. Thus it can be seen that line are more horizontal in cases with the higher interest rates. If calculations are done with interest rates of 0 % the diagram shows only straight lines.

In the following subsections different solutions will be analyzed for how the operation of a public charging station can be made more profitable. One possibility is to lower costs. A known and proven solution for reducing costs is to install charging stations in parking garages, where network connection costs can be much cheaper [407]. Another possibility is to install stations with multiple charging points. This lowers the average cost per charging point [277] [32] [407]. The first solution provides semi-public charging stations with restricted access. The second solution is not interesting as long as single point charging stations still remain under-utilized. These case will not be considered in more detail in the following.

In the case of a single-point charging station on the curbside costs can be reduced by attaining an exemption from having to pay parking rent, which is a big part of the operating costs in the basic case. Another possibility to lower costs is to use technologically simpler charging stations which cost less. If they do not communicate with a central control system, operating costs can also be lowered significantly

The other possibility to improve the business model is to increase revenues. Here it will be analyzed if a public infrastructure operated by an electric utility could be cross-financed from profits generated by EVs charging at home or at work. It is also analyzed how additional revenues from advertisement displayed at charging stations can improve the basic business model.

The final business case considers fast charging with 50 kW using a CCS plug. These kinds of charging stations are much more costly than 22.2 kW Type 2 charging stations. However, these stations are used in a different way, reaching higher levels of utilization. Therefore, this case is also analyzed in the following.

5.2.3.2. Reducing costs 1: exemption from parking rent

As was shown above, the basic business case seems to be feasible only under optimistic assumptions. Now it will be analyzed if the business case can be made more profitable by decreasing costs. The biggest yearly operating expense, apart from electricity costs, is the parking space rent of 403.34 €/a (without VAT). But a municipality or private company can provide parking spaces to a charging station operator free of charge. In this case these costs don't just disappear, they are opportunity costs in the form of a decrease of revenues on the part of the parking space provider, due to keeping the place reserved for EVs (with or without parking fees). For the charging infrastructure operator, however, this significantly reduces costs.

Fig. 5.4 shows the result with the same parameters as in the basic case, but without parking space rent. It can be seen that the modeled scenarios are more favorable in this case. The most optimistic scenario achieves payback within a shorter duration of 8 years. The next optimistic scenario comes close to achieving payback within the considered 19 year period. Still, high levels of utilization and high prices for charging remain necessary. The overall profitability remains problematic.

5.2.3.3. Reducing costs 2: technologically simpler charging stations

Apart from the exemption of parking space rent, another possibility to reduce costs is to install technologically much simpler charging facilities. The high-tech charging station considered above costs 4 400 €. A technologically simple charging facility could be implemented by mounting a wallbox on a post, instead of using full pillars. The user pays in cash to be able to use the charging station for a certain amount of time. There is no identification mechanism and no communication with a back-end system. It is assumed that such a simple charging facility could be offered for 1 500 € without VAT (based on the simple charging facility [418]).

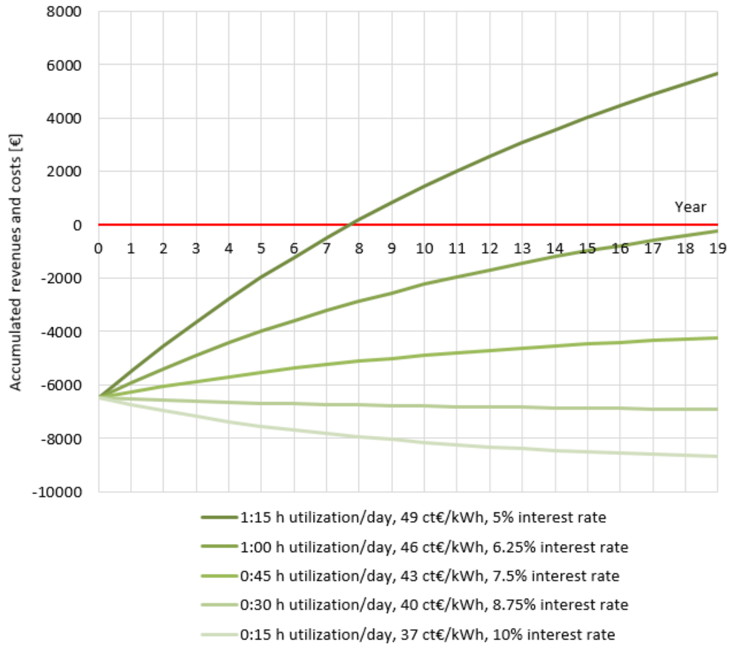

Figure 5.4.: Accumulated revenues and costs for a 22.2 kW AC charging station with an exemption from paying parking space rent

In the model the reduced cost of the charging facility also reduces maintenance and repair costs, which are assumed to be 5 % of the cost of the charging station per year. The depreciation allowance is also adjusted accordingly. Because there is no communication with a back-end system, there are no telecommunication costs and no costs for the operating of the control center. Possible higher operating costs for collecting the money from the charging stations are not considered here.

Fig. 5.5 shows the calculation for such a technologically simpler charging station. The initial investment cost is lower, which pushes the curves up in the diagram. Operating costs are slightly lower which lead to better amortization of costs. The overall impact of the change is stronger than in the case for exemption from parking rent, with the two most optimistic scenarios reaching a payback point within the considered time horizon.

Both of the above measures can be combined. The operator can install simple charging stations at parking spaces where he does not have to pay a parking space rent. Fig. 5.6 shows the case for technologically simpler charging stations with an additional exemption from parking space rent. The overall profitability is significantly improved. Payback is achieved for even the medium scenario. In all considered cases, revenues exceed running costs.

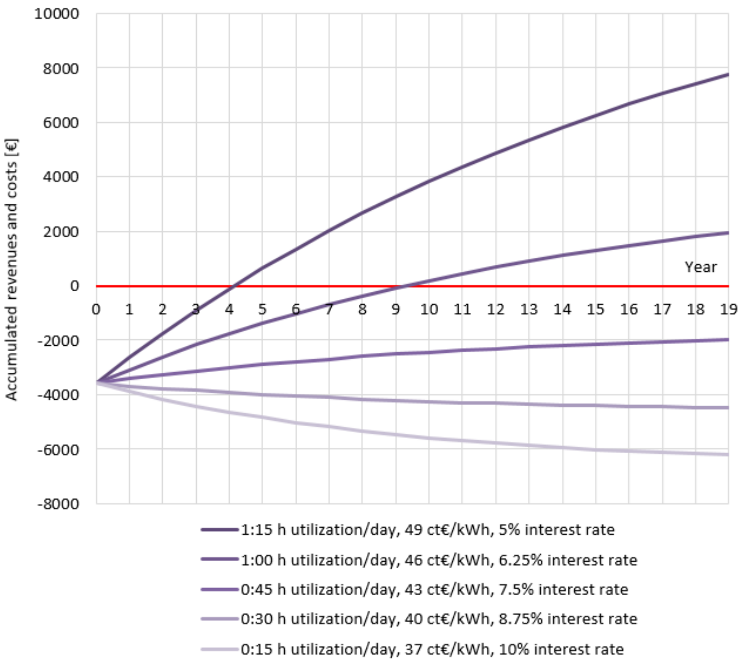

Figure 5.5.: Accumulated revenues and costs for a technologically simple 22.2 kW AC charging station

5.2.3.4. Increasing revenues 1: cross-financing from home charging

In the previous two sections, possibilities have been analyzed which lower the costs for building and operating the charging infrastructure. Now possibilities will be discussed which add new revenue streams.

Most charging stations in Germany have been set up by big electric and smaller municipal utilities in the last years. These electricity providers say that this charging infrastructure cannot be operated in a self-sustaining way, and that the state should therefore pay subsidies [366]. However, electricity providers also make profits from EV owners who charge their vehicles at home. In Sec. 3.3.5 is has been shown that the use of an EV can increase a household's electricity consumption by 65 to 90 %. In the following it is estimated how much profits electric utilities can make from EVs charging at home and whether these gains could be used to cross-finance public charging infrastructure.

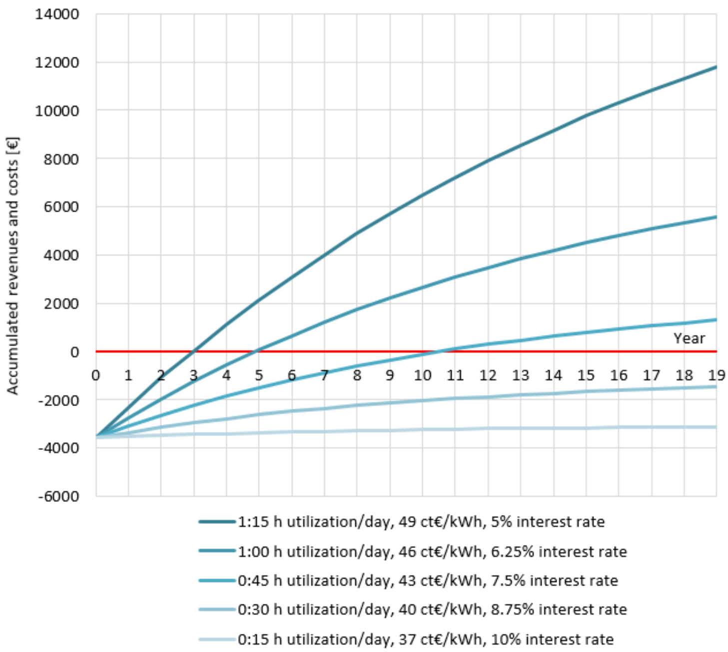

Figure 5.6.: Accumulated revenues and costs for a technologically simple 22.2 kW AC charging station with an exemption from paying parking space rent

The *profits an electric utility makes per public charging point from EVs charging (at home or otherwise)* can be estimated by:

$$P[\tfrac{€}{a}] = n \cdot (d \cdot e) \cdot (p \cdot s_e \cdot s_p)$$

With the variables:

n: number of EVs per public charging point. This number is varied from 10 to 30.

$d\,[\frac{km}{a}]$: average distance driven by an EV each year. This value is set at 13 000 km (slightly above the average in Germany according to [222]).

$e\,[\frac{kWh}{km}]$: average energy consumption of an EV per km. This value is set at 0.228 kWh/km (based on [220]).

$p\,[\frac{€}{kWh}]$: household electricity price paid by the customer. The average price in Germany in 2014 was 0.2913 €/kWh [381].

s_e [%]: share of the electricity price that makes up the electricity providers revenues. In average this is 25.1 % in Germany [381].

s_p [%]: share of the electricity providers revenues that makes up his profits and can be used to cross-finance a public charging infrastructure. This is assumed to be 10 %.

These profits from charging are added to the *Revenue* as defined in Eq. 5.4 above to test the overall profitability.

The model neglects that electric utilities can acquire electricity much cheaper than at household prices, and can thus take a bigger margin for public charging. This is partially compensated here by calculating the profits that occur during home as well as public charging. Thus an additional profit for the electricity provider is implicitly included in the price the EV driver pays at a public charging station. The model also assumes that the EV drivers have a home electricity contract with a provider as well as using his public charging stations. In reality not all users of the public charging infrastructure would have such a home electricity contract. This can be seen as an argument against roaming solutions. If an electric utility provides expensive public charging infrastructure, it also wants to be certain to profit from the additional electricity consumption due to charging at home.

According to this estimate, an electric utility makes only 21.67 € additional profits per EV per year, which might be used to cross-finance the public charging infrastructure. For 10, 20 or 30 EVs per public charging point this would be an amount of 215.72, 433.43 or 650.15 € per year per charging point. Fig. 5.7 shows the result when additional revenues from home charging are added for a quota of 30 EVs for every public charging point. It can be seen that the overall profitability is better than in the basic case, but still not very convincing. High margins on electricity prices and high utilization rates are still required to reach a break even point within the relevant time span.

According to the above estimations, electric utilities are right when they claim that public charging infrastructure cannot be operated in a self-sufficient way today, even when taking additional revenues from home charging into account.

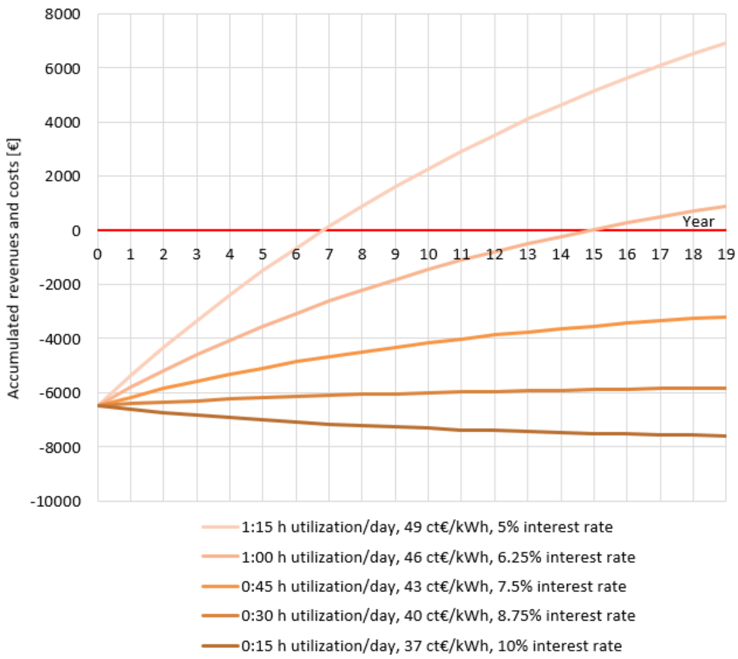

Figure 5.7.: Accumulated revenues and costs for a technologically 22.2 kW AC charging station with cross-financing from 30 EVs charging at home

5.2.3.5. Increasing revenues 2: advertisement

Another possibility to increase revenues from a charging station is to use it to display paid advertisement. Charging station manufacturers are already building facilities which allow to display advertisement in digital form (see Fig. 2.26) or as a poster (see Fig. 2.13). If advertisement is displayed, this might not be in the interest of the city which makes public parking spaces available to an EV infrastructure operator. Cities can demand higher special use fees or demand a share of the profits if public space is used to display advertisement [419]. In the following case it is assumed that the city allows the display of advertisement in public space, and the parking rent remains the same as in the basic case.

Prices for advertisement on posters lie in the price range of 0.70–1.33 € per sheet per day on public advertising pillars (bigger posters consist of several sheets), 6.20–52.10 € per day on exclusively used advertising pillars, and 8.50–26.00 € per day for backlit presentations in the "City Light" format [420] [421] [422]. It is assumed here, that charging stations, allowing to display advertisement to an affluent "Early Adopter" target group, can attain advertisement prices which lie above those of posters on public advertising pillars, but due to the limited size, below those achieved by bigger poster formats.

The calculation is done here with a revenue of 5 € per day for advertisement, which amounts to 5 * 365.25 = 1826.25 €/a. This revenue is added to the *Revenue* defined for charging above. All other parameters are kept as in the basic case. Possibly slightly higher operating expenses due to advertisement (exchange of posters for instance) are not considered.

Fig. 5.8 shows the result of the calculation. It is visible at first glance, that additional revenues from advertisement can be a "game changer" for the operation of public charging infrastructure. All but the most pessimist case reach a payback within the considered time horizon. If revenues from advertisement are larger than assumed here and/or an additional exemption from paying parking fees is in place, it might even be possible to profitably operate a public charging infrastructure independent of any revenues from EV charging.

The analysis indicates that this might be a viable business model for the operation of public charging infrastructure. The city provides public parking places to a public EV infrastructure operator for no or a low rent. The charging infrastructure operator generates additional revenues from displaying advertisement at these stations, to compensate for the lack of revenues that can be generated by the charging service alone.

In fact, this general model for the financing of public infrastructure is already being practiced by the companies Wall/WallDecaux [423] and JCDecaux [424]. The companies install, operate, and clean street furniture such as public transport shelters and public toilets for cities without charge. In return the companies are allowed to display advertisement at this public infrastructure. For charging stations this does not seem to have been done yet by these or other companies.

The result can also be interpreted in another way. If electric utilities set up charging pillars with their logos at inner-city parking spaces, this investment can make sense from a marketing perspective, even when these "advertisement pillars" themselves do not generate enough revenues.

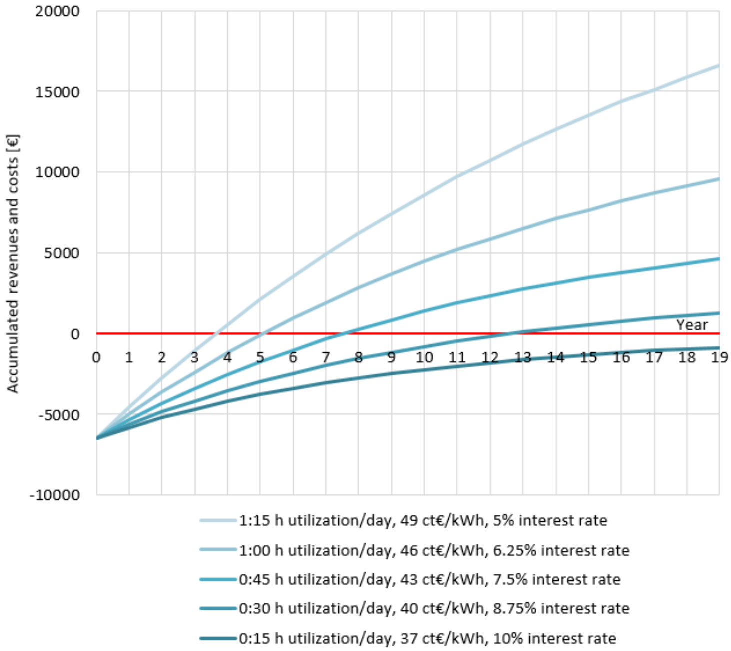

Figure 5.8.: Accumulated revenues and costs for a 22.2 kW AC charging station with additional revenues from advertisement

5.2.3.6. Increasing revenues 3: state subsidies and levels of cost coverage

The developed model also allows to quantify the amount of state subsidies that would be necessary to achieve a payback point for the infrastructure operator in different scenarios. Subsidies might be given for the costs of installation of public charging facilities. However, an approach that seems more promising would be to subsidize the charged energy, similar as is done for renewable energies in Germany. The operator would thus receive a fixed amount for every kWh recharged at his charging points. This does not simply give an incentive to install public charging stations, but to do so at highly frequented locations where they are actually being used, for this analysis the payback period needs to be fixed in order to be able to compare the different scenarios. A payback period of 15 years is taken here.

Subsidies are assumed to be tax free. They are included in the *Revenue* without taxation but with discounting. All other parameters are left as in the basic case. To determine the necessary subsidies for the targeted payback period, subsidies are increased by whole cents until a payback period below 15 years is reached. The result can be seen in Fig. 5.9. The scenarios require subsidies of 0.79, 0.32, 0.15, 0.6 and 0.0 €/kWh. The corresponding total subsidies per year amount to 1 601.43, 1 297.00, 912.20, 486.50 and 0.0 € per year for the single charging station.

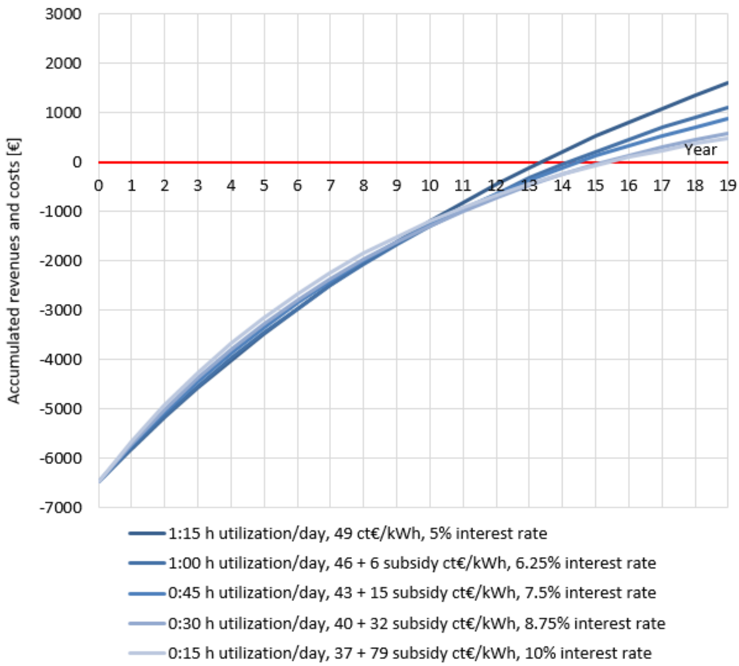

Figure 5.9.: Accumulated revenues and costs for a 22.2 kW AC charging station with untaxed subsidies per charged kWh

An indicator that is often used for public infrastructure that needs to be subsidized, for instance public transport, is the *level of cost coverage*. This is the actually achieved revenue divided by the costs for providing the infrastructure.

To apply the concept here, the achieved revenues are divided by the revenues that would be necessary to attain a 15 year payback period. The interest rate of the investor is included as a cost component. The subsidies above were calculated free of taxes, which does not allow to compare them directly to the achieved revenues which are taxed. Thus the above procedure is repeated for taxed subsidies. The result can be seen in Tab. 5.2. The most pessimistic scenario reaches a level of cost coverage of only 26 % while the most optimistic scenario achieves a cost coverage over 100 % as it already reaches payback before the 15 year period without any subsidies. To set these values in perspective: the public transport sector in Germany has a high level of cost coverage of 77.1 % [425].

Table 5.2.: Comparison of the level of cost coverage for different scenarios

Scenarios: **Utilization [h/d]** **Price [€/kWh]** **Interest rate [%]**	 0:15 0.37 10.00	 0:30 0.40 8.75	 0:45 0.43 7.50	 1:00 0.46 6.25	 1:15 0.49 5.00
Revenues before taxes [€/a]	750.04	1621.70	2615.00	3729.9	4966.5
Required subsidy before taxes to achieve payback [€/kWh]	1.03	0.43	0.21	0.08	0.0
Associated added revenues before taxes to achieve payback [€/a]	2087.95	1743.00	1277.00	648.70	0.0
Level of cost coverage (including interest) [%]	**0.26**	**0.48**	**0.67**	**0.85**	**> 1.00**

5.2.3.7. The business case of fast charging

In this section calculations are done for a 50 kW charging station, with a CCS socket, allowing one EV to charge at a time. Identification is again assumed to occur via RFID. Communication with a back-end control center is assumed to take place.

Several parameters are modified in comparison to the basic case above. Fast charging stations are much more expensive. The lowest found price for a 50 kW CCS station of 23 157 € without value added tax is taken (based on [426] [427]). In the model, this also entails higher repair and maintenance costs (5 % of the cost of the charging station) and a higher depreciation allowance (5.26 % of total Capex per year).

With a higher power demand for the network connection, the operator has to pay additional network enforcement costs of 1 331.40 € to the DSO [264]. This increases the overall costs for network connection and reinforcement to 1 351 + 1331.40 = 2 682.40 €.

The use of fast charging stations with high charging powers differs from that of normal charging stations. Slow and normal charging is usually done while the driver parks at a destination where he follows an activity. When the car is fully charged it often remains parked for a while, until the driver returns. But fast charging is more similar to refueling a gasoline vehicle. The EV driver stops at a fast charging station which is located at a motorway service area or a central city location. The driver waits a few minutes in the proximity of his car while it is charging and afterwards immediately drives on. In pilot trials, fast charging stations have been found to have a substantially higher utilization rate (in time per day) than normal charging stations (see Sec. 4.2.6). In the calculation done here, it is assumed that fast charging stations have twice the utilization of normal charging stations, resulting in a maximal considered use of 2:30 h and minimal use of 0:30 h per day.

As has been shown in Sec. 4.2.5, EV drivers seem to be willing to pay more for fast charging than normal charging. However, in the basic case the maximal price of about 0.4995 €/kWh has already been used, which leads to a similar price for driving with electricity and gasoline with the reference vehicle Toyota Prius plug-in hybrid. Therefore, no further raising of prices above this level are done here. All other parameters are left as in the basic case above.

The result of the calculation can be seen in Fig. 5.10. The diagram is not directly comparable to the previous ones, because the utilization rates for all scenarios have been increased by a factor of 2. Under the given assumptions the business model for fast charging does not seem fully convincing either. Though EV drivers will probably be willing to pay high prices of 0.46 or 0.49 €/kWh for fast charging, a high utilization of more than 2 hours per day is needed to achieve payback.

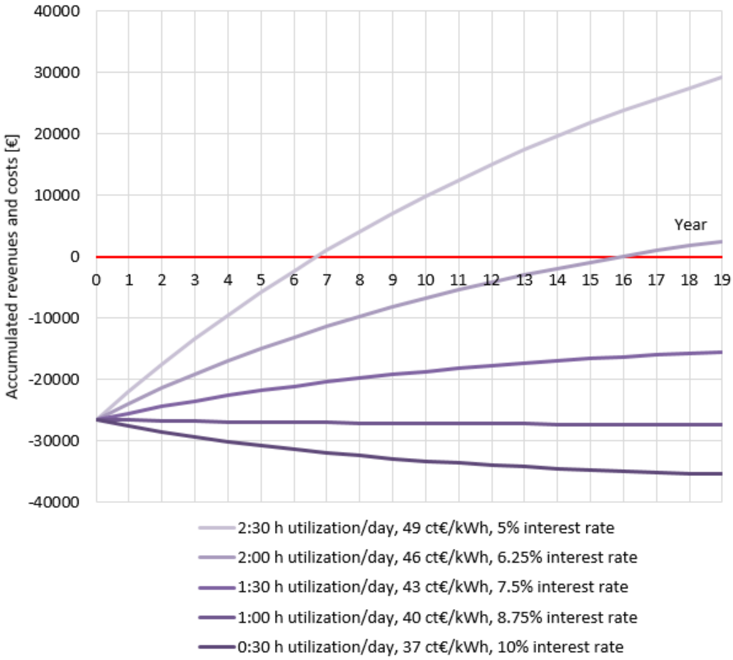

Figure 5.10.: Accumulated revenues and costs for a 50 kW DC fast charging station (with twice the utilization of a normal station as above)

5.3. Interactions between the economics of EV ownership and infrastructure operation

In Sec. 5.1 the economics of EV ownership have been discussed on the basis of different variants of the Smart Fortwo vehicle available in 2014: an electric version, an electric version with rented battery, and a gasoline version. The analysis has shown that the electric version with included battery has significantly lower running costs than the gasoline vehicle. But, due to the much higher purchasing price, the total cost of ownership remains significantly above that of the gasoline vehicle. When a very high distance of 30 000 km traveled per year is assumed, the EV attains an equal TCO than the gasoline vehicle after 15 years and 450 000 km traveled. However, it is uncertain whether the battery of the EV can have such a long lifetime. The offered battery renting option was found to be more costly than both other variants in the long run, due to the very high battery rent, which pushed its running costs above those of the gasoline vehicle.

The initial analysis was done for EVs which only charge at home using a normal household socket. As has been shown in the previous sections, charging at public stations costs more per kWh because an additional fee is required in order to recover investment and operating expenses for the public charging stations. Thus, when public charging is included the operating costs of EVs rise. In this section the initial TCO calculation will be revisited, this time including additional costs for public charging

Of the different prices for charging considered in the above analyses on the economics of public charging infrastructure, the highest price for public charging of 0.49 €/kWh is taken here. This can be interpreted as the worst case for the EV owner in this context.

The total electricity costs per year is increased, with 5, 10, 20 and 100 % of electricity charged at public stations at a price of 0.49 €/kWh, while the rest is charged at the household price of 0.2913 €/kWh. The low percentages model a situation where an EV driver charges his vehicle at home or workplace and only occasionally uses a public charging station. The 100 % model a situation where an EV owner does not have a private charging possibility and thus has to do all his charging at public stations. For the battery rental option only home charging, as before, is considered.

Fig. 5.11 shows the situation for 13 000 km traveled each year. It can be seen that small percentages of public charging hardly change the overall TCO results. For 5, 10, and 20 % of energy charged publicly, the cost of electricity rise only 25.60, 51.20 and 103.39 € each year. This is a lot less than, for instance, maintenance costs of 182.40 € or insurance costs of 348.00 € per year. The overall TCO of the EV is thus not significantly altered by the use of public charging. But the increase in charging price becomes relevant when all charging is done at public stations. Here the electricity costs rise to an amount of 511.97 € per year. This increases the overall TCO of the EV considerably in the long run.

Fig. 5.12 shows the calculation for 30 000 km traveled each year. The same tendency as before is visible. Low shares of public charging increase the TCO of the EV, but do not alter the picture in relation to the other alternatives. Charging only publicly does however have a significant impact on TCO in the long run.

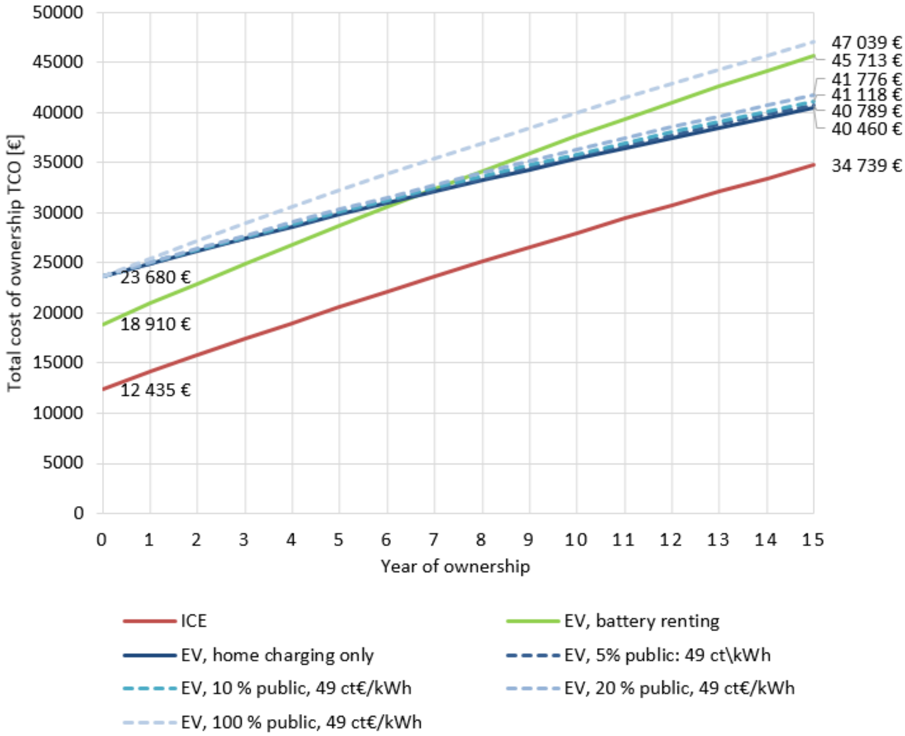

Figure 5.11.: TCO comparison of a Smart Fortwo EV with different percentages of public charging, with battery renting option, and gasoline vehicle for 13 000 km driven per year

In Fig. 5.11 and 5.12 it can be seen that the EV which charges all electricity publicly has slightly higher operating costs than the gasoline vehicle, as the grade of the line is higher. This contradicts the idea of 0.49 € being the price for which the costs for electric and gasoline are the same per km. This is because another vehicle, the Toyota Prius plug-in hybrid, has been used as the reference vehicle above. The electricity-gasoline equivalent is slightly different for the Smart Fortwo. For the calculation an electricity price of 0.2913 €/kWh [381] is again used and a gasoline price of 1.5595 €/l [382]. The gasoline variant of the car consumes 4.3l/100 km [380], or assuming 25 % fuel consumption above the NEDC specification: 4.3l/100 km * 1.25 = 5.375 l/100 km. This corresponds to costs of 5.375 l/100 km * 1.5595 €l/l = 8.3832 € /100km. The energy consumption of the electric variant of the Smart Fortwo [379], again taking 25 % additional fuel consumption as well as 5 % charging losses into account is: 15.1 kWh/100 km*1.25*1.05 = 19.8188 kWh/100 km. The price for public charging, based on the rationale of equivalent costs for gasoline, should therefore not exceed 8.3832 €/19.8188 kWh = 0.4229 €/kWh. This limit for the Smart Fortwo EV is thus significantly lower than the one of 0.4995 € kWh for the Toyota Prius PHEV. But, as has been shown here, higher prices for public charging are not problematic for the total costs of driving an EV, if public charging is only done occasionally.

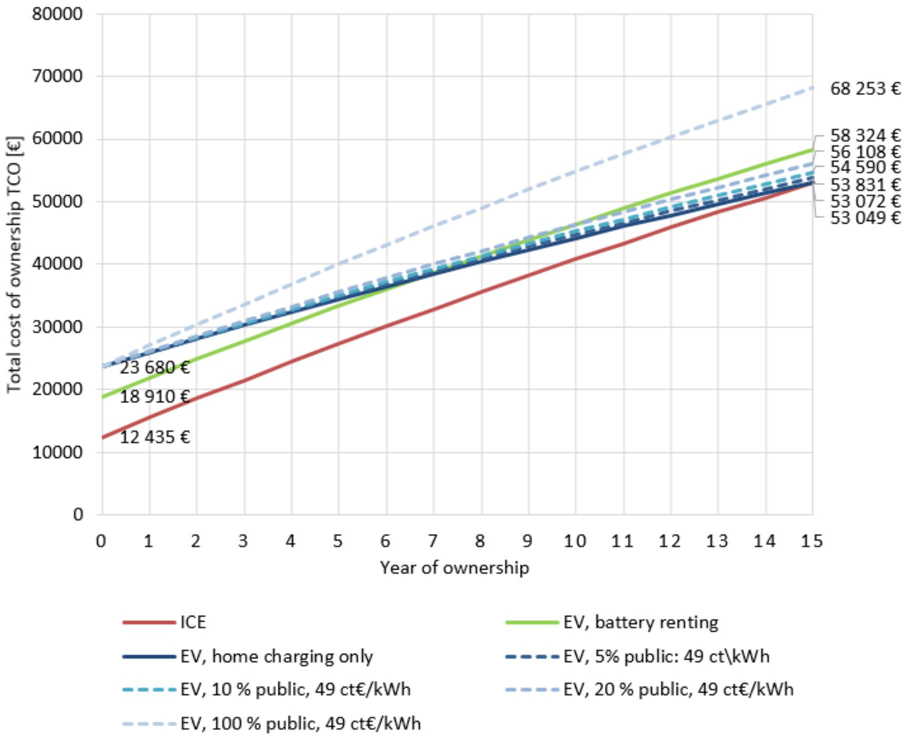

Figure 5.12.: TCO comparison of a Smart Fortwo EV with different percentages of public charging, and with battery renting option, and gasoline vehicle for 30 000 km driven per year

5.4. Retaking a closer look at the business model of gasoline stations

The analyses in this chapter have shown that it is difficult to operate public charging infrastructure profitably. Revenues from sold electricity can be expected to be low, while investment costs are quite high. Several possibilities have been analyzed in this chapter to improve the overall business model by reducing costs and adding additional revenue streams.

For vehicles powered by gasoline and diesel, a widespread refueling infrastructure in the form of gasoline stations exists in Germany as in other countries. In Germany in the year 2014 there existed 14 622 public gasoline stations, 350 of them situated at rest areas of motorways [279]. At the same time, there were 43 171 486 cars powered by gasoline and diesel (not including hybrid vehicles and trucks) in Germany [280]. That makes one gasoline station for 2 953 cars.

The gasoline stations at motorway rest areas were owned by the Germany state until 1998 when they were privatized [428]. Therefore, today the "public" infrastructure of gasoline stations is provided entirely by private companies, without any direct state support. The market shares concerning the sales of fuels in 2013 were 22.5 % for the company Aral, 21.0 % for Shell, 14.0 for % Bundesverband Freier Tankstellen (federal union of independent gasoline stations), 10.5 for % JET, 8.0 % for Total, 7.0 % for Esso, and 17.0 % for other companies [429]. Private gasoline stations for company-internal use are operated by the German army, public transport companies, and by companies with big vehicle fleets such as logistic companies [430].

The similarities between refueling with gasoline and recharging with electricity should not be overemphasized. Nevertheless, it is interesting to learn why gasoline stations are profitable in a free market environment while, according to the above analyses, the profitability of public charging stations for EVs seems uncertain at the moment.

The operators of gasoline stations usually rent the gasoline station from the mother company. For every liter of fuel sold, they receive a part of the price as a provision. In 2012 the provision for gasoline station operators was in average 0.1005 €/l for Eurosuper gasoline [429]. At a price of 1.646 €/l for gasoline at that time [431], the provision was only 6.1 % of the selling price of gasoline.

However, gasoline stations in Germany make a big share of their revenues from selling products in their shop. The actual profit margins on these sales is not known, but gross revenues can be compared. In 2012 gasoline stations operating under the provision model made only about 31 % of their revenues from selling fuel, while about 64 % of revenues were made from selling shop products. The biggest part of shops sales made up tobacco, followed by drinks and prepaid mobile phone cards. Car washing made up only 3 % of revenues, and other services about 2 % (own calculations based on [430]).

Gasoline stations in Germany have developed from gasoline stations with integrated shops to shops which also sell gasoline. Gasoline is apparently becoming the lure to attract customers for following shop sales [430]. Transferred to charging stations for EVs this would mean that charging stations would not have to be totally self-sustaining if they are set up at locations were additional revenues are generated from other services or products. Thus, charging stations could be set up at retail stores, restaurants, cinemas, or at gasoline stations. Fast charging stations are more suited for locations where people stop only for shorter durations. If big parking garages install charging stations, they can make a big part of the revenue from parking fees, and not from the charging service. Such additional revenues can be included in an economic model of charging stations, as was already done in [408], but it seems difficult to precisely quantify them.

5.5. Conclusion: the economics of EV charging infrastructure

In this chapter the economics of a public charging infrastructure for EVs has been analyzed. The main findings will now be summed up again.

The economics of EV ownership have been demonstrated with the Smart Fortwo vehicle. When the EV is charged at home, running costs are considerably lower than for a gasoline vehicle. However, currently the initial purchasing price of the EV lies so far above that for the gasoline version that under realistic conditions the EV still remains more costly over the total time of ownership. Only with very high distances of 30 000 km traveled per year were the calculated TCO of the EV and gasoline vehicle similar after 15 years and a total of 450 000 km traveled. The currently offered battery renting option lowers the initial purchasing price, but the battery rent pushes the running costs so far up that this variant is more expensive than both the EV with battery and the gasoline vehicle in the long run.

The general frame conditions for the operation of public charging infrastructure for EV were discussed. Such an infrastructure is not a typical public good, because it is both rivalrous and excludable in consumption, i.e. only one person can use a charging point at a time, and it is easy to assure technologically that only people who pay have access to the charging service. Such an infrastructure also does not form a natural monopoly because little economies of scale occur. Both of these aspects indicate that the infrastructure should be provided by private companies in a free market, rather than by the state.

The provision and distribution of electricity is strongly regulated in Germany. But within the given legal framework there seem to be no barriers which might hinder the installation and operation of public charging stations. Operators can set up charging stations and make contracts with their clients as they see fit. They can allow clients of other operators to access their charging stations via roaming solutions, but they are not obliged to do so.

Different business models for public charging infrastructure differ in the way the user pays (no fee, pay per use, basic fee and additional pay per use, flatrate) and what he pays for (charged energy, fixed fee per charge, charging time, parking time). The operator can generate additional revenues from displaying advertisement or bundling the charging service with other services.

Profitability analyses were done for selected business models. In the basic case, a charging station on the curbside offering one 22.2 kW Type 2 charging point was modeled. It was found that initial costs are quite high and expected revenues rather low. Only under very optimistic assumptions could a payback be reached within the considered 19 year time horizon.

It was then analyzed if the business model could be improved by lowering costs. An exemption from parking rent, a case that occurs when a city allows the operator to use public parking spaces free of charge, slightly improved the situation. Using technologically simpler charging stations, which are cheaper to purchase and cheaper to operate, also has a positive impact. Both measures together make a visible difference. The more optimistic scenarios reached a payback within the considered time horizon. Operating costs could be covered by revenues even in the most pessimistic case.

It was then tested how revenues could be increased. Cross-financing public infrastructure from revenues an electricity provider generates from EVs charging at home does not seem to be feasible. These additional revenues were found to be too low. But displaying advertisement at the charging station seems to be a very promising approach. In all but the most pessimistic scenario could a payback be attained within the considered time horizon. The financing of public infrastructure by advertisement is also a business model which has already been successfully applied to infrastructure such as public transport shelters and public toilets.

A third possibility of making public charging stations profitable would be the payment of state subsidies. Here it was modeled that a subsidy is paid for every kWh charged at a station, similar to the subsidy of the generation of renewable energies in Germany. This does not only incite private companies to install public stations, but to do so at highly frequented locations where they are actually being used. The required subsidies were found to amount to as much as about 1 600 € per year per charging station in the most pessimistic case. When the level of cost coverage was calculated it was found to be well below that of public transport in Germany of 77.1 % for all but the more positive cases.

The business case of fast charging was also explicitly considered. Investment costs for such charging stations are much higher, but utilization rates and willingness to pay higher charging prices can also be expected to be higher. It was found that the overall profitability is also uncertain in this case. High utilization of more than 2 hours per day seems to be necessary to regain the high investments.

After the thorough investigation of infrastructure economics, the economics of EV ownership was revisited, taking additional costs due to public charging into account. It was found that the overall impact of occasional public charging of 5, 10, or 20 % of the consumed energy on the total operating costs is very small, even for high costs for public charging of 0.49 €/kWh. When an EV is solely charged at public stations the impact becomes noticeable, however.

Finally, the business model of gasoline stations in Germany was discussed. Gasoline stations make only a part of their revenues from selling gasoline. The biggest part of the revenues is made from selling products in the associated shop. The same approach can be transferred to normal or fast charging stations. They can be installed at locations where the main revenue is made from other products and services and not from the charging service itself. Such locations could be retail stores, restaurants, cinemas, gasoline stations, or parking garages.

Overall, the discussion in this chapter has shown that the economic feasibility of public charging stations for EVs is intricate. Under today's circumstances it is improbable that they can be operated profitably, even when taking into account that the electric utilities which have mainly installed them also profit from EVs charging at home. The business case can be improved by reducing costs, increasing revenues, notably by displaying advertisement, and direct or indirect subsidies by cities or the state. Alternatively, revenues can be generated from additional services provided at the location. The high margins on publicly charged energy, required for the payback of investment and operating costs, do not have a big impact on the total operating costs of EVs when public charging is used occasionally.

6. Public policy and external effects

In the previous chapter the economics of EV ownership and of the operation of public charging stations have been discussed. For the considered vehicle it has been found that the total cost of ownership is higher than that of the equivalent gasoline vehicle for a private person under current circumstances. Public charging stations can only be operated profitably when adaptions to the current standard situation are made, such as reducing costs and adding further revenue streams, for instance by advertisement.

In this situation it is consequent that customers are hesitant about buying EVs. In the end of 2014, there were only 26 006 EVs registered in Germany, among them 7 058 PHEVs [4]. It is also consequent that operators of public charging infrastructure are reluctant to install more stations and are calling for subsidies [366].

In 2009 the German government published its *national development program for electric mobility* [1]. In this strategic document the government explains why the development of electric mobility is important for Germany. Expected benefits are the reduction of CO_2 emissions in the traffic sector, the reduction of dependency on petroleum, the development of the industry, the reduction of local emissions and noise, the improvement of the efficiency of electricity networks and better integration of renewable energies, and the development of intelligent and multi-modal mobility concepts for the future [1]. The target of 1 million EVs on German streets by the year 2020 is stated.

In the current situation it seems unlikely that the target of 1 million EVs by 2020 will be met. However, unlike other states, the German state does not pay direct subsidies for EVs and for charging infrastructure. In the *government program* *for electric mobility* of 2011 it is argued that "free competition has often turned out to be the best driver of innovation: the better the market develops, the lower are the costs" [294]. The government program also states: "the development of the non-public as well as public charging infrastructure is strictly a duty of the private sector", and "the development and financing of this infrastructure is the duty of the industry" (author's translations) [294].

It seems that the free market for EVs and public charging in Germany does not lead to the desired results. An intervention of the state into free markets can be warranted if *externalities* occur. Externalities are side effects of the consumption or production of a good which have an impact on a third party and which are not considered in the market price (compare [282]). Externalities can be positive if additional benefits are created, or negative if additional costs are created.

In situations in which externalities occur, the demand curve of consumers and supply curve of producers (see Sec. 4.1.1) do not reflect additionally caused social costs and benefits. The price and quantity attained in the market equilibrium is not optimal in relation to *all* incurred costs and benefits. The state can therefore *internalize* external benefits and costs by introducing subsidies (in the case of positive externalities) or taxes (in the case of negative externalities). Demand and supply are then shifted to result in more of a product being traded (in the case of subsidies) or less of a product being traded (in the case of taxes) than without a state intervention (for a formal discussion see for instance [432] [433]).

The benefits stated in the national government program on electric mobility, such as lowering CO_2 emissions, lowering local pollutant and noise emissions, developing the industry, and others, can all be interpreted as positive externalities of EVs and their infrastructure. These are benefits for society as a whole, that do not play a role for the direct market transactions between car manufacturers, EV drivers, and public charging infrastructure operators.

In the context of public charging infrastructure for EVs it is difficult to pinpoint the origins of external benefits. Public charging points which remain unused and unseen do no create positive externalities. They do so only when EVs recharge at them and people are aware of them. A pragmatic approach here is to think of EVs and charging infrastructure as one inseparable system. For a specific number of EVs there should be a certain number of public charging points available. The European union proposes a ratio of 1 publicly accessible charging point for every 10 EVs [43], the German platform on electric mobility a ratio of 1 semi-public or public charging point for every 6.3 vehicles [276].

Taking a minimal level of utilization of charging points into account, the ratio should be considerably lower (see Sec. 4.3).

The analysis of external effects and of associated public policy has already been done in previous publications. The report [434] contains a detailed discussion which has been prepared for the German Bundestag. The report deals with the impacts of electric mobility on the environment, the German industry, resource imports, traffic noise levels, and the development of future mobility systems. Current Germany policy is compared to policies of other countries, and possible further policies are recommended. The report [435] also treats several of these externalities.

Costs of policy instruments such as subsidies, tax exemptions, or provision of public infrastructure by the state can be put in relation to benefits via *cost-benefit analyses*. Here external benefits such as lower CO_2 emissions are expressed in monetary terms, using for instance a cost per emitted ton of CO_2. The costs and potential benefits of different policies can then be compared. A policy is worth implementing if the overall benefits exceed the costs. If several mutually exclusive policies have a positive benefit-cost relation, the one with highest benefit-cost relation should be chosen.

An extensive cost-benefit analysis of different policies to support the diffusion of EVs in Germany has been done in [436]. In the developed model, costs and benefits are calculated for consumers, producers, the state, and the environment. All monetarized costs and benefits are summed up to attain the overall social cost or benefit. The calculations come to the result that several different policies can effectively increase the number of electric vehicles bought until 2020. Especially the introduction of a bonus-malus system, where vehicles with low emissions are subsidized while vehicles with high emissions have to pay a fee, or a direct subsidy for the purchase of EVs, have significant positive impacts on the number of EVs. However, according to the model, the large majority of policies has a negative balance concerning the relation of overall costs to benefits. Only policies with a small overall impact result in overall social benefits. Such policies are tax incentives for EVs used as business vehicles and the use of PHEVs and REEVs in fleets of public authorities. If EVs are exempt from paying car taxes, the balance is neutral because consumers gain as much as the state looses. These seem to be those policies which have already been implemented or are about to be implemented by the German government. The authors come to the conclusion that the state should not intervene in the domain of electric mobility. State incentives can accelerate the diffusion of EVs, but only against market mechanisms at a high overall cost.

Within this thesis, a detailed cost-benefit analysis is deemed to be too extensive. Therefore, only a qualitative discussion is done here. The approach taken is similar to that of the report [434]. First, different externalities of EVs and their infrastructure are treated in Sec. 6.1. Then current policies on the level of the Europen Union and in Germany are presented in Sec. 6.2.2. Finally, prospective policies for Germany are discussed in Sec. 6.3.

6.1. External effects of EVs and an associated public charging infrastructure

In this section positive external effects of EVs and the associated charging infrastructure will be discussed. The aspects that will be discussed are the lowering of CO_2 emissions, the lowering of air pollutant emissions, the lowering of noise emissions, the lowering of the dependency on resource imports, impacts on employment, the development of future mobility systems, the development of smart grid and renewable energies, and image factors. The named aspects correspond to the expected benefits named in the German national development plan for electric mobility [1]. The aspect *lowering the dependency on petrol imports* [1] is interpreted in a wider sense of *lowering the dependency on resource imports* here. The factor of image is added as an implicit aspect. Most of these effects have also been treated extensively in the report [434] and several in the report [435].

The discussion here does not aim at precisely quantifying the size of external effects. The aim is to provide general background information which helps to understand the benefits of electric mobility. For most benefits a "Yes, but ..." situation exists. For instance the use of EVs can lower the emissions of CO_2, *but* this depends on how the electricity used for charging the EV is generated. Such limitations exist for most aspects.

Besides many positive effects, several small negative external effects are also expected when more EVs are used. EVs could lead to a rebound effect. Due to the lower fuel costs per km, owners of these vehicles can be incited to use them more than they would a conventional vehicle (compare Sec. 4.2.6). Some people who had used bicycles or public transport before, might buy an EV instead [434].

EVs are generally not a solution for the problem of traffic congestion, road wear, and lack of parking space in city centers. When inner city parking places are reserved for EVs or EVs are allowed to use special lanes, they can even aggravate some problems.

The use of EVs in the large scale can lead to less tax revenue for the state. This is because the small electricity tax only makes up about 7 % of its price, while the mineral oil tax on gasoline make up about 42 % of its price. The mineral oil tax is intended to be used to maintain the public road system, while no such contribution exists for electricity. Many other contributions are, however, included in the final electricity price to finance different parts of the electricity system (see Sec. 5.2.1.4).

6.1.1. Lowering of green house gas emissions

The emission of green house gases (GHGs) into the atmosphere contributes to global warming. This involves the melting of snow and ice, the warming of the atmosphere and oceans, and the rising of sea level. Extreme weather events such as storms, floods, and droughts are occurring more often. These changes in weather patterns can have severe impacts on natural and human systems [437].

The main green house gases listed in the Kyoto protocol are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) [438]. These and further gases have differing global warming potential, which is expressed in relation to that of CO_2 (carbon dioxide equivalent). For instance, for a time horizon of 20 years, methane has 85, nitrous oxide 264, and sulphur hexafluorid 17 500 times the global warming potential of carbon dioxide per emitted ton [439]. Still, due to the high amounts emitted, CO_2 is the most relevant green house gas [437].

In the Kyoto protocol of 1998 Germany agreed to reduce its green house gas emissions to 92 % of the level of 1990 within the years 2008–2012 [438]. This target seems to have been met, as in the year 2010 the level of GHG emissions in Germany had already decreased to 75.16 % of the emissions of the year 1990 [440]. In the Doha amendment to the Kyoto protocol of 2012 Germany committed itself to reduce its GHG emissions to the level of 80 % of that of the year 1990 within the years 2013–2020 [440].

The transport sector was responsible for 16.7 % of GHG emissions in Germany in 2012 [441]. Replacing gasoline and diesel vehicles by EVs thus provides a chance to reduce GHG emissions.

In scientific studies two methods are mainly used to compare emissions of EVs and conventional vehicles. In a *well-to-wheel analysis* the total energy consumption and emissions in all stages of production, distribution, and consumption of different energy carriers for mobility (electricity, gasoline) are compared. A *life cycle analysis* usually goes a step further by looking a the entire life cycle of vehicles, consisting of the stages production, use, and disposal. A few selected studies are summarized in the following.

The study [442] takes a well-to-wheel approach to compare CO_2 emissions of EVs and gasoline-powered vehicles during operation. The study shows that the overall results depend on how the electricity used for charging EVs is generated. Whether charging is uncontrolled or controlled also has an impact. Calculations are done for the anticipated power plant mix in Germany in the year 2030. With uncontrolled charging and no additional renewable power plants, emissions of EVs are slightly higher than those of gasoline vehicles. With the average emission value of electricity generation, emissions of EVs are slightly lower than those of gasoline vehicles. With the installation of additional wind power plants to generate electricity for EVs, their emissions become considerably smaller than those of gasoline vehicles. If additionally controlled charging is implemented, this further decreases the CO_2 emissions. Then EVs can be charged selectively using the electricity generated by the wind power plants. However, when these additional renewable power plants do not exist, and charging is controlled, it takes place at night when electricity is generated by brown and black coal power plants. Controlled charging thus increases the emissions in this case.

The study [443] looks at the entire life cycle of vehicles including the well-to-wheel flow of their energy carriers. The calculation shows that EVs lead to more GHG emissions during production, but less during their operation. Using an average German electricity mix, the calculations show that EVs emit slightly higher amounts of GHG over their entire lifetime than diesel vehicles and slightly lower amounts than gasoline vehicles. When vehicles are charged uncontrolled in the evening they cause new demand peaks. The electricity generated by old power plants used for this peak power entails an increase in GHG emissions in comparison to the average mixed case. When controlled charging is implemented even more GHGs are emitted, as EVs are then charged at night when electricity is generated cheaply by coal power plants. Only when charging is controlled to use electricity generated by renewable sources can GHG emissions be significantly reduced.

The report [435] quantifies CO_2 emissions of vehicles during operation. For this a well-to-wheel approach is taken. It is found that EVs lead to significantly lower emissions of CO_2 if they are charged with renewable electricity. If the current German electricity mix is used, they emit similar amounts as gasoline and diesel vehicles. If they are charged with the cheapest currently available electricity (merit-order principle), they emit slightly less if electricity is generated by gas power plants and significantly more if it is generated by coal power plants.

The life cycle analysis [444] shows that EVs and ICE vehicles consume a similar amount of total energy. Producing an EV consumes more energy than an ICE vehicle, but less energy is needed for operating an EV. Over the entire lifetime, with the German energy mix of 2012, EVs would lead to only slightly lower emissions of GHG than gasoline or diesel vehicles. In Germany 44.1% of the energy was generated by black and brown coal plants in 2012 (compare the slightly higher value of 45.2 % for the year 2013 shown in Fig. 3.5). This leads to the overall poor environmental advantages of EVs over ICE vehicles.

The four studies shortly summarized above show a consistent overall picture. Whether the use of EVs leads to lower GHG emissions strongly depends on how the electricity for powering them is generated. If renewable energies are used, emissions are reduced. Assuming the current German electricity mix, the emissions are similar to conventional vehicles. If electricity from coal power plants is used, EVs can lead to overall higher emissions of GHGs. Controlled charging can both lower and decrease GHG emissions. If charging is controlled to specifically use only electricity from fluctuating renewable sources, such as wind energy, GHG emissions can be further reduced. However, if charging is controlled to specifically use cheap energy generated by coal plants at night, GHG emissions rise. When the production of the vehicles is also taken into account, the situation becomes slightly less advantageous for EVs as their manufacturing is more energy intensive.

6.1.2. Lowering of air pollutant emissions

In the previous section the effects of green house gasses have been discussed. Motorized road transport also emits other substances that cause direct harm to people and the environment.

The European Union issues emission standards for road vehicles. These standards have to be fulfilled by vehicles in order to be approved within the European Union. The Euro 5 and 6 standards contain limits in the form of mg/km for the substances carbon monoxide (CO), total and non-methane hydrocarbons, nitrogen oxides (NO_x), and particulate matter (total mass and number of particles) [445]. It is surprising that the standard does not include limits of CO_2 emission. Such limits might be introduced in the norm in the future [446].

These substances have a wide range of different harmful effects on humans and the environment. Carbon monoxide is poisonous to humans when inhaled in large doses. Hydrocarbons contribute to the forming of summer smog, that is high levels of ozone in the air on the ground level. Some hydrocarbons can cause cancer. The hydrocarbon methane is a green house gas. Nitrogen oxides contribute to the forming of acid rain and summer smog. The emission of fine particles can cause smog and lead to respiratory diseases.

A substance which does not play a big role for the emissions of vehicles, but for the emissions of coal and gas power plants, is sulfur dioxide (SO_2). This gas also contributes to the forming of acid rain.

It is clear that the use of EVs instead of conventional vehicles leads to less *local* air pollutant emissions. In the following a few selected studies will be discussed to see whether these emissions are also reduced on a global scale, when taking the production of vehicles and generation of electricity into account. It seems that much less studies are available on this topic than on the topic of GHG emissions.

The report [447] performs a life cycle analysis of vehicles. The calculations show that for many substances the main part of emissions of EVs are caused by the production of the battery. For the situation in 2010 it is found that EVs lead to overall higher emissions of acidic substances than conventional vehicles over their entire lifetime. EVs emit slightly more substances which contribute to eutrophisation than gasoline and less than diesel vehicles. Eutrophisation is the collection of organic substances in lakes and rivers. This leads to the growth of algae, which reduce the oxygen content in the water. EVs contribute more to summer smog (forming of ozone) than diesel and less than gasoline vehicles. EVs lead to more emission of fine dust particles over their lifetime than conventional vehicles.

The article [448], by the same authors as the previous report, points out that alike to CO_2 emissions, the life cycle acidification of EVs strongly depends on the way the charged electricity is generated. If coal power plants are used, acidification potential is higher than for conventional vehicles. If the current German electricity mix is used, it is slightly lower according to these calculations. Using gas power plants or renewable energies it is much lower.

The article [449] performs a life cycle analysis based on the European electricity mix. The calculation shows a similar potential of acidification for EVs and conventional vehicles. EVs lead to higher emissions of substances which lead to freshwater eutrophisation than gasoline or diesel vehicles. EVs lead to lower emission of substances which lead to the forming of ground level ozone. The results show a higher emissions of particulate matter for EVs over the entire life cycle. EVs lead to higher overall emission of substances which are toxic to humans, mainly caused by the production of the batteries. The article points out that results can vary depending on the assumed lifetime of the vehicles.

According to the life cycle analysis of vehicles in [444], EVs would lead to an overall significantly higher emission of substances which lead to the forming of acids, such as SO_2 and NO_x. These emissions are mainly caused by the nickel and cobalt production for the batteries. EVs tend to emit more substances leading to eutrophisation of waters than gasoline vehicles and less than diesel vehicles. EVs tend to emit less substances leading to the creation of summer smog (ozone) than conventional vehicles.

The above overview of selected studies shows some repeating trends, but results seem to vary depending on initial assumptions. Still some patterns can be seen. EVs seem to lead to a reduction of some emissions while increasing others in comparison to gasoline and diesel vehicles. The amount of emissions over the life time is shifted to the production of the vehicle, especially the battery, and the production of the electricity. This again points out the importance of charging EVs with electricity from renewable sources, in order for them to be environmentally friendly. The overall environmental impacts depend on how the resources for the battery and the battery cells themselves are produced. Batteries and materials can be expected to be manufactured outside of Germany and the European Union for the most part. This can result in a negative effect of "exporting" air pollution to countries where less strict environmental regulations are in place.

6.1.3. Lowering of noise emissions

Exposure to environmental noise can lead to a high number of health problems such as cardiovascular disease, cognitive impairment, sleep disturbance, and tinnitus [450]. EVs have the potential to reduce the noise created by road traffic.

The analysis [444] contains a comparison of noise emissions between EVs and internal combustion engine (ICE), i.e. gasoline- and diesel-powered, vehicles. The noise made by cars is mainly produced by two components: the car's motor and the rolling of the tires. An EV's motor is more silent and produces no sound at all when the vehicle is stopped. The rolling noise depends on the type of tire used, the road surface, and is proportional to the root of the vehicle's speed. Above a certain speed the rolling noise becomes so dominant, that no differences exist between the levels of noise emitted by EVs and ICE vehicles. Different sources see this threshold at different speeds of 25 km/h [451] or 50 km/h [444]. Measurements were made to determine the quantitative differences between noise emissions of individual vehicles in [452]. Different EVs were compared with their ICE counterparts. At 30 km/h the EVs were less noisy by 2–4.5 dB. A reduction of 2 db translates into a sound that is being perceived as being only 87 % as loud, a difference of 4.5 corresponds to a sound that is only perceived as 73 % as loud [453]. So it can be said that EVs are slightly less noisy than ICE vehicles when they are driven at low speeds, which will often be the case for inner-city mobility.

Different studies analyze how the introduction of EVs into the vehicle fleet might lead to lower overall noise emissions. In [444] a situation in which 1 000 vehicles per hour pass at 25 km/h is modeled. At a penetration rate of 5 % of EVs the noise emission is reduced by a negligible 0.2 dB. In [451] similar figures are stated for a typical road with a 30 km/h speed limit in Germany. If the goal of 1 million EVs by 2020 is reached in Germany, this would correspond to 2 % of EVs in the vehicle fleet. The calculated noise reduction would then be only 0.1 dB.

Both studies [444] and [451] therefore conclude that overall noise reductions by the introduction of EVs will be negligible with the low envisioned shares of EVs in the near future. A potential for noise reduction is, however, seen in the use of electric utility vehicles (busses, garbage collection vehicles) and electric scooters and motorcycles in [444], as these vehicles make more motor than tire noises at low speeds. The main potential for lowering noise emissions is also seen for electric utility vehicles rather than private EVs in [454].

The lower levels of noise produced by EVs at low speeds can also be seen as an disadvantage. Pedestrians, bicyclists, and other car drivers might not notice an approaching EV. Societies of blind and visually impaired people fear that silent EVs might pose a new threat [455].

An evaluation of accident data in the USA found that hybrid EVs (not necessarily plug-in) were significantly more often involved in crashes with pedestrians or bicyclists than ICE vehicles in some situations [456]. Only vehicles of model year 2000 or later were considered in the study. Hybrid EVs were found to be two times more likely to be involved in a crash with pedestrians when slowing or stopping, backing up, or entering or leaving a parking space. Crashes with bicyclists also occurred more often in such situations, but also more often at intersections and interchanges [456]. In the article [457] a survey among EV drivers is reported. 30 % of them reported that they experienced dangerous situations which they attributed to the cars silence. These situations were encountered when driving in or out of a road or a parking space.

In April 2014 the European Parliament passed a regulation which requires manufacturers to install Acoustic Vehicle Alerting Systems (AVAS) into hybrid electric and electric vehicles [458]. The regulation becomes operative on July 1st 2019 for all new vehicles. The AVAS has to generate a sound from startup to 20 km/h and when reversing. It “should sound similar to the sound of a vehicle of the same category equipped with an internal combustion engine” [458]. The use of such systems of course lessens the already small advantage EVs have over modern ICE vehicles concerning noise emissions.

6.1.4. Lowering the dependency on resource imports

Germany and many other countries support the development of EVs with the aim of reducing their country’s dependency on petroleum imports. But if EVs are used in the large scale, this will also lead to other resources needing to be imported. A risk lies in simply exchanging one resource dependency for another. In the following it will be discussed which other resources will need to be imported if EVs are used in the large scale. One aspect is the import of resources directly related to the production of electricity, another aspect is the import of resources which are needed to manufacture electric vehicles.

The German transport sector is strongly dependent on petroleum imports. In 2012 97.1 % of crude oil procured in Germany came from foreign sources. Of this, 45 % came from the Commonwealth of Independent States (Russia and other former Soviet Union states), 27 % from the north sea countries, and 22 % from OPEC countries [459]. This petroleum was used for producing gasoline and diesel but also for producing oil for heating and other purposes.

If ICE vehicles are replaced by EVs, electricity will be used as fuel instead of gasoline or diesel. Electric motors have high degrees of efficiency, much higher than gasoline or diesel motors. In an electric motor about 90 % of the energy is turned into movement, whereas it is only about 32 % in a diesel motor and about 27 % in a gasoline motor, where the largest amount of energy is dissipated as heat [460]. However, when the overall efficiency "from well to wheel" is considered, taking all losses during conversion and transmission of energy into account, electric vehicles lie in a similar range of efficiency as ICE vehicles. The calculations in [460] result in an overall efficiency of 31 % for the electric, 20 % for the gasoline, and 25 % for the diesel engine. So exchanging ICE vehicles by EVs will result more in a shift to different energy sources, than to a large decrease in energy need. Other resources than oil play a role for generating electricity. In 2011 German power plants consumed 1 482 PJ equivalents of brown coal, 1 179 PJ of nuclear fuel, 1 106 PJ equivalents of black coal, and 867 PJ of gas [459]. Except for brown coal, Germany needs to import the majority of these resources. However, it can be argued that the diversification of energy sources that electric mobility allows is already a big advantage.

There is no import of brown coal to Germany. Only national resources are used [459]. In 2011 black coal was imported to Germany in an amount of 45 million tons. This coal came mainly from the USA, Canada, and Russia. In the same year German coal mines produced 12 million tons of black coal [459]. The mining of black coal in Germany is not economically viable, as due to geological reasons it can be mined much cheaper in other countries. Currently, the black coal industry in Germany is strongly subsidized by the state, but these subsidies will end in 2018 and black coal mining along with them [461].

The gas used in Germany is also mostly imported. In 2012 gas was produced in Germany in an amount of 0.3 million TJ. In the same year 1.4 million TJ of gas was imported from Russia, 1.3 million TJ from Norway and 0.8 million TJ from the Netherlands [459].

Uranium for nuclear reactors is also a resource which needs to be imported. Germany imports natural uranium via long-term contracts with distributors in France, the UK, USA, and Canada. In 2009 enriched uranium was mainly imported from France, Russia, and the Netherlands [462]. The German government has enforced a shutdown of all nuclear plants in the country by the end of 2022 [195].

Renewable energies do not require import of resources for the generation of energy. However, some kinds of renewable energy plants need special materials for their manufacturing. Neodymium and other rare earth metals are used for manufacturing permanent magnets for wind turbines [463]. Photovoltic cells contain gallium and indium, materials which are rated as critical resources by the EU [464].

Electricity is also directly exported and imported to and from European neighbor states via cross-border transmission lines. In 2012 Germany exported 20.5 TWh more electricity than was imported. The imported electricity mainly came from France, Denmark, and the Czech republic [459]. The French electricity generation mix is strongly dominated by nuclear power [465], the Danish electricity system generates power mainly from coal and wind turbines [466], and the Czech system mainly generates energy from coal and nuclear power [465].

So in summary it can be said that using EVs might lead to an overall lower dependency on energy resource imports. The very high dependency on petroleum imports will be diversified and shifted to energy resources where dependency is not quite as high, such as electricity generated by coal and gas. The German exit out of black coal production by 2018 and out of nuclear power by 2022, might however lead to more overall energy resources or electricity needing to be imported. The development of wind and solar power needs rare materials which need to be imported to manufacture such plants.

The other aspect of resource dependency concerns *resources needed for manufacturing EVs*. If batteries and electric motors are manufactured in Germany, special materials need to be imported. High amounts of lithium, cobalt, and rare earth metals will be required in the future. If such parts are not manufactured in Germany, these parts need to be imported, leading to an import dependency on finished parts instead of raw resources. EU law requires that by 2015 at least 85 % of a vehicle's mass is on average reused or recycled [467]. But with lifespans of several years for vehicles, significant amounts of recycled materials will only become available in the long term, while demand will strongly increase in the short term [468]. The problem does not seem to lie in the actual geological shortage of specific materials. The European Comission sees *critical raw materials* as *economically important materials whose production is concentrated* *on a few countries and a few companies.* Also, such critical materials *cannot be easily substituted by other materials* [464].

Lithium is required for producing EV batteries. The worldwide production of lithium is strongly concentrated. In 2010 76.1 % of the known reserves were located in Chile, where it is found in salt lakes. In 2007 the EU imported 63.9 % of its lithium from Chile, followed by 16.7 % from the USA and 16.0 % from China [469]. However, lithium is the 27th most abundant element on Earth [469]. And lithium batteries actually only include small shares of the material. A 24 kWh battery with a weight of 275 kg only requires about 3 kg of lithium, making up about 1 % of its weight [444]. Overall, the European Commission does not rate lithium as a critical material [470]. A study on critical materials done for Germany also comes to the conclusion that lithium is not among the most critical materials [463]. A further study, explicitly focusing on the importance of lithium for batteries for EVs, comes to the conclusion that there will be no shortage of reserves even until the year 2050 [471].

Cobalt is used for cathodes of batteries. The worldwide production of cobalt is also strongly concentrated on a few countries. In 2010, 52.5 % of known reserves were located in the Democratic Republic of Congo and 22.7 % in Australia. In 2007 the EU imported 70.3 % of its cobalt from the Democratic Republic of Congo and 19.1 % from Russia [469]. A study for Germany has identified cobalt as a medium critical resource [463]. The European Commission also sees cobalt as a critical element but on a moderate level [470].

Rare earth elements is a name for a group of 17 metals, which are scandium, yttrium, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium [469]. In the context of electric vehicles especially the element neodymium plays an important role, as it is used to manufacture strong permanent magnets for electric motors. The production of rare earth elements in strongly concentrated in China. In 2007 89 % of imports of these materials into the EU came from China, although the country only contains only about a third of the worldwide reserves [469]. China has introduced export quotas and export taxes for these materials. It is feared that China might further restrict the export of rare earth elements, as they are needed by the country's own industry [469]. In studies on the scale of the European Union [470] and Germany [463] rare earth metals have been identified as being very critical.

In conclusion it can be said that new import dependencies will probably arise from substituting ICE vehicles by EVs. There will apparently be no shortage of lithium for EV batteries, but cobalt for cathodes of batteries and rare earth elements for manufacturing permanent magnets for EV motors might become difficult to import in large quantities. If new battery and motor types are developed in the future, the dependency on these materials could however be reduced, or new resource dependencies could arise.

As an overall conclusion it can be said that the use of EVs in the large scale can lead to a reduced dependency on petroleum imports, but this dependency will be replaced by other dependencies. There will be a higher dependency on resources needed for generating more electricity (black coal, gas) or on the direct import of foreign electricity. Dependency will rise for materials needed for building renewable energy plants (photovoltaic cells, wind turbines). A higher dependency will also exist on materials needed for the manufacturing of EV batteries and motors, notably lithium, cobalt, and rare earth elements.

6.1.5. Creation of jobs, notably in the automobile industry

The manufacturing of EVs, PHEVs, and REEVs, their parts and infrastructure can lead to the creation of new jobs in the German industry. However, the replacement of gasoline and diesel vehicles by vehicles with alternative drive trains could also lead to a reduction in jobs in conventional vehicle and parts production. Within this section the most important information about these effects will be laid out.

The automobile industry is economically important in Germany. In 2013 there were about 773 000 people directly employed in the manufacturing of cars and their components [472]. That corresponds to 10.4 % of all people working in the manufacturing industry and 1.8 % of the entire German workforce [473]. Many jobs in other industries such as the steel, chemical, and electronics industry also depend on automobile production. It is estimated that 900 000 additional jobs in other manufacturing industries depend on automobile production [474].

In 2013 the German automobile industry generated revenues of about 364 billion €. About 35 % of this revenue was made in Germany, while 65 % was made in foreign countries [472].

The rising importance of EVs, PHEVs, and REEVs leads to a shift in the relative importance of vehicle components. Batteries, battery chargers, electric motors, and power electronics become more important. Especially batteries make up a large part of the value of an EV. The large differences between the costs of conventional vehicles and EVs (see Sec. 5.1) are mainly caused by the high costs of the batteries. It seems that German companies will be able to compete in the domain of electric motors, battery chargers, and power electronics, but that there are little capacities in the domain of battery production [434]. Fig. 6.1 shows the diverse cooperation and supply relationships between German car manufacturers (on the right) and battery producers (on the left) in 2012. The listed battery producers are based in Germany (Akasol, VARTA Microbatteries, Evonik Industries), the USA (Johnson Controls, Molicel, AC Propulsion), Japan (Enax, Toshiba, Panasonic/Sanyo), and South Korea (Samsung). The only large scale battery plant for batteries cells for EVs in Germany is operated by the company Li-Tec, a joint venture between Daimler and Evonik Industries. It has about 250 employees. Daimler announced that the plant will be closed by the end of 2015 because the manufactured cells are too expensive in the currently manufactured low quantities [475]. Worker representatives of big German car manufacturers and politicians are demanding that battery cells for EVs be manufactured in Germany in the future [476].

Several studies have attempted to quantify the overall impacts of the uptake of EVs on the German industry. The German national platform on electric mobility has performed calculations for several scenarios in [373]. The simulation shows a slight decline in employment if the German government and industry remain passive in relation to electric mobility. Conventional vehicles of German manufacturers are then replaced by EVs from foreign companies. If policies are implemented that lead to reaching the goal of 1 million EVs in Germany by the year 2020, 21 500–30 000 new jobs are created, among them 3 500 for the installation and operation of charging infrastructure. In a third scenario, if electric mobility is strongly supported by the state, 31 500 jobs are created.

The report [478] performs an analysis for the German federal state of Baden-Württemberg only. Several car manufacturers as well as component manufacturers are based in the area, employing about 200 000 people in total. If 1 million EVs are on German roads by 2020, the potential is seen for 10 130 additional jobs in the manufacturing of conventional vehice components and 9 850 additional jobs in the manufacturing of EV components. The report points out that this potential might not completely be filled out by companies in Baden-Württemberg, and that the parts might be manufactured elsewhere.

The report [474] also presents results of several scenarios of the development of the automobile industry in Germany. In the scenario relevant for electric mobility 50 % of vehicles sold in 2030 are powered by alternative drive trains.

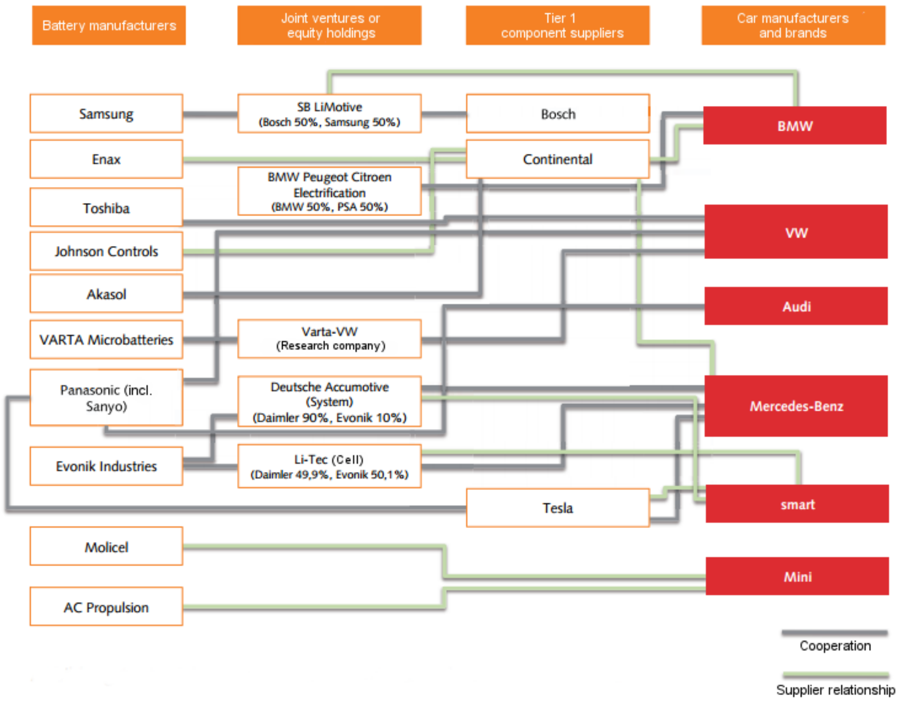

Figure 6.1.: Relationships between battery manufacturers and German automobile manufacturers in 2012 [477] (translated)

The resulting development of employment also depends on efficiency gains in production technology. A higher gain in production efficiency leads to less people being employed. In the most pessimistic case 68 000 jobs are eliminated by 2020 and 131 000 by the year 2030. In the most optimistic case an additional 138 000 jobs are created by 2020 and 267 000 by the year 2030. These results are so spread out that they do not allow to identify a clear trend in relation to electric mobility.

The report [434] simulates a scenario in which there are 1 million EVs in Germany by the year 2020 and 6 million by 2030. In comparison to a conservative reference scenario the electric mobility scenario results in 69 000 more jobs in all sectors in Germany by 2020 and 230 000 more jobs by 2030. The overall trend in employment is negative according to both reference and electric mobility scenarios. The uptake of electric mobility only partially compensates the overall reduction of number of employed persons in Germany.

The impacts of the uptake of EVs on the German automobile industry is also analyzed in [477]. The model calculates the number of people who are required to produce one million drive trains of a differing technological mix according to scenarios. For 2010 a number of 6 000 required employees is set. In the reference case, with 10 % EVs, 10 % REEVs, and 20 % hybrid electric vehicles, the number of people employed rises to 7 213 in the year 2030. In a scenario which strongly favors the internal combustion engine the number of people employed rises to 6 607. In a scenario which strongly favors EVs, employment rises in the mid term until 2020, as the manufacturing of hybrid components becomes more important, but then drops in the long term, as the manufacturing of hybrid and conventional motors loses importance. This results in 6 173 people employed in the year 2030. All the scenarios thus show a positive trend in employment, with the scenario that strongly favors electric vehicles showing the lowest value in 2030.

The five studies shortly summarized above indicate that the uptake of EVs may lead to an increase of employment, notably in the automobile sector. The manufacturing of EVs will lead to a shift in emphasis, away from conventional engines towards electric motors, power electronics, and batteries. The risk for the German industry is that many of these parts, especially batteries, might be manufactured by competitors in other countries. However, with revenues of 65 % in foreign countries, the German automobile industry is not solely dependent on a good market development for EVs in Germany, but also profits from the large scale uptake of EVs in other countries.

6.1.6. Development of future mobility concepts

The introduction of EVs is seen as a possibility to develop future mobility concepts, such as multi-modal travel and sharing concepts. Such developments in urban mobility take place within larger social changes, such as a rise of environmental awareness, the developing omnipresence of ICT in the form of smart phones, and declining car ownership and use by young adults [479].

The driving range of current EVs is limited to 100–150 km. Instead of using one vehicle to go everywhere, EV owners have to switch to conventional (rented) cars or trains for longer distance trips (see Sec. 4.2.3). This calls for an effortless transition between these modes. Public transport operators are providing smartphone applications that facilitate multi-modal trips by showing real-time public transport data and allowing multi-modal ticketing.

Carsharing systems have been on the rise in the last years. Internationally, carsharing systems have been established which make use of high numbers of EVs, such as Autolib in Paris and car2go in San Diego and Amsterdam. Big German operators are also integrating EVs into their fleets [434]. The lower range of EVs is not seen as a problem because usually customers can also choose a conventional vehicle from the available fleet. Carsharing operators see a good fit between carsharing and EVs because both have an environmentally friendly image. Making EVs available also attracts new clients who want to use these kinds of vehicles without having to buy them [480]. However, carsharing operators also note that EVs and associated public charging stations are currently too expensive to be economical without subsidies [480] [481] (also compare the economics of private use of EVs discussed in Sec. 5.1). An analysis of the use of carsharing vehicles in Karlsruhe including economic considerations in [482] comes to the conclusion that maximally 6.35 % of vehicles could be replaced by EVs by 2015. If a subsidy of 5 000 € is paid per vehicle, maximally 12.7 % of carsharing vehicles could be replaced by EVs.

Carsharing and public transport operators are cooperating to provide both services combined at reduced fees [434]. If EVs are used as carsharing vehicles, they can lead to a better utilization of the installed public charging infrastructure, as has been observed in Amsterdam [309] and San Diego [346].

Bike sharing systems have also been implemented in many cities in the last years. In some cases electric bicycles are being used. This makes the use of bicycles less exhausting to occasional users, especially in hilly areas. An example of this is the e-Call a Bike system in Stuttgart [483].

It seems that there are applications in urban transport for which EVs are especially suited. The uptake of EVs seems to coincide with larger societal trends which favor multi-modal travel and sharing models. It should be noted, however, that most of these mobility forms do not depend on the use of EVs, and could also be realized with conventional vehicles.

6.1.7. Development of the smart grid and better integration of renewable energies

Electric vehicles are seen as a possibility to develop smart grid applications and to better integrate renewable energies into the electricity system. The interactions between EV charging and the German electricity system have been extensively discussed in Chap. 3. Only the main points will be summed up again here.

If controlled charging of EVs is implemented, this can be used for nighttime demand valley filling, which leads to a better utilization of available power plants. EV charging can be timed to occur especially during peak generation times of solar and wind power plants. This is also possible on the level of individual buildings when the EV is directly charged with the electricity from a solar panel. This mitigates the impacts of strongly fluctuating generation peaks on the electricity network, which has to take up electricity generated from renewable sources whenever technically possible according to German regulations.

If V2G is implemented, batteries are used as intermittent electricity storage. The electricity can be fed back into the electricity network during times of high demand, leading to a peak shaving effect. Pumped water storage plants are already applied in this way in Germany. Again this can be implemented on the level of individual buildings, mitigating impacts on the local distribution grid. Both controlled charging and discharging could be used to provide balancing power to transmission system operators.

The potential benefits of controlled EV charging and discharging are manifold. However, as has been shown in Chap. 3, the overall magnitude of effects will be negligible on the national scale in the near future. The electricity consumption of 1 million EVs would correspond to about 0.45 % of the electricity produced in Germany in the year 2013. It would only make up 9.5 % of the electricity generated by solar power alone or 5.4 % of the electricity generated by wind power alone in 2013 (see Sec. 3.3.1). This puts the magnitude of potential benefits into perspective. Effects can similarly be expected to be negligible on the scale of transmission systems. Only on the level of local distribution networks and individual buildings can the charging of EVs have significant impacts in the near term. Impacts can be positive if controlled charging and V2G is implemented, but might also be negative if charging is not controlled (see Sec. 3.3).

It seems that the main benefit of EVs in the near future in this domain is to provide a testbed, theoretical and practical, for diverse smart grid and demand management applications, algorithms, and communication protocols. EVs are being integrated into smart home prototypes. Demand side management algorithms are being developed to coordinate renewable energy generation and EV charging. The communication protocol for EVs being specified in ISO 15118 can also propel other smart grid applications forward.

6.1.8. Image factors

The aspect of image is less tangible than the aspects already discussed above. If Germany successfully develops electric mobility, this should strengthen the image of Germany as a technologically innovative and environmentally aware country. This image is not only relevant on the national level but also on the level of municipalities, individual businesses, or individual consumers. A city which uses EVs and develops a charging infrastructure or an EV carsharing scheme can integrate this into its city marketing concept and make itself more attractive to tourists. Electric utilities that develop public charging infrastructure show that they are innovative, ecological, and take their corporate responsibility serious. Businesses that use EVs in their vehicle fleet can strengthen their ecological image. User of EV in business fleets currently see this as a clear benefit of using EVs [331]. Finally, private customers also buy EVs, like any other car, out of image considerations.

The limitations of EVs concerning their positive external effects, as discussed in the previous sections, could lead to lowering the image of EVs in the long term when these aspects become more widely known to the general public.

6.1.9. Overview: externalities and their preconditions

Tab. 6.1 summarizes the previous discussion of externalities of EVs and a corresponding infrastructure as well as the preconditions necessary to realize them. It can be seen that there are many more anticipated positive than negative external effects. A careful analysis, however, reveals that many positive effects require preconditions for them to be realized. These preconditions can be interpreted as a call for action. The German government and industry should take actions so that the frame conditions for EVs are set in a way that allows for their benefits to be realized: EV charging should be done with energy from renewable sources, battery cell production should be done in Germany with high environmental standards, batteries should be recycled to reduce dependency on resource imports etc.

Table 6.1.: External effects of EVs and their infrastructure, and their limitations

Positive external effects	**Preconditions, limitations**
Lowering green house gas emissions	Requires electricity from renewable sources. Higher emissions of EVs than conventional vehicles when coal power plants are used.
Lowering air pollutant emissions	Air pollution is shifted to battery production and electricity generation. To achieve lower global pollution high environmental standards for battery production necessary.
Lowering noise emissions	Only at low speeds. Only at a small band of speeds once acoustic vehicle alerting systems are used up to 20 km/h. Higher potential for electric scooters and delivery vehicles.
Lowering dependency on resource imports	Electrification allows diversification of primary energy carriers. Remaining or higher dependency on resources for electricity generation (black coal, gas), renewable power plant production (rare earth metals, gallium, indium), EV production (lithium, cobalt, rare earth elements). Recycling of materials necessary to reduce import dependency in the long term.
Creation of jobs	Battery cell manufacturing should take place in Germany.
Development of future mobility concepts	Integration of EVs into carsharing systems only feasible in low percentages. Sharing systems and inter-modal travel also interesting for conventional vehicles.
Development of smart grid, integration of renewable energies	Overall low impact on the national level. Interesting more as a testbed for smart grid applications (development of standards, communication protocols, demand side management algorithms).
Image factors	Partially based on overly optimistic expectations, see all of the above.
Negative external effects	**Limitations**
Rebound effect	Same as for any other technology which reduces fuel consumption.
Traffic congestion, lack of parking space	Same as for conventional vehicles.
Lower tax revenues	Possibility to introduce additional EV charging taxes on electricity in the long term. Can be interpreted as indirect subsidy.

6.2. Current European and German policy regarding EVs and their infrastructure

In the previous sections the externalities of electric mobility have been discussed in detail. These are the *reasons why* and the *motivations* for public governments to get involved in the sector of electric mobility if the free market does not lead to the desired results of high numbers of EVs and widespread public charging infrastructure.

In the following it will be discussed what governments *are in fact doing*. An overview will be given on the most important regulations concerning EVs and their infrastructure that are in place on the level of the European Union (Sec. 6.2.1) and in Germany (Sec. 6.2.2).

6.2.1. Current European policies

The most important policies on the European level which concern EVs are discussed in the following paragraphs. Then the European policies concerning the charging infrastructure for EVs will be discussed.

The *Regulation (EC) No. 443/2009* and subsequent amendments of 2013 and 2014 [484] set CO_2 emission targets for passenger vehicles. The regulation obliges manufacturers to reach an average emission of 95 g CO_2/km for all newly registered cars in the EU in 2020. Emissions are measured using the new European drive cycle (NEDC). Manufacturers can profit from "super-credits" for vehicles with emissions below 50 g CO_2/km, such as EVs. Such vehicles count as 2 vehicles in 2020, 1.67 vehicles in 2021, 1.33 vehicles in 2022, and 1 vehicle in 2023. If manufacturers miss these fleet targets, they have to pay a penalty.

The *Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles ("Green vehicles directive")* [485] was issued in 2009. It obliges national, regional, or local authorities and public transport providers to take environmental impacts of vehicles into account when buying new vehicles. Such impacts include the lifetime energy consumption, CO_2, and pollutant emissions. The directive includes specific values in €/kg to be used for pollutants when calculating lifetime costs of pollution. The directive does not explicitly include EVs. Therefore it is unclear how their emissions should be calculated. The directive aimed at creating more demand for clean vehicles from public vehicle fleets, in order for them to become cheaper in the long term.

The European Commission published *Guidelines on financial incentives for clean and energy efficient vehicles* [486] in 2013. The guidelines describe how EU member states can introduce financial incentives which are in line with EU laws for clean vehicles. A mandatory point is that incentives must be non-discriminatory concerning the origin of the vehicles, i.e. it is not permissible to support national products only. The document recommends to implement incentives technologically neutrally, that is taking into account environmental performance, for instance in the form of CO_2 emissions, and not a specific drive train technology. It is also recommended that the incentive does not exceed the additional costs of alternative technologies, as this would result in subsidies for the concerned manufacturers. In 2014 financial incentives of different amounts for EVs were in place in of 18 of 28 states in the European Union, among them Germany, France, the UK, Italy, Norway, and Sweden [487].

The *Regulation (EU) No 540/2014* [458] requires manufacturers to install Acoustic Vehicle Alerting Systems (AVAS) into hybrid electric and electric vehicles. The regulation becomes operative on July 1st 2019 for all new vehicles. The AVAS has to generate a sound from startup to 20 km/h and when reversing. It "should sound similar to the sound of a vehicle of the same category equipped with an internal combustion engine" [458].

The European Union is financing research and development of EV technology. Such funding has for instance taken place within the *Green cars initative*, with calls for proposals in the years 2009–2012, the *7th Framework Programme for Research and Technological Development*, running from 2007–2013, and the *Horizon 2020* program for the period of 2014–2020.

The most important European policies which consider EVs have been discussed in the previous paragraphs. Now policies will be presented which concern the charging infrastructure for EVs.

The *Directive 2014/94/EU on the deployment of alternative fuels infrastructure* [43] sets the target of at least 1 publicly accessible charging point for every 10 EVs in each member country. The directive "is not intended to place an additional financial burden on Member States or on regional and local authorities. It should be possible for Member States to implement this Directive by making use of a wide range of regulatory and non-regulatory incentives and measures, in close cooperation with private sector actors, who should play a key role in supporting the development of alternative fuels infrastructure" [43]. The directive demands that normal and fast AC charging points are equipped at least with one Type 2 socket or plug according to the standard EN 62196-2.

Fast DC charging points should be equipped at least with one plug of type Combo 2 (i.e. CCS) according to the standard EN 62196-3. Publicly accessible charging points should make it possible to charge at them ad hoc, i.e. without having a contract with the charging station operator. National governments have to submit their planned policy frameworks to implement this directive to the European Commission by November 18th 2016. National policy measures can include direct purchase, tax, or non-financial incentives for EVs and infrastructure, public procurement, revised technical and administrative procedures, funding of research and development, and others [43].

Within the European program *Trans-European Transport Networks (TEN-T)* the buildup of fast charging stations is being financially supported in cross-border projects in Ireland and the UK [51], in Sweden and Denmark [488], and the Netherlands and Germany [489].

6.2.2. Current German policies

Policies on the EU level were examined in the previous section. Now policies on the national and regional levels in Germany will be discussed. First, general activities will be treated which concern both EVs and their infrastructure. Then, specific regulations applying to EVs will be treated, followed by specific regulations concerning infrastructure.

In 2009 the German government published a national development plan for electric mobility (*Nationaler Entwicklungsplan Elektromobilität* [1]). In this strategic document the government set the goal of Germany becoming the lead market for electric mobility, thus maintaining the leading role that the German industry plays in the manufacturing of cars. The target of 1 million electric vehicles (pure EVs, REEVs, and PHEVs) on German roads by 2020 was set up. The document lists numerous benefits that a transition from conventional to electric vehicles is expected to bring about. These are the reduction of CO_2 emissions in the traffic sector, the reduction of dependency on petroleum, the development of the industry, the reduction of local emissions and noise, the improvement of the efficiency of electricity networks and better integration of renewable energies, and the development of intelligent and multi-modal mobility concepts for the future. These expected benefits, i.e. positive externalities, have been critically examined above. The main areas are identified where research and development are necessary, such as battery technology, drive trains and components, and smart grid applications. The areas in which new regulations are required are also identified. It was announced that research and development on electric mobility will be supported with 500 million €from the economic recovery package II (*Konjunkturpaket II*).

In May 2010 the national platform on electric mobility (*Nationale Plattform Elektromobilität (NPE))* was founded [490]. It is an advisory board for the German government, in which stakeholders from the industry, science, politics, unions, and organizations participate. The NPE regularly publishes reports which give an overview of the status quo of electric mobility in Germany (see for example [276]) and recommends the implementation of further policies. Scientists seem to be underrepresented within the NPE. The progress report of 2014 lists only 3 representatives of independent scientific institutions, among 46 contributors in total [276]. The reports of the NPE therefore have to be read with caution, as they may be influenced by particular industry interests.

In 2011 the government program on electric mobility (*Regierungsprogramm Elektromobilität* [294]) concretized and continued the strategy previously set up in the national development plan on electric mobility. The government program also took up recommendations made by the NPE. The goal of 1 million EVs, (including PHEVs and REEVs) by the year 2020 was again stated. For 2030 the goal of 6 millon EVs was set. The document states the government's position that the *development and financing of a public charging infrastructure for EVs is the duty of the private industry*. Municipalities may establish the frame conditions for the buildup of this charging infrastructure, but there is no legal obligation for them to do so. Several areas were identified where regulations need to be changed, such as laws concerning construction and the use of public parking spaces. Some of these points were later implemented in the form of incentives for EVs (see below) and setting frame conditions concerning infrastructure (also see below). It was announced that the government will continue funding of research and development on electric mobility topics.

Research and development of electric mobility was strongly financially supported by the government from 2009 onward. Within the recovery package II (Konjunkturpaket II) 500 million € were allocated to electric mobility projects. Of this, 130 million € were allocated to the testing of electric vehicles and charging infrastructure in 8 *Modellregionen* (model regions) distributed all over Germany from 2009 to 2011 [491] (see Fig. 6.2). From 2012 to 2015 four regions, so-called *Schaufenster* (showcases), were financially supported with 180 million €. These regions were Baden-Württemberg, Berlin/Brandenburg, Niedersachsen, and Bayern/Sachsen [492] (see Fig. 6.2). Diverse specific research projects on electric vehicle and charging technology were supported in parallel to the tests in these regions.

Figure 6.2.: Model regions (in red) and showcases (in grey) in Germany [161]

Several incentives have been implemented in Germany to support the uptake of EVs by the general public and by businesses. Pure EVs are exempted from car taxes (KFZ Steuer) for the first 10 years if they are first registered before 2016 and from then on for 5 years if they are first registered before 2021 [377]. This exemption remains valid when the car changes its owner. Car taxes for conventional vehicles are calculated according to their technical specifications. As seen in Sec. 5.1, for the Smart Fortwo car taxes are 26 € per year. Thus the tax exemption translates into a relative saving of about 10 * 26 = 260 € for the Smart Fortwo EV.

When an employee receives a business vehicle from his employer which he also uses privately, he has to declare this as a monetary benefit in his income tax declaration. The monetary benefit is set at 1 % of the purchase price of the vehicle per month, with further benefits depending on the distance traveled between home and workplace. Because EVs tend to have higher purchase prices, this puts them at a disadvantage in comparison to conventional vehicles. The regulation [378], introduced in 2013, allows a calculatory reduction of the purchase price of pure EVs, PHEVS, and REEVs, depending on the capacity of the battery. The reduction is intended to compensate for the additional costs incurred by the battery, with 500 € per kWh in 2013 and 50 € less every subsequent year.

The German government has also introduced regulations to support the development of a public charging infrastructure for EVs. The installation of public charging stations has been financially supported by the state within the model regions and the showcases. About 1 201 publicly accessible charging points have been installed within the model regions, partially financed by the state [274]. In 2012 and 2013 the federal state of Baden-Württemberg supported the development of charging infrastructure in Stuttgart and the surrounding region with 2.4 million €. The electric utility EnBW, which realized the infrastructure, invested an additional 2.5 million € [493].

From 2012 to 2014 the Kreditanstalt für Wiederaufbau (KfW), a public bank providing loans with low interest rate for infrastructure development, provided a loan program for cities and public companies which wanted to build up energy efficient lighting. Within such projects the buildup of public charging stations could also be covered by the loan [494]. In 2014 the KfW introduced a loan program for the purchase of EVs and other low emission vehicles by companies. The buildup of EV charging stations could be included in the loan [495].

In 2011 and 2014 official street signs were issued to be placed at charging stations and for directing drivers to charging stations (see Sec. 2.2.2).

The German electric mobility law (Elektromobilitätgesetz [160]), issued in June 2015, paves the road for the implementation of non-monetary incentives for EVs. It gives the federal ministry of traffic and the federal ministry for the environment the possibility to introduce decrees granting special rights to EVs. EVs may be allowed to park on public parking spaces, park for lower or no fee, and drive on streets not accessible to conventional vehicles. The governments of the federal states may introduce special clauses for EVs in their regulations concerning the fees for parking on public parking spaces. The federal state governments may also authorize lower level instances to introduce such fee regulations.

In January 2014, before the introduction of the electric mobility law, EVs were already exempted from having to pay parking fees for public parking spaces in the German cities of Stuttgart, Esslingen am Neckar, Böblingen, Sindelfingen, Ludwigsburg, Konstanz, and Garmisch-Partenkirchen [496]. In most cases, drivers needed to apply for a municipal EV parking permit, which they then displayed on their windshields.

In September 2015 the German minister of traffic announced that fast charging stations will be installed at all approximately 400 highway service stations of the company Autobahn Tank & Rast by the year 2017. The approximately 30 highway service stations operated by other companies can also join the program under the same conditions. The German Federal Ministry of Traffic and Digital Infrastructure will partially pay for the hardware and the installation of the charging stations. Operating and maintenance costs will have to be fully paid by the service station operators. According to the first photos of installed charging facilities published, they will support 43 kW AC charging with a Type 2 connector, 50 kW DC using a CHadeMO connector, and 50 kW DC using the CCS connector [71].

In autumn 2015 the German government published a draft of a charging pillar decree (Ladesäulenverordnung) which implements technical parts of EU directive 2014/94/EU [43] in German law. The decree makes the provision of at least one Type 2 socket outlet/connector obligatory for AC normal and fast charging points and the provision of at least one CCS connector for DC fast charging points) [53].

6.3. Prospective German policies

In the previous sections policies concerning EVs and their infrastructure have been discussed on the level of the EU and of Germany. In this section an outlook will be given which further policies could be implemented by German authorities within the next years. A detailed discussion on the EU-wide level is not done here. First, an outlook will be given for policies which concern the purchase of EVs. Then, possible future policies which concern charging infrastructure will be discussed.

6.3.1. Prospective German policies concerning EVs

As discussed above, in Germany the purchase of EVs is supported with the exemption from car taxes and regulations which compensate the higher purchase value of EVs used as business vehicles in income tax declarations. There is a program from the KfW bank which provides loans with low interest rates to companies which want to buy EVs and charging infrastructure. The regulatory framework has been put in place which allows municipalities to implement further incentives for EVs. Parking spaces can be reserved exclusively and parking fees can be reduced for EVs. EVs can also be allowed to access specific zones and use bus lanes. Exempting EVs from paying parking fees for public parking has already been implemented in several German cities.

The monetary incentives provided in Germany for the purchase of EVs are lower than in other countries. Many countries directly subsidize the purchase of EVs. In 2014 in France a bonus of up to 7 000 € was paid. In the UK it was up to 5 900 €, in Sweden up to 4 600 €, in the US up to 5 500 €, in Japan up to 6 500 €, and in China up to 7 200 €. In Norway EVs were exempt from value added tax, which makes up 25 % of the purchase price of the vehicle [497]. Such purchase subsidies intend to decrease the still large gap between the total cost of ownership of EVs and conventional vehicles (see Sec. 5.1).

EV drivers in the German model regions have been asked for which incentives they would be willing to pay more for an EV [331]. The highest approval was seen for cheaper electricity, cheaper car taxes (which are implemented by now), and cheaper car insurance. These incentives were followed by free parking, reserved parking, and lastly, use of bus lanes.

Norwegian EV users were asked to name the most important incentives in [338]. The incentives were named in the order of importance of: free toll roads, no purchase tax, low fuel costs, access to bus lanes, free parking, low annual road fee (a car tax in Norway), free charging, availability of a public charging network, free ferries. The article notes that the answers depend on the use of the EV and where the driver lives.

Both surveys indicate that direct monetary incentives are considered to be more important by EV drivers than indirect incentives such as free and reserved parking and use of bus lanes. Such incentives, made possible by the German electric mobility law of 2014, can therefore be expected to have only little impact on the uptake of EVs in Germany.

During the development of the electric mobility law, the responsible traffic secretary again affirmed that there will be no direct purchase subsidies for EVs in Germany in the next years [498]. However, the government plans to implement a further subsidy via taxes, which was recommended by the national platform on electric mobility in its report of 2014 [276]. The planned regulation would allow businesses to use a special depreciation allowance for EVs [499]. To increase the overall demand for EVs it is also planned to introduce a public procurement program for EVs [499].

6.3.2. Prospective German policies concerning charging infrastructure

As has been discussed above, the German government financially supported the buildup of charging stations within the model regions and showcases. In some situations, the public KfW bank provides loans for the buildup of charging infrastructure. The legal framework has been put in place which allows local authorities to put up signs for charging stations, reserve parking places for EVs, and exempt EVs from parking fees.

With the privatization of traditionally public infrastructures such as railway, postal, and telecommunication services in Germany in the last decades, it seems very unlikely that a public operator for charging infrastructure for EVs will be installed on the national scale. The government plan on electric mobility of 2011 stated that the German government sees the private sector in the responsibility of financing and implementing a public charging infrastructure [294].

However, the EU directive on the deployment of alternative fuels infrastructure of 2014 obliges member states to implement such an infrastructure [43]. The directive states that 1 public charging point should be provided for 10 EVs in average. The directive also states that no financial burden is intended to be put on public authorities and that the private sector should play a key role in the implementation of this infrastructure. Germany and other EU member states have to submit their planned national policies to the EU by the 15th November 2016.

It is not clear how Germany will react to the request. There are two main approaches to getting private stakeholders to take on responsibility for the provision of infrastructure. *Push* policies force private companies to do so, by new laws and regulations. *Pull* policies provide incentives, so that companies are encouraged to take on this role. These two main kinds of policies are discussed in the following.

Building constructors and owners could be pushed to install infrastructure by *introducing requirements for charging points into construction laws.* Currently, German construction law already includes regulations concerning the provision of associated infrastructure, such as parking spaces, depending on the building's use. To name a specific example, in the German federal state of Baden-Württemberg, the construction code requires that for big shops without public transport accessibility one parking space is built for every 10–30 m^2 of shop surface. For buildings with high number of visiting clients (doctor's office etc.) one parking place is constructed for every 30–40 m^2 of office space [360] (also compare [361]). If the building constructor does not comply, he has to pay a compensating fee, as the required parking demand then spills over into public space. The article [362] criticizes the use of such parking requirements in the USA, as these requirements seem to be based on little factual information, and can lead to high construction costs and high land occupation by unnecessary free parking spaces.

Still, such construction regulations can be extended to also include charging points for EVs. An obvious approach would be to link the number of charging points to the number of parking places. For instance it could be required that 1 charging point needs to be installed for every 25 parking spaces, for facilities with at least 25 parking spaces. The government can thus require private companies such as parking garage operators, malls, supermarkets, and big cinemas to provide semi-public charging infrastructure. With semi-public infrastructure it is meant that the charging points are publicly accessible, but located on private ground. The French government already took this approach via the directive [363] in 2011. The issued regulation requires that buildings with residential and tertiary use being built from 2012 on need to be equipped with the necessary cabling to allow 10 % of the associated parking spaces to be equipped with charging points. From 2015 on, office buildings also need to be equipped with cabling as well as the charging points at 10 % of the associated parking places. From 2015 on, the regulation also applies for all existing buildings not just those being newly built.

A policy which combines pushing and pulling elements would be *an official assignment of responsibility from the government to local authorities*. The provision of public charging infrastructure for EVs could be seen as a responsibility of municipalities, or of the local distribution system operator. In the first case the organization of charging infrastructure would be similar to that of public transport. A wide range of public-private partnership forms could then be applied, such as rewarding a concession or creation of a joint venture. In the straight-forward concession mode, municipalities or regions would give out calls for tender to pull private sector stakeholders into providing public infrastructure.

The winner of the tender would receive an exclusive concession for the installation and operation of public charging infrastructure in the area for a specific duration.

Because it is unlikely that the charging infrastructure operator could operate the infrastructure profitably (see Sec. 5.2.3), the municipality would have to pay a financial support to the private operator. Additional funding for a specific number of charging points per region, for instance based on the number of inhabitants, could come from the state and the federal states. This kind of subsidy scheme was envisioned by the national platform on electric mobility in [373]. To further reduce the infrastructure costs for the municipality, it could allow the operator to display advertisement at the charging stations, thus generating additional revenues (see Sec. 5.2.3.5).

Alternatively to pushing building owners or local public authorities to take on responsibility for infrastructure provision, private stakeholders could be pulled to provide (semi-) public charging stations by offering incentives. Subsidies to charging station providers would have to be implemented in accordance to EU regulations. For instance, it would probably not be possible to demand that the installed charging stations are manufactured in Germany (compare [486]).

Subsidies of public and semi-public charging infrastructure might take several forms:

- *Exemption from special usage fee for charging stations installed in public space*: this indirect subsidy seems to have been implemented in all of the model regions where private companies installed charging stations at public parking spaces. Because a private company then makes use of public space to run a private business, it would have to pay a special usage fee to the municipality. The municipality can, however, exempt the private company from paying this fee, as the provision of this infrastructure serves the common good [399].
- *Direct subsidies for the installation of public charging stations*: in this case a direct financial subsidy is paid to compensate for the high investment costs of charging stations. A subsidy of several thousand € per charging point or a percentage of the investment costs up to a certain threshold can be paid. It makes sense to demand quantified requirements for the public access to charging stations, for instance demanding that the station be accessible at least 10 hours per day on 5 days a week.

- *Subsidies for the electricity charged:* an alternative subsidy scheme to the previous one would be to pay subsidies based on the amount of electricity charged at a station. A specific amount is then paid per kWh. Such a subsidy scheme was considered in the profitability calculation in Sec. 5.2.3.6. The advantage of such a scheme is that it would provide an incentive not simply to install charging stations, but to do so at attractive, highly frequented locations. A drawback is that such a subsidy scheme would be more bureaucratic, requiring the transferal of metering values once a year or more often. It would also have to be assured that the charging infrastructure owner cannot acquire a disproportionate benefit by charging his own EVs at the charging station.
- *Exemption from electricity cost elements*: the final price of electricity contains several contributions and taxes (see Sec. 5.2.1.4). These made up about 52.4 % of the final customer price for electricity in 2014. Regulations can be issued which free electricity used for charging from some cost elements, such as value added tax (16 %) or electricity tax (7%) [373]. Electricity charged at public charging stations can also be (partially) exempted from network fees [373]. Such measures would allow public charging station operators to increase their profit margin per sold kWh and/or provide the charging service for a lower price.
- *Higher depreciation allowances for charging stations*: current regulations specify a quite long usage time of 19 years for charging facilities [417]. This regulation can be changed, so that installed charging stations can be depreciated faster. The specified usage time can be shortened or special depreciation allowances [373], for instance in the form of a specific high percentage in the first year, can be introduced. Depreciation allowances reduce the taxed revenues of a business, thus resulting in higher remaining profits (see Sec. 5.2.3.1).

6.4. Conclusion: external effects and public policy

In the previous chapter 5 the economics of EV ownership and charging infrastructure operation have been analyzed. It was found that currently EVs tend to have too high purchase prices for them to be more economic over their entire lifetime than conventional vehicles. Looking at different business models for the operation of charging infrastructure, it was found that profitability is uncertain.

Thus, under current free market conditions, customers are buying less EVs than anticipated. Electric utilities are reluctant to install more public charging points, as they are rarely being used. However, the German state has a high interest in the development of electric mobility in the country, because this creates diverse positive externalities.

Based on anticipated positive externalities listed in the national development plan on electric mobility of 2009 [1], externalities have been discussed one by one within this chapter. It was found that many initial expectations were overly optimistic. In many cases replacing conventional vehicles by EVs creates positive effects only under specific circumstances.

EVs can lead to lower emissions of CO_2. This requires that the recharged energy is generated from sources with low emissions, notably renewable sources, and not from coal power plants.

Unexpectedly, EVs may lead to higher emissions of some kinds of air pollutants over their lifetime than conventional vehicles. This is because high amounts of air pollutants are emitted during battery production. Also, pollution is shifted to the production of electricity in power plants. It is therefore necessary to develop energy efficient and environmentally friendly processes for battery production in the future. It also should be assured that the electricity used for powering EVs is generated by low-polluting sources.

EVs are slightly less noisy than modern conventional vehicles at low speeds, where motor noise plays a bigger role than the noise made by the rolling tires. The advantage will be diminished down to a narrow band of moderate speeds, as the EU demands acoustic vehicle alerting systems to be used for EVs at speeds up to 20 km/h from the year 2019 on. A bigger potential for reducing traffic noise might lie in the use of electric scooters and electric delivery vehicles.

The use of EVs allows to reduce Germany's dependency on petroleum imports. Using electricity to power vehicles allows to diversify the use of primary energy carriers. However, it has to be taken into account that resources for generating electricity, such as black coal and gas, and materials for producing renewable energy power plants, such as photovoltaic cells and wind turbines, also need to be imported. Lithium and cobalt need be imported for the production of EV batteries and rare earth materials for the production of electric motors.

The production of EVs has the potential to create jobs in Germany. Currently, the German industry has little capacities to produce batteries for EVs. A risk is that this production, making up a big part of the value creation for EVs, takes place outside of Germany.

EVs can be integrated into modern mobility concepts such as carsharing and inter-model travel. Most such projects could also be realized with conventional vehicles, however.

Positive and negative impacts of EV charging on the national electricity system can be expected to be small in the near future. However, EVs provide an interesting testbed for smart grid protocols and algorithms, for instance when integrated into smart homes.

Currently, EVs have a positive image as a future-oriented and environmentally friendly technology. This provides an indirect incentive for customers to buy EVs and for cities to set up charging stations. The positive image might be put into perspective in the future, as the limitations of the benefits of EVs become more widely known to the general public.

In order to realize the potential positive externalities of EVs and an associated charging infrastructure, the EU and Germany are setting up policy frameworks to support this development. The most important regulation on the EU level is the directive on the deployment of alternative fuels infrastructure of 2014 [43]. The directive obliges EU member states to hand in policies for the development of such infrastructure by the end of 2016. A target of 1 publicly accessible charging point for every 10 EVs is set up.

The German government is strongly supporting research and development of electric mobility. Diverse projects have been realized, mostly within the eight model regions and the four showcases. Purchase incentives for EVs are lower in Germany than in many other countries. EVs are exempt from car taxes for 10 years. EVs used as business vehicles can be assigned a lower purchase value for calculating the monetary benefit in income tax declarations. Businesses buying EVs can profit from a KfW bank loan with low interest rate. The German government has put the legal framework in place which allows local authorities to implement reserved parking, lower parking fees, use of bus lanes, and access to restricted zones for EVs. Free parking for EVs is already realized in several German cities. Official street signs for charging points have been introduced. The installation of charging stations is supported via loans from the public KfW bank. Installation of public charging points has been supported within the model regions, showcases, and by the federal state of Baden-Württemberg.

After having discussed the status quo of policies on the level of the EU and in Germany, an outlook was given for future policies in Germany. The German government is reluctant to introduce direct purchase subsidies for EVs. However, it is planning to introduce a special depreciation allowance for EVs used in business fleets. The government is also planning to introduce a public procurement program for EVs in the next years.

It is not clear yet how Germany will implement the EU alternative fuels infrastructure directive. It seems highly unlikely that the German state will take on the role of an EV infrastructure provider on the national scale. To get private stakeholders to provide public charging stations, the government can implement pushing and pulling policies. Building owners and constructors can be pushed to provide (semi-) public charging points by including this as a requirement in construction law, as is the case for parking spaces today. The government can assign responsibility to municipalities and regions for the provision of public charging infrastructure. They can then organize the infrastructure in a similar way as is done for public transport today, by giving out a concession or by different public-private partnership constellations. The government can also implement pulling policies which incentivize the provision of public charging points with subsidies. Exempting a public charging station operator from usage fees for public parking spaces is already done today. Further subsidies could be paid for the installation of charging stations, per charged electricity, by exempting the used electricity from some taxes and contributions, and by implementing higher depreciation allowances.

In summary this chapter has shown that the anticipated benefits of EVs and their infrastructure can only be realized under specific preconditions. The EU obliges member states to implement policies to build up public charging points in the next years. Therefore the German government will have to take on a more active role concerning the public charging infrastructure for EVs in the coming years.

7. Stakeholder cooperation for the development of an EV infrastructure

A charging infrastructure for EVs is connected to the electricity distribution network and makes use of parking places. Thus, this new infrastructure is dependent on already existing infrastructures which are controlled by different organizations. A targeted involvement of stakeholders is especially important in situations such as these when "*no organization 'contains' the problem*", and instead "*many individuals, groups and organizations are involved or affected or have some partial responsibility to act*" [500].

Initially, the concept of "stakeholder" was introduced into management thinking in the 1960s as an extension of the term "stockholder" [501]. Whereas previous management philosophies focused on leading a firm in the interest of stockholders, i.e. those people owning stock of a corporation, the stakeholder approach extended the group of people in whose interest a firm should be managed. All those groups should be taken into account that have a stake in the company. These are stockholders, but also employees, customers, suppliers, lenders, and society. An often cited definition of the concept of stakeholder is given in R. E. Freeman's book from 1984: Strategic management: A stakeholder approach [502]: "*Stakeholder = any group or individual who can affect or is affected by the achievement of the firm's objectives*".

The concept was later transferred from firms to individual projects, taking those groups into account that have a stake in the outcome of project. Today stakeholder analysis is an important tool in project management, urban development, and foreign development aid. Though stakeholder analysis techniques are in widespread use, there seem to be no generally accepted standard methods. The article [503] from 2012 points out that there is not even a generally accepted definition of the term “stakeholder”, with hundreds of differing definitions in use. The terms “actor”, “agent”, and “player” are also often used to describe similar concepts with slightly different emphases. The apparent lack of standard methods for stakeholder analysis lead the author of this thesis to use his own formats for such an analysis, which are loosely based on previously used stakeholder analysis techniques.

A stakeholder analysis usually starts with the identification and description of individual stakeholders. Then, relationships or rankings between stakeholders are analyzed. Stakeholders can be mapped according to a selection of different dimensions such as power, interest, need, attitude (supportive or adverse), awareness, and others.

A stakeholder analysis done at the start of a project brings several benefits [504]. The analysis allows to better understand the interests of concerned stakeholders. It can help to identify which stakeholders should participate in which stage of a project and which stakeholders should be kept informed. It also helps to avoid negative impacts on a project due to stakeholders’ opposition.

Several publications have already presented stakeholder analyses with different scopes within the domain of electric mobility. The interactions of stakeholders during the installation of public charging stations in the city of Berlin is described in the report [505]. The report is based on 13 interviews with people who were involved in the implementation process. The causes of occurred conflicts are identified in hindsight. Sec. 7.2.5 below takes up one of those points. The article [506] describes experiences made by public and private sector representatives within stakeholder forums for the development of electric mobility in several European cities. The article contains several tips for successful stakeholder cooperation, which are discussed below in Sec. 7.3.

Stakeholders have been analyzed in relation to business models for public EV charging infrastructure in the article [507]. The article describes the roles of stakeholders and the flow of money and services between them. The report [408] also treats stakeholders within the context of business models for charging infrastructure. The report treats costs and benefits for stakeholders which install charging infrastructure at their premises. Such stakeholders can be municipalities, parking garages, retailers, utilities, and others.

Stakeholder interactions within new electricity market models for EVs have been treated in several reports. In [508] it is analyzed which stakeholders might provide new services for EVs, such as operation of charging infrastructure, operating battery swapping facilities, aggregation of EV charging, operating of central clearing house, and others. The report [509] shows the interactions of different stakeholders for different charging station constellations: controlled charging/uncontrolled charging/V2G, in private/public space, with private/public access. The report [510] also treats stakeholder interactions within electricity markets, differing between a business view and a technical view.

The master's thesis [511] presents an extensive stakeholder analysis for the management of information on electric vehicles and charging infrastructure. The author conducted interviews with 20 stakeholder representatives. Stakeholders are described via their interests, information, network, and resources. Based on existing relationships between stakeholders, they are categorized into three groups with differing information needs: infrastructure administrators, EV providers, and e-mobility sponsors.

Studies have also been done on the national level, analyzing the interactions of stakeholders in the development of electric mobility within a country. The article [512] investigates the situation in the Netherlands. The study is based on interviews with 38 representatives. The article describes stakeholders via their interests, expectations, and strategies in relation to electric mobility. Several conflicts of interest are identified, one of which is discussed in Sec. 7.2.5 below. The article [513] treats the situation in China. Several interviews with company representatives were done and publications on EV related policies and research programs were evaluated. The authors map stakeholders via their functional roles and stakeholder classes over time. They find that the position of stakeholders varies over different stages of market development.

The stakeholder analysis for the development of a local charging infrastructure for EVs carried our below first describes the situation, then discusses how coordination can be realized practically. First, individual stakeholder categories are described in Sec. 7.1. Afterwards, the relationships between these stakeholder categories are described in Sec. 7.2. The following sections then treat the practical implementation of stakeholder cooperation. Sec. 7.3 discusses how a stakeholder dialog can be organized. The implementation of citizen participation is discussed in Sec. 7.4. Finally, Sec. 7.5 treats possibilities of how cooperation can be formalized.

7.1. Stakeholder analysis: description of stakeholder categories

In this section the most relevant stakeholder categories will be discussed. The term "stakeholder categories" is used in the sense of generic industry sectors, i.e. no specific individual organization or person is meant. The stakeholder categories are described via two aspects. The first aspect is the *interests* a stakeholder category has in regard to the local development of a charging infrastructure. The second aspect is the *resources and actions* it can contribute to the development. The description via these two aspects is a simplification of stakeholder description templates used in previous publications (compare [511] [512]).

No direct interviews were conducted for the following stakeholder analysis. The analysis is based on evident common knowledge, personal experience of the author gathered during EV infrastructure projects, and documents, such as written statements made by organizations (press releases, presentations), existing analyses, and published surveys and interviews.

The aim of this analysis is to provide the background information about what can generally be expected from different stakeholder categories. In the context of a local EV infrastructure development, an analysis should be done for the specific local stakeholders. These might also contain several stakeholders of one category, for instance different parking space operators or retailers with different profiles.

The following stakeholder categories are considered here, which can be grouped into several overarching groups for better oversight (also see Fig. 7.1):

- Clients and citizens:
  - EV drivers
  - Local citizens
- Public authorities:
  - Local authorities
  - National and federal state authorities

- Electricity sector companies:
  - Distribution system operators
  - Electricity providers
  - Municipal utilities
  - Electric installers and ICT companies
- EV infrastructure sector companies:
  - EV charging facility manufacturers
  - EV infrastructure companies
- Passenger transport sector companies (in a broad sense):
  - EV manufacturers
  - Passenger transportation companies
  - Paid parking operators
  - Client parking operators
  - Gasoline station operators

Several categories of stakeholders are not considered relevant enough to be included in a detailed analysis. The above list only contains electricity providers, i.e. those companies with whom a contract for the provision of electricity exists. The actual *producers* of electricity, which operate the power plants, can be other companies. Similarly, only operators of distribution networks are included, with whom a network connection contract exists, not the operators of the overlying transport networks.

If charging facilities communicate with a back-end control system, a telecommunication contract needs to exist with a company from this sector. These companies are required as technical service providers, but are assumed to otherwise not have a relevant stake in EV infrastructure development.

Construction companies do the groundwork for the installation of public charging stations. But these companies are contracted when needed and thus are also not considered of having a relevant stake in the development of a local charging infrastructure.

Standardization organizations play an important role in defining the framework for the charging infrastructure. However, these are also not considered to be locally relevant stakeholders.

Consulting and engineering companies, or research institutions can contribute to a local infrastructure development, for instance by doing a location planning for charging stations. These companies are involved as subcontractors and thus are also not assumed to play an important role.

The individual stakeholder categories, their interests, resources, and possible actions are discussed in the following sections.

7.1.1. EV drivers

EV, PHEV, and REEV drivers are the final clients of the service, those people for whom the infrastructure is being installed. The different aspects of demand for charging infrastructure from the EV drivers' point of view is extensively discussed in Sec. 4.2.

EV drivers' *interests* are the following. EV drivers want a public charging infrastructure that is functioning [514] [515] [516], provides good areal coverage [517] [518], is openly accessible [514] [515] [517], technically compatible to their vehicle [514] [516] [517], at low charging costs [519] [520]. Functioning means here that the charging stations installed are actually working, i.e. that they are maintained regularly and repaired promptly when out of order. Good areal coverage involves the availability of charging stations at attractive locations, as well as fast charging stations along major motorways. Openly accessible means that EV drivers can use a charging station in an ad-hoc fashion even when they are not a registered customer of the specific provider. The charging station should also be accessible at all hours and on the weekend. Technically compatible means that the charging station provides a plug type that can be used for the driver's car without having to use an adapter.

Drivers of pure EVs can be expected to compare the price of public charging to the price they pay for charging at home. Drivers of PHEVs and REEVs can be expected to compare the price of public charging to the both equivalent price of gasoline as well as the price for charging at home (also see Sec. 4.1.1).

Drivers prefer the location of the charging station to be well lighted at night [341]. Some drivers want to park their EV at a well visible spot in order to show off their car [341]. Drivers of company fleet vehicles see less need for public charging stations than private users (see Sec. 4.2.5).

EV drivers' *resources and actions* will now be discussed. EV drivers are the final clients of a public charging infrastructure. Their use or disuse of the infrastructure determines whether the infrastructure implementation can be considered as a success and whether it is economically viable (see Sec. 5.2.3).

EV drivers can provide feedback to infrastructure providers. They can report broken charging stations and propose locations for new charging stations. Some websites and smartphone apps allow to give direct feedback to the charging station operator (for instance [132]).

Many early EV enthusiasts were organized in EV clubs. Some drivers of EVs, displeased with the state of the public charging infrastructure for EVs, have started their own initiatives to provide more publicy accessible charging points. The German initiative Drehstromnetz is a grass roots movement of EV drivers [521]. Each participant provides a charging point with high triphase power, which can be accessed at all hours without advance notification. Each participant can use all other charging points of the network. A donation should be given to cover the electricity costs when charging. The U.S. and international initiative PlugShare also allows EV drivers to share their private charging points with others [522]. In Austria the Elektrotankstellen-Verzeichnis also lists charging points provided by private persons, restaurants, hotels, and companies [523]. The German research project CrowdStrom investigates such bottom-up approaches for the implementation of (semi-) public infrastructure [524].

7.1.2. Local citizens

In this context, local citizens are residents living in a neighborhood, owners of stores, visitors and clients, taxi drivers, and other users of public space and public parking spaces that do not own an EV themselves.

Local citizens' *interests* will be discussed first. A phenomenon that can occur in all kinds of infrastructure developments is the so called NIMBY syndrome, standing for "Not In My Backyard" [525]. In the case of public charging stations, local citizens might not be opposed to the installation of public charging stations *per se*, but they may not want them to be located in front of *their* apartment buildings and stores.

The reservation of public parking spaces for EVs can lead to frustration for other drivers needing a parking space, be it local residents or clients. This can especially be the case when there is a high number of such reserved parking spaces which remain unused much of the time [526] [527].

The charging of an EV, be it with an onboard AC or an offboard DC charger, produces low levels of noise [528]. In very silent surroundings or at night, this may be perceived as disturbing by residents. In 2013 a company manufacturing charging stations praised its DC charging station as having a "low operational noise" of 45 dB [73]. This is corresponds to the sound level of a normal conversation and would already be too loud for use at night in residential-only areas or near hospitals [528] [529].

Local citizens can also have a positive opinion towards public charging points. Residents can see it as a possibility to buy an EV of their own. Store owners might see it as positive marketing when an EV charging station is installed at a public parking spot in front of their store.

Now *local citizens' resources and actions* will be treated. Local citizens can block charging stations by parking their conventional vehicle at the associated parking places. They might vandalize charging stations. It is possible, but seems unlikely, that local citizens file a lawsuit against the installation of charging stations, or that local citizens form an opposing citizen's group. A local citizen might be incited to buy an EV when he sees a public charging station being installed in his neighborhood.

7.1.3. Local authorities

Local authorities operate on the city district, municipality, city, or regional level. The role of such authorities in Germany, notably municipalities, in the process of establishing electric mobility is already discussed in detail in several publications. The report [530] discusses the different strategies of German and international cities concerning electric mobility. The report [531] lists a wide array of possible actions of municipalities in the domain of electric mobility and evaluates their priority, impact, feasibility, and time and money costs. The report [532] discusses recent electric mobility projects in Germany from the perspective of local urban and transport planning. Lessons learned, difficulties, and required further knowledge is listed. The report [533] takes on an action-oriented approach. A set of instruments is presented which allows local authorities to plan and implement electric mobility projects. New methods are shown, but it is also demonstrated how municipalities can integrate electric mobility in their traditional planning processes. The document [534] shows a survey among communes in Germany in 2014 concerning electric mobility.

For local authorities the implementation of a public charging infrastructure for EVs usually is only one action within a wider strategy of supporting the uptake of EVs. But the following discussion only focuses on interests and actions concerning public charging infrastructure.

This stakeholder category's *interests* are treated in the following. Local authorities usually take on a more holistic way to the development of electric mobility than private businesses. Their aim is to bring business interests within electric mobility projects in line with local policy [506]. Electric mobility is usually seen as a means to reach local policy goals [534].

Local authorities are motivated by the diverse positive external effects that are associated with a transition to EVs (compare [530] [533] [534]). Positive externalities and their limitations are discussed in detail in Sec. 6.1 of this document. The use of EVs lowers *local* CO_2 and pollutant emissions. Use of EVs can lead to a slight lowering of noise emissions. If more EVs are used locally and a charging infrastructure for them is built up, this can create jobs at local vehicle manufacturers, electric utilities, and electric and ICT companies. A public call for tenders, however, usually does not allow to favor local businesses. Developing electric mobility locally can involve the development of innovative mobility concepts, such as EV and electric bicycle sharing systems, and intermodal travel schemes. The local implementation of charging infrastructure and large scale use of EVs can involve a positive image gain for a city, which can be used for city marketing purposes to attract businesses and tourists.

On the other hand local authorities can also have some reservations about supporting the use of EVs. They can argue that the switch from conventional to electric vehicles does not improve problems relating to congestion [526] or shortage of parking places in city centers. A reservation of parking places for EVs, which then remain unused, could even lead to further shortage of parking spaces [526]. In some cities (conventional) carsharing and bicycle sharing systems have been implemented in public space in the last years. Additionally installing public charging stations leads to rising usage conflicts around public space. Some cities therefore prefer charging stations to be installed in semi-public space, such as parking garages and retailers' parking spaces, instead of at public curbside parking places [535]. Local urban planners want charging stations to blend in well with the existing urban surroundings and existing other street furniture [536]. Local authorities may fear that the promotion of electric cars leads to a mode shift away from active modes (walking and bicycling) or public transport [526].

Local authorities *resources and actions* are now discussed. Electric mobility still being a recent and unsettled topic, local authorities often lack the technical expertise to understand all relevant aspects, such as standardization of charging plugs [506]. The topic lies somewhere in between the typical responsibilities of administrative departments in municipalities, such as departments for urban planning, road maintenance, environmental protection, protection of historic monuments etc. To integrate the topic into current administrative structures, a new administrative department with dedicated staff can be created. Alternatively, a working group can be formed that involves representatives of different departments. A third alternative is to form a steering committee for the local development of electric mobility in which representatives of administrative units as well as private companies join [533]. Independent of organizational structure, it is recommended to install one central contact person for electric mobility in a municipality [533].

Local authorities can set up publicly accessible charging stations at municipal buildings as a symbolic act or install restricted-access charging stations for city employees' use.

Local authorities control one of the most important resource for the implementation of a local public charging infrastructure: public parking spaces. The local administration has to issue the permits which allow to install charging stations at public parking places and possibly reserve them exclusively for EVs. This may require the cooperation of diverse administrative units (road construction, parking management, protection of historic monuments, and others). Local authorities can develop and streamline the new permitting process. The process of obtaining permits for the buildup of public charging stations is treated in more detail in Sec. 9.2. Local authorities also often indirectly control big public parking garages operated by concessionaires.

If a private company uses public parking spaces for an EV charging system, it might have to pay a special usage fee, because it is using public space to operate a commercial business (also see Sec. 5.2.1.4). The local special usage fee regulation can be adapted to exempt charging stations from such fees, or a special usage fee contract can be set up between the local authority and the concerned private company [533].

The electric mobility law (*Elektromobilitätsgesetz* [160]) issued in 2015 paves the way for local policies to support the use of charging infrastructure and EVs. EVs can be allowed to park at special parking spaces, for instance at charging stations, or without such facilities in inner city areas. Parking fees can be reduced for them. Such vehicles can be allowed to use specific roads or lanes, for instance bus lanes. Zones can be implemented where only EVs may enter. Several German cities had already implemented free parking for EVs on public parking spaces prior to the introduction of the electric mobility law. In January 2014 these cities included Stuttgart, Esslingen am Neckar, Böblingen, Sindelfingen, Ludwigsburg, Konstanz, and Garmisch-Partenkirchen [496]. In these cities the drivers of EVs can obtain a special permit from the city administration, which they display on their windshields.

Construction codes which determine the requirements for parking spaces for new buildings are usually determined on the level of federal states in Germany (for the regulation in Baden-Württemberg see [360]). However, the city of Offenbach (in the federal state of Hessen) has issued a regulation valid for specific zones within the city. The regulation demands that for construction projects which require more than 20 parking spaces, 25 % of them need to be equipped with an electricity connection for the charging of EVs [537].

Local authorities can integrate the development of public charging infrastructure and related activities such as the development of EV or electric bicycle sharing schemes into local planning documents. Electric mobility can be integrated as a new aspect into traditional strategic planning documents, such an urban development concept, traffic development plan, public transport plan, climate protection plan, air protection plan, and noise reduction plan [533]. Alternatively a separate master plan for electric mobility can be set up [538] [533]. The development of such strategic documents can be taken as an opportunity to get relevant local stakeholders involved.

The conversion of old industrial areas into residential city quarters can be taken as an occasion by municipalities to integrate public and private charging infrastructure into urban development from the start. This is being done in Mannheim for the conversion of former military barracks [539].

Many municipalities in Germany are lacking the funds to invest in roads and other public infrastructure [540]. They can therefore also be expected to lack the funds to build up large scale public charging infrastructure on their own account and thus require additional funding from the state, federal state, and private partners.

7.1.4. National and federal state authorities

National and federal state authorities determine the regulatory frame conditions for local developments. In Germany the big cities of Berlin, Hamburg, and Bremen have the status of federal states, locating them in a position between local authorities and federal state authorities

National and federal state authorities' *interests* are discussed first. Like local authorities, national and federal state authorities are motivated by the diverse positive externalities associated with the use of EVs. In 2009 the German government has explicitly listed the advantages it sees in the use of EVs in the national development plan for electric mobility [1]. Potential positive effects on the national scale are the lowering of green house gas, pollutant, and noise emissions, the lowering of the dependence on resource imports, the creation of jobs, the development of future mobility concepts, and the development of the electricity system. These effects and their limitations have been discussed in the light of current research in Sec. 6.1.

The German government maintains the position that the implementation of a public charging infrastructure for EVs is the responsibility of the private sector [294]. Municipalities can establish frame conditions for the buildup of this charging infrastructure, but are not legally obliged to do so [294].

Now the stakeholder category's *resources and actions* are treated. National and federal state authorities determine the frame conditions for the buildup of local charging infrastructure. Current and prospective policies on the German national scale are discussed in detail in Sec. 6.2.2 and 6.3 respectively.

The German government has provided a vision for the future of electric mobility in Germany via the national development program electric mobility of 2009, in which the target of 1 million EVs (pure EVs, REEVs, and PHEVs) has been set up [1]. The government program of electric mobility of 2011 has again emphasized and concretized this vision [294]. The dialog with the private industry has been established in 2010 with the national platform on electric mobility [490].

The German government and the federal states have financially supported the buildup of charging stations for EVs within the model regions and showcase projects (see Sec. 6.2.2). The frame conditions for the financing of charging infrastructure have been slightly improved via the introduction of loans with low interest rates by the public KfW bank. These loans were available to municipalities within projects for updating street lighting [494] and are now available to companies buying EVs to use in their fleets [495] (see Sec. 6.2.2).

The German government has put the regulations in place that specify standardized signs for charging stations [157] (see Sec. 2.2.2), allow to reserve parking spaces for EVs, and exempt EVs from paying parking fees [541] (see Sec. 6.2.2).

In the next years the German government will have to decide how it can adjust the frame conditions for public charging infrastructure so that the European directive on the deployment of alternative fuels infrastructure can be realized [43].

7.1.5. Distribution system operators

Distribution system operators (DSOs) are regional monopolists within their network areas. They are service providers which are obliged to provide a network connection to a client under the condition that the client's facility does not cause significant disturbances. Still, they should be thought of as full partners for the successful implementation of public charging infrastructure, because network connection costs and time required for the network connection can have big impacts on the overall implementation process.

Distribution system operators' *interests* are discussed in the following paragraphs. The impacts of EV charging on distribution systems and power lines are discussed in detail in Sec. 3.3.4 and Sec. 3.3.5. The technical threats and opportunities identified there are linked to the interest of DSOs. They are interested in the integration of EV charging stations in current distribution systems in a cost-efficient manner. DSOs want to avoid having to reinforce local electricity networks [542].

The main concern of DSOs is to avoid negative impacts of EV charging on the distribution system. Negative impacts can occur in the form of new demand peaks which exceed the capacities of power lines and transformers. Operating a transformer close to its maximal capacity can shorten its lifespan due to heat development. If V2G is implemented, the feeding back of electricity can likewise exceed the installed capacities. DSOs are therefore interested in controlling the charging of EVs while taking distribution system constraints into account. If the monophase charging of EVs is unevenly distributed among the phases in a triphase distribution system, a voltage imbalance can occur. Charging stations can also cause a deterioration of power quality on the power line level, due to the creation of start-up current peaks and voltage harmonics.

But the charging of EVs can also bring about positive effects from the point of view of DSOs. If EVs are charged in the nighttime demand valley (see Sec. 3.2.2), this leads to a better utilization of the installed capacities and more income for the DSO, as they receive a fee for each kWh transferred (see Sec. 5.2.1.4). If EVs are charged directly with electricity generated by a local photovoltaic installation, this decouples both the EV charging's and local generation's impacts on the distribution grid, which are possible demand peaks and load flow reversal respectively.

DSO's *resources and actions* are now treated. DSOs' technicians need to connect charging stations to the network, if the stations are not located behind already existing household connections. A network connection contract is established between the client and the DSO. The requirements for clients' facilities for the connection to the distribution system are stated in the DSOs' technical connection requirements for the connection to the low voltage network (Technische Anschlussbedingungen TAB für den Anschluss an das Niederspannungsnetz) [251]. Local DSOs can adapt the current rules to account for the connection of charging stations. But if charging stations fulfill current norms concerning electromagnetic compatibility no problems should occur (see Sec. 3.4 for details on the electric installation process).

The DSO demands from the client to pay the costs for establishing the network connection. Usually these costs are higher, the higher the length of the connection and the higher its ampere rating is. The DSO can additionally demand fees for maintenance and upgrading the distribution network (example for such fees in [264]). In order to keep such fees low, a network planner from the local DSO can actively participate in the location planning of charging stations on the street scale. DSOs can also streamline the administrative and electric installation process, to allow implementing public charging stations within a short time frame.

In the long run, DSOs could control the timing of EV charging via ripple control or other technologies. This would allow them to schedule EV charging to occur during times of low electricity demand in the distribution system. Such an application, however, seems more suitable for charging EVs at homes or work places than for public charging, where drivers want to have their EVs charged within a short time span.

7.1.6. Electricity providers

Electricity providers provide the electricity required by charging stations. Electricity providers produce electricity in their own power plants and/or buy electricity from electricity producers and traders. A contract is established between the electricity provider and the organization which operates the charging station. The consumed electricity is measured by an electric meter.

Electricity providers' *interests* are first discussed in the following paragraphs. For electricity producers, EV charging is a chance to sell more of their product "electricity". Because many clients want their EVs to be charged with electricity from renewable sources, more expensive renewable energy contracts can be sold. Products can also be bundled, for instance, an electricity contract for a house, as well as a contract for the use of public EV infrastructure. By being involved in electric mobility projects, electricity producers can position themselves as innovative, environmentally conscious companies. If electricity providers are also active as electricity producers or network operators, the charging of EVs can serve as a stepping stone for the development of future technologies and services such as smart home, smart grid, and better integration of renewable energies [543].

Electricity providers are demanding subsidies for public charging infrastructure. In 2011 the Federal Association of the Energy and Water Industry (BDEW) stated that public charging infrastructure would not be self-sustaining in the near future and should therefore be financially supported by the state [366] (compare the discussion of different business models in Sec. 5.2.3, especially the business model for electricity providers with cross-financing from home charging in Sec. 5.2.3.4).

Electricity providers' *resources and actions* are discussed now. In Germany, public EV charging stations have mainly been installed by electricity providers, including municipal utilities, in the last years, partially subsidized by the state within the model regions and showcase projects.

An electricity provider is required to supply charging stations with electricity. Because electricity provision is organized in a free market structure in Germany, and there are many electricity providers active in Germany (1 117 in 2013 [189]), in theory almost any of them can be chosen. However, involving big electricity providers or local municipal utilities can be favorable, as they bring further resources in the form of funding, manpower, and know-how into a local development of charging infrastructure.

7.1.7. Municipal utilities

Municipal utilities (Stadtwerke) are small local utilities, usually majority-owned by the municipalities in which they operate. They can provide a wide array of public services, which differ between municipal utilities. Such public services can be electricity provision, distribution system operation, operation of parking garages and public parking spaces, public transport, and others.

This stakeholder category's *interests* are discussed now. Municipal utilities can have the interests of those kinds of companies whose services they provide: distribution system operators, electricity providers, passenger transportation companies, and parking garage operators (see previous and following sections). However, they tend to be less profit-oriented than private companies. They are usually well embedded in their local communities and see their role in providing public services for the common good [544]. They are interested in maintaining municipal control over public infrastructure systems [545].

Municipalities utilities' *resources and actions* are treated now. Municipal utilities have the resources and actions of those companies which they encompass. Because they contain several services, and are linked closely to the municipalities in which they are located, it is easier for them to take an integrated approach to the planning of a charging infrastructure for EVs. The cooperation of stakeholders from different sectors, required for a local charging infrastructure development, partially become the working together of colleagues within one company (compare the fulfillment of different roles in the development of charging infrastructure in Sec. 7.2.2).

Municipal utilities have the advantage of knowing the cities in which they operate well [546]. Because municipal utilities only operate within their own limited areas, they do not directly compete with each other and can thus form cooperations among themselves easily.

7.1.8. Electricians

The installation and maintenance of charging facilities needs to be done by certified electricians, for whom this is a relatively new task.

Eletricians *interests* are discussed in the following. The installation of private or public charging facilities provides new orders for electricians. They can use the opportunity to also sell additional installations of products, such as smart home energy management systems and photovoltaic panels [547].

Now, electricians *resources and actions* are discussed. In order to do a professional installation, electricians need to acquire the necessary knowledge. This especially involves an up-to-date knowledge about standards and technical requirements (see Sec. 3.4). They can participate in professional trainings for EV charging facility installation [258] [259]. In the future this topic will have to be included in the formation of apprentices [548].

The regular checking of charging facilities also needs to be done by certified electricians. Companies active in this domain can extend their services to also include maintenance and operation of charging facilities.

7.1.9. EV charging facility manufacturers

These are the companies that manufacture charging facilities and associated hard- and software.

EV charging facility manufacturers' *interest* is to sell their products and associated services. They want to provide design and functionalities in their charging facilities that differentiates their product from that of competitors. It can be expected that manufacturers prefer to sell variants of their charging facilities with many features, which are more highly priced. Many EV charging facility manufacturers also produce other electric products and thus are not solely dependent on producing charging facilities (for example the companies Schneider Electric, Mennekes, and Bosch).

EV infrastructure manufacturers' *resources and actions* are to produce and sell EV charging stations and associated products, such as back-end communication systems. Manufacturers can provide location planning and installation services. Such companies may also provide maintenance and operating services for their charging stations making them full-fledged EV infrastructure companies (see next section).

7.1.10. EV infrastructure companies

EV infrastructure companies are specialized to provide all the services around EV charging infrastructure.

It is the *interest* of these companies to profit from providing private and public charging infrastructure and associated ICT services.

EV infrastructure companies' *resources and actions* are treated now. Such companies install, maintain, and operate charging facilities for EVs. They also run the associated ICT services for the operation and use of charging infrastructure (see Sec. 2.2). They can provide this service to EV drivers, owners of parking spaces, and to local authorities as a public service.

In the last years notable EV charging infrastructure companies such as Better Place [367] and Ecotality [369] have gone bankrupt. It seems that the straightforward business model of providing a charging service directly to EV drivers is not economically viable. Possible solutions to this problem could be public subsidies or additional revenue streams, for instance by advertisement. The economics of building and operating public charging infrastructure are discussed in detail in Chap. 5.

7.1.11. EV manufacturers

EV manufacturers are a heterogeneous group with different strategies. Some EV manufacturers solely build EVs (for instance Telsa), some see the manufacturing of EVs as a key strategy (for instance Renault, Nissan, Mitsubishi), while others see it more as a niche product which complements their portfolio of conventional vehicles (most German manufacturers). In the following, car dealerships are also included as the common contact point between EV manufacturers and EV buyers.

The *interests* of this stakeholder category are discussed first. Manufacturers of EVs are dependent on the availability of public charging points to sell their vehicles in large numbers. This is because many potential users of an EV see the lack of charging infrastructure as an impediment to buying an EV (see Sec. 4.2.5).

Several car manufacturers have a high interest in the manufacturing and selling of EVs and thus in the availability of public charging stations (see the actions of some EV manufacturers below). But for many manufacturers, EVs are only a niche product, while the core business remains the manufacturing of ICE vehicles. For such manufacturers the lack of public charging infrastructure can be a welcome excuse to keep on doing business as usual.

In [549] the results of a 2014 survey of 200 executives from the automotive sector is presented. Executives from OEMs (original equipment manufacturers) from Europe, North America, and Japan were asked in which technology their company was planning to invest most until 2019. 75 % responded with ICE (internal combustion engine) downsizing. 5 % responded each with hybrid fuel systems, plug-in hybrids, and range extended battery technology. Not a single one (0 %) answered pure battery technology. OEMs from the emerging countries (China, India, Russia, Brazil) seem to be more open to alternative drive train technologies. Here 19 % responded that their company would invest most in pure battery electric technology in the coming years.

Concerning the infrastructure for EVs some interesting insights can be also be found in same survey [549]. 40 % of the participants of the study stated that co-operation between relevant stakeholders is the best way to implement a national infrastructure for EVs. Almost a third of the respondents said that gas stations and oil companies should also assume some responsibility for the infrastructure buildup.

An incident from the year 2013 indicates that German manufacturers are reluctant to build cars with lower emissions. When the EU planned to lower the CO_2 fleet emissions for car manufacturers, Mathias Wissman, head of the German federation of the automobile industry (VDA), wrote a direct letter to chancelor Angela Merkel [550]. In this letter he argued that such emission targets would endanger jobs in the premium segment in the German automobile industry. Premium brands in Germany are notably Mercedes, BMW, Audi, and Porsche. The letter demanded the abolition of these emission targets, as well as the introduction of higher “super credits” for EVs and other alternative drive train cars. Super credits allow manufacturers to count such vehicles multiply, thus allowing them to sell more vehicles with high emissions on the other hand, while keeping the emission average low.

The above information indicates that many vehicle manufacturers want to keep doing business as usual, building ICE vehicles. The responsibility for the buildup of charging infrastructure is seen on the part of other partners, or even as the responsibility of traditional gasoline stations.

On the other hand, some trends indicate that car manufacturers are moving away from their traditional role. When asked about the potential future structure of the automotive industry in the survey [549], 77 % of respondents rated it as extremely or very likely that OEMs will become pure mobility solution providers. The trend towards such a role can already be seen now, with many car manufacturers also providing car rental, car sharing, and intermodal travel services. Electric mobility can be an opportunity for car manufacturers to extend their activities. They can get involved in the operation of public EV charging infrastructure and sell complementary products to EVs, such as home charging stations and home energy management systems [551].

In the following, *EV manufacturers' resources and actions* will be discussed. Traditionally, the manufacturing of vehicles and the operation of gasoline stations have been in the hands of different organizations in Germany. With the arrival of EVs, some manufacturers are also getting directly involved in the provision of private and public EV charging infrastructure.

The sale of EVs can be bundled with associated products and services. Electric vehicles can be sold in combination with corresponding charging facilities for use in private garages or parking places. The sellers of EVs can organize the charging facilities' installation by an accordingly trained electrician [552]. In the future, car manufacturers might also sell associated home energy management, solar power, V2H (vehicle to home) and V2G equipment [551]. The EV can be sold together with an access card to public charging infrastructure provided by partner companies. BMW's ChargeNow is such a service. Clients receive one single bill from BMW at the end of the month [553].

Car manufacturers can provide publicly accessible charging stations at their car dealerships. Since autumn 2014 Nissan dealerships in Germany are providing free Type 2 and ChaDeMo charging points to all drivers of EVs, not just drivers of Nissan vehicles [554]. Mitsubishi dealerships in Germany are also providing publicly accessible charging points [555].

EV manufacturers can get indirectly involved in the provision of public charging stations within EV car sharing schemes. The mixed company Bolloré implemented the large scale EV car sharing scheme Autolib' in Paris, using the Bolloré Bluecar EV [556]. The Daimler company deploys its Smart Fortwo EVs within its carsharing scheme Car2Go [557].

Car manufacturers can partner with providers of public charging infrastructure. The ChargeNow service of BMW has already been mentioned, which allows drivers of a BMW EV to charge at charging stations of contracted partners [553]. The Nissan-Renault alliance partnered with the infrastructure provider Better Place (which was dissoluted in 2013 [367]). Nissan and Renault vehicles could be bought from Better Place and could use the company's charging stations and battery swapping facilities.

Some car manufacturers are going even further and are building up charging networks of their own. The Tesla company has installed fast charging stations called Superchargers along major motorways in the USA, Norway, Germany, and other European countries. The stations use a specific plug format, currently only supported by Tesla vehicles. The company states that it is providing the service "for free" because it "want[s] to encourage Model S owners to take road trips" [558]. In June 2013 Tesla has announced that it will additionally implement battery swapping facilities for its customers [90].

In Juli 2013 the car manufacturers Toyota, Nissan, Honda, and Mitsubishi have announced that they will work together to develop the charging infrastructure for EVs and PHEVs in Japan [559]. Before, each company had already invested in different providers of public charging infrastructure. From mid 2013 on they plan to coordinate their actions. The companies will bear part of the installation and maintenance costs of the public charging infrastructure. The other part of the investment will be covered by government subsidies. The companies also wants to work directly with local authorities and government agencies for the development of infrastructure. They motivate their involvement by the "critical need to swiftly develop charging infrastructure facilities to promote the use of electric-powered vehicles" and that there are "about 1 700 quick chargers and just over 3 000 normal chargers in Japan, which is generally recognized to be insufficient" [559].

German car manufacturers seem to take advantage of plug standards to exclude vehicles of competitors from using charging stations. In the project SLAM, fast charging stations are being installed along German highways. These charging stations only provide the CCS plug format. It is supposed that the involved German companies BWM, VW, Daimler, and Porsche [560] are doing this purposefully, in order to exclude EVs of foreign companies, which mainly support the ChaDeMo fast charging standard, from using these charging stations [561].

7.1.12. Passenger transportation companies

Different kinds of companies fall into this category, for instance companies providing public transport by trams, trains and buses, taxi companies, or carsharing companies.

Such companies' *interest* may be to integrate EVs in their vehicle fleets, to profit from their image as environmentally friendly vehicles and from lower fuels costs (see Sec. 5.1). If they do so, they also require the associated charging infrastructure. Railway companies are traditional operators of electrified forms of transport. They may therefore wish to extend their services to also cover road based electrified transport.

Passenger transportation companies' *resources and actions* are the following. Companies using electric buses or taxis can be expected to install infrastructure for their own use, possibly also using inductive charging [86] or battery swapping [101] [102]. Electric taxis can make use of normal publicly accessible conductive charging stations.

Carsharing vehicles can use existing public charging infrastructure, leading to a higher level of utilization of this infrastructure [309] [346]. For this constellation the carsharing company needs to establish a contract with the infrastructure provider. Alternatively the carsharing company can install and operate its own charging stations, which it can also make accessible to private owners of EVs [562].

Railway companies can install charging stations for private electric vehicles at train stations, in order to encourage intermodal trips [563], or they can provide electric rental cars along with charging facilities at the train stations [564]. Some railway companies operate their own electricity distribution grids and are active as electricity providers. They can thus use these infrastructure services to also charge EVs.

7.1.13. Paid parking operators

These are companies that provide parking spaces for a parking fee, be it in parking garages or open parking lots.

This stakeholder category's *interests* are discussed now. These companies may want to integrate EV charging as a part of their service. In the long term EV drivers may expect charging facilities to be available in every big parking garage and paid parking lot. If paid parking operators do not provide this service they can lose those clients. Providing paid parking is a profitable business as it is, thus additional high revenues from EV charging may not be required.

Paid parking operators' *resources and possible actions* are discussed in the following. These companies can form cooperations with operators of charging infrastructure, which install, maintain, and operate charging facilities on their parking spaces [565] [566]. They can also install charging facilities of their own which they integrate into their own payment systems [567].

In the case of curbside parking or open parking lots, parking ticket machines can be used that also provide charging points for EVs [106].

7.1.14. Client parking operators

Many companies provide parking places for their clients for free. Such companies are for instance retailers, restaurants, cinemas and other cultural institutions, and sports institutions.

Client parking providers' *interests* are discussed first. These companies may want to provide charging stations in order to attract customers who drive EVs. Installing charging stations also provides the opportunity for companies to show themselves as being innovative and environmentally conscious.

These kinds of companies generate revenues from customers buying products and services from them. Thus the provision of charging stations does not have to be profitable. That EV drivers solely stop to charge at the location, but do not buy anything, may not be in the interest of client parking providers.

Client parking providers' *resources and actions* include forming partnerships with charging infrastructure operators, which install, operate, and maintain charging stations at their parking places [568] [569]. Alternatively, they can install charging stations of their own. They may provide EV charging for their clients for free.

An example for this is the retail group Aldi Süd, which in 2015 installed 50 charging stations supporting Type 2, CCS, and CHAdeMO at retail locations in urban agglomerations. The charging stations are available during opening hours of the supermarkets. The charging service can be used for up to one hour, free of costs, and requires no registration [72] [570].

7.1.15. Gasoline station operators

Gasoline station operators are the traditional suppliers of fuel for vehicles. It would be straightforward if they also provided charging for EVs.

Gasoline station operators' *interests* are discussed in the following paragraphs. Gasoline stations are traditionally owned by petrol companies. Such companies cannot be expected to endorse the replacement of gasoline and diesel by electricity for driving.

However, nowadays the tenants of gasoline stations make a big part of their revenues not from selling fuels, but from sales in their integrated shops and bistros. The basic business model of gasoline stations is discussed in more detail in Sec. 5.4. From the point of view of the tenant, who receives only a small provision on each liter of fuel sold, attracting more customers by also installing charging stations for EVs can be attractive.

Now gasoline station operators' *actions* are treated. Gasoline station operators can install charging facilities at their sites or enter into cooperations with companies who install and operate these charging stations for them. Because EV drivers then purposefully drive to these locations to charge, fast charging facilities are more appropriate.

A safety distance has to be kept between the fuel dispensers and charging facilities. The article [571] names a minimal safety distance of 18 meters for China.

Several gasoline stations companies have already implemented charging stations at selected sites in several countries [572] [573] [574] [575]. The company Autobahn Tank & Rast which operates the service areas along German motorways was involved in establishing a corridor of fast charging stations between Cologne and Hamburg [576]. From 2015 on the company is involved in a project which plans to install fast charging stations at all highway service areas, with financial support from the government [71].

7.2. Stakeholder analysis: relationships between stakeholder categories

The interests and possible actions of stakeholder categories have been discussed in the previous sections. Now these stakeholder categories will be discussed in relation to each other in the following sections. First, the traditionally existing relationships between these stakeholder categories will be treated. Then, it will be discussed how different stakeholder categories might fulfill different roles in a local charging infrastructure development. Then, the different spatial frames of reference of different stakeholder categories will be investigated. Several of the discussed points will then be summarized in form of a power-interest diagram. Finally, possible conflicts between stakeholder categories will be identified.

7.2.1. Traditional relationships between stakeholders

Fig. 7.1 shows traditional connections between the stakeholders discussed in the previous section.s The listed stakeholders can be categorized into five big groups which show strong inner connections: public authorities, the electricity sector, the passenger transportation sector (in a broad sense), citizens and clients, and specific EV infrastructure companies, which are new entrants into the existing network of stakeholders.

The shown relationships are meant to represent regular everyday working relationships or contracts. Some connections or non-connections can be a matter of debate.

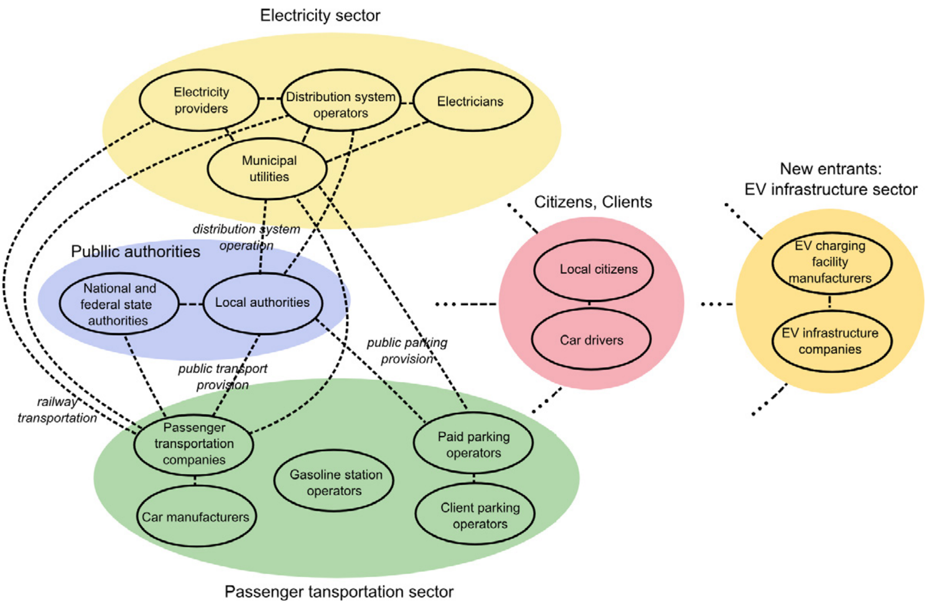

Figure 7.1.: Mapping of traditional relationships between stakeholder categories

Several insights can be drawn from the overview shown in Fig. 7.1. The main task of a stakeholder dialog for a local infrastructure development is to establish a relationship between the electricity and the passenger transport sector, which currently have little to do with each other.

An already existing link between these two sectors is formed by railway transportation companies. For instance, the Deutsche Bahn AG has subsidiary companies which are responsible for managing the railway infrastructure (DB Netz AG) and for managing electricity distribution and provision (DB Energie GmbH) [577]. However, apart from installing charging stations at train stations to encourage intermodal trips, it seems unlikely that railway companies will get involved in electrified road transport on the bigger scale.

Local authorities are in a good central position to establish a dialog between stakeholders. As the responsible authorities for public roads and spaces, they are used to working together with infrastructure providers from all sectors, be it distribution system operators, passenger transportation companies, paid parking operators, and others. Municipal utilities have a similar central position. They usually provide infrastructure services across several sectors and can easily acquire the technical know-how to implement charging infrastructure for EVs. New EV infrastructure companies entering the market can try to take on the position of a central coordinating node in the stakeholder constellation.

Other traditional stakeholder types, such as electricity providers, car/EV manufacturers, and gasoline station operators seem to be in a poor position concerning traditional relationships. If they get involved, they have to make big efforts to establish new relationships.

7.2.2. Roles in the development of public charging infrastructure

A possible way to make sense of the many different stakeholder constellations that can realize a public charging infrastructure for EVs, is to think in terms of *roles*. A role is associated with specific actions and resources that are required for the implementation of the infrastructure.

In the following, the abbreviation CF stands for charging facility. These roles are used for the analysis:

- *CF Manufacturer*: the organization that manufactures the charging facilities and associated ICT systems.
- *CF funder and owner*: the organization that provides the financial funds for installing, maintaining, and operating the charging stations. Except for the case of public subsidies, this organization will then be the owner of the charging facilities.

- *CF installer and maintainer:* the organization that installs and maintains charging facilities and associated ICT systems.
- *Distribution system operator:* the organization that operates the distribution system to which the charging facility or the overlying building connection is connected.
- *Electricity provider:* the organization which provides electricity to the charging facilities or to the overlying building connection.
- *Parking space operator:* the organization that operates the parking spaces associated to a charging station.
- *CF operator:* the organization that operates the charging facilities and associated ICT systems. Operation involves everyday tasks, such as giving access to the charging facilities to new clients, providing a hotline for users, and dispatching service teams when a broken charging facility is reported or detected.
- *CF user:* the final user of charging facilities.

Several less significant functions which may also need to be provided for the development of a local charging infrastructure are not included. These are the role of *groundwork constructor*, filled out by a construction company, and the role of *telecommunications provider*, filled out by a telecommunications company.

The stakeholder categories and the possible roles they can fulfill are shown in Tab. 7.1. For a successful implementation of EV charging infrastructure, a group of stakeholders needs to cooperate that covers *all required roles.* CF users are not necessarily required for the implementation of the charging infrastructure. However, it can be reasonable to integrate them in the planning process via forms of citizen participation (see Sec. 7.4). Cooperations can be realized where some roles are covered several times, for instance when several different parking space operators are involved.

This perspective shows that municipal utilities are in the best position to implement local public charging infrastructure. If they also control public parking spaces in their area, they simply need to buy charging stations, and then they have all the resources required.

For electricity providers, who installed high numbers of public charging in Germany in the last years, the situation is more difficult. They need to work together with DSOs which is unproblematic, but also establish new partnerships with companies who provide parking spaces, such as municipalities, paid parking and client parking operators.

Table 7.1.: Stakeholder categories and their possible roles: ✓, limited fulfillment of roles: (✓)

Stakeholder category	CF manufacturer	CF funder and owner	CF installer and maintainer	Distribution system operator	Electricity provider	Parking space operator	CF operator	CF user
EV drivers		(✓)				(✓)	(✓)	✓
Local citizens						(✓)		
Local authorities		✓				✓	✓	(✓)
National and federal state authorities		✓						(✓)
Distribution system operators		✓	✓	✓			✓	(✓)
Electricity providers		✓	✓		✓		✓	(✓)
Municipal utilities		✓	✓	✓	✓	(✓)	✓	(✓)
Electricians			✓				(✓)	(✓)
EV charging facility manufacturers	✓		✓				✓	
EV infrastructure companies	(✓)	✓	✓				✓	
EV manufacturers	(✓)	✓				(✓)	✓	
Passenger transportation companies		✓					✓	✓
Paid parking operators		✓				✓	✓	
Client parking operators		✓				✓	✓	✓
Gasoline station operators		✓				✓	✓	

EV manufacturers and gasoline station operators are in a bad position to get involved, as they lack almost all required resources. Tab. 7.1 also shows that many organizations could be possible funders and owners, and also the operators of public charging infrastructure.

7.2.3. Spatial frames of reference of stakeholder categories

Different stakeholder categories' interests and actions tend to take place on different spatial scales. Different political authorities can be responsible for processes on the level of city quarter, municipality, region, federal state, nation, or world. Big industrial companies, such as EV manufacturers or charging facility manufacturers, act on the national and international scale, while small companies, such as electricians, are rooted in their municipalities or regions. Some paid and client parking operators can be active on one single location only (street scale) or be big chain stores active internationally.

Tab. 7.2 gives an overview of the spatial frames of reference of the different stakeholder categories. Specific entries can be a matter of debate. Different stakeholders within one category can operate on different spatial scales.

The overview demonstrates that interests and actions of different stakeholder categories take place on varying spatial scales. Therefore, cooperations between stakeholders are also bound to specific spatial scales. The smaller spatial scale determines the scale of the cooperation.

For instance, if an electric utility wants to implement a public charging infrastructure for EVs which covers an entire federal state, it suffices to cooperate with single partners that act on the federal state, national, or international scale (big chain stores, big car park providers). However, it needs to cooperate with a high number of different partners who can only act on the regional or municipal scale, for instance local authorities and distribution system operators.

This view may also help to avoid needless debates and conflicts among partners. If an electric utility has the vision of implementing a public charging infrastructure for a region or federal state, it can leave the decision of the precise location of the stations on the street scale up to local partners, such as local authorities, local EV drivers, and distribution system operators. For the one partner such details are of little importance, while the other partners may assign high importance to whether a charging station is installed on this street or the next (compare [578]).

Table 7.2.: Spatial frames of reference of stakeholder categories: relevant spatial scale: ✓

Stakeholder category	Street	Munici-pality	Region	Federal state	Nation	World
EV drivers	✓	✓	✓	✓		
Local citizens	✓	✓				
Local authorities	✓	✓	✓			
National and federal state authorities				✓	✓	
Distribution system operator	✓	✓	✓			
Electricity providers			✓	✓	✓	
Municipal utilities	✓	✓	✓			
Electricians	✓	✓	✓			
EV charging facility manufacturers					✓	✓
EV infrastructure companies			✓	✓	✓	✓
EV manufacturers					✓	✓
Passenger trans-portation companies			✓	✓	✓	✓
Paid parking operators	✓	✓	✓	✓	✓	✓
Client parking operators	✓	✓	✓	✓	✓	✓
Gasoline station operators					✓	✓

7.2.4. Power and interest of stakeholder categories

The following mapping of stakeholder categories sums up some of the points made in the previous sections. A power-interest diagram maps stakeholders along the two dimensions power and interest [500].

An exact quantification of these dimensions difficult. A qualitative rating was done based on the discussion in the previous sections, notably the interests and actions in Sec. 7.1, traditionally existing relationships in Sec. 7.2.1, and possibility of filling out roles in Sec. 7.2.2.

The *level of interest* in the development of a charging infrastructure on the regional scale is assessed to be:

- *High* for EV drivers, EV manufacturers, EV charging facility manufacturers, EV infrastructure companies.
- *Rather high* for local authorities, distribution system operators, electricity providers, municipal utilities.
- *Rather low* for national and federal state authorities, electricians, passenger transportation companies, paid parking operators, gasoline station operators.
- *Low* for local citizens, client parking operators.

The *level of power* to contribute to the development of a charging infrastructure on the regional scale is assessed to be:

- *High* for local authorities, national and federal state authorities, municipal utilities.
- *Rather high* for distribution system operators, electricity providers, EV infrastructure companies.
- *Rather low* for EV manufacturers, electricians, EV charging facility manufacturers, passenger transportation companies, paid parking operators, client parking operators, gasoline station operators.
- *Low* for EV drivers, local citizens.

The resulting two-dimensional mapping is displayed in Fig. 7.2. Based on the placement of stakeholder types within this two dimensional space, they can be classified into four groups [500]. These groups of stakeholders categories should be involved in different ways in the local implementation of a charging infrastructure.

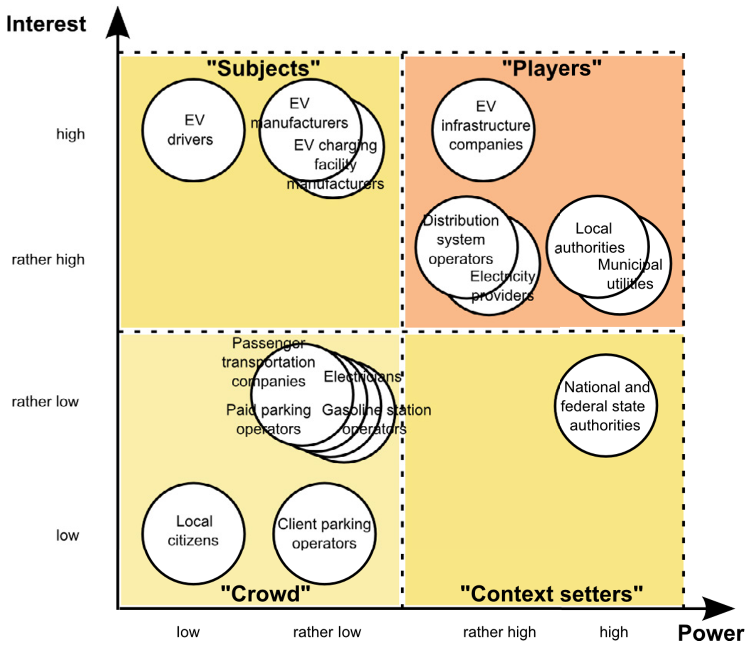

Figure 7.2.: Mapping of power and interest of stakeholder categories

- *Players* with high power and high interest: EV infrastructure companies, distribution system operators, electricity providers, local authorities, and municipal utilities. These stakeholder categories control key resources and are highly affected by the outcome of an infrastructure implementation. The relevant stakeholders within the given setting may vary. A municipal utility may take on the role of both electricity provider and distribution system operator, and a specific EV infrastructure company might not be involved. A stakeholder within this group can initiate a local infrastructure implementation and take on a leading role. The group of stakeholders should form the core group of a local stakeholder dialog and partnership.
- *Context setters* with high power and low interest: national and federal state authorities. These institutions have a high level of power. They control large budgets for research and infrastructure projects. These institutions also set the regulatory frame conditions for charging infrastructure on the local scale. However, the German national state shows little interest to get directly involved in the implementation of local infrastructure (see Sec. 7.1.4). Therefore, local authorities and others within the group

of players should communicate their needs to these institutions, in order to raise their level of interest and involvement.

- *Subjects* with low power and high interest: EV manufacturers, EV charging facility manufacturers, EV drivers. These stakeholder categories have little power to influence the outcome of a local infrastructure project, even though they may be highly affected by it. Especially EV drivers should be *empowered* by the players to contribute to local infrastructure planning, by using methods of citizen participation (see Sec. 7.4).
- *The crowd* with low power and low interest: passenger transportation companies, paid parking operators, electricians, gasoline station operators, client parking operators, local citizens. These stakeholder categories may not be involved in a local charging infrastructure implementation at all. They can be included in a stakeholder dialog at later stages in the development. Is is noticeable that the performed assessment especially places those stakeholder categories in this group that control parking spaces. Though no one private company controls all parking spaces within a city, it might be obligatory to incorporate *some* of them, in order to acquire locations for the placement of charging stations.

7.2.5. Possible conflicts between stakeholder categories

The different interests of the stakeholder categories, listed in Sec. 7.1, may lead to typical conflicts between stakeholders.

- *Different uses of public space*: if EV charging stations with associated reserved parking spaces are implemented, this further reduces the availability of parking spaces for conventional vehicles. This is a conflict of interest between EV drivers and companies involved in infrastructure implementation on the one hand, and local citizens not driving EVs and possibly local shop owners on the other hand [527]. Local authorities see it as their responsibility to mediate between different interests concerning the use of scarce public space [14]. In order to not use further public space they may prefer charging stations to be installed in semi-public and private space instead [535].
- *Good visibility or blending in of charging stations*: EV drivers and private companies involved in a charging infrastructure implementation may want charging stations to be well visible from a distance, to find them easily and

for better marketing effects. Urban planers from local authorities and local citizens however, may prefer charging stations to blend in well with the local urban surroundings. They may not want charging stations to further clutter up the streetscape already crowded with all kinds of different street furniture (compare [536]) (also see the discussion of urban design issues in location planning on the street level in Sec. 9.1.6).

- *Immediate fast charging or timed slow charging*: EV drivers are looking for convenience when charging their car. This may involve charging an EV with a depleted battery spontaneously and using the highest charging power possible, in order to be able to drive on as fast a possible. This can contradict the interests of electricity providers, who can prefer EV charging to take place during times when renewable energy sources such as wind and solar power plants produce high amounts of electricity. The interests of distribution system operators can contradict both of the previous stakeholder categories interest, as they can prefer charging to take place at low powers and not simultaneously, in order to avoid demand peaks in local distribution networks [512].
- *Competition between different companies from the same sector*: in some situations, direct competition between stakeholders from the same sector can arise. In Germany, charging stations are provided with electricity from only one electricity provider. An electricity provider may demand from a city that it is given the exclusive right to install public charging stations. This occurred in Berlin, and the local authorities denied the request [505]. Competition also seemed to play a role when German car manufacturers were involved in the buildup of a fast charging infrastructure, which only made use of the CSS standard. By not additionally supporting the CHAdeMO standard, EVs from foreign manufacturers were effectively excluded from using this infrastructure [561]. On the other hand, it can also be observed that several operators of public charging infrastructure are joining roaming platforms, in order for their clients to also be able to charge at other operators' charging stations [148] [150].
- *Different ways of working in the private and public sector*: partners from private companies and public authorities tend to work in different ways. Private companies are usually more up-to-date concerning technical specifics of charging infrastructure. They like to talk about diverse aspects, such as parking and land use within one meeting. However, responsibilities for such domains often lie in different departments within local authorities.

Approval and other bureaucratic processes require longer time frames in the public sector. Public authorities want to reach a consensus, and ensure that business interests are in line with public policy [506].

- *Winners and losers of change*: almost every change in society results in some people and organizations losing something while others gain something. The implementation of public charging infrastructure for EVs results in benefits for EV drivers, involved electricity providers, and public authorities (due to positive externalities). On the other hand, gasoline stations can lose clients. Local citizens and shop owners might lose public parking spaces for conventional cars. For distribution system operators the technical problems that EV charging causes could outweigh the additional income by network fees and connection costs.

7.3. Entering into a stakeholder dialog

The previous sections have treated the interactions of stakeholders in an analytical way. In this and the following sections a more action-oriented approach will be taken.

In this section it will first be discussed how stakeholders can enter into a dialog. Then, the interaction with a special category of stakeholder, the local citizens, will shortly be discussed in the following Sec. 7.4. Finally, different possibilities of formalizing stakeholder cooperation will be treated in Sec. 7.5.

An example of a stakeholder dialog forum is found in the European EVUE project. Participating cities were instructed to implement *local support groups* for electric mobility. How such local support groups are formed and how they operate is explained in the publicly available manual [579]. The following paragraphs sum up the main points from this manual.

The work of such a local support group revolves around developing a document called a *local action plan*. The specific form of the plan can vary. It should state the initial context within the given city, the objectives of the plan, specific actions with an associated schedule and a framework for delivery, a funding scheme, a risk analysis, and similar elements [579].

A local support group *coordinator* is appointed. He may be from the initiating organization, or he may be an external consultant. The coordinator is responsible for organizing meetings, overseeing the development of the action plan, communicating results to other partners, and similar tasks [579].

Before forming a new group it should be checked whether a similar group does not already exist. If not, the organization which initiates the local support group has to identify relevant local stakeholders. These are approached by individual invitations, phone calls, and small meetings. The initiating organization should motivate stakeholders by showing them what benefits they can have from joining the group: opportunity to learn, local networking opportunity, opportunity for funding etc. The initially formed group may do a further stakeholder analysis and invite further participants. The group has to decide on its structure, way of reporting, and calender of activity. Group structure my be *open*, with varying participants, *closed*, with a small number of fixed participants, with *topic-subgroups*, or with *multiple levels*, implemented by a core group and further stakeholders which are involved to lesser degrees. Local support groups are typically formed for a duration of 1–2 years. The local action plan should be drafted within 12–14 months [579].

Based on experiences in the EVUE project, the article [506] lists several tips, some obvious, some not so obvious, about holding a stakeholder dialog. Among the tips are these:

- Communication should be open, honest, and transparent.
- The forum should be used to really listen and to ask questions.
- Neutrality can be achieved by holding meetings at neutral locations and by inviting neutral speakers.
- Knowledge gaps can be filled in by inviting experts.
- Time should be found to get together in between meetings to establish relationships. [506]

Another example of a successfully implemented stakeholder dialog forum is the *steering committee for electric mobility* in the city of Dortmund. The committee was created by the city and is under its direction. The aim is to facilitate the communication between public authorities, private companies, research institutions, and citizens. 14 different organizations are represented in the forum [580]. The committee follows the different projects taking place and coordinates the agreements with the city's administration. It also provides one central contact point for all questions concerning electric mobility [581]. However, details of how this steering committee works do not seem to be published.

7.4. Citizen participation

EV drivers and local citizens belong to special categories of stakeholders in infrastructure development. These are the final users of the infrastructure, those who may be most concerned. However, traditional planning by public authorities and technical experts does not foresee citizens' participation or only foresees it to a low degree and at a very late stage during the process. The power-interest analysis in Sec. 7.2.4 reflected this. EV drivers were placed in the group of "subjects" with high interest but low power. Local citizens were identified as part of the "crowd" with low interest and low power. It can make sense to "empower" such stakeholders in order to exchange information and experiences, to enhance the traceability of decisions, to increase public acceptance of the project, and to avoid delays and extra costs [582].

In the last years several big infrastructure projects in Germany have been met by strong resistance by local citizens. The train station in Stuttgart and the airports in Frankfurt and Munich are notable examples [583]. Apparently following a larger societal trend, public authorities in Germany and other countries have recently published several handbooks on citizen participation [583] [584] [582].

German law foresees formalized forms of citizen participation in large scale traffic development and land use planning [583]. For the development of a local charging infrastructure for EVs, with impacts only on the small local scale, such an obligation does not seem to exist. The publication [585], however, sees citizen participation as the initial step in an idealized EV infrastructure development process.

Simple forms of participation have been implemented in some EV infrastructure projects. An example is to give EV drivers the chance to propose new locations for charging stations on the infrastructure operator's website [132]. Citizens can be represented by organizations in a stakeholder dialog. For example, the steering committee for electric mobility in Dortmund also included a local EV drivers' club [580]. In the city of Bottrop citizens participated in a workshop treating electric mobility [532].

There are many other possible ways of allowing local citizens to participate in the planning process. Citizen participation can be implemented on the levels of *information*, *consultation*, and *cooperation* [583] [584].

In *informing participation*, citizens are merely informed, without them being given an active role. Information can be distributed via the press and media, by distributing flyers, by displaying plans and documents in a publicly accessible place, by publication on the internet, by holding public information meetings, and by other forms [583].

In *consultative participation*, citizens are asked to give suggestions, comments and objections, or answer specific questions. For this, they first need to be informed as already mentioned above. Surveys, interviews, and focus groups can be done with citizens. Public events can be organized in which citizens can ask their questions. Citizens can also provide their feedback via internet forums [584], via email, or mail.

In *cooperative participation*, citizens are given the active right to decide. For this, workshops or round tables can be installed [584]. It needs to be clarified beforehand what the scope of participation is and whether the participatory decisions are binding [582].

In general, if citizen participation is implemented, it should allow citizens to get involved in the process at an early stage and allow for their continuous participation [583].

7.5. Formalization of stakeholder cooperation

The initial step in a stakeholder involvement process is to do a stakeholder analysis, as has been shown in Sec. 7.1 and 7.2. The relevant stakeholders are then involved in a stakeholder dialog process (see Sec. 7.3). Citizens can also be involved in the planing and decision making process (see Sec. 7.4). At some point, the cooperation between stakeholders has to be formalized. This can take place some time after the stakeholder dialog has taken place, or even before establishing a regular dialog forum. This formalization is treated within this section.

In general, it makes sense to differentiate between vertical and horizontal cooperation. In a *vertical cooperation*, the partners work in different sectors and provide different services and products within the overall value chain. An example of such a vertical cooperation is when an electricity provider, a distribution system operator, and a local authority (which contributes public parking spaces) form a partnership. *Horizontal cooperation* takes place between companies which work in the same sector. Examples for such cooperations are partnerships between different EV manufacturers for the buildup of publicly accessible charging stations [560] [559] or roaming agreements between different charging infrastructure operators [148] [150]. Such cooperation between companies that would normally be competitors is also called “coopetition” [403]. Cooperation between companies is limited in scope by the German law against restraints of competition (Gesetz gegen Wettbewerbsbeschränkungen) [586], which generally forbids “agreements between companies, decisions of associations of companies, or concerted behavior, which aims at or results in preventing, limiting or tampering with competition” (authors translation) [586]. An example of such a forbidden behavior would be price agreements for charging among different charging station operators.

Cooperation can be formalized in a wide array of different ways:

- *Signing a memorandum of understanding*: two or more organizations sign a document in which they state their intention to work together in the development of a local charging infrastructure. The signing of such a memorandum is a first symbolic step, communicated widely to the media, but is normally not legally binding.
- *Forming an alliance which hands in a research proposal*: different organizations form a cooperation with the limited scope of working together within a (partially) publicly funded research project.
- *Forming a joint venture* [403]: two or more companies can form a joint new company which takes on key responsibilities in infrastructure development, for example manufacturing of charging facilities, their installation and operation.
- *Call for tenders and a buyer-supplier relationship* [403]: one leading organization or a core group of organizations asks further companies to hand in their tenders for required services and products. A required product can for instance be a given number of charging facilities with a given minimum technical capabilities. A required service can be the installation of charging facilities. If a local public authority publishes a call for tenders, it must respect the applying regulations for public procurement [587]. In

general, the higher the (estimated) monetary value of the tenders is, the more elaborate the public call for tenders procedure is. If the monetary value exceeds certain thresholds, for instance above 207 000 € (in 2014) for delivery and service contracts, the public call for tenders must be published EU-wide [587].

- *Granting of a concession by a public authority*: the local public authority grants a concession to a company which allows it to use public parking space to operate charging stations. The company receives fees from the users of the infrastructure. The company may additionally receive payments from the local authority for providing the service.

- *Public-private partnerships (PPP)*: this term stands for a wide array of differently structured partnerships between public authorities and private companies for infrastructure and construction projects. For the public sector this has the benefit that additional funds from private companies can be used. More efficiently working private companies can reduce costs and increase quality. They can also speed up the development process [588]. However, evaluations of PPPs in the UK, where a high number of such projects have been realized, could not show that projects realized in this way are generally more cost efficient. No clear evidence was found that PPPs' savings and benefits outweigh the higher cost of capital in the private sector [589]. It is criticized that public debts within PPP schemes are often not listed in the official debt or deficit figures [589]. Some of the forms of cooperation listed above can be interpreted as PPP schemes, such as public calls for tenders or granting of a concession by a local authority. Also, a local authority can form a joint venture together with private companies. In other specific PPP variants, the private company funds, builds, and operates the charging infrastructure. The public partner then pays a regular fee to repay the investment over many years, after which the infrastructure belongs to the public partner (purchaser model [590]). Alternatively the public partner pays a leasing fee for many years, after which he chose whether to buy the infrastructure according to its residual value or leave it to the private partner (leasing model [590]). Another possibility is for the public partner to rent the infrastructure from the private partner without a change in ownership (rental model [590]). More PPP variants are described in the publications [590] [588].

7.6. Conclusion: stakeholder cooperation for the development of charging infrastructure

This chapter has treated the interactions of different stakeholders for the development of a local charging infrastructure for EVs.

First, a stakeholder analysis was done. Relevant stakeholder categories in the domain were identified to be: EV drivers, local citizens, EV manufacturers, local authorities, national and federal state authorities, distribution system operators, electricity providers, municipal utilities, electricians, EV charging facility manufacturers, EV charging infrastructure companies, passenger transportation companies, paid parking operators, client parking operators, and gasoline station operators. These stakeholder categories were described via their interests and possible actions in contributing to the development of a local charging infrastructure for EVs.

Then, the relationships between these stakeholders categories were analyzed under a variety of different perspectives. The traditionally existing relationships between the stakeholder categories were mapped. It could be seen that new relationships especially have to be established between the electricity sector and the transport sector. Local authorities and municipal utilities, responsible for different kinds of local infrastructure, are already well linked to both sectors, and are therefore in a good position for coordinating the development.

Then the interaction of different stakeholder categories was analyzed from the perspective of roles in a local infrastructure development. As relevant roles those of charging facility (CF) manufacturer, CF funder and owner, CF installer and maintainer, distribution system operator, electricity provider, parking space operator, CF operator, and CF user were identified. It could be seen that almost all stakeholder categories could take on the role of CS funder and owner and that of CF operator. Municipal utilities could, depending on the local situation, fulfill almost all required roles. They simply need to buy charging facilities from a CF manufacturer.

A further perspective to set different stakeholder categories in relation to each other is to look at their spatial frames of reference. Big companies tend to think on the national or international scale, while local authorities or local citizens care more about what happens on the street scale. Whether a charging station is located on one side of the street or the other might be an important issue for a local partner while being of little interest to a stakeholder acting on the national scale. Partnerships are always limited in scope by the smallest spatial scope among the involved parties. Thus, a nationally acting stakeholder may have to partner with a high amount of locally acting stakeholders.

Stakeholder categories were also mapped using a power-interest diagram. The most important stakeholders ("players") with high levels of power, as well as high levels of interest for the development of a local charging infrastructure were identified to be: EV infrastructure companies, distribution system operators, electricity providers, and municipal utilities. EV drivers have a high level of interest, but low power. It can be worthwhile to empower them for a better local infrastructure development.

Possible conflicts between the stakeholder categories were also analyzed. Potential for conflict was found to lie in different uses of public space, good visibility or blending in of charging stations, immediate fast charging or timed slow charging, competition between different companies from the same sector, different ways of working in the private and public sector, and winners and losers of change.

Following the extensive stakeholder analysis, more practical aspects of stakeholder interactions were then treated. Based on best practices established in EV projects, it was discussed how a stakeholder dialog can be established. Then different possibilities of involving citizens, via informative, consultative, or cooperative forms of participation were shown.

Finally, it was discussed how stakeholder cooperation can be formalized. This can take place via signing a memorandum of understanding, forming an alliance which hands in a research proposal, forming a joint venture, publishing a call for tenders and establishing a buyer-supplier relationships, granting a concession by a public authority, and different kinds of public-private partnerships.

Overall this chapter has shown how complex the interactions of stakeholders for the development of a local charging infrastructure for EVs is. Usually a high number of stakeholders from different sectors have to be involved to implement a local charging infrastructure for EVs. Thus, the management of stakeholder interaction is one of the most important points in a local EV infrastructure development project.

8. Location planning of an EV charging infrastructure on the scale of cities and regions

Planning the charging infrastructure for EVs in a city or region involves solving a location planning problem: *where should how many charging points of which type be placed?*

The problem can be broken down into two sub problems for easier handling. First, locations need to be decided on a *macro scale* of city quarters or in proximity of specific points of interest. Then, individual locations can be planned on the *micro scale*, taking the specific urban surroundings of parking spaces in the specific street into account. Planning on the macro level is treated within this chapter. Urban planning on the micro level is treated in the next Chap. 9.

The following Sec. 8.1 will first give an overview of the different methods that have been published on the location planing of EV charging stations. Afterwards a short explanation will be given in Sec. 8.2 on how the spatial planning of charging infrastructure fits into the political framework of spatial planning in Germany. Then, two specific location planning methods and applications, developed by the author, are shown. In Sec. 8.3 a method of decision support for location choice is shown. An application is shown here for the Province of Liège in Belgium. Then, a method of prioritization among a given list of locations is presented in Sec. 8.4. This method is applied to supermarkets in the Austrian federal state of Styria. Finally, the main points of the chapter are summed up again in Sec. 8.5.

8.1. Diversity of methods for spatial planning of EV charging infrastructure

When the author started working on the topic of spatial planning of EV charging infrastructure in the year 2009, only a handful of publications on the topic were available. In the following years, with EV infrastructure deployments taking place all over the world, the number of publications steadily increased. Conducting a literature survey in April 2015 showed more than 200 publications on location planning of charging infrastructure for EVs. The body of published material is so vast by now, that a thorough literature analysis is a scientific project in itself. The published literature shows a wide range of different methodological approaches. The following is an attempt to identify underlying patterns within the published material. For simplicity's sake only a few exemplary references are named for each point. The overview also allows to position the author's own location methods, presented in the following sections, within this scope of possibilities.

A few researchers can be identified who have extensively published on the topic. Concerning the diverse approaches and possibilities for the location planning of charging infrastructure, the following aspects can be identified. Differences exist in the situation that is being modeled, determined by charging technology, context of charging (public, private), type of EVs, size and structure of the considered region, and the different aspects that are being taken into account (demand for charging, economics, impacts on the distribution grid). Different methodological approaches are used, such as ad-hoc pragmatic methods, analysis in geoinformation systems (GIS), optimization, clustering, game theory, and others. These aspects will be discussed in more detail the following.

Research on the spatial planning of charging infrastructure is done by many different *researchers* all over the world. Internationally, a few researchers stand out as having treated the topic in different publications considering different aspects. *Fumiko Koyanagi* from Japan published on the topic starting as early as 2001 [119] [591] [592]. *Yin-Wei Wang* from Taiwan published on the topic from 2007 on [593] [594] [595]. The work of *Michael Kuby and colleagues*, USA, originally on the siting of alternative fuel stations, such as hydrogen stations [596] [597] [598], is cited and built on by many other articles which treat the planning of fast charging or battery switching networks [599] [600]. In the last years, a high number of articles on spatial EV infrastructure planning was written by different Chinese researchers.

Published articles can be differentiated in regard to the *types of charging facilities* and *types of vehicles* that are being considered. The applied technologies determine the aspects that are taken into account when locating the stations. Normal/slow conductive charging stations are the most commonly treated case. Many articles deal with the planning of fast charging stations [601] [595] [600]. Location planning of battery switching stations is also considered in several articles [602] [603] [604]. Special cases such as *mobile* charging stations [605] or mobile battery swapping stations [606] are also treated. Inductive charging while driving on a highway is considered in [599]. Another special case is battery switching stations with separated central battery recharging centers [607]. Several articles treat the combined use of several different charging technologies [595][599] [608]. Charging stations are usually planned for the public context usage only, but some articles also consider the placement of charging stations at homes and workplaces [609]. Charging stations are usually assumed to be used by private EV and PHEV drivers. But other cases are also treated, for the instance the usage by company fleet vehicles [610], taxis [611], public buses [612], or scooters for tourism [593].

Differences can also be seen in the *size and structure of the region* for which the planning is being done. Few articles merely demonstrate the feasibility of a method using small artificial examples [613] [599] [614]. Most studies use real data from areas of the size of parts of cities [615], cities [616], regions [603], islands [593] or entire states [600].

Different methods vary in the *aspects that are taken into account* for determining suitable locations for charging stations. The majority of models includes the users' demand for EV charging. However, many different indicators are used to quantify and locate this demand. How difficult it is to precisely describe the demand for (public) charging infrastructure has already been discussed extensively in Chap. 4 within this thesis. Data that is used, often in combination, include sociodemographic data (such as population, occupation, income) [609], employment data [119], building data [609], data on registered vehicles [591], proximity to public transport connections [592], proximity to major motorways [592], origin-destination traffic data [602], traffic flow data for roads [616], and parking data [617].

Besides the demand for charging, other factors taken into account are connection costs and/or impacts on the electricity distribution grid [618] [604] [615], and the cost or economics of building and/or operating the infrastructure [593] [603] [619].

In multi-objective optimizational models, individual aspects can each be monetarized to obtain one global objective [615], several objectives can be normed and weighted and thus combined into one global objective [620], or the Pareto set of optimal solutions can be determined [621].

After having shown the wide range of *what* is being considered in different location planning models, now it is shown *how* the location planing is done via different methodological approaches.

The considered *spatial entities* (aspects of the demand for charging EV, the electricity distribution system etc.) can be modeled in different ways. In classic facility location theory is seems to be common to model demand and supply in the form of points (compare the discussion in [611]). Spatial entities are represented as points in several articles [622] [613] [615]. Alternatively areas can be used for representation, either unevenly sized [609] or in the form of an uniform raster [591]. Area datasets can be transformed (with information loss) into point datasets, by using the centroids of the areas [619]. When focusing on road networks it is common to use graphs, possibly with traffic flows along arcs or on longer paths within the graph [594] [601] [603].

The location choice can be either *discrete or continuous*. In the discrete case, the potential locations for charging stations are predefined. Usually existing infrastructure locations such as cities within a road network [594], road junctions/intersections [616], parking lots [622], or gasoline stations [623] are used as candidate locations. In the continuous case, EV charging stations can be located anywhere within the given area [119] [613] [619].

Planning methods vary in their *level of formalism*. Several methods follow informal ad-hoc approaches, which leave space for intuitive decisions. The chosen locations can correspond to the sites where partners involved in the given project are located [624]. Locations can be suggested by local representatives who have local knowledge of their area [625]. More formally, decisions can be loosely based on overlay analysis of geographic data [626] [627]. Within the German model regions, location planning was apparently done mainly by different pragmatic, semi-formal methods [14].

Within the scientific literature mathematically formalized methods predominate. The wide scope of different *methodological approaches* used will be discussed in the following. Location choice is commonly formulated as an optimization problem. When formulated as a (mixed) integer linear problem, concepts such as the p-median problem [611], p-center problem[608], set covering [594], and flow refueling location model [596] can be used. Heuristic approaches that have been applied to the location planning of EV charging infrastructure include particle swarm algorithms [619], genetic algorithms [615], bee colony algorithms [604], ant colony optimization [618], or greedy algorithms which sequentially decide the next optimal location [602] [628].

Another approach to finding good locations is to perform a spatial cluster analysis of data representing the demand for charging [629] (also used as a preprocessing step in [630]). A further possibility is to model location choice within the framework of game theory, where a good combination of locations corresponds to a game theoretic equilibrium [631] [616].

Several authors have implemented simulations of EV mobility and charging which allowed them to also analyze locations of charging infrastructure. Existing traffic models have been extended [632] [633] [634] and new agent-based models have been implemented [635] [636]. The advantage of using simulation is that it allows to model the diverse aspects that determine individual EV drivers' need for charging in more detail. Instead of using static land use data or single trip data, trip chains can be modeled. Such simulation models can serve to identify areas of high charging demand [636] [633] [634] or evaluate given alternative charging infrastructure layouts [635] [637]. Going a step further, in a simulation-optimization approach, the location plan is repeatedly changed and the simulation reperformed, in order to find an optimal layout [632].

Within the diverse models and optimizational approaches discussed above, previously known concepts are applied to model specific aspects of EV charging infrastructure. For instance, service areas of charging stations can be modeled as Voronoi areas [119] [613]. Waiting times at fast charging stations and battery switching stations can be analyzed using queuing theory [606] [638].

8.2. The political framework for spatial planning in Germany

Before treating details on specific methods for the location planning of EV charging stations in the next sections, the general political framework for spatial planning in Germany will shortly be discussed here. Spatial planning processes take place on the political levels of the EU, Germany, the federal states, regions, municipalities, and individual construction sites.

The spatial planning framework in Germany is governed by two principles: the subsidiary principle and the counter flow principle (see Fig. 8.1). The *subsidiary principle (Subsidiaritätsprinzip)* states that every decision should be made on the lowest level possible. A higher level organization should only get involved if a lower level organization is not able to cope with a problem on its own. This also involves respecting the local planning autonomy of municipalities which have the right and competence to plan their own spatial development to a certain extent [639]. The *counter flow principle (Gegenstromprinzip)* states that planning on the lower levels has to be in accordance to planning on higher levels. Also, the concerns of lower levels have to be taken into account for higher level planning [639].

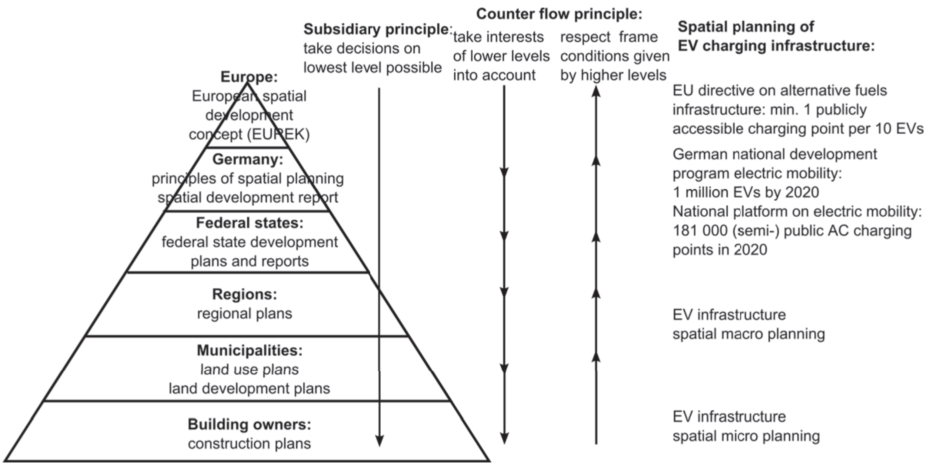

Figure 8.1.: Existing framework for spatial planning in Germany (inspired by [639]), and the spatial planning of EV charging infrastructure

Different kinds of spatial plans are prepared on different political levels (see Fig. 8.1). In the following, only the most important generic planning documents are mentioned. Planning of road infrastructure, for instance, is also done in further separate documents. The European Union has prepared an European *spatial development concept (Europäisches Raumentwicklungskonzept) (EUREK)* in 1999 [640]. Concerning infrastructure, one important point is the development of transeuropean networks (TEN) in the sectors of transportation, telecommunication, and energy.

On the national level of Germany the *principles of spatial planning (Leitbilder der Raumentwicklung)* [641] are issued. The most recent version is available as a draft from 2013. Among many other points the report mentions the importance of accessibility of regions, of public transport, and of intermodal forms of transport. The *spatial development report (Raumentwicklungsbericht)* [642] is also published on the national level. The most recent one dating from 2011 reports on many different aspects including mobility and energy. The arrival of electric mobility and the development of the corresponding infrastructure is mentioned as one upcoming challenge for spatial planning.

On the level of the federal states, *federal state development plans* (*Landesentwicklungspläne*) are issued. In the federal state of Baden-Württemberg the most recent plan dates from 2002 [643]. Among other points the document states general goals for the development of traffic, energy and telecommunications infrastructure, and lists a few big infrastructure projects.

On lower levels the spatial development documents become more and more specific. For example the *regional plan (Regionalplan)* of the Region Mittlerer Oberrhein of 2002 [644] lists a high number of specific infrastructure development projects in the domain of road-based and public transport, energy and other infrastructure, and reasons for their implementation.

Within municipalities the use of parcels of land and the use of space for infrastructure, such as roads and railways, are fixed in *land use plans (Flächennutzungspläne).* The planning is further detailed for specific areas by *land development plans (Bebauungpläne).* Technical *construction plans (Baupläne)* for specific sites then lie in the responsibility of buildings owners.

It is not clear yet how the spatial planning of the charging infrastructure for EVs will fit into this framework (see Fig. 8.1 on the right). General goals for the number of charging points have been issued by the European Commission in its directive on the deployment of alternative fuels infrastructure in 2014 [43]. The directive sets the goal of minimally 1 publicly accessible charging point for every 10 EVs in each member state. On the national scale, the German governments' national development plan for electric mobility has set the goal of 1 million EVs (pure EVs, REEVs, and PHEVs) on German roads by 2020 [1]. The German national platform on electric mobilty sees a demand for 111 000 AC charging points in semi-public space and 70 000 in public space for the case of 1.134 million EVs in the year 2020 [276].

How and whether the planning of charging infrastructure will be incorporated into the mentioned and further planning documents in the future depends on whether public authorities are seen as being responsible for the provision of this infrastructure. If charging infrastructure is considered as a purely private industry matter it needs not be included in public spatial planning, alike to gasoline stations today. That the European Union is pushing member states to guarantee a minimal provision of such infrastructure indicates that public authorities will have to get involved to a higher degree in the future.

The spatial planning methods presented in the following are applied on the macro scale of regions and municipalities (within this chapter) and on the micro scale of individual streets (see next Chap. 9).

8.3. A method of decision support for the location planning of charging points in a city or region

Within this section a method will be presented which serves as decision support for the location planning of charging points. In the years 2009–2013, the author, working with the colleagues Anne-Sophie Fulda and Dr. Susanne Linder at the European Institute for Energy Research (EIFER), applied variants of the method to seven different geographic areas (see Fig. 8.2). These were the cities of Stuttgart, Karlsruhe and Kehl in Germany [645], the city of Nice in France [646], the Agglomération Maubeuge-Val de Sambre in France [647], the Communauté Urbaine de Strasbourg and Kehl on the French-German Border [648], and the Province of Liège in Belgium [649]. The results of the application in Liège will be shown in the following

The general characteristics of the method can be described similarly to the above overview of different models published in the literature. The method is used for the location planning of slow/normal conductive charging points, i.e. locations are identified where cars remain parked for longer durations. All usage contexts are taken into account: charging at (semi-) public locations, at work, and at home. The method is intended for locating charging points which are used by private drivers of EVs (pure EVs, as well as PHEVs, and REEVs). It can be applied to areas of the size of cities and regions. The choice of location is done based on the expected demand for charging by EV drivers, which is quantified based on data on areas (city quarters, communes) and data on individual points. The location choice method can be considered as discrete, because the method only allocates charging points to areas and points which have been previously entered into the underlying geodatabase. The relative distribution of demand is determined via weights which form external parameters to the method. Thus, the method does not aim at generating *one optimal* solution, rather it aims at showing several different possibilities for locating charging points within the given area. The method is a pragmatic engineering approach to charging infrastructure planning.

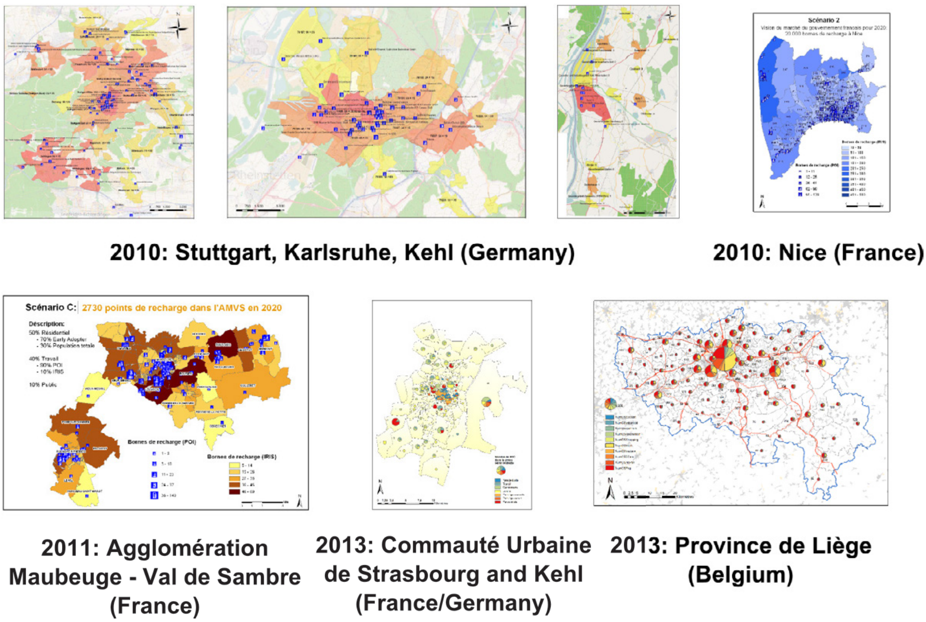

Figure 8.2.: Applications of the method of decision support to different regions

Initially, one of the motivations for leaving the weights for different aspects of demand unfixed was the high uncertainty concerning the demand for charging infrastructure. At the time that this thesis is being written in 2015, the nature of the demand for charging points and the way it can reliably be located and quantified still remains unclear (see Chap. 4 and the overview in above Sec. 8.1 on data used to quantify demand). In the author's opinion the main weakness of many optimization models is the often somewhat arbitrary definition of demand, which serves as the basis for the optimization process.

Another reason for using variable weights to generate several scenarios instead of a single optimized result is the diversity of reasonable strategies that can be followed in building up a local charging infrastructure for EVs. A strategy for infrastructure development should be in line with local policy and take existing infrastructure into account. For instance, in many cities a large number of public parking garages are operated by a municipal company. A public charging infrastructure can thus be easily built up by placing charging points in every car park. However, other cities prefer charging points to be located on public curbsides for good visibility of the stations. Some cities want charging points for EVs to be placed at intermodal park and ride points. Other cities want charging points to be located at symbolic places and public locations such as the city hall. A framework for the location planning of charging infrastructure should therefore also be able take such political frame conditions and requests into account.

The generation of scenarios can be done in collaboration with local representatives. In one application, the parameterizations of scenarios were directly discussed with local representatives (in Maubeuge [647]). In later applications, only qualitative tendencies were discussed with local representatives using a questionnaire (in Strasbourg/Kehl [648] and Liège [649]). These were then translated into quantitative weights by the researcher. This process ensures that the infrastructure plan is aligned with local policy. Deciding collaboratively also leads to a better acceptance of the results of the process. Meetings with local representatives were held in a workshop form, where background information on charging infrastructure planning was given. Then a questionnaire was filled out (see below for details). The ensuing discussion lead local representatives to think about local needs and wishes and the different possibilities of implementing the infrastructure. It was found that the involved raising of local awareness for the topic was just as valuable as the specific obtained results in form of maps and lists.

Fig. 8.3 shows the overall process in which this decision support method usually takes place. The process is usually carried out in five steps. In the first step the contact with local representatives is established. For this a kickoff meeting is scheduled, in which the general background of the method is explained. Local partners are asked about the availability of required geographic data. In the second step this data is collected and prepared in a geoinformation system (GIS). Some of the data is directly given by the local partners, other data has to be collected from public sources or purchased from data companies. In the third step the parameters for the scenarios are decided. For this a meeting is held with local representatives, in which main trends for the scenarios are determined using a questionnaire. The researcher translates these main trends into specific quantitative weights. In the fourth step the researcher uses the location planning method within the geoinformation system to prepare the results of the scenarios as maps and as lists. Finally, in the last step the results are presented and explained. For this the third meeting in the process takes place.

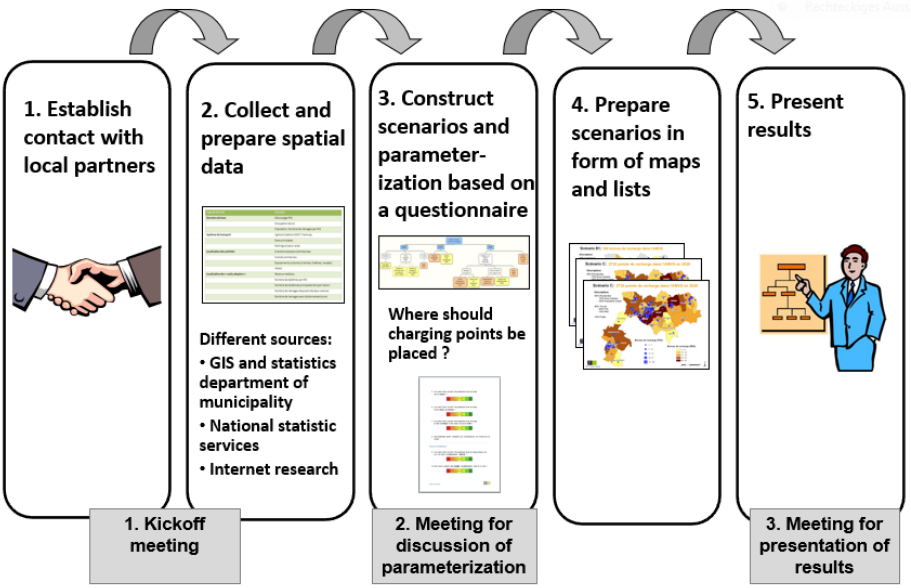

Figure 8.3.: The planning process with the method of decision support

8.3.1. The algorithmic principle behind the method of decision support

Within this section the algorithmic principle underlying the method of decision support will be explained. In general the method is based on an explicit *enumeration of candidate locations, which are sorted into distinct location categories*, and a *proportional distribution according to respective indicators of relative importance among these locations*. The overall number of charging points is given as an input parameter. This overall number is then distributed among different location categories according to the weights specified by the user. The number of charging points per location category is further proportionally distributed among the specific locations within each category. The mathematics behind the method are quite simple. However, many aspects have to be considered during practical application. These practical aspects are also discussed in the following.

As a unit for planning, the number of *charging points* is used, i.e. the number of connection possibilities of EVs. A *charging pillar/facility* can provide several charging points, and a *charging station* can contain several charging pillars (see the definition of used terminology in Sec. 2.1.1). The unit *charging point* maintains consistency among charging possibilities in different contexts (mostly single charging points at homes vs. mostly multiple charging points in public) and among different models of pillars and wallboxes used.

The planning method makes use of two kinds of locations: *zones* and *points*. The reason behind this is the differing practical availability of data for these two types of spatial entities. Data describing the population (number of households, household incomes, registered cars etc.), for instance, is commonly only available aggregated for specific zones such as city quarters or communes. However, some possible locations for charging points can be listed explicitly, for instance intermodal points at public transport stations or big parking garages. For other aspects again, the most pragmatic approach is to use both zonal and point-based data to model the geographic distribution of an activity. For instance, the total number of employees in each zone, as well as the explicit location of the biggest companies combined give a good representation of the geographic distribution of workplaces. During presentation of results to different local representatives it was also found that results on the level of zones seem rather abstract, but naming and showing exemplary landmark locations make the results much more tangible to people who know the area.

Concerning the integration of zone and point data into the planning algorithm several different methods were tested during different applications. The approach that was finally adopted was to calculate full results on the level of zones and additionally show candidate locations on the micro scale as specific points. For location categories with a limited number of points, such as big public car parks, and park and ride stations, all point locations are included in the database. For locations such as work, shopping, sports, and culture, only the most important point locations (i.e. with the highest values in regard to the chosen indicator) are included in the database.

Fig. 8.4 shows the overall *distribution scheme*. The distribution scheme can be thought of as consisting of three steps: first, the distribution among different location categories (upper three layers in Fig. 8.4), second, the distribution among categories of locations within zones according to underlying data (second layer from the bottom), third, the the distribution of charging points among specific points, again using underlying data (lowest layer).

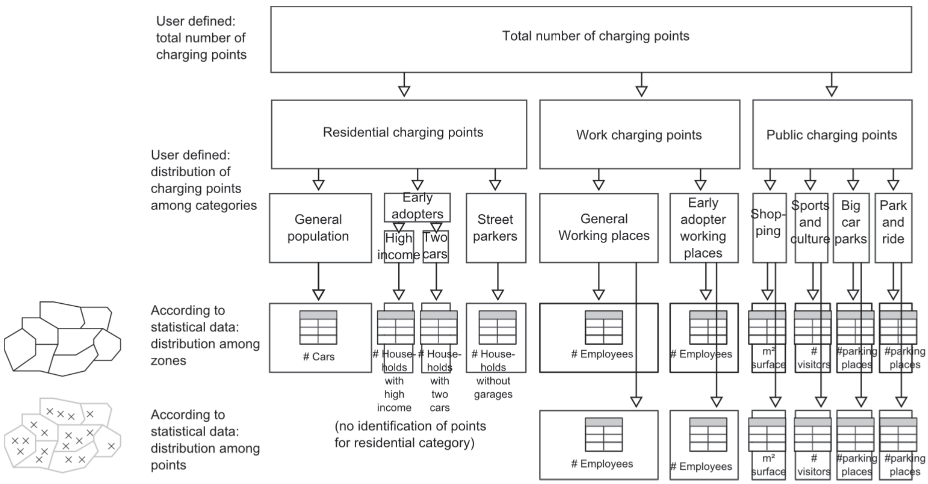

Figure 8.4.: Top down distribution of the number of charging points among locations of different categories

In the first step, shown in the top three layers in Fig. 8.4, the given total number of charging points is subsequently subdivided among different categories, until the number of charging points allocated to each location category is determined. This is done via percentage distributions on each branch (see example below). Deciding on percentages only within subsequent branches makes it easier for the user to take the distributing decisions than deciding on all final percentages at once.

The *number of charging points* N_i *allocated to locations of category* i is calculated by:

$$N_i = \prod_k p_k \cdot N$$

With the variables:

k: the branching levels

N: total number of charging points to be located in the region

p_k: the percentage allocated to the branch within branching level k

An example with specific numbers is shown in Fig. 8.5. The total number of charging points to be distributed (500 in the example, shown at the top) is multiplied with the percentages of each branching to obtain the number of charging points per category (shown at the bottom). The resulting numbers can be uneven. Final results are rounded for individual areas and points (see below).

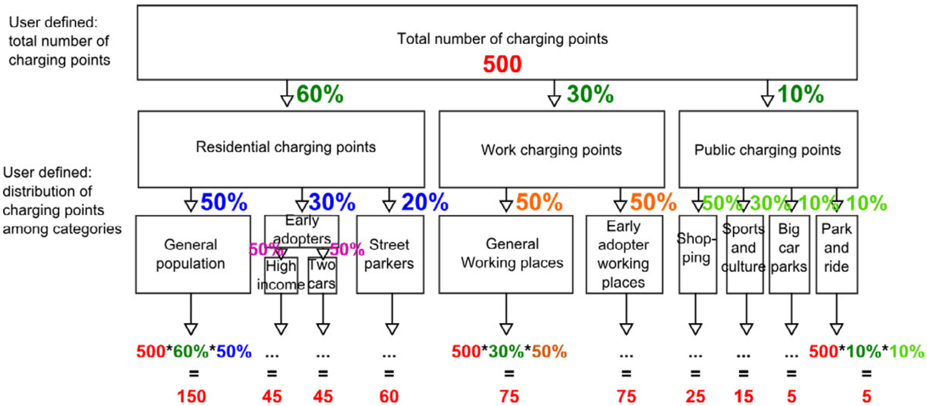

Figure 8.5.: Specific example of the top down distribution of the number of charging points among locations of different categories

Fig. 8.4 and 8.5 show a generic distribution with generic location categories: the homes of the general population, the homes of early adopters determined by a high income, the homes of early adopters determined by (more than) two cars per household, the homes of street parkers who have no private parking spaces, working places in general, working places of early adopters in innovative sectors (for example IT, engineering, research), shopping locations, sports and cultural institutions, big car parks, and intermodal park and ride stations. The branching structure and the used location categories can be adapted for the specific application. For instance, for the application of the method in Nice, where tourism plays a big role, hotels have been added within the residential branch. In the application for the Province of Liège, so-called EcoVoiturage stations, stations where people can park and form a carpool, have been added within the public branch (see below for details). If no suitable data is available, the location categories of early adopter homes and early adopter workplaces can be omitted, and only data for the general population can be used.

Next, the number of charging points per category are distributed among the zones of the given planning area. The given statistical data usually determines the zoning to be used, i.e. the finest zoning is used for which statistical data is available. This can be communes, city districts, or specific statistical zones, such as the IRIS statistical zones used in France. The method remains consistent if different kinds of zones are mixed, for instance city districts for a central city, and communes for the surrounding small towns (this is because absolute indicator values are used, see below).

Each zone has to be characterized with *indicators of relative importance* for each location category. These indicators express the importance/demand of placing charging points in one area in linear (proportional) relation to the others. For this the indicators have to be expressed in absolute terms, not in densities or averages per area or inhabitants. It is possible to choose the indicators depending on the available data. For instance for charging points to be placed at homes of the general population, the indicators number of registered cars, number of households, or number of inhabitants in the zones can be used. For charging points to be placed at early adopter homes, the number of households with two or more cars, the number of households with a high income, the number of residents with a high level of education, the number of detached and semi-detached houses, or combinations of them can be used. For charging points at homes of street parkers, the number of households without a private parking place is used. For charging points at working locations, the number of employments is used. For charging points at early adopter working locations, the number of employments in innovative sectors with high incomes such as IT, engineering, science, finance can be used. For shopping locations, the number of employments in the sector of commerce, or the total sum of the sales area in the zone can be used. For sports and cultural locations, the number of employments in the sectors of sports and culture, or the total number of visitors in these institutions can be used. Data on big car parks is usually given as specific point data. But an indicator on the level of zones is necessary in order to fully represent the data. The number of parking places in all big car parks per zone can be used. Similarly, data on park and ride station is usually given as point data. As an indicator for zones, the total number of parking spaces in all park and ride stations can be used or the number of passengers entering at these stations.

Data from household traffic surveys can also be used to formulate indicators of relative importance. For instance, the number of car trips to a zone separated by motives (home, work, shopping, recreation etc.) can be used or the sum of the length of the (individual) car trips separated by motives. The latter puts more emphasis on recharging after longer trips. During such an application for the city of Strasbourg in France, however, it was found that the traffic analysis zones were much larger than the IRIS zones for which statistical data was available. This has to do with the statistical significance of the household traffic survey results. When only a few thousand persons are surveyed, the results are only representative for large zones of the city. As a workaround the data on trips on traffic analysis zones was desegregated to IRIS areas. For instance the number of trips with the motive work was distributed among the contained IRIS zones according to the number of employments per IRIS zone.

In principle any other suitable indicator of relative importance can be used if the data is available. It has to be kept in mind that the used indicator influences the overall results. Different indicators emphasize slightly different aspects.

The *number of charging points* n_{ij} *of one location category* i *to be allocated to a zone* j is determined by:

$$n_{ij}(x_{ij}) = round(\frac{N_i}{\sum_k x_{ik}} \cdot x_{ij})$$

With the variables:

N_i: total number of charging points to be distributed among locations of category i

x_{ij}: indicator of relative importance for location category i of zone j

k: zones

Tab. 8.1 shows an example calculation for the distribution of charging points at working locations among different zones. The total number of charging points to be distributed among the locations of one category (50 in the example) is divided by the sum of the indicators (2 200 in the example) and multiplied by the indicator of the specific zone (example calculations see Tab. 8.1). This corresponds to a proportional distribution. After rounding the values for individual zones, the overall sum can deviate from the initial number of charging points.

Table 8.1.: Example calculation: distribution of 50 charging points at working locations among 5 zones

Zone name	**Number of employed persons** (indicator for working locations)	(Calculation)	**Number of charging points for working locations**
Zone 1	1000	$round((50/2200) \cdot 1000) =$	23
Zone 2	500	$round((50/2200) \cdot 500) =$	11
Zone 3	300	$round((50/2200) \cdot 300) =$	7
Zone 4	250	$round((50/2200) \cdot 250) =$	6
Zone 5	150	$round((50/2200) \cdot 150) =$	3
	Sum: 2200		Sum: 50

From an abstract viewpoint the above formula models the demand for charging points for a location category in a zone as a *linear function of a single variable*. The variable is the indicator used for the location category. The reasoning behind this is the following. If there are n times the number of employees in a given zone compared to another zone, the allocated number of charging points should be n times as much. If there are no employees working in an area, no charging points for working locations should be set up at all.

The resulting *total* number of charging points t_j of *all* location categories to be allocated to a zone j is:

$$t_j(x_{1j}, x_{2j}, x_{3j}, ...) = \sum_i round(\frac{N_i}{\sum_k x_{ik}} \cdot x_{ij})$$

With the variables:

i: location categories

k: zones

N_i: total number of charging points to be distributed among locations of category i

x_{ij}: indicator of relative importance for location category i of zone j.

Though the author was not aware of this when initially devising the method, a link exists here to the classic linear trip generation models which can be used within the traditional four step transport planning model [650]. There the number of trips generated by or attracted to a zone is expressed as a linear function of zone properties, such as number of registered cars, number of households, household income etc. Linear regression of household traffic survey results and statistical data is done to determine the coefficients of the linear function. It is argued that simple linear models fail to reproduce non-linear effects which might be occurring [650]. The same holds true for the linear functions used above to model the demand for charging points.

In recent years, with large datasets on the actual use of public charging points becoming available, researchers have applied regression analysis to understand the link between their utilization and their locational properties [628] [651] (compare also [652]). This is a promising path, in order to base charging stations planning methods such as the one presented here on solid empirical data in the longer term.

After having explained the distribution among different location categories and among different zones, now the allocation of charging points to specific location points is explained. The included points belong to the same location categories already introduced above for areas. Points are again characterized by *indicators of relative importance* for each location category. Most points are only relevant within one category, and thus have one indicator value > 0, while all indicators for all other categories are 0. A few points can be relevant within more than one category. For instance a big department store can be relevant as a shopping location and additionally as a big employer.

For the residential location categories specific location points are not included. Working places can be included if they employ more than 50–100 employees. The number of employees serves as the indicator of importance. Working locations in innovative sectors and high-earning sectors, such as IT, engineering, research, and finance, can be included as early adopter working points, using the same limit and indicator. Shopping locations can be included if they have more than 200–300 m^2 of floor space or belong to specific categories ("supermarkets with more than 50 parking spaces" or similar). The shopping floor space can be used as the indicator of importance. Alternatively, the number of employees of shopping locations can be used. Sports and cultural institution can be included if they receive more than ca. 10 000–20 000 visitors per year. The number of visitors per year can be taken as an indicator. Often this value has to be approximated or estimated because no reliable statistical data is available. Alternatively, the number of employees at these locations can be taken as an indicator. Usually, all big public car parks are included, using the number of parking spaces as the indicator of importance. Park and ride stations are also usually all included. The number of parking spaces can be used as an indicator. Alternatively, the number of accessing passengers can be used, or stations can be classified based on the kind of public transport which stops there (buses, trams, regional trains, inter-regional trains).

The location points included in the database usually only stand for a part of the determined demand for charging points in a city or region. The used algorithm has to ensure that results on the level of points are consistent with those on the level of zones. If the same indicator of importance is used for zones and points of one location category, the same ratio of charging points per indicator value ($N_i / \sum_k x_{ik}$ in the above formula) can be used to calculate a consistent proportional distribution for the points. If different indicators are used, a conversion factor for them has to be added: c_i = indicators zones / indicators points. Performing a proportional distribution in this fashion results in a consistent allocation of charging points: the same criteria are used for allocating charging points to areas and to points. If the underlying data is correct, the number of charging points for a location category allocated to points within a zone cannot exceed those of the zone. The number is the same if the listed points represent all locations of one category in the zone, for instance parking garages (not taking rounding effects for individual zones and points into account).

However, because indicator values of individual points tend to be quite small in relation to the sum of all indicator values of the entire region, many parameterizations result in only very few location points being identified for the placement of charging points by the method. For instance, if 100 000 people work in the considered city or region, and 200 charging points are to be distributed among working locations, an employer would have to have at least 250 employees ($n \cdot 200/100000 \geq 0.5$) to be allocated one charging point. But in practical applications it is often desirable to show more specific candidate locations as points. Therefore, factors of overemphasis have been integrated into the formula. These factors are defined for each location category where points are included, but do not represent the entirety of the locations of the category.

Thus, the *number of charging points* m_{ir} *of the location category* i *to be allocated to a point* r is determined by the function:

$$m_{ir}(y_{ir}) = round(\frac{N_i}{\sum_k x_{ik}} \cdot c_i \cdot y_{ir} \cdot w_i)$$

With the variables:

N_i: total number of charging points to be distributed among locations of category i

x_{ij}: indicator of relative importance for location category i of area j

y_{ir}: indicator of importance for location category i of point r

c_i: conversion factor for location category i, for conversion between indicator for zones and indicator for points

w_i: factor of overemphasis (≥ 1) to allocate more charging points to point locations than a proportional distribution would, can be set to 0.0 to cancel the use of a category of points

k: all points

An example calculation is shown in Tab. 8.2. The example is an extension of the previously shown example of Tab. 8.1 where 50 charging points were distributed among 5 areas with a total of 2 200 employees. A conversion factor between indicators of importance of 1.0 is used, because the same indicator "number of employees" is used for zones as well as points. A factor of overemphasis of 1.5 is used to allocate more charging points to point locations.

Table 8.2.: Example calculation: distribution of 50 charging points for 5 working points

Point name	**Number of employed persons** (indicator for working points)	(Calculation)	**Number of charging points for working points**
Point 1	150	$round(50/2200 \cdot 1.0 \cdot 1.5 \cdot 150) =$	5
Point 2	100	$round(50/2200 \cdot 1.0 \cdot 1.5 \cdot 100) =$	3
Point 3	80	$round(50/2200 \cdot 1.0 \cdot 1.5 \cdot 80) =$	3
Point 4	70	$round(50/2200 \cdot 1.0 \cdot 1.5 \cdot 70) =$	2
Point 5	50	$round(50/2200 \cdot 1.0 \cdot 1.5 \cdot 50) =$	2
	Sum: 450		Sum: 15 (= $50/2200 \cdot 1.0 \cdot 1.5 \cdot 450 \pm 5$ (# of points))

The method described above was implemented by the author as a tool written in the programming language Python within the geoinformation system ESRI ArcGIS. Fig. 8.6 shows the tool interface on the left of the screen. The tool was adapted to each application case. The figure shows the tool for the application in the Province of Liège in Belgium. The user enters the total number of charging points as well as their distribution percentages. The tool then calculates a location plan of charging points and displays it on the screen in a visual form. Functionalities included in the ArcGIS geoinformation system can be used to export the results in the form of maps and lists.

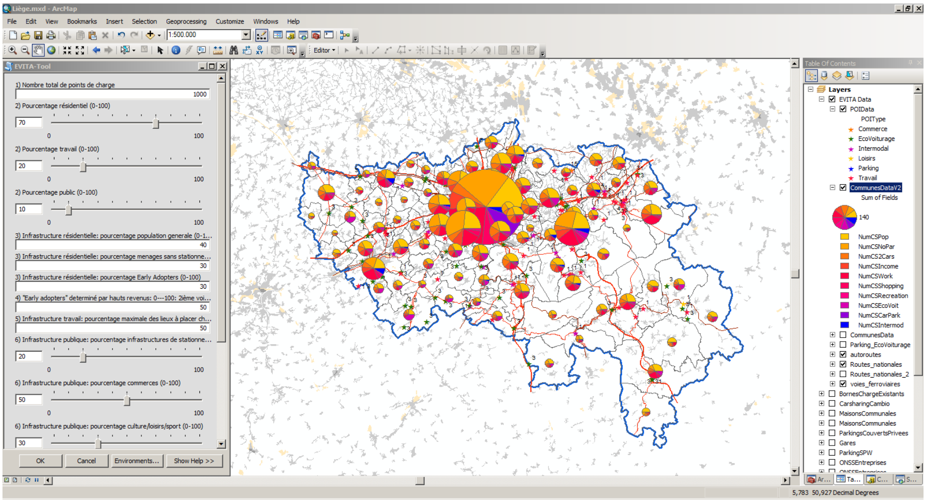

Figure 8.6.: Interface of the decision support tool developed within the geographic information system ESRI ArcGIS

8.3.2. Application: scenarios of a charging infrastructure for EVs in the Belgian Province of Liège

The method of decision support for the location planning of charging points described above was applied to the Province of Liège in Belgium in 2013. The details of this application are presented in the following.

The Province of Liège is one of the ten provinces of Belgium. It lies in the southeast of the country, bordering on Germany and Luxembourg (see Fig. 8.7). A population of 1.083 million live in the area of 3 863 km^2. The province is divided into 84 communes. Its capital is the city of Liège, located at the center of the province [653].

In the following, first an overview of the used data will be given. Then it will be explained how the general alignment of the charging infrastructure was discussed with local representatives making use of a questionnaire. Finally, the resulting scenarios will be shown and discussed.

Figure 8.7.: Geographic location of the Province of Liège in Belgium (adapted from [654])

8.3.2.1. Data preparation for the Province of Liège

The following Tab. 8.3 lists the data used for the application in the Province of Liège. Part of the data was supplied by the *Infrastructure et Environnement* department of the province. Other data was collected from several different public sources. Access to the listed websites was done in April and May 2013. Data noted in *italics* in the table was prepared in the GIS in order to better visualize and check the plausibility of results, but did not enter into the location planning algorithm. The data type *shapefile* is a file format used in geoinformation systems for storing data with spatial references. This data format supports geographic entities in the shapes of either polygons, lines, or points. The entities stored in a shapefile can be described with further attributes. In this application the indicators of importance are included as attributes for the zones and individual points.

Table 8.3.: Data used for the application in the Province of Liège

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
Basic data	Shapes and location of communes (used zoning)	Shapefile: polygons	Province de Liège, Infrastructures et Environnement: communes
	Land use: built-up area (used for visualization and plausibility checking only)	*Shapefile: polygons*	*European Environment Agency: CORINE land cover data 2006:* `http://www.eea.europa.eu/data-and-maps/data/clc-2006-vector-data-version-2`
Residential	Number of households per commune (used for calculating other data)	List of the number of households per commune	Province de Liège, Infrastructures et Environnement: households 2010
	Number of registered vehicles per commune	List of the number of registered vehicles per commune	Province de Liège, Infrastructures et Environnement: registered vehicles 2011

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
	Number of households having two or more vehicles per commune	List of the number of households having two or more vehicle per commune	SPF Economie, P.M.E., Classes moyennes et Energie: Enquête socio-économique 2001: Le mouvement pendulaire en Belgique: percentage of households disposing of two or more vehicles (data taken from map): `http://statbel.fgov.be/fr/binaries/Total-Mouvement_Pendulaire_FR_tcm326-34227.pdf` In order to obtain absolute indicator value multiplied with: number of households per commune (source see above)
	∼ Total revenues per commune	List of the ∼ total revenues per commune	Province de Liège, Infrastructures et Environnment: average revenue per tax declaration per commune (year unknown) In order to obtain absolute indicator value multiplied with: number of households per commune (source see above)
	Number of dwellings which do not have a private parking space	List of number of dwellings that do not have a private parking space	Approximated by: number of dwellings − number of garages, according to: Province de Liège – Infrastructure et Environnement: building stock 2011

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
	Number of commuters to Brussels per commune	List of the total number of commuters to Brussels per com- mune	SPF Economie, P.M.E, Classes moyennes et Energie: Enquête socio-économique 2001: Le mouvement pendulaire en Belgique: commuters toward the agglomeration of Brussels in percentages of the active working population (data taken from map) `http://statbel.fgov.be/fr/binaries/Total-Mouvement_Pendulaire_FR_tcm326-34227.pdf` In order to obtain absolute indicator value multiplied with: SPF Economie, P.M.E, Classes moyennes et Energie: fiscal statistic of taxed revenues of physical persons per commune of residence 2012: number of tax declarations per commune: `http://bestat.economie.fgov.be/BeStat`
Work	Total number of employees per commune	List of the number of employees per commune	Office National de Sécurité Sociale (ONSS): number of employees according to NACE classification, in the communes of the Province Liège on 31.12.2010 (purchased data)
	Big establishments/ businesses with 50 or more employees	Shapefile: points with attribute: number of employees	Office Nationale de Sécurité Sociale (ONSS): repertoire of active employers which occupy 50 persons or more, in the Province Liège on 31.12.2010 (purchased data) Addresses geocoded using GPSVisualiser: `http://www.gpsvisualiser.com`

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
Shopping	Number of employees in the domain of retail per commune	Shapefile: points with attribute: number of employees	Office National de Sécurité Sociale (ONSS): number of employees according to NACE classification, in the communes of the Province Liège on 31.12.2010 (purchased data): retail
	Big retailers with 50 or more employees	Shapefile: points with attribute: number of employees	Office Nationale de Sécurité Sociale (ONSS): repertoire of active employers which occupy 50 persons, in the Province Liège on 31.12.2010 (purchased data): retail Addresses geocoded using GPSVisualiser: `http://www.gpsvisualiser.com`
Culture, sports, and gastronomy	Total number of employees in the domain of culture, sports, and gastronomy per commune	List of the number of employees in the domain of culture, sports, and gastronomy per commune	Office National de Sécurité Sociale (ONSS): number of employees according to NACE classification, in the communes of the Province Liège on 31.12.2010 (purchased data): culture, sports, gastronomy

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
	Big establishments in the domain of culture, sports, and gastronomy with more than 50 employees	Shapefile: points with attribute: number of employees	Office Nationale de Sécurité Sociale (ONSS): repertoire of active employers which occupy 50 persons or more, in the Province Liège on 31.12.2010 (purchased dataset): culture, sports, gastronomy Addresses geocoded using GPSVisualiser: `http://www.gpsvisualiser.com` Additional sports establishments added from: `http://www.liege.be/vivre-a-liege/mes-activites-sportives`
Diverse other infrastructure	*Existing charging stations (finally not included in method)*	*Shapefile: points*	*ASBE (AVERE Section Belge): `http://www.asbe.be/fr/locations`*
	Existing car sharing stations (finally not included in method)	*Shapefile: points*	*Cambio carsharing: `http://www.cambio.be/cms/carsharing/nl/2/cms/stdws_info/stationen.html`*

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
	Town halls, city quarter halls, institutions of the Province of Liège (finally not included in method)	*Shapefiles: points*	*Town halls: Annuaire Mairie:* `http://www.annuaire-mairie.fr/province-liege.html` *City quarter halls: Ville de Liège:* `http://www.liege.be/etat-civil-et-population/antennes-administratives/antennes-administratives` *Institutions of the Province Liège: Province de Liège:* `http://www.provincedeliege.be/fr/gestionetpolitique` *Addresses georeferenced using GPSVisualiser:* `http://www.gpsvisualizer.com/`
Transport and parking system	Publicly accessible roofed car parks	Shapefile: points with attribute: number of parking spaces Data also aggregated for all points within a zone to obtain indicator value for zones	Addresses and number of parking spaces: Liège Centre Gestion Centre-Ville: `http://www.liegecentre.be/commerces/index.php?page=1296` Checked using Michelin: `http://fr.viamichelin.be/` Addresses georeferenced using GPSVisualiser `http://www.gpsvisualizer.com`

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
	Planned EcoVoiturage parking lots	Shapefile: points with attribute: calculated priority indicator Data also aggregated for all points within a zone to obtain indicator value for zones	Province de Liège, Infrastructures et Environnement: planned EcoVoiturage parking lots Priority indicator calculated from data in which the point is located: $(\frac{Househ2Vehicles}{MAX_{Com \setminus Liege}\{Househ2Vehicles\}} + \frac{TotalRevenues}{MAX_{Com \setminus Liege}\{TotalRevenues\}} + \frac{CommutersBrussels}{MAX_{Com \setminus Liege}\{CommutersBrussels\}}) \cdot \frac{1}{3} \cdot \frac{1}{NumberEcoVoitStationsInCommune}$ Source for total revenues: SPF Economie, P.M.E, Classes moyennes et Energie: fiscal statistic of taxed revenues of physical persons per commune of residence 2012: total revenues per commnune: `http://bestat.economie.fgov.be/BeStat` Other sources: see above
	Highways and national routes (used for visualization and plausibility check only)	*Shapefile: lines*	*Province de Liège, Infrastructures et Environnement: highways and national routes*

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
	Intermodal connection points: train stations, airports, (bus stops, ports)	Shapefile: points with attribute: number of daily voyagers Data also aggregated for all points within a zone to obtain indicator value for zones	Train stations: Wikipedia: `http://fr.wikipedia.org/wiki/Catégorie:Gare_de_la_province_de_Liège` Missing train stations completed using google maps: `https://www.google.de/maps/` Number of voyagers at train stations: Société Nationale des Chemins de fer Belges (SNCB): 2009 Comptages voyageurs: `http://bib.urbagora.be/chemin-de-fer.html` Liège airport: number of voyagers: Région Wallonne website: `http://aeroports.wallonie.be/opencms/export/sites/be.wallonie.airport/fr/eblg/statistiques/eblg2010_v20110913.pdf` *Bus stops: Transport en Commun en Wallonie: `http://www.infotec.be/Files/TECBW/R%C3%A9seau_40x70_Recto.pdf` (data finally not used)* *Ports: Port Autonome de Liège website: `http://www.portdeliege.be/de/liege-port-autonome-visite-ports` (data finally not used)*

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Table 8.3 – *Continued from previous page*

Data category (overarching)	**Data category (location category)**	**Data type**	**Source** (websites accessed 04/05.2013)
	Railroad lines (used for visualization and plausibility check only	*Shapefile: lines*	*Province de Liège, Infrastructure et Environnement: railroad lines*

The preparation of the geographical data is by far the most time-consuming task within this method, making up about 2/3 of the working time. The data on zones and points is transferred into two shapefiles. The first shapefile with polygons contains the zones with all their indicators as attributes, as well as fields for the number of calculated charging points separated by location categories. The second shapefile contains all points, their respective location category, indicators for all location categories (most of which are 0, except for the category for which they are relevant), and a field which contains the number of calculated charging points for the location point. Other datasets such as land cover, roads, or existing other infrastructure, which are used as contextual information, are left as separate shapefiles.

The geodata on zones is usually constructed starting from a shapefile defining the shapes of the communes. The names of the zones, as well as a zone identifier (the statistical code for the communes or similar) are also included in the initial shapefile. The separate datasets containing the indicator data are usually given as lists in Excel sheet (.xls, .xlsx) or dBASE database files (.dbf) and are then joined to the shapes using the zonal code.

Usually it is easier to construct the points of each location category in separate files. They are then sequentially imported into a single shapefile, each time setting the indicator values of all other irrelevant location categories to 0. The location of points in shapefiles can be entered manually in the GIS. Alternatively geographic latitude and longitude coordinates can be written into a list, which is then converted to a shapefile. Often point data is only given with addresses as location information. These can be converted to geographic latitude/longitude coordinate data using georeferencing services such as GPSVisualiser [655].

Data availability strongly varies between countries and regions. The data collection done for the Province of Liège shows some elements commonly occurring during data collection for the method. The local administration of the region for which the planning takes place often already has a part of the data available for their own urban planning work (example: data from Province de Liège, Infrastructures et Environnement). The other data needs to be collected and prepared especially for the method. In the best case, formatted data can be procured from reliable public sources (examples: data from SPF Economie, P.M.E., Classes moyennes et Energie). Sometimes data needs to be redigitalized from lists of maps shown in official documents (example: SPF Economie, P.M.E., Classes moyennes et Energie: Enqûete socio-économique 2001). A part of the data may need to be bought from public or private sources (example: data from Office National de Sécurité Social (ONSS)). Smaller datasets usually have to be prepared by hand, often combining and crosschecking the information given in less reliable sources (examples: data on big public roofed car parks, data on intermodal connection points). For some location categories none of the available data may be directly usable as an absolute indicator. Approximative indicators can be calculated by combining several values (example above: data used for number of dwellings without private parking space, total number of commuters to Brussels).

The location category EcoVoiturage stations stands for parking lots where people can meet and park to form a carpool. These stations were still under development while the EV charging infrastructure planning method was being applied. For this category an artificial indicator was constructed in order to establish priorities between the different locations. The indicator is calculated by an equally weighted sum. The three criteria are each normed by a division by the highest occurring value of all communes except for the city of Liège. This was done because the city of Liège was an outlier with very high values in all three categories, and there were no EcoVoiturage stations in the city. The equally weighted sum is divided by the number of EcoVoiturage stations in the commune, in order to model a distribution of the potential among these stations. Alternative indicators could be constructed for this category in order to establish priorities.

8.3.2.2. Understanding local policy and wishes using a questionnaire

To understand the existing local policy and local wishes concerning the charging infrastructure for EVs in the Province of Liège, a small workshop was held with local representatives. The outcome of this workshop served to construct plausible scenarios for a charging infrastructure. A presentation was shown which explained the planning process with this method of decision support. The current situation in Belgium concerning EVs and their infrastructure was also recapitulated.

A discussion was then held making use of questions embedded in the presentation. Fig. 8.8 shows a typical example slide.

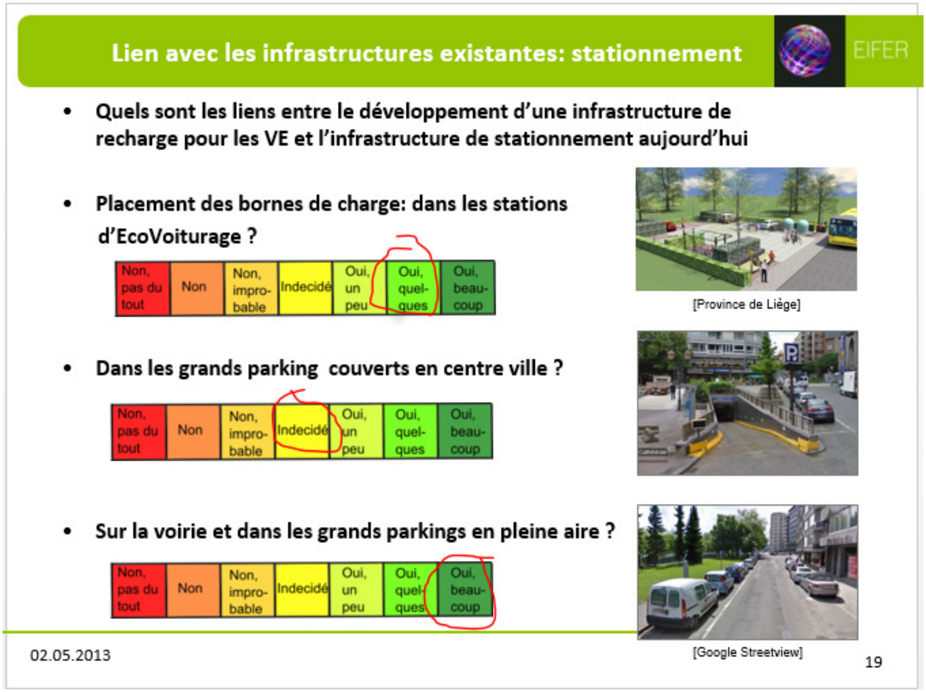


Figure 8.8.: Questions embedded into a presentation (example slide)

On the left of the slide, questions are posed concerning the placement of charging points in different usage contexts. The questions are to be answered on a qualitative ordinal scale with seven steps: “No, not at all”, “No”, “No, unlikely”, “Undecided”, “Yes, a few”, “Yes, some”, “Yes, many” (translated from French). In hindsight these generic formulations were not always appropriate to the posed questions. They were intended to signal strong disagreement, medium disagreement, weak disagreement, an undecided attitude, weak agreement, medium agreement, and strong agreement. The answers were directly annotated on the slides during the presentation and discussion. On the right side of the slide, photos of prominent example locations in the province are shown. These serve to concretize the abstract questions.

The questions were also included in a three-page paper questionnaire. During a previous application in Strasbourg [648] the questionnaire was filled out by several persons in parallel. In the application in Liège, however, the questions were answered together in the group during the presentation, making annotations into the slides. The results were later transferred to one questionnaire (see Fig. 8.9).

The following questions and answers were given in the Province of Liège (translated from French, the originally used expression “borne de charge” is translated by “charging point” here):

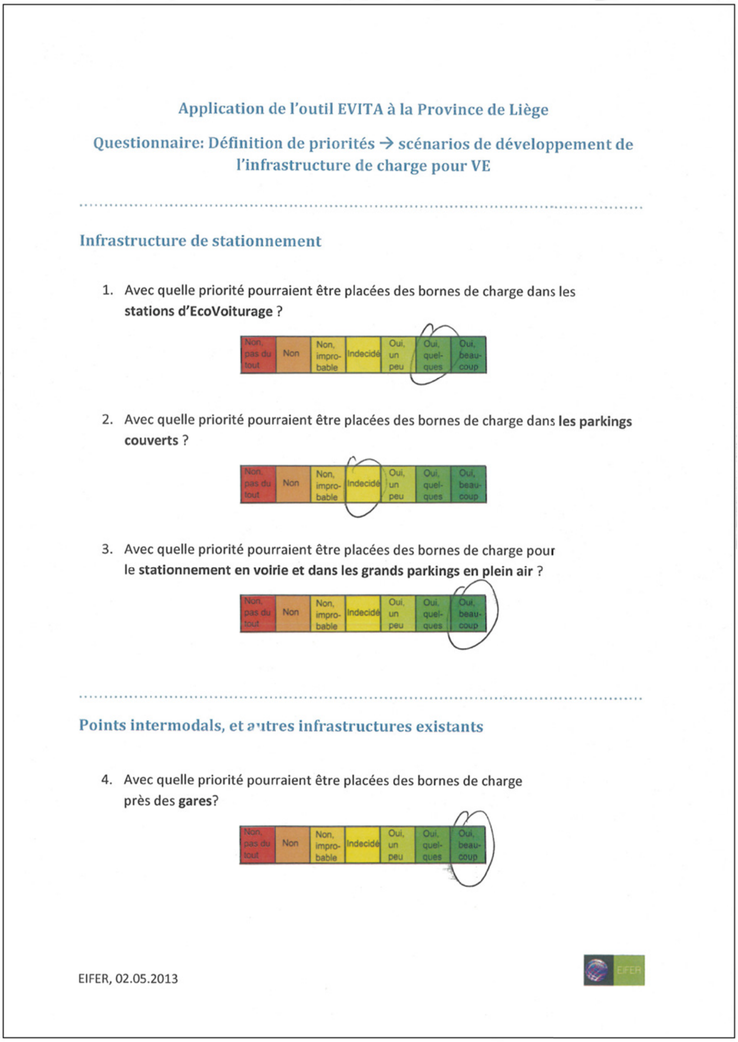
Q1: Should charging points be placed in the EcoVoiturage stations?
A1: Yes, some.
Q2: ... In the big roofed parking garages in the city center?
A2: Undecided. (Reason: this also depends on the operating companies.)
Q3: ... At curbside parking spaces and big open air parking lots.
A3: Yes, many.
Q4: Should charging points be placed near train stations?
A4: Yes, many.
Q5: What role does the airport play for a charging infrastructure? Is it appropriate to place charging points near the airport?
A5: Yes, a few.
Q6: Is it planned to electrify the Cambio carsharing system? Should charging points be placed at carsharing stations?
A6: Undecided. (Reason: the province cannot answer this, it is for the company to decide)
Q7: Is it planned to use the charging infrastructure for EVs for city-marketing? Should charging points be placed at symbolic and well visible places?
A7: Yes, some.
Q8: Is it interesting to install *public* charging points for residential parking on the street?
A8: Yes, a few.
Q9: ... Rather aimed at people who do not have a private parking space?
A9: Yes, some / Yes, many.
Q10: ... Rather aimed at the potential “Early Adopters” of EVs?

A10: No. (Reason: It is not the province's task to install charging infrastructure for affluent people.)
Q11: Would it be appropriate if big companies installed charging points for their employees?
A11: Yes, many.
Q12: Does the province wish to place public charging points *on the street* in city quarters "dense" with work?
A12: Yes, some / Yes, many.
Q13: Does the province wish to support big companies in installing charging points for their employees?
A13: No.
Q14: Would it be appropriate if big retailers (malls, supermarkets etc.) installed charging points for their clients?
A14: Yes, many.
Q15: Does the province wish to place public charging points *on the street* in city quarters "dense" with retailers?
A15: Yes, a few.
Q16: Does the province wish to support big retailers to install charging points for their clients?
A16: No.
Q17: Would it be appropriate if big cultural establishments (cinemas, swimming pools, ...) installed charging points for their clients?
A17: Yes, many.
Q18: Does the province wish to place public charging points in city quarters " dense" with culture and sports?
A18: Yes, some.
Q19: Does the province wish to support big cultural and sports institutions to install charging points for their clients?
A19: Yes, many. (Reason: these establishments are often public institutions)

These answers were interpreted as the following trends concerning a future charging infrastructure for EVs in the Province of Liège. The general trends concerning the *link with the parking infrastructure of today* are: in the long term the majority of charging points will be placed on the street and on open air parking lots. The participation of big parking garages in the city center is not clear.

The general trends concerning the *link with transport and intermodal infrastructure* are: Some charging points will be placed in the new EcoVoiturage stations. Many points will be placed in the parking lots near train stations. It is also interesting to place charging points at the airport. It is not possible to say whether the electrification of the carsharing system is interesting.

The general trends concerning the *integration into a city marketing concept* are: some charging points can be placed at symbolic and well visible locations, such as the institutions of the province, of the communes, and of the city quarters.



Application de l'outil EVITA à la Province de Liège

Questionnaire: Définition de priorités → scénarios de développement de l'infrastructure de charge pour VE

Infrastructure de stationnement

1. Avec quelle priorité pourraient être placées des bornes de charge dans les **stations d'EcoVoiturage** ?

Non, pas du tout	Non	Non, impro-bable	Indecidé	Oui, un peu	Oui, quel-ques	Oui, beau-coup

2. Avec quelle priorité pourraient être placées des bornes de charge dans **les parkings couverts** ?

Non, pas du tout	Non	Non, impro-bable	Indecidé	Oui, un peu	Oui, quel-ques	Oui, beau-coup

3. Avec quelle priorité pourraient être placées des bornes de charge pour le **stationnement en voirie et dans les grands parkings en plein air** ?

Non, pas du tout	Non	Non, impro-bable	Indecidé	Oui, un peu	Oui, quel-ques	Oui, beau-coup

Points intermodals, et autres infrastructures existants

4. Avec quelle priorité pourraient être placées des bornes de charge près des **gares**?

Non, pas du tout	Non	Non, impro-bable	Indecidé	Oui, un peu	Oui, quel-ques	Oui, beau-coup

EIFER, 02.05.2013

Figure 8.9.: Questions in the form of a paper questionnaire (example page)

The general trends concerning the *separation between a public infrastructure, for which the province is responsible, and charging points under private management* are: it is interesting to place charging points on the street for residents who do not have a private parking space. The province also wants to install charging points in city quarter where many people work. However, it is the organizational and financial responsibility of employers to install charging points for their employees on their own private parking lots. Big retailers are also organizationally and financially responsible for installing charging points for their clients. Additionally, the province will install charging points on the street in city quarter with many shopping possibilities. For the big cultural and sports institutions the situation is different. A big part of them are public institutions (for example museums, swimming pools, sports complexes), where the province intends to support the installation of charging points. Additionally, charging points will be installed on the street in city quarters with many cultural and sports opportunities.

8.3.2.3. Basic conditions for all scenarios

Before specific scenario results will be shown in the next sections, basic aspects concerning all scenarios will shortly be explained. First, the hierarchy of location categories used will be presented. Then, it will be shown how the total number of charging points to be distributed in the province was determined.

The hierarchy and indicators shown in the following are used. Final location categories on the lowest levels are marked in italics.

- Residential
  - *General population (indicator: registered vehicles)*
  - *People without private parking spaces (indicator: households without garages)*
  - Potential early adopters
    - *Potential early adopters with two or more cars (indicator: households with two or more cars)*
    - *Potential early adopters with high income (indicator: ∼ total income in commune (as defined in Tab. 8.3))*
- *Work (indicator: employees), with specific points (indicator: employees)*
- Public

◇ Parking infrastructure
  ▷ *EcoVoiturage stations (indicator: calculated indicator), with specific points (indicator: calculated indicator)*
  ▷ *Big car parks (indicator: parking spaces), with specific points (indicator: parking spaces)*
  ▷ *Train stations and airport (indicator: number of passengers) with specific points (indicator: number of passengers)*

◇ *Shopping (indicator: employees) with specific points (indicator: employees)*

◇ *Culture, sports, and gastronomy (indicator: employees) with specific points (indicator: employees)*

Location categories for which the geographic data was collected, but which were finally not included in the method and thus in the scenarios, are carsharing stations and symbolic public institutions. From the province's perspective it was not known if an electrification of the carsharing system was planned by the operating company. Also, at the time of the study there were only eight such stations, all located within the city of Liège. Town halls and similar public institutions of the province and the city quarters of Liège were also finally not included. Setting up charging points at these locations would be a pragmatic ad-hoc method of developing a public charging infrastructure. This would lead to a good areal coverage of the Province (see Fig. 8.10). However, such an approach would place charging points also in peripheral villages, where little need for them is to be expected. These locations could later be interesting on the micro-level if the need of placing charging points in a commune is identified by another criterion (for instance, many shopping locations in the commune's center where such public institutions are usually also located).

The method of distribution of charging points among different location categories requires a total number of charging points as an input parameter. Belgium does not seem to have official national targets for the number of public charging points for the near future. However, in January 2013, the European Union released its *Clean fuel strategy* [51] which proposes the target of 21 000 publicly accessible charging points in Belgium in the year 2020. Publicly accessible charging points are intended to make up 10 % of all charging points. In 2014, the EU relativized these targets in the *Directive 2014/94/EU on the deployment of alternative fuels infrastructure* [43] to at least 1 publicly accessible charging point for every 10 EVs in each member country.

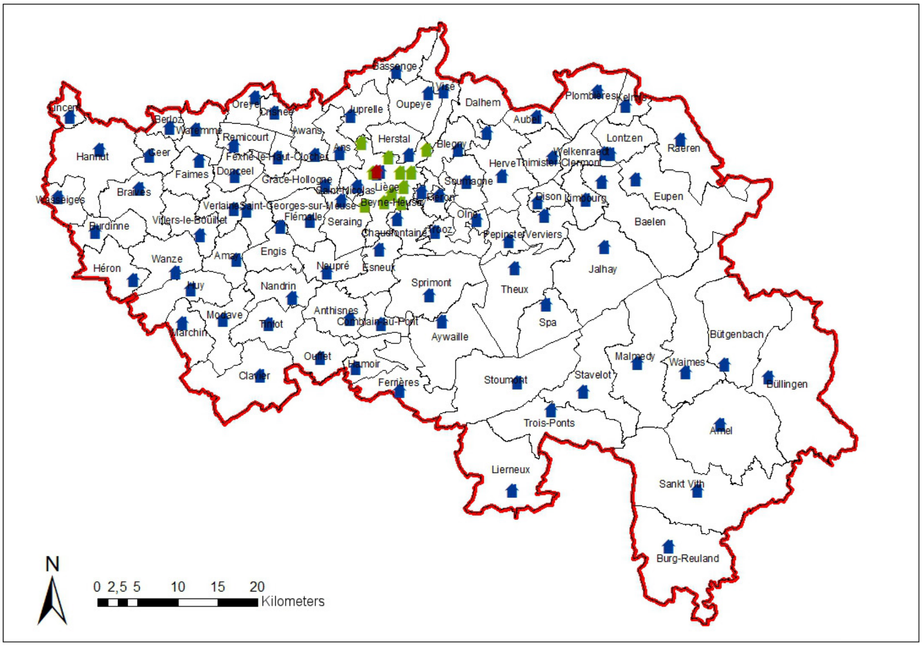


Figure 8.10.: Town halls and equivalent public institutions of the province (in red), of communes (in blue), and of the city quarters of Liège (in green) (data sources see Tab. 8.3)

The number of 21 000 publicly accessible charging points for Belgium is broken down for the Province of Liège using the number of cars. In 2011, there were 501 590 cars registered in the Province of Liège and 5 407 015 in entire Belgium [656]. Therefore about (501 590/5 407 015) * 21 000 = 1 948 publicly accessible charging points, or 19 480 in total, should be located in the Province of Liège. The rounder values of 1 950 and 19 500 charging points are used for the scenarios in the following.

Fig. 8.11 shows the publicly accessible charging points already existing in the Province of Liège in May 2015 (according to the source LEMnet, see Tab. 8.3). Seven of these 16 points were installed by the private initiative of car sellers (Renault (2x), Nissan (2x), Citroën, Mercedes, Opel) and two by electronic companies. Other charging points were installed by companies for their clients (retailers (2x), hotel). 15 of the charging points provide a household socket (in France: CEE 7/5), one a Yazaki connector (SAE J1772 used in Japan and the

USA, but rarely in Europe). These already existing charging point locations are not included in the scenarios shown in the following.

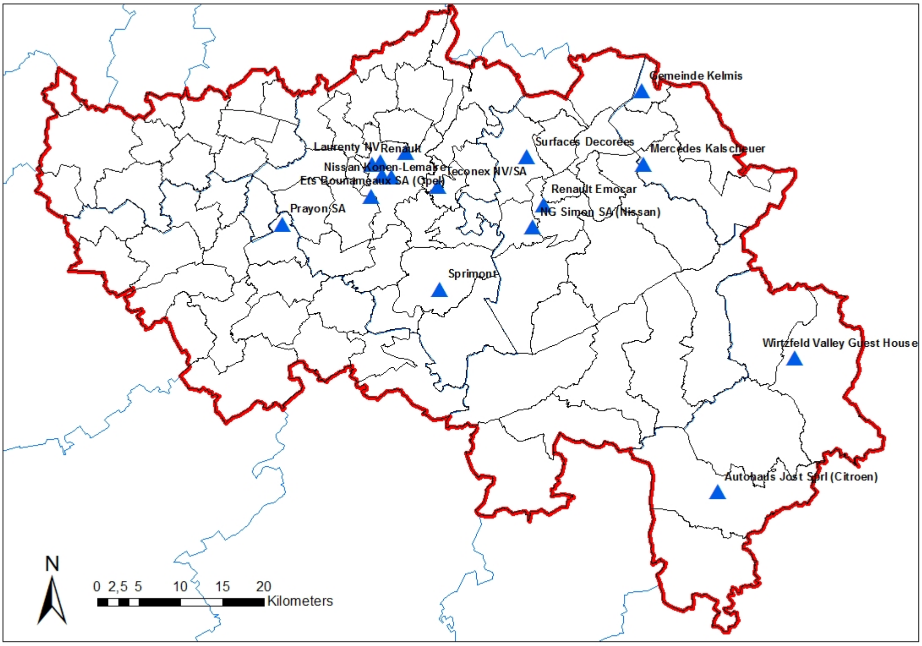


Figure 8.11.: Existing charging points in the Province of Liège in May 2013 (data source: ASBE, see Tab. 8.3)

8.3.2.4. Scenario 1: publicly accessible infrastructure completely under public management in 2020

This scenario simulates a situation in which the Province of Liège solely provides a charging infrastructure of 1 950 publicly accessible charging points in the year 2020. The scenario models a politically pessimistic situation in which private stakeholders do not contribute locations/charging points to a publicly accessible infrastructure.

Charging points are mainly placed at curbside parking spaces. The placement of these charging points concentrates on zones with many cultural/sports/gastronomy locations, zones with many shopping locations, and at EcoVoiturage stations.

Charging points are also placed in zones where many people do not have a private parking space and in zones where many people work. Locations under private management, such as big parking garages, parking spaces at train stations, and at the airport, are not included.

In the following lists, the percentages refer to each branching level. The absolute percentages for basic location categories are noted in parentheses. A total of 1 950 charging points is distributed by:

- ◦ Residential: 20 %
  - ◇ *General population: 0 %*
  - ◇ *People without private parking spaces: 100 % (absolute: 20 %)*
  - ◇ Potential early adopters 0: %
    - ▷ *Potential early adopters with two or more cars: percentage irrelevant*
    - ▷ *Potential early adopters with high income: percentage irrelevant*
- ◦ *Work: 15 % (absolute: 15 %)*
- ◦ Public: 65 %
  - ◇ Parking infrastructure: 30 %
    - ▷ *EcoVoiturage stations: 100 % (absolute: 19.5 %)*
    - ▷ *Big car parks: 0 %*
    - ▷ *Train stations and airport: 0 %*
  - ◇ *Shopping: 30 % (absolute: 19.5 %)*
  - ◇ *Culture, sports, and gastronomy: 40 % (absolute: 26 %)*

Specific big retailers and big employers do not contribute publicly accessible locations in this scenario. This is modeled by using an overemphasis factor of 0.0 for these points, effectively canceling the use of these points. Culture, sports, and gastronomy locations are used with a neutral overemphasis factor of 1.0. Because quite many charging points are allocated in this scenario, no overemphasis to determine specific points of this category is necessary. The category of EcoVoiturage stations is fully represented as points in the database, therefore no additional emphasis is done.

Results of the calculation are shown for the communes in Fig. 8.12 and for identified specific points in Fig. 8.13. During applications of the method, local representatives were also given the results in the form of lists, one with the number of charging points in different categories per commune, and one listing the identified points and the located number of charging points. These detailed lists will not be presented here.

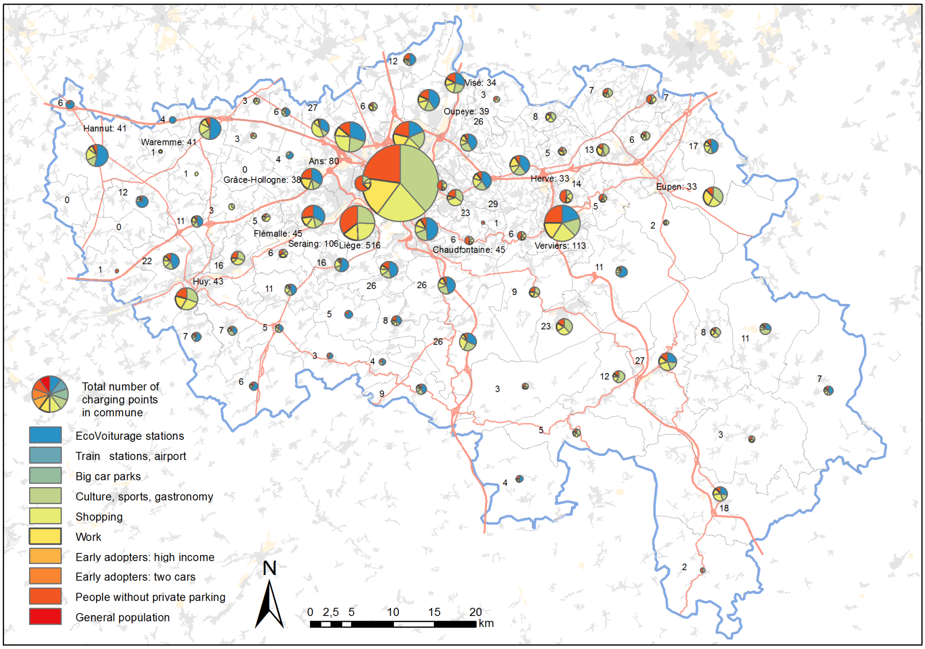


Figure 8.12.: Scenario 1: public infrastructure under public management in 2020: number of charging points per commune

Looking at Fig. 8.12 it is striking that by far the largest number of charging points is located in the city of Liège. Of the 1 950 distributed charging points, 516, about 1/4, is located there. It becomes apparent why the Province of Liège carries this name. The city of Liège is the dominant center, with a big share of work places, recreational and shopping possibilities. The radial network of major roads with Liège as the center, shown in red in the figure, also indicates this. The distribution of charging points also reflects how the city is surrounded by a ring of small satellite towns. In the east lies the the second biggest town in the province, which is Verviers.

Differences can be found in the relative percentages of the different categories of charging points in different municipalities. The EcoVoiturage stations, shown as the blue partition, are not located in the center, but in the periphery. In several small peripheral communes with good connection to the road network, more than half of the assigned charging points are located in the EcoVoiturage stations. In Seraing, directly southeast of Liège, the proportion of located residential charging points is much larger than in Liège. The city seems to be more of a residential city than a city of shopping and recreation.

Specific points at which charging points are located are shown in Fig. 8.13. In this scenario the province installs charging points at the planned EcoVoiturage stations. This forms a network mainly along the main roads, covering the entire province. Specific prominent locations of culture, sports, and recreation, shown in green in the figure, lie predominantly in the city of Liège, with a few locations also in other peripheral communes.

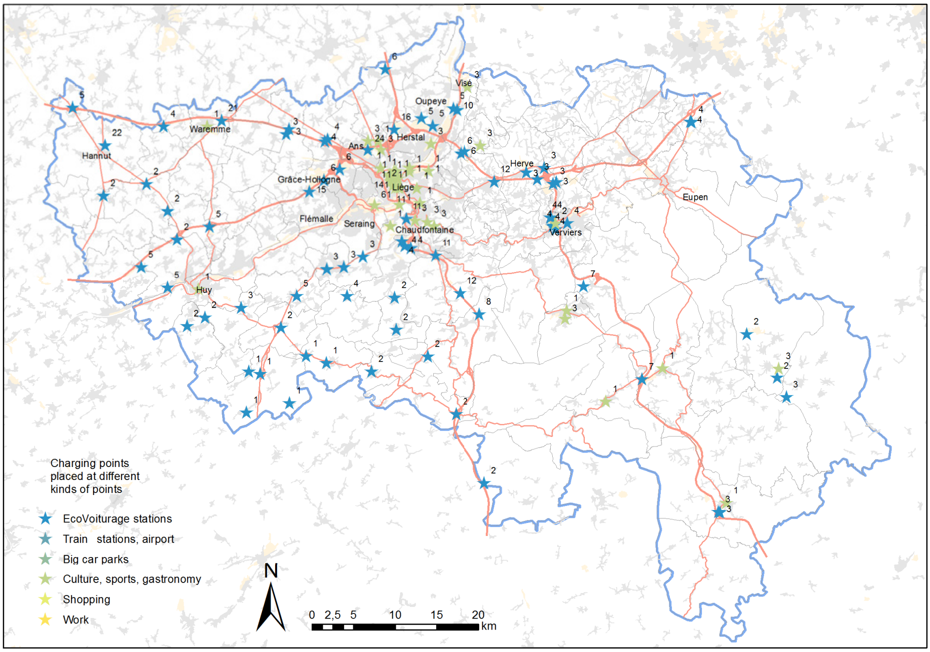


Figure 8.13.: Scenario 1: public infrastructure under public management in 2020: number of charging points at specific points

8.3.2.5. Scenario 2: publicly accessible infrastructure provided by public and private stakeholders in 2020

This scenario simulates a situation in which an infrastructure of 1 950 publicly accessible charging points is being set up by the province in collaboration with private partners. Therefore, in this scenario the operators of big parking garages, train stations, and the airport also contribute locations/charging points. Other aspects remain the same as in the previous scenario. The province places charging points at curbsides in zones where many people do not have a private parking space and where many people work.

A total of 1 950 charging points is distributed by (compare changes to scenario 1):

- ◦ Residential: 20 %
  - ◇ *General population: 0 %*
  - ◇ *People without private parking spaces: 100 % (absolute: 20 %)*
  - ◇ Potential early adopters 0: %
    - ▷ *Potential early adopters with two or more cars: percentage irrelevant*
    - ▷ *Potential early adopters with high income: percentage irrelevant*
- ◦ *Work: 15 % (absolute: 15 %)*
- ◦ Public: 65 %
  - ◇ Parking infrastructure: 30 %
    - ▷ *EcoVoiturage stations: 30 % (absolute: 7.8 %)*
    - ▷ *Big car parks: 40 % (absolute: 5.85 %)*
    - ▷ *Train stations and airport: 30 % (absolute: 5.85 %)*
  - ◇ *Shopping: 30 % (absolute: 19.5 %)*
  - ◇ *Culture, sports, and gastronomy: 40 % (absolute: 26 %)*

Big employers again do not contribute publicly accessible locations in this scenario. This is modeled by using an overemphasis factor of 0.0 for these points. Specific big retailers do however participate. Tor these a neutral overemphasis factor of 1.0 is used. The same is done for culture, sports, and gastronomy locations, as in the previous case. The categories of EcoVoiturage stations, big parking garages, train stations, and the airport are fully represented as points in the database, therefore no additional weighting is done for them.

The calculation results are shown for the communes in Fig. 8.14 and for specific points in Fig. 8.15. In this scenario, big car parks, train stations, and the airport are included as location categories. The number of charging points located in the city of Liège is 723, considerably larger than in the previous scenario. This is mainly due to the placing of charging points in the big car parks which all lie in the city center of Liège (see green/blue partition in the pie chart for the city of Liège). The main train station of Liège, the most important intermodal point in the province, also contributes a considerable number of charging points (see dull blue partition). The small airport of Liège located in Grâce-Hollogne, east of the city of Liège, is discernible in the partition, but does not play a major role.

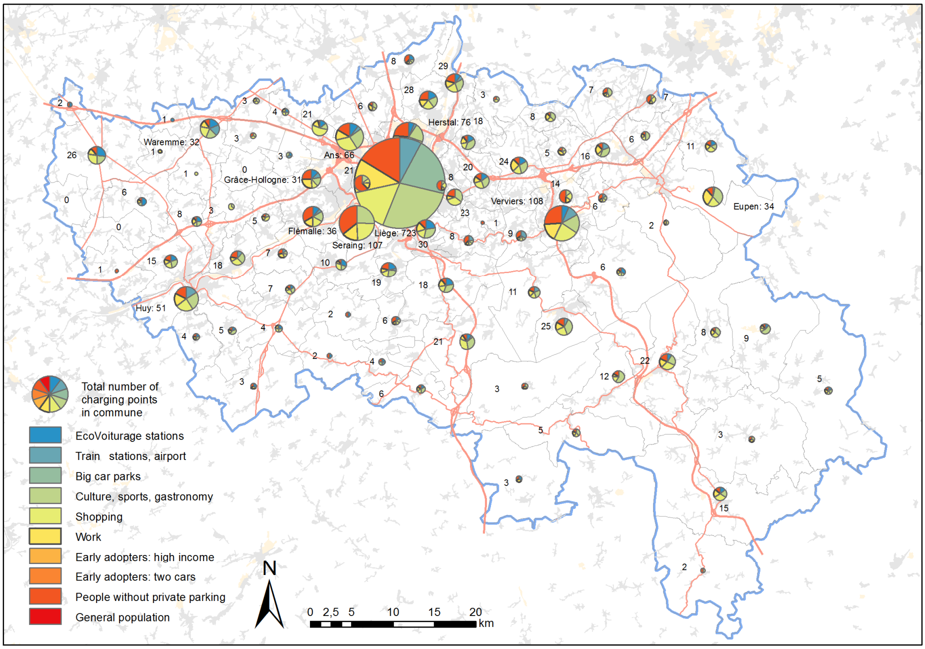


Figure 8.14.: Scenario 2: public infrastructure provided by public and private stakeholders in 2020: number of charging points per commune

Specific points where charging points are located are shown in Fig. 8.15. In comparison to the previous scenario, new specific locations are train stations and the airport, big car parks, and shopping locations. The train stations are distributed all over the province (shown in a dull blue). The big car parks all lie concentrated in the center of Liège. Many big retailers lie in the periphery of the city of Liège (shown in yellow/green). The figure thus shows how many more specific locations become available when private stakeholders, such as the railway company, big car parks, and retailers are involved in the buildup of publicly accessible charging points.

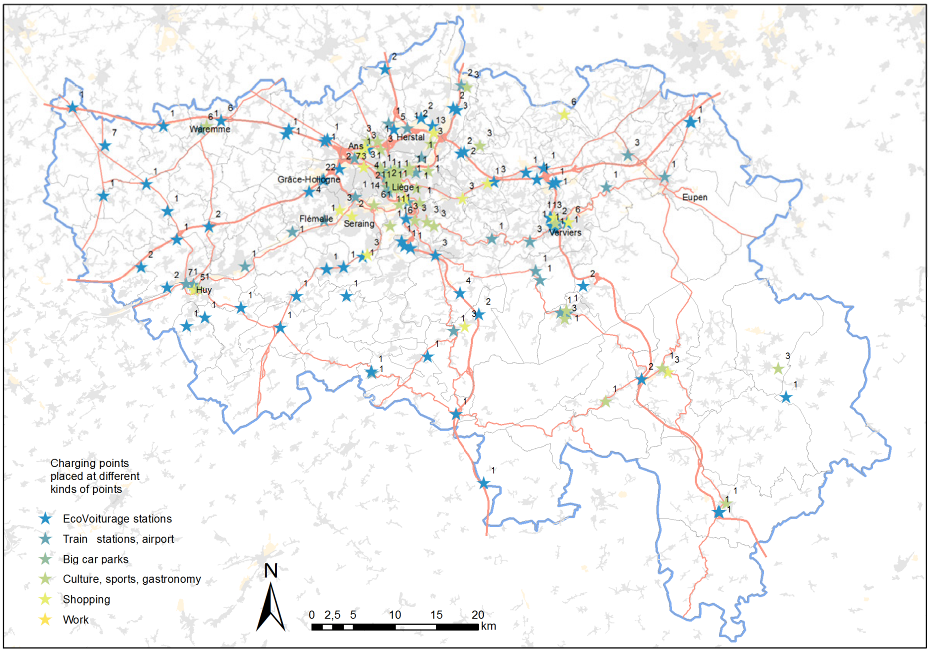


Figure 8.15.: Scenario 2: public infrastructure provided by public and private stakeholders in 2020: number of charging points at specific points

8.3.2.6. Scenario 3: infrastructure covering all usage contexts in 2020

This scenario simulates a situation in which 19 500 charging points in total, among them 1 950 publicly accessible, are located in the Province of Liège in the year 2020.

The publicly accessible charging points are included as in the previous scenario 2. Additionally, large numbers of private charging points are being set up by private owners of EVs at their homes and by companies for their employees and for use by their business fleets. Quantitatively this is modeled in a ratio of 3 residential charging points per 1 working charging point. Charging points between the general population and early adopters are also distributed in a ratio of 3 to 1. These proportions lead to the uneven percentages used below.

A total of 19 500 charging points is distributed by:

- Residential: 70.12 %
  - *General population: 72.86 % (absolute: 51.09 %)*
  - *People without private parking spaces: 2.86 % (absolute: 2.00 %)*
  - Potential early adopters: 24.28 %
    - *Potential early adopters with two or more cars: 50 % (absolute: 8.51 %)*
    - *Potential early adopters with high income: 50 % (absolute: 8.51 %)*
- *Work: 23.38% (absolute: 23.38 %) (includes 1.5 % of charging points installed by the province at curbsides)*
- Public: 6.5 %
  - Parking infrastructure: 30 %
    - *EcoVoiturage stations: 30 % (absolute: 0.585 %)*
    - *Big car parks: 40 % (absolute: 0.78 %)*
    - *Train stations and airport: 30 % (absolute: 0.585 %)*
  - *Shopping: 30 % (absolute: 1.95 %)*
  - *Culture, sports, and gastronomy: 40 % (absolute: 2.6 %)*

For the points of the categories work, shopping, and culture/sports/gastronomy a neutral overemphasis factor of 1.0 is used.

The results of the calculation are shown in Fig. 8.16 for communes and in Fig. 8.17 for specific points. A zoom on the points located in the city of Liège and the surrounding cities is shown in Fig. 8.18.

The overall percentages shown in Fig. 8.16 put the publicly accessible charging points, which overall make up only 10 % of all charging points, into perspective. When private residential points are included, the contrast between the city of Liège and the other communes in the province becomes less stark. In this scenario 3 923 charging points are located in the city, about 20 % of all charging points. The relative difference between Liège and the next biggest commune

Verviers also becomes considerable smaller (in scenario 3: $3923/925 \approx 4.24$, in scenario 2: $732/108 \approx 6.77$). For the city of Liège it can be seen that about half of the charging points are located in the residential context (red and orange colors), while in other communes, the residential share is in the scale of 2/3 - 3/4 of the charging points. Working places, shown as the yellow partitions, mainly lie in the city of Liège, but are also well visible for all bigger cities in the province. The same can be observed for specific points.

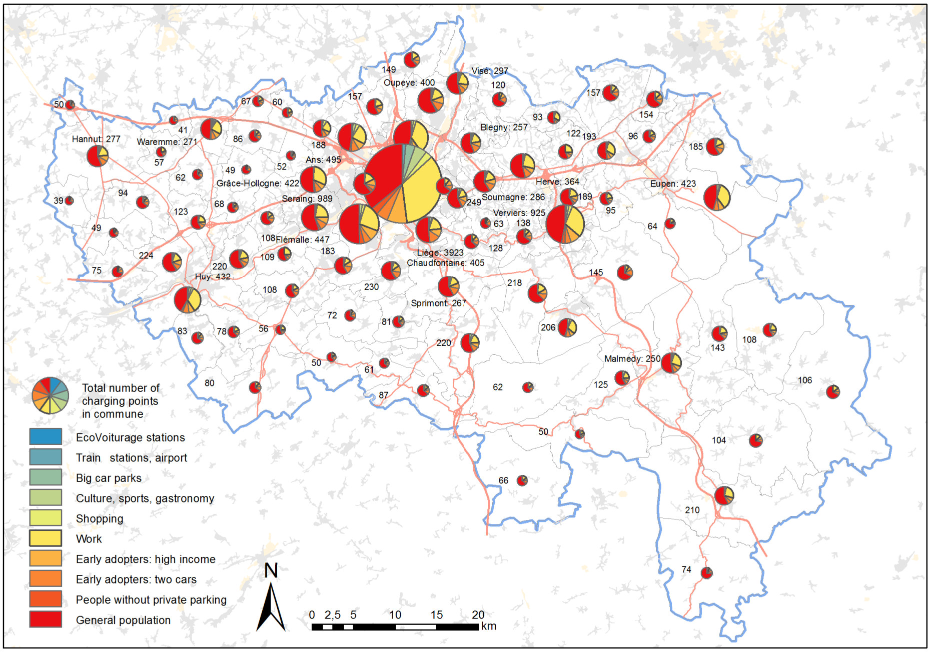


Figure 8.16.: Scenario 3: infrastructure covering all contexts in 2020: public, working and residential: number of charging points per commune

Fig. 8.18 shows the same points for all categories except for work as in the previous scenario 2. The prominent working locations are well visible in yellow, scattered all over the province, but mainly located in the city of Liège and its surrounding communes.

Fig. 8.18 shows the specific points identified within scenario 3, with a zoom on the city of Liège and the surrounding cities. Here an OpenStreetMap background is shown to provide contextual information (data from `http://www.`

openstreetmap.org is directly available in ESRI ArcGIS as a base map). This also demonstrates how the transition between the planning on the macro level and on the micro level is done. The model locates a number of charging points in zones (the communes in this application). For several location categories, such as big car parks and intermodal points, the charging points can directly be located at specific points. For other categories, such as working locations, shopping locations, and culture/sports/gastronomy locations, the method proposes prominent locations which would be good candidate locations. For some categories of locations, such as charging points for residents who do not have private parking spaces and therefore park their cars on the public curbside, no specific locations can directly be proposed. This requires further planning by urbanists on the micro level using areal photos and similar information. Such micro planning issues are treated in more detail in the next Chap. 9.

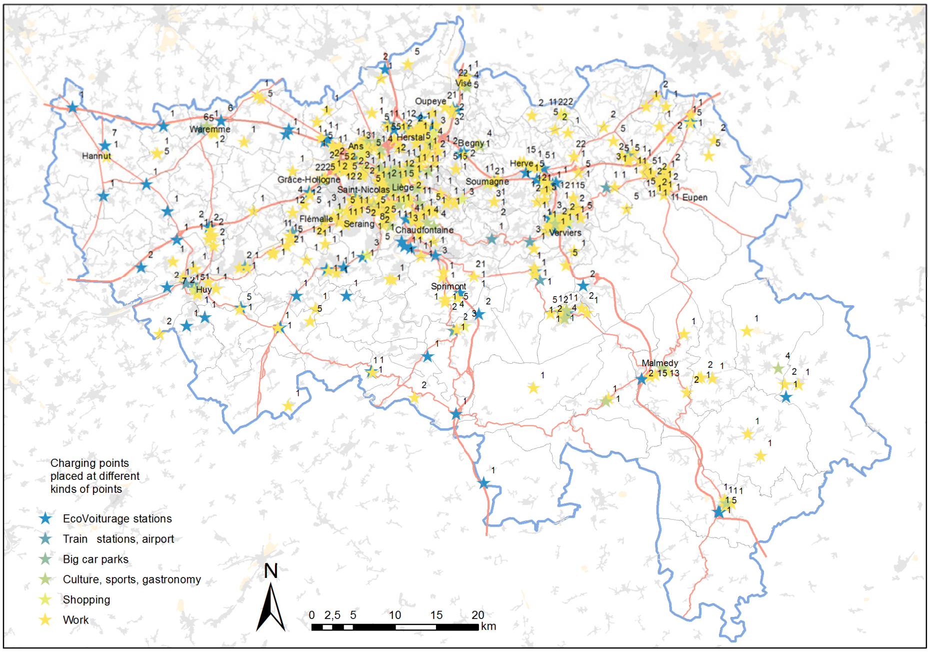


Figure 8.17.: Scenario 3: infrastructure covering all contexts in 2020: public, working and residential: number of charging points at specific points

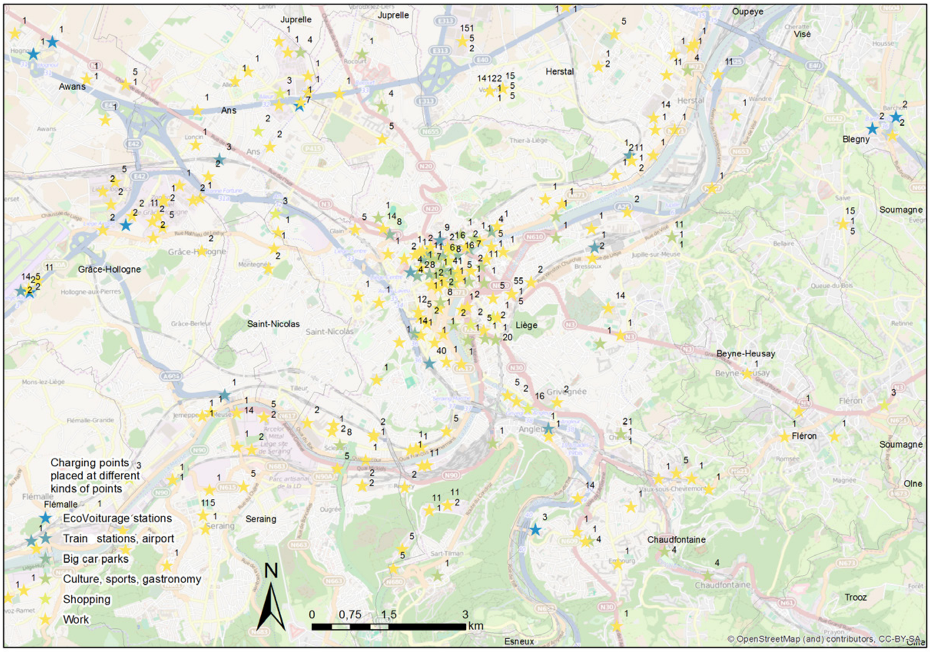


Figure 8.18.: Scenario 3: infrastructure covering all contexts in 2020: zoom on charging points located in the city of Liège and the surrounding communes (background image: OpenStreetMap)

8.3.3. Merits and disadvantages of the method

In the previous sections a method of decision support for the location planning of a charging infrastructure for EVs has been demonstrated. During the last years the author has applied variants of the method to seven different cities and regions. This has revealed the merits but also the disadvantages of the method.

One of the major advantages of the method is its simplicity and adaptability. Location categories can be defined or left out as seen fit for the specific region. For instance, if private charging points at homes or workplaces are of no interest for the planning of a publicly accessible charging infrastructure, these categories can be left out. Indicators of importance can be chosen depending on the available statistical data. If data from household traffic surveys is available, it can also be included as indicator data into the method. Any kind of zoning can be used. Specific points can be integrated into the method in a consistent fashion.

Point data can also be left out altogether and results only generated on the level of zones. As such the method is more a flexible planning framework than one fixed method.

The method generates results in the form of several scenarios instead of one "optimal" result. During applications it has been found that discussing plausible scenarios with local representatives has a big positive side effect. Small workshops were done in which a questionnaire was collaboratively filled out. Among the local representatives this raised awareness of how to approach the planning of such an infrastructure. As more reliable information on the use of and demand for charging points become available, some parameters can be set with higher certitude, while other parameters will remain uncertain or highly depend on local policies and wishes. The advantage of generating scenarios over generating a single "optimal" result will therefore remain for future applications.

The biggest downside of the method is the large amounts of geographic data that it requires as input. Data is required which allows to locate many different kinds of activities taking place within cities. It was found that the local administrations themselves usually do not dispose of geographic data of this detail, such as an geographic inventory of shopping locations or an inventory of the biggest employers in the city. For the planning of only a handful of public charging points in a city the method is too elaborate in the form shown here. An option might be to search for data only as it is required for the final results. For instance, if the 10 most important shopping locations are needed, they are determined then, instead of preparing all important shopping locations beforehand.

A theoretical weakness of this method is that its calculations are purely list-based, i.e. it neglects the spatial interaction of locations. If two big shopping centers lie directly next to each other, they receive the same number of charging points, as if they were 2 km apart. It could be argued that less charging points would be necessary in the first case, as such charging points could serve both destinations at once. It would be good to include measures of areal coverage and density of charging points into the method. A minimal acceptable density of publicly accessible charging points could for instance be defined and all further charging points assigned according to demand.

8.4. A method of prioritization among a given set of candidate locations

The method of decision support presented above selects candidate locations from a large set of many locations of different categories. In some planning situations a smaller selection of candidate locations can be given beforehand. Examples of this might be a selection of parking garages, park and ride stations, or shops of one chain where installation of charging infrastructure is envisioned. The planning task is then to generate a prioritization among these given locations or to select the most suitable subset of them.

A connection can be made to the previously presented method. The indicator of importance used for one location category can be interpreted as an implicit prioritization of the locations, be it zones or specific points. For the location category of EcoVoiturage charging points an indicator was calculated that established a quantitative prioritization between them.

The publications [591] and [592] have already approached the spatial planning of EV charging infrastructure as a problem of prioritization. While the model in [591] calculates priorities for grid cells based on geographic statistical data, the article [592] calculates priorities for specific candidate points. The unpublished master's thesis [657] also takes a prioritization approach to determine in which parking garages charging points should be set up. The prioritization is calculated based on a weighting of different kinds of establishments within a given distance to the parking garage. In [602] a greedy algorithm is presented that places battery switching stations sequentially at the next best location. This can also be interpreted as setting up priorities for the station installation.

In the following sections the algorithmic principle behind the method used here will be shown. Then, a specific application for supermarkets in the Austrian federal state of Styria (Steiermark) will be presented. Finally, the merits and the disadvantages of the method will be discussed.

8.4.1. The algorithmic principle behind the prioritization among given locations

Within this section it will be explained how priorities of supermarkets for the placement of slow/normal charging stations are determined. The model does not make any assumptions or statements about the exact *number of charging* *points* at each of these charging stations. Fig. 8.19 shows how a priority score is calculated from a *weighted sum of different aspects which indicate the suitability of the supermarket.* The first group of aspects (starting from the top) in Fig. 8.19 considers how the markets themselves seem suitable for charging station installation. Relevant and available data of the markets themselves are the number of parking places and the number of clients per day. A high number of parking spaces indicates that many clients of the supermarket drive to the market by car. Also, if a supermarket has no parking spaces at all, the supermarket cannot set up any charging stations on its own. The number of clients per day documents the importance of markets in relation to each other.

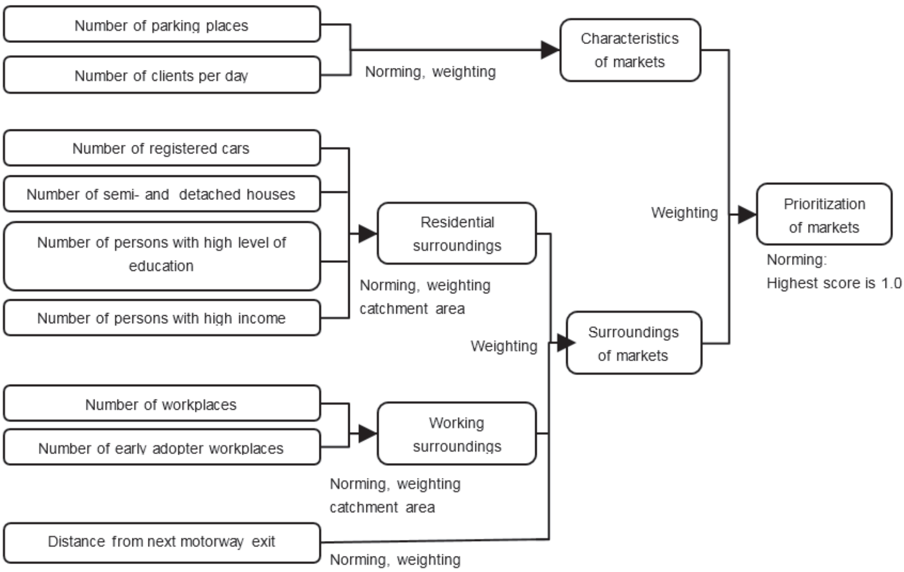


Figure 8.19.: Combing different quantitative indicators (on the left) to determine an overall priority score (on the right)

The other aspects model how charging an EV during shopping could occur within trip chains. Fig. 8.20 shows the most common trip chains observed in four different Austrian transport surveys. People usually depart from their homes to go shopping (trip chains marked in red in Fig. 8.20). The second most common point of departure to go shopping is from the workplace (marked in green in Fig. 8.20). The number and characteristics of homes or workplaces in the proximity of the market therefore seem to be a good indicators to estimate the number and characteristics of people that frequent a supermarket.

Die 10 häufigsten Ausgangswegekettenmuster in Wien, im Wiener Umland 1995, Niederösterreich 2003 und in der Stadt Salzburg 2004
(werktäglicher Personennormalverkehr) in [Prozent]

Wien 1995		Wien Umland 1995		Niederösterreich 2003		Stadt Salzburg 2004	
Wegekette	Anteil in %	Wegekette	Anteil in %	Wegekette	Anteil in %	Wegekette	Anteil in %
W-E-W	21,2%	W-A-W	25,5%	W-A-W	18,6%	W-A-W	18,7%
W-A-W	19,6%	W-E-W	21,5%	W-F-W	11,4%	W-E-W	13,1%
W-F-W	15,9%	W-F-W	15,1%	W-E-W	11,0%	W-F-W	12,6%
W-S-W	12,2%	W-S-W	14,7%	W-S-W	10,0%	W-S-W	9,4%
W-E-E-W	3,3%	W-E-E-W	3,0%	W-PE[1]-W	6,0%	W-PE[1]-W	6,0%
W-A-E-W	2,2%	W-R-W	2,9%	W-B[3]-W	4,0%	W-F	3,5%
W-R-W	1,9%	W-A-A-W	1,4%	W-W	2,6%	W-B[3]-W	3,2%
W-A-F-W	1,3%	W-A-E-W	1,1%	W-D[2]-W	2,4%	W-D[2]-W	1,4%
W-E-F-W	1,2%	W-E-F-W	1,0%	W-F	1,9%	W-E-F-W	1,1%
W-F-F-W	1,1%	W-A-A-A-W	0,8%	W-A-E-W	1,1%	W-A-E-W	1,1%
Summe	**79,9%**	**Summe**	**87,1%**	**Summe**	**69,0%**	**Summe**	**70,1%**

W... Wohnen; A ... Arbeit/dienstlich; S ... Schule/Ausbildung; E ... Einkauf/private Erledigung; F ... Freizeit/Besuche; R...anderer Zwecke

HERRY 2011

[1] PE ... private Erledigung; [2] D ... Dienstlich; [3] B ... Bringen u. Holen von Personen

Quelle: HERRY Consult, Stadt Wien MA18, Datengrundlage: BMWV - Bundesverkehrswegeplan; HERRY Consult, Mobilitätserhebung 2003 in NÖ. Im Auftrag der NÖ Landesakademie; HERRY Consult, Mobilitätsanalyse 2004 der Stadt Salzburg und Umgebung. Im Auftrag des Magistrates der Stadt Salzburg, der Landesregierung Salzburg, der Landkreise Berchtesgadener Land und Traunstein

Figure 8.20.: The ten most common trip chain patterns observed in four Austrian transport studies (W: home, A: work, E: shopping, red marking: from home to shopping, green marking: from work to shopping)

Based on this analysis of trip chain patterns, the second group of aspects in Fig. 8.19 indicates the potential of EV owners coming directly from their homes, and shopping and charging at a nearby supermarket. Characteristics of the residential surroundings taken into account are the number of registered cars, the number of semi- and detached houses, the number of persons with a high level of education, and the number of persons with a high income. While the first of these aspects just looks at car ownership at homes in general, the other three aim at locating the places of residence of potential early adopters of EVs.

Also based on the analysis of trip chain patterns above, the third group of aspects in Fig. 8.19 aims at determining the potential of EV owners stopping from their way back from work at a nearby supermarket, to shop and charge there. Aspects of the working surroundings considered are the number of employees in general and the number of employees associated with potential early adopters of EVs.

The fourth general aspect in Fig. 8.19 aims at determining the potential for EV drivers to stop at a supermarket for an intermediate charge on longer trips.

Here the homes and working places of EV drivers are expected to lie farther away from the supermarket. The used indicator is the distance from the next motorway, indicating a good accessibility of the supermarket for people driving along the motorway.

All these indicators, shown on the left side of Fig. 8.19 are *normed by a division through the highest occurring value within each dataset.* Thus, after norming the highest occurring indicator is always 1.0 for each aspect. All aspects are combined into one score, using percentages, which add up to 100 % (i.e. 1.0) (for examples see scenarios below). The final combined score is then again normed by a division by the highest occurring score. Thus the highest overall priority assigned is 1.0.

The priority scores determined in this fashion are not absolute, but always relative to those of the other supermarkets considered. If a supermarket having a highest value in some aspect is removed from the dataset, recalculation will lead to other priority scores for the remaining supermarkets.

The method shown here has obvious similarities to the method of decision support previously presented. Whereas a tree hierarchy with weights was used in the previous method to distribute a number of charging points, here it is used to calculate an overall priority score from different indicators. In the application here the weights are again varied to generate different scenarios. The aim is again to show different reasonable possibilities, rather than to calculate a single optimal solution.

How this calculation is done procedurally is shown in Fig. 8.21. Input parameters are the weights of the different aspects, as explained above, and the (fixed) radius of the catchment areas of the supermarkets. Input datasets are the supermarkets with the corresponding data, the locations of motorway exits, the communes with the corresponding sociodemographic data, and the built-up area. The procedure was implemented in ESRI ArcGIS 10.1 in the Model Builder environment. This is a visual programming environment, which allows to connect the tools provided by ESRI ArcGIS to executable programs. As the final result of the process, the markets and their prioritization is output, as well as the calculated catchment areas.

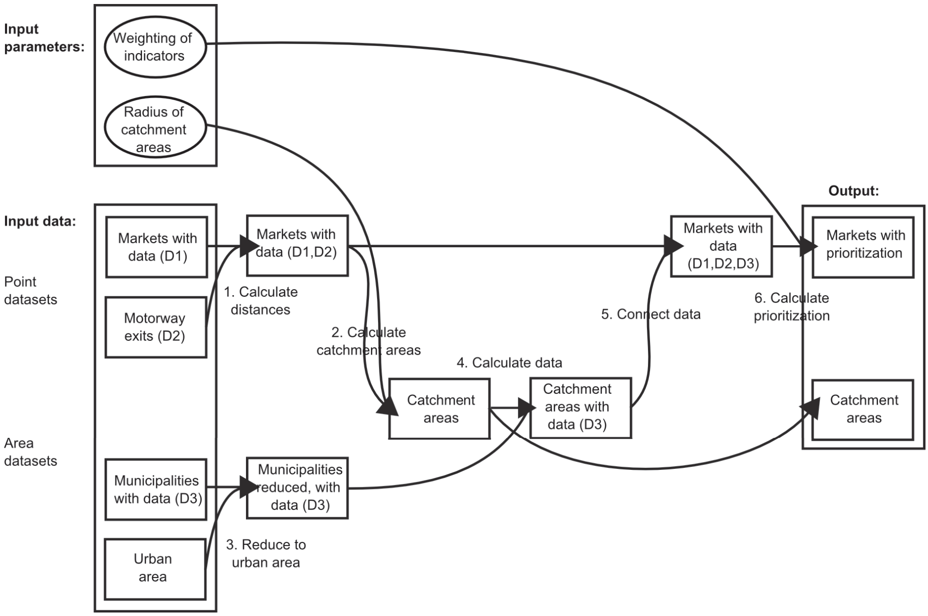


Figure 8.21.: Process for the calculation of prioritization of markets

The procedure shown in Fig. 8.21 is executed as follows:

1. **Calculate distances from motorway exits:** For every market the Euclidian distance to the next motorway exit (which corresponds to the inverse distance) is calculated (ArcGIS tool: Distance to). In order to obtain an indicator value in the interval [0,1], where the best value, i.e. minimal distance, obtains a rating of 1.0 and the worst value, i.e. maximal distance, a rating of 0.0, the following calculation is done:

$$Ind_j = (Max(d_i) - d_j)/(Max(d_i) - Min(d_i))$$

With the variables:

d_j:	distance for supermarket j
$Max(d_i)$:	maximal distance of all supermarkets
$Min(d_i)$:	minimal distance of all supermarkets

The calculated distance indicators are joined to the markets (ArcGIS tool: Join field).

2. **Calculate catchment areas**: for every supermarket the corresponding catchment area is calculated. This area consists of all locations that have an Euclidian distance to the market which is smaller or equal to the catchment area radius given as an input, and for which the given market is the closest of all markets. This is implemented in ArcGIS by intersecting generated Thiessen polygons with Buffers with the given radius (what this means can be seen looking at the scenario results below).

3. **Reduce to built area**: the data given for communes is reduced to the built area. This is done to take into account that the sociodemographic data of communes concerning residents and employees is distributed over the built-up area only, and not over agricultural or forest areas (ArcGIS tool: Intersect).

4. **Calculate data for catchment areas**: in this processing step the data for the built-up area of communes is transferred to the catchment areas. The commune data is first recalculated in the form of densities by a division by the surface of the built-up area (ArcGIS tool: Calculate field). The previously determined catchment areas are cut/overlayed with the built-up area of the communes (ArcGIS tool: Overlay). For the thus created area fragments absolute indicator values are calculated: IndicatorDensity * FragmentSurface (ArcGIS tool: Calculate field). The area fragments belonging to each catchment area are then connected and their absolute indicator values summed up (ArcGIS tool: Dissolve). Thus, the data given for communes is transferred to the catchment areas of the supermarkets.

5. **Connect data**: the data calculated for the catchment areas is joined to the corresponding supermarkets (ArcGIS tool: Join).

6. **Calculate prioritization**: the data on markets, distance from motorway exits, and sociodemographic data for catchment areas is now used to calculate priorities (ArGIS tools: Add field, Calculate field). First, scores B_j are calculated for each market j. The final priority values P_j are then obtained by norming the B_j values:

$$B_j = \sum_i w_i \cdot (Ind_{ij}/Max_i(Ind_{ij}))$$

With the variables:

w_i:	weights for each aspect, determined by multiplying percentages along the branching structure (see above)

Ind_{ij}: indicator value of aspect i for supermarket j

$Max_i(Ind_{ij})$: maximally occurring value for aspect i among all supermarkets j

The resulting values are again normed, so that the highest final priority score is 1.0:

$$P_j = B_j/Max(B_i)$$

With the variable:

$Max(B_i)$: maximal value of all supermarkets i

8.4.2. Application: prioritization of supermarkets in the Austrian federal state of Styria for the placement of charging stations

The method of prioritization for the placement of charging stations has been applied to a supermarket chain in the Austrian federal state of Styria (Steiermark). This is one of nine federal states of the country. It has a size of 16 401 km^2, and consists of 287 communes. In 2014 the federal state had 1 215 246 inhabitants [658]. It is located in the Alps, therefore urban areas and streets mainly lie sparsely distributed along the existing valleys.

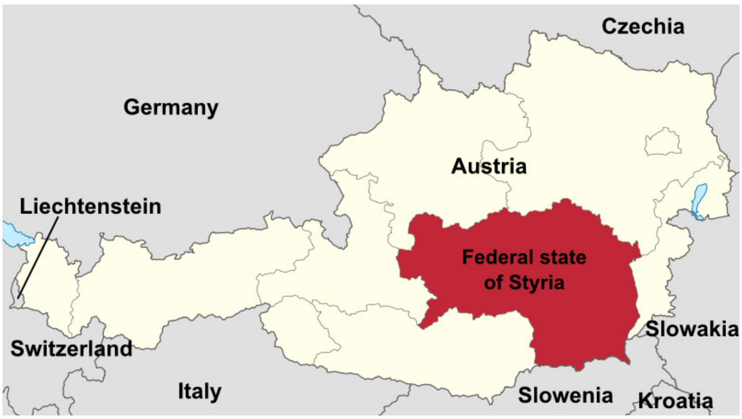


Figure 8.22.: Geographic location of the federal state of Styria in Austria (adapted from [659])

The supermarket chain for which the study was originally done did not allow market data and calculation results to be published. The results shown below were obtained using publicly available data of the supermarket chain *Billa* of which 151 supermarkets are located in Styria. Client statistics were not available for this supermarkets chain and were therefore approximated (see below).

At the time when this study was done there were still very few EVs and charging stations in Austria. At the end of the year 2013 there were 2 070 electric cars registered in Austria. This corresponds to 0.04 % of all registered cars. Gasoline hybrid electric cars were 10 049 in number, corresponding to 0.2 %, and diesel hybrid electric cars were 455 in number, corresponding to 0.01 % [660]. Fig. 8.23 shows how the number of electric and hybrid cars were distributed among the Austrian federal states. In the federal state of Styria there were only 233 electric cars registered.

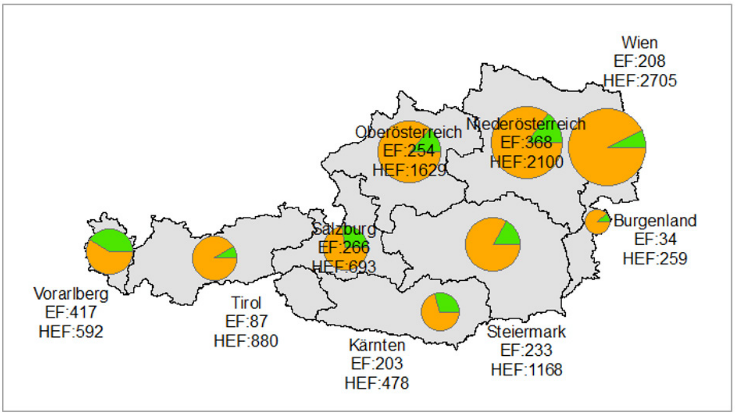


Figure 8.23.: Registered EVs (EF) and hybrid electric vehicles (HEF) in the federal states of Austria on 31.12.2013 (data from [660])

Accordingly, publicly accessible charging stations were also rare during these years. At the beginning of 2014, the website LEMnet [661] listed 561 publicly accessible locations of charging stations for Austria. Their geographic locations are shown in Fig. 8.24. It can be seen that clusters of charging stations mainly occur in big cities. The other source [662] specifically lists 59 locations of charging stations in the federal state of Styria in 2014.

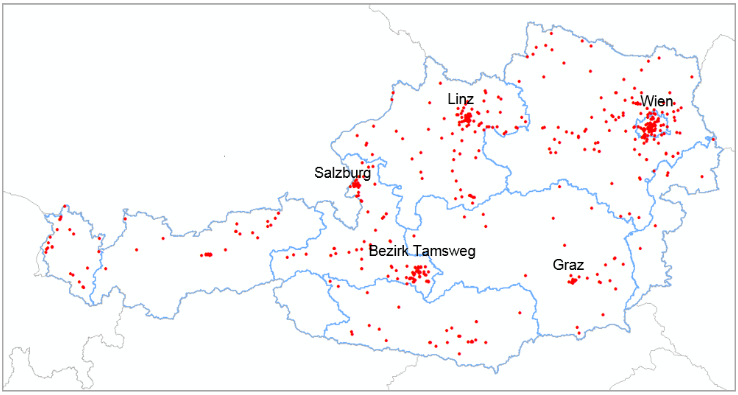


Figure 8.24.: Charging stations in Austria in February 2012 (according to data from [661])

8.4.2.1. Data preparation for the federal state of Styria

Tab. 8.4 lists the data that has been used for the application. The dataset noted in italics (number of households) was not directly used, but served only to perform calculations for another dataset. The statistical data on communes was joined to the communes shapefile in order to receive the required dataset. The built area and the motorway exits entered the algorithm as separate shapefiles (see Fig. 8.21).

Table 8.4.: Data used for the application in Styria

Data category (overarching)	**Dataset**	**Data type**	**Source** (websites accessed 01/02.2014)
Basic data	Communes	Shapefile: polygons	Land Oberösterreich, Abteilung Geoinformation und Liegenschaft: generalized commune borders based on the DKM (Status 10/2012): http://www.data.gv.at/datensatz/?id=ooe-DD110579032A41A9AE646A0493932D34 Change of commune codes in the years 2010 to 2012 reconstructed using: http://www.statistikaustria.eu/web_de/klassifikationen/regionale_gliederungen/gemeinden/index.html
	Land use data (built up area)	Shapefile: polygons	European Environment Agency and Umweltbundesamt Österreich: CORINE land cover 2006: https://secure.umweltbundesamt.at/data/download?cgiproxy_skip=true&id=1
Data on supermarkets	Locations of supermarkets	Shapefile: points	Billa markets taken for case study here: https://www.billa.at/Footer_Nav_Seiten/Filialsuche/dd_bi_channelpage.aspx accessed 20.01.2015 Addresses georeferenced using GPSVisualiser: http://www.gpsvisualizer.com/
	Number of parking spaces at supermarkets	(Excel-) List with reference to markets	Billa website: https://www.billa.at/Footer_Nav_Seiten/Filialsuche/dd_bi_channelpage.aspx accessed 20.01.2015

Continued on next page

Table 8.4 – *Continued from previous page*

Data category (overarching)	**Dataset**	**Data type**	**Source** (websites accessed 01/02.2014)
	Number of daily clients in supermarkets	(Excel-) List with reference to markets	Data not available for Billa markets, therefore artificially constructed based on the original market data, as a function of the number of parking spaces: 0 parking spaces: 1500 clients/day 1–49 parking spaces: 950 clients/day 50–74 parking spaces: 800 clients/day 75–150 parking spaces: 850 clients/day
Residential surroundings	*Number of households*	*(Excel-) List with reference to communes*	*Statistik Austria: register count 2011: commune table Austria:* `http://www.statistik.at/web_de/static/registerzaehlung_2011_gemeindetabelle_oesterreich_073982.xlsx`
	Number of registered cars	(Excel-) List with reference to communes	Statistik Austria: statistics on motor powered vehicles: stock on 31.12.2013 (purchased dataset) Dataset only available on the level of political districts. Therefore disaggregated to the level of communes using the number of households in communes (source see above)
	Number of semi- and detached buildings	(Excel-) List with reference to communes	Statistik Austria: register-based census 2011: building census (data downloaded for a fee from `http://www.statcube.at`)

Continued on next page

Table 8.4 – *Continued from previous page*

Data category (overarching)	**Dataset**	**Data type**	**Source** (websites accessed 01/02.2014)
	Number of persons with a high level of education (tertiary education degree)	(Excel-) List with reference to communes	Statistik Austria: register Count 2011: commune table Austria: `http://www.statistik.at/web_de/static/registerzaehlung_2011_gemeindetabelle_oesterreich_073982.xlsx`
	Number of persons with a net income of more than 50 k€ per year	(Excel-) List with reference to communes	Statistik Austria: Direktion Volkswirtschaft Veranlagte Steuern: data on income in communes (purchased dataset) Communes for which no number was given due to privacy issues: number set to 2 (1 lower than lowest occurring value of 3)
Working surroundings	Number of employees	(Excel-) List with reference to communes	Statistik Austria: register-based census 2011: persons employed on the local unit (data downloaded for a fee from `http:\www.statcube.at`)
	Number of potential early adopter employees	(Excel-) List with reference to communes	Statistik Austria: register-based census 2011: persons employed on the local unit (data downloaded for a fee from `http:\www.statcube.at`) Subset of employees selected according to their working sector: electric utilities, IT, finance and insurance, science and technology
Motorway network	Motorway network, including exits and entrances	Shapefile: lines, points	Open Street Map: Austria, roads: `http://download.geofabrik.de/europe/austria-latest.shp.zip`

8.4.2.2. Introductory remarks for all scenarios

In the following sections four different scenarios for the prioritization of supermarkets for the placement of charging stations will be presented. For the radius of the catchment area of supermarkets a value of 7.5 km is used each time. The first three scenarios are calculated with strongly biased parameterizations in order to show distinct strategies of location choice. The first scenario aims at placing charging stations mainly at big inter-regional markets with good connection to the motorway network. The second scenario puts the emphasis on markets for local supply. The third scenario aims at placing charging stations at locations which are expected to be frequented by early adopters. Finally, the fourth scenario mixes all considered aspects.

The scenario names and results presented here make it seem like the three main location strategies were already known beforehand. But actually they evolved during the generation of different scenarios. Previously generated mixed scenarios showed little difference. Generating more contrasting scenarios finally lead to the three main approaches.

8.4.2.3. Scenario 1: charging stations at big inter-regional supermarkets

This scenario aims at placing charging stations mainly at big inter-regional supermarkets. This is realized by putting the main weight on supermarkets with many parking places. The second major aspect is the proximity of the market to a motorway exit. The number of daily clients in the supermarket is also included as a relevant aspect.

The weights chosen for the scenario are:

- ∘ 70% Supermarkets:
    - ⋄ 75 % Number of parking places (absolute: 52.5 %)
    - ⋄ 25 % Number of clients per day (absolute: 17.5 %)
- ∘ 30 % Surroundings of supermarkets:
    - ⋄ 0 % Places of residence:
        - ▹ 0 % Number of registered cars
        - ▹ 0 % Number of detached and semi-detached houses
        - ▹ 0 % Number of persons with high level of education
        - ▹ 0 % Number of persons with high income

- ◇ 0 % Places of work:
    - ▷ 0 % Number of employees
    - ▷ 0 % Number of early adopter employees
- ◇ 100 % Proximity to motorway (absolute: 30 %)

The results of the priority calculation can be seen in Fig. 8.25. The markets with the highest priorities (shown in deep red in the figure) are located along the major motorways (shown in light blue in the background in the figure), and in a ring around the city of Graz, located in the southeast of the state. The supermarket with the highest priority score of 1.0 is located right to the northeast of Graz.

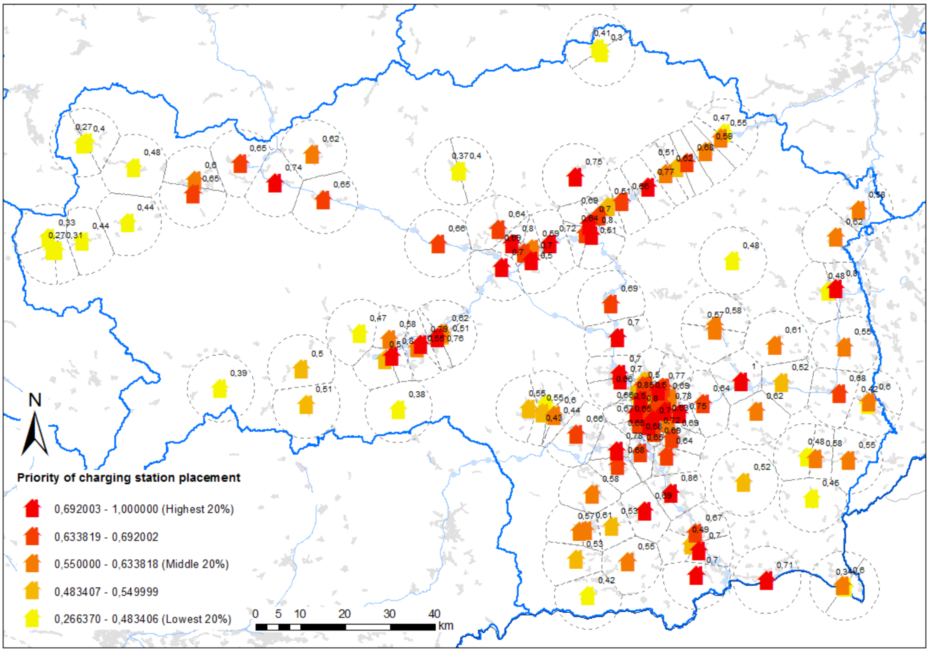


Figure 8.25.: Prioritization results for scenario 1: charging stations at big inter-regional supermarkets

8.4.2.4. Scenario 2: charging stations at supermarkets for local supply

This scenario puts the emphasis on markets used for local supply. The number of registered vehicles and the number of employees in the supermarkets catchment area are taken as the aspects with the highest relevance. The number of parking spaces and the number of clients per day are added as minor aspects.

The weights used for the scenario are:

- ◦ 30% Supermarkets:
  - ◇ 50 % Number of parking places (absolute: 15 %)
  - ◇ 50 % Number of clients per day (absolute: 15 %)
- ◦ 70 % Surroundings of supermarkets:
  - ◇ 50 % Places of residence:
    - ▷ 100 % Number of registered cars (absolute: 35 %)
    - ▷ 0 % Number of detached and semi-detached houses
    - ▷ 0 % Number of persons with high level of education
    - ▷ 0 % Number of persons with high income
  - ◇ 50 % Places of work:
    - ▷ 100 % Number of employees (absolute: 35 %)
    - ▷ 0 % Number of early adopter employees
  - ◇ 0% Proximity to motorway

The results of the priority calculation are shown in Fig. 8.26. In comparison to scenario 1 it can be seen that the markets with the highest priority scores lie mainly in the south, in a ring around Graz, and in smaller communes in the periphery. Surprisingly, the supermarket with the highest priority score of 1.0 is the same as in the previous scenario, lying to the northeast of Graz. This seems to be due to the fact that the market catchment area covers a big part of urban space, where many people work and live, which is relevant for this scenario, as well as lying close to the motorway, a point relevant for the previous scenario.

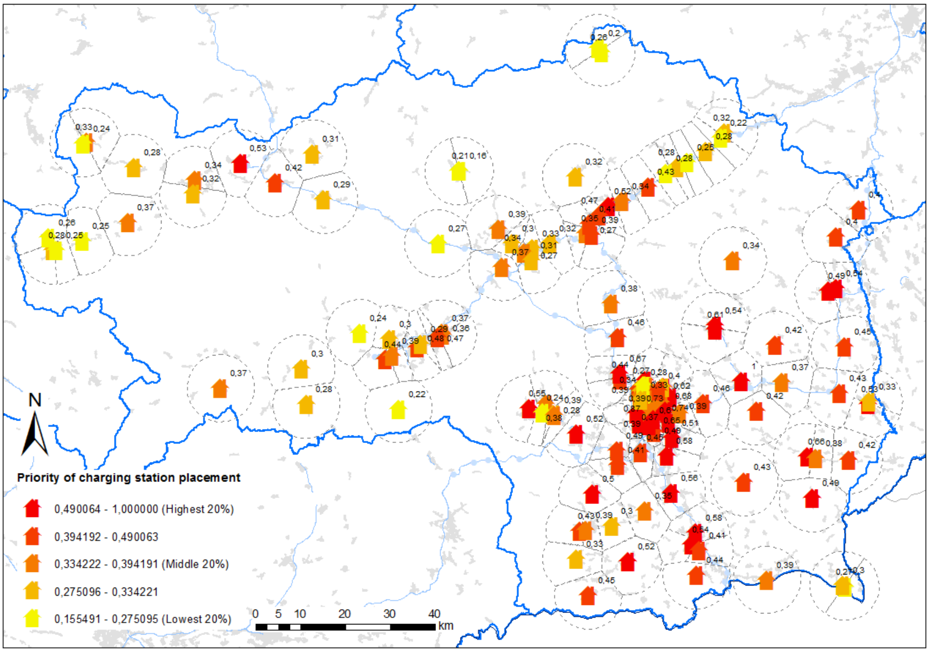


Figure 8.26.: Prioritization results for scenario 2: charging stations at supermarkets for local supply

8.4.2.5. Scenario 3: charging stations at supermarkets frequented by potential early adopters

The third scenario aims at placing charging stations at supermarkets that might be frequented by early adopters of EVs. The number of people with an early adopter profile that work and live in proximity to the market are considered.

Early adopter working sectors are considered to be electric utilities, IT, finance and insurances, and science and technology. Employees working in these sectors can be expected to have a high level of education, to have a high level of income, and to be affine to new technologies. The number of employees working in these sectors in proximity to the market are considered. Concerning the home of potential early adopters of EVs, they can be expected to live in semi- and detached houses. Such houses are usually equipped with private garages where the owner can charge his own EV. The aspects of high education and high income of residents are also considered.

The weights used for the scenario are:

- ◦ 0% Supermarkets:
  - ⋄ 0 % Number of parking places
  - ⋄ 0 % Number of clients per day
- ◦ 100 % Surroundings of supermarkets:
  - ⋄ 50 % Places of residence:
    - ▷ 0 % Number of registered cars
    - ▷ 50 % Number of detached and semi-detached houses (absolute: 25 %)
    - ▷ 25 % Number of persons with high level of education (absolute: 12.5 %)
    - ▷ 25 % Number of persons with high income (absolute: 12.5 %)
  - ⋄ 50 % Places of work:
    - ▷ 0 % Number of employees
    - ▷ 100 % Number of early adopter employees (absolute: 50 %)
  - ⋄ 0% Proximity to motorway

The results of the priority calculation can be seen in Fig. 8.27. In comparison to the previous scenarios it can be seen how the periphery of Graz is strongly emphasized. The supermarket with the highest priority score lies just outside the city to the east. Supermarkets in satellite towns lying around Graz also receive high priority scores. This distribution is reasonable. High earning innovative jobs can be expected to mainly lie in the big city of Graz. Affluent residents can be expected to live in the suburbs and satellite towns of the city.

8.4.2.6. Scenario 4: combination of all aspects

This scenario combines all aspects into one priority score. The aspects are included with descending weight of residential surroundings, supermarket characteristics, working surroundings, and proximity to motorways.

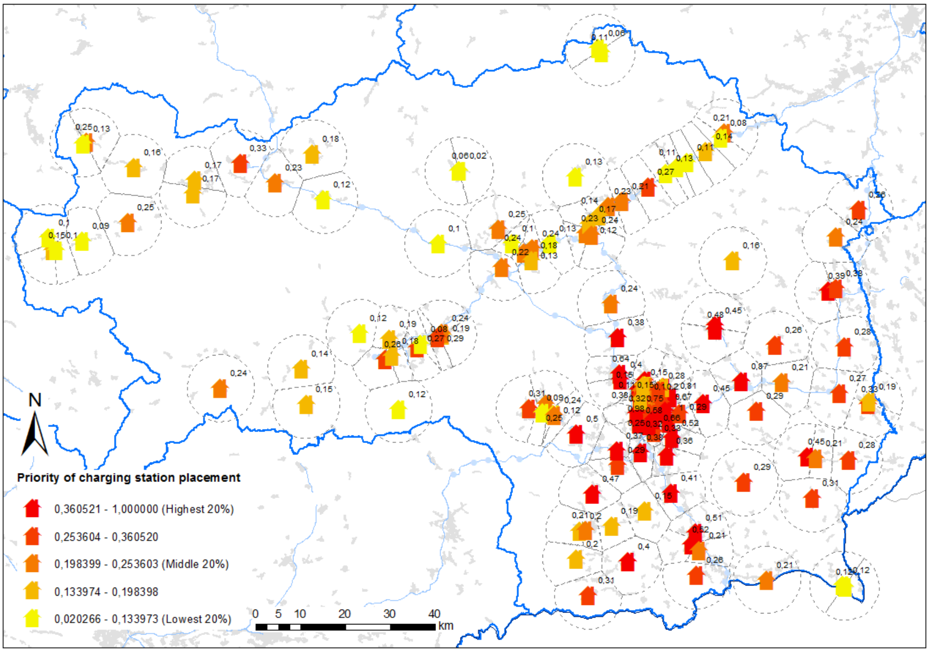


Figure 8.27.: Prioritization results for scenario 3: charging stations at supermarkets frequented by potential early adopters

The used weights are:

- 30% Supermarkets:
  - 50 % Number of parking places (absolute: 15 %)
  - 50 % Number of clients per day (absolute: 15 %)
- 70 % Surroundings of supermarkets:
  - 45 % Places of residence:
    - 50 % Number of registered cars (absolute: 15.75 %)
    - 20 % Number of detached and semi-detached houses (absolute: 6.3 %)
    - 15 % Number of persons with high level of education (absolute: 4.725 %)
    - 15 % Number of persons with high income (absolute: 4.725 %)
  - 35 % Places of work:

  - ▷ 50 % Number of employees (absolute: 12.25 %)
  - ▷ 50 % Number of early adopter employees (absolute: 12.25 %)
- ◇ 20% Proximity to motorway (absolute: 14 %)

The results of the priority calculation are shown in Fig. 8.28. The tendencies observed in the previous scenarios are again visible here in a more diffuse form. High priorities are calculated for supermarkets in a ring around Graz, in the surrounding satellite towns, and, to a lesser degree in this scenario, also to those located along the major motorways.

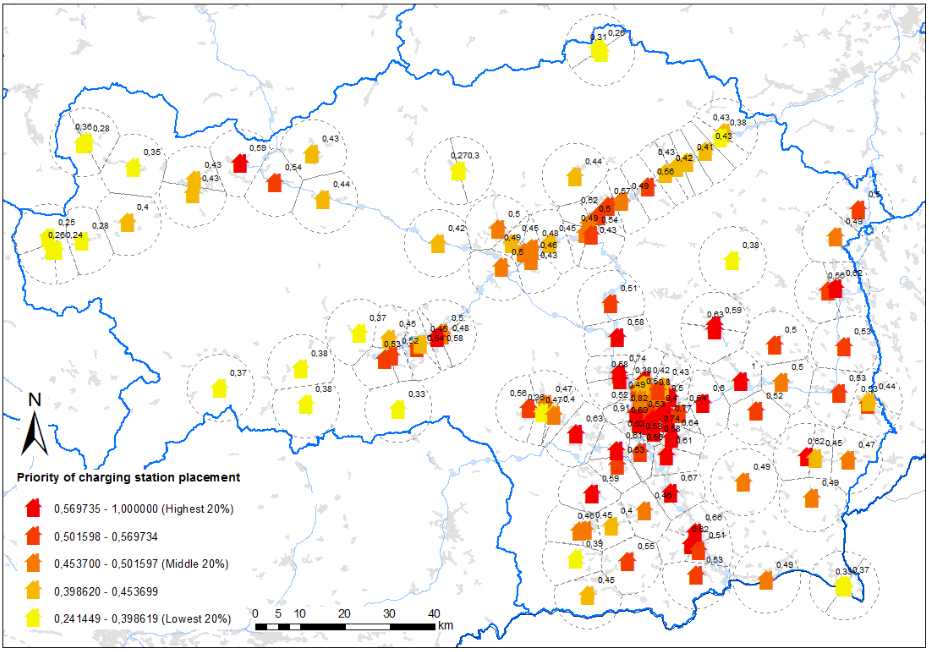


Figure 8.28.: Prioritization results for scenario 4: combination of all aspects

8.4.3. Merits and disadvantages of the method

The method of prioritization of supermarkets for the placement of charging stations for EVs shown above allowed to explore different location strategies. Charging stations can be placed at big inter-regional markets along the major motorways, where they can also be used for immediate recharging on longer trips. Alternatively, they can be placed in supermarkets which rather serve local demand from residents and employees. If this strategy is followed, the immediate area around Graz and supermarkets in peripheral towns are chosen. If more emphasis is put on locating charging stations in areas where potential early adopters live and work, supermarkets in the suburbs and satellite towns of Graz become more important. These three approaches can be combined in one plan, as has been demonstrated in the fourth scenario.

The main point where further refinements to the method could be made is the way the catchment areas of the supermarkets are modeled. Instead of using the Euclidian distance, the distance could be calculated based on the existing road network. This seems relevant in such a mountainous region as in this application, where roads follow mountain valleys and not shortest distances on a plain. However, with the relatively short radius of 7.5 km used here, this should not influence results to a large extent. The actual road distance could also be used to refine the distance calculation from the next motorway exit. Sensitivity analyses for the assumed size of the catchment areas could also be done. The implemented catchment areas assume that residents and employees drive to the nearest supermarket. But the dataset only includes the supermarkets of one chain. It is not clear how the competitors' supermarket locations or the location of other charging stations influences the choice of shopping and charging at a supermarket.

Previously generated exploratory scenarios (not presented here) showed that the results of the prioritization tend to be similar when many aspects are included. This indicates that some of the used indicators might be correlated. The scatter plot matrix shown in Fig. 8.29 confirms this. The diagram shows scatterplots of each combination of indicators as they were calculated for the above method. The size of the catchment areas is also included as an additional variable.

Strong linear relationships can be seen between the number of employees, the number of employees in early adopter sectors, the number of persons with high income and the number of persons with a high level of education (scatter plots within small red box in Fig. 8.29). A linear relationship is clearly visible in the plots. The corresponding Pearson correlation coefficients confirm this. The number of persons with high income and the number of persons with high education have a very high coefficient of 0.96. The number of semi- and detached houses and the number of registered cars also seems to be linearly correlated to these variables and to each other (scatter plots within big red box in Fig. 8.29). The two variables have a correlation coefficient of 0.84.

Figure 8.29.: Scatter plot matrix of used indicators and size of the calculated catchment area ("CatchmArea") (all normed so that maximal value is 1.0), Pearson correlation coefficients as red numbers in upper diagonal half

That the size of the catchment area does not seem to be directly correlated to any other variable is a positive finding in this context. Otherwise the specific way in which the catchment areas are calculated, with the chosen radius and their spatial constellation, would have a (too) strong influence on the result. The catchment areas were an auxiliary construct to be able to transfer data given for the level of communes to individual supermarkets in a plausible and consistent manner.

The staggered patterns visible for the number of clients per day are due to the fact that these values were approximated as a function of the number of parking places at the supermarket (see Tab. 8.4).

An interesting pattern is also visible in the scatter plots for the distance from the next motorway exit and the last variables in Fig. 8.29, especially in the case of number of persons with high income and high level of education. The plot indicates that supermarkets in whose surrounding people with high levels of income and education live also have a good connection to the motorway.

Further statistical analyses in this direction, such as main component analysis or factor analysis, could be used to reduce the number of used indicators, or identify further underlying patterns in such a dataset.

8.5. Conclusion: location planning of electric vehicle infrastructure

This chapter has begun with an overview of publications which treat the spatial planning of EV charging infrastructure. The survey shows that a very high number of methods have already been published. The published methods vary in the type of charging facilities and types of vehicles that are considered, the size and structure of the region, the aspects that are taken into account (demand for charging, impact on electricity network, economic factors, and others), the way spatial entities are modeled (points, areas, networks), whether the location choice is done discrete or continuous, the level of formalism of the method, and the specific algorithmic approach taken (mixed integer linear programming, meta heuristics, game theory, (agent-based) simulation, and others).

In Germany the spatial planning of infrastructure takes place within a given regulatory framework. Plans are set up on different political levels (EU, Germany, federal states, regions, municipalities, construction sites). Generally the spatial plans are prepared in more and more detail the lower the planning level is. It is not clear yet how the spatial planning of EV infrastructure will fit into the given framework. The EU and the German government have already set up targets for the number of charging points to be set up in the future. In the next years the spatial planning of charging points could be integrated in the spatial planning documents prepared by the federal states, regions, and municipalities.

Within this chapter two specific methods for the location planning of charging points have been presented. The first method aims at providing decision support for the development of charging infrastructure in a city or region. The method requires an enumeration of possible candidate locations within a geographic database. Locations can be defined in the form of zones or can be defined as specific points. A given total number of charging points is distributed among different location categories, according to weights defined within a hierarchical tree structure. Within one location category, charging points are proportionally distributed according to indicators of relative importance (number of employees, number of registered cars, number of parking spaces etc.). The algorithm has been implemented as a tool in GIS, which allows to easily generate different scenarios. In order to generate scenarios which are in line with local policy and local wishes, workshops with local representatives have been done, in which a prepared questionnaire has been filled out. During applications it has been found that these discussions create a high amount of added value, as they lead to a local raising of awareness on possibilities on how to approach the task of charging infrastructure planning. Next to the case study of the Province of Liège in Belgium shown here, variants of the method have been applied to six other case studies in Germany and France. A big advantage of the method is its simplicity and adaptability, which allows its application in different situations. The biggest disadvantage is the large amounts of geographic data that it requires as input.

The other method presented in this chapter calculates priorities for the setting up of charging stations at given supermarket locations. Priority scores are calculated by a weighted sum of different aspects. The aspects taken into account are characteristics of the supermarkets themselves (number of parking spaces, of daily clients), the characteristics of residents living in the supermarkets' surroundings (number of registered cars, of detached and semi-detached houses, of persons with high level of education, of persons with a high income), the characteristics of people employed in the supermarkets' surroundings (number of employees, of employees in sectors attributed with an an early adopter profile), and the distance from the next motorway exit. Transferring statistical data given for communes to individual supermarkets requires the modeling of catchment areas of the supermarkets. The generated scenarios show three different strategies for the location choice of charging stations. Charging stations can be placed at inter-regionally used supermarkets with a good motorway connection, at markets used for local supply, or at supermarkets in the surroundings of which many people live and work, that have the characteristics of potential early adopters of EVs. The main improvement that could be made to the method is the refinement of the calculation of the catchment areas, for instance by calculating distances within the road network. Linear correlations and other patterns in the data could be used to lower the number of used variables, or to generate further sets of contrasting scenarios.

Overall the methods presented in this chapter show how diverse the aspects are that should to be taken into account for the spatial planning of EV charging infrastructure. Large amounts of spatial data are required to perform the planning. The author is in favor of showing different possibilities of implementing infrastructure in the form of different scenarios, instead of calculating one "optimal" result. Due to the varying interests of local stakeholders and due to the fact that the diverse aspects of the demand for charging infrastructure by EV drivers are not yet fully understood, it does not seem reasonable to define single fixed criteria of optimality.

9. Location planning of an EV charging infrastructure on the street scale

In the previous Chap. 8 different methods were shown for the location planning of charging points on the level of city districts or communes, or near specific points of interest. Following the location planning on this *macro scale* further location planning has to be done on the *micro scale*. The charging facility and further components, such as associated signs and protective pollards, have to be integrated into the existing parking spaces and local streetscape.

Within this chapter micro location planning will be considered for conductive (i.e. using cables) slow/normal charging stations located on public streets. The legal framework in place in Germany, specifically in the federal state of Baden-Württemberg, is taken into account. Some specifics for the placement of charging stations in publicly accessible parking garages will also be discussed. Planning of charging stations in the private context, at homes and workplaces, will not be considered. Specific issues for fast charging stations, inductive charging stations, and battery swapping stations also will not be discussed in detail here (for information on these topics please see the given references below).

The criteria for location planning on the micro level are rather diverse and qualitative in form. Thus, it is not practicable to do this location planning in a structured mathematical manner, as has been done before for the location planning on the macro scale. Instead, it is reasonable to use only semi-formalized location planning frameworks, which allow urban planners to take the decisions in a partially intuitive form.

Several good handbooks on location planning on the micro level are already publicly available. In Germany such publications have emerged from the model regions of electric mobility. The guideline [12] treats aspects of location planning, approval processes for the installation of charging stations, and shows best practices from the model regions. The report [585] focuses on issues involved in the approval process and contains a model contract between a charging station company and a municipality. The report [14] contains a chapter on the location planning of charging stations which shows examples of methods from the model regions on the macro and micro scale. The research report [663] contains an analysis of the interaction of stakeholders during the approval process for charging stations in Berlin, as well as a discussion of aspects to consider during micro planning. The regulative framework for the installation of commercially operated charging stations on public ground in Germany is discussed in the article [400]. The above mentioned report [12] builds on work of the author of this article. Specific aspects to be taken into account for the planning charging stations in parking garages are treated in [32]. The technical guideline [39] mainly treats the electric installation of charging facilities, but also contains some tips on general micro planning.

Specific applying regulations vary from country to country. Thus, micro planning handbooks from other countries cannot be used directly. Still, many general principles remain relevant. Good publications from countries other than Germany are the handbook [177] for the San Diego area in the USA and the guideline [10] for London in the UK.

Specific aspects to consider for the micro location planning of *fast charging stations* are treated in the publication [664] from Sweden. Some micro planning issues for *battery swapping stations* are addressed in the report [665] from Denmark. For these kinds of facilities existing best practices for the implementation of gasoline stations should also be taken into account [666].

Within this chapter first the diverse aspects are examined that should be considered for the placement of charging facilities and associated components on the micro level. Then, it will be discussed how the many required permits can be acquired from the responsible municipal departments and technical service providers. Finally, it will be shown how the diverse criteria and requirements of permitting procedures can be combined in operational location planning methods. The contents of this chapter are partially based on work done at the European Institute for Energy research together with Anne-Sophie Fulda in the years 2009–2010 [645].

9.1. Aspects to consider for micro planning

Many diverse aspects need to be considered when planning charging stations on the micro scale. In the following sections technical prerequisites, possible spatial configurations of charging stations, parking regulations and signage, weather protection and lighting, impacts on other traffic participants, and issues of urban design will be discussed. Finally it will also be discussed which further points need to be considered when placing charging stations in parking garages instead of on the street.

9.1.1. Technical prerequisites

Several technical prerequisites need to be fulfilled in order for it to be feasible to install charging facilities at a location. The *required number of parking places needs to be available* at a location. It makes sense to install charging stations at locations where several parking places remain available for conventional vehicles. Otherwise drivers of conventional vehicles might park on the parking spaces intended for EV charging.

The *ground owner of the parking spaces needs to give his permission* for the installation of a charging station. In Germany the responsibility of operating curbside parking spaces usually lies with the municipality. The installation of public charging stations is usually interpreted as a *special use (Sondernutzung)* of public ground for commercial purposes [12] [400] [585]. Thus, the operator usually needs to acquire a special use permit from and pay a special use fee (Sondernutzungsgebühr) to the municipality. The municipality can exempt the operator from paying such a fee, for instance by acknowledging that the setting up of charging infrastructure is "predominantly in the public interest" [399]. The exemption is reasonable, as it currently seems quite difficult to operate public charging stations profitably (compare Sec. 5.2.3.2). The municipality can impose further conditions to be fulfilled by the operator for issuing the permit for the special use (an example contract is shown in [585]).

Existing land use plans seem to pose little obstacles for the setting up of charging stations. If charging stations are interpreted as nondisruptive businesses (nicht störende Gewerbebetriebe), they cannot be installed within residential-only areas. They can exceptionally be installed in small residential estate areas and general residential areas. They are allowed in all other areas [400] [667].

Facilities which emit sound levels of over 35 dB are not allowed to be operated near hospitals or nursing homes at night according to German law [529]. This low threshold can be exceeded by fast DC charging stations when they are charging and EV [73]. A cautious approach is therefore to keep a distance to such establishments when locating charging stations.

Another important technical prerequisite is the *easy connection of the charging facilities to the electricity distribution grid*. This aspect has already been treated in detail in Sec. 3.4 within this document. The costs of the ground works depend on the distance between the branching point of the distribution network and the charging facilities (see Sec. 5.2.3.1). In Germany distribution network cables are usually installed underground on both sides of the street. If street lighting is located on one side of a street, underground distribution network cables are usually also located there [174]. Connection and ground work costs can thus often be reduced by moving a charging station to the other side of the street or a few meters further down the road. If the local transformer is operating close to its maximal capacity, it can also be reasonable to move a charging station to a nearby location where it can be connected to another transformer station. This reduces incurred network reinforcement costs. Such plannings should be done in collaboration with network planners of the local distribution system operator.

If charging facilities are to communicate with a back-end system, it must be assured that a *cable-bound or mobile telecommunications connection is available* at the location. At most inner-city locations mobile connectivity should not be a problem nowadays.

Another technical aspect to take into account is that of *fire safety*. There seem to be no specific legal requirements concerning the fire safety of charging stations. Still, common sense should be applied, for instance by not installing charging facilities directly near fuel dispensers or gas tanks.

9.1.2. Spatial configurations of parking spaces and charging facilities

The spatial configuration of parking spaces, charging facilities, and possible further components needs to be considered. It is not possible to find generic "ideal" configurations because the location of the socket inlet can vary among different models of EVs, PHEVs, and REEVs. This is shown in Fig. 9.1. The majority of EVs, especially from German manufacturers, seem to have the socket on the right rear side. This is also the location where the tank lid is usually located on conventional vehicles. However, other locations are also implemented. Some EVs even have sockets on several locations, such as the Renault Fluence with normal charging sockets on the left and right front side, or the Mitsubishi Electric Vehicle with a normal charging socket on the left rear side and a fast charging socket on the left right side.

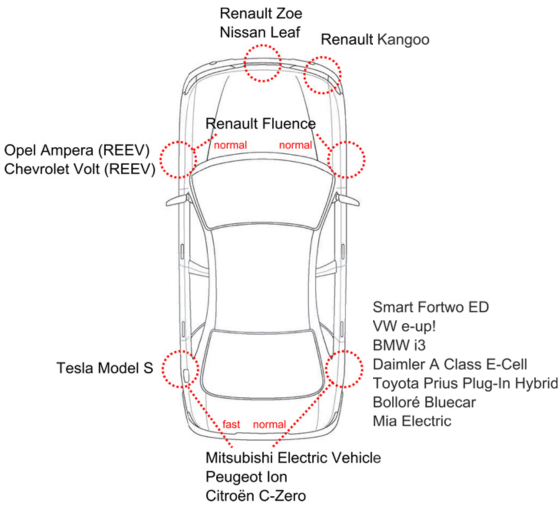


Figure 9.1.: Location of the socket inlet for different EV, PHEV, and REEV models (based on internet picture evaluation, diagram of car from [668])

Urban planners and architects have developed best practices for the planning of streets and integration of urban furniture. For instance, recommendations for the construction of parking places and garages are given in [669]. The book [670] contains a large collection of best practices for the planning of different kinds of sites. But for the spatial planning of charging stations no commonly accepted best practices seem to exist yet.

The report [663] shows specific layouts for the planning of charging stations at public parking spaces. The layout plans have been prepared for charging pillars which provide two charging points and assume that sockets are located at the front or back of EVs. They could easily be adapted to charging pillars providing 1 or 4 charging points. The site plans for parallel parking, bay parking, and angle parking are shown in Fig. 9.2, Fig. 9.3 and Fig. 9.4 respectively. The given distance measures are based on existing recommendations for the construction of parking spaces and city streets [663]. A generic approach would be to place charging stations at the same distance to the curbside as already existing street furniture such as lamp posts and signs. A further parking constellation not shown in the figures is that of block (bay) parking. If a charging facility is placed centrally between the parking spaces, up to four EVs can recharge at one charging facility at once [32].

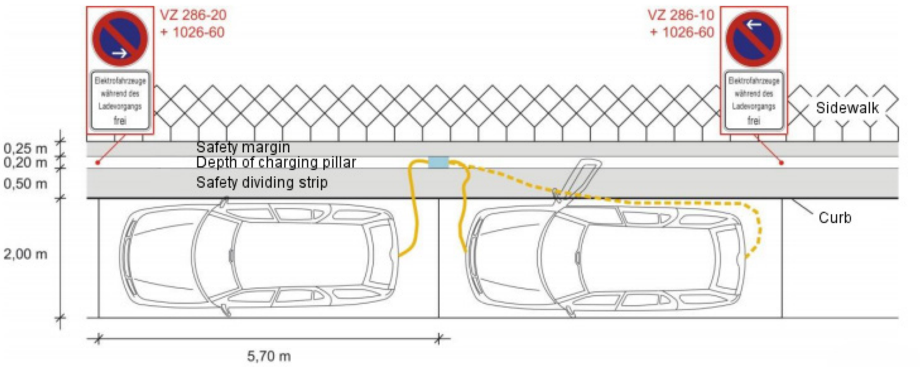


Figure 9.2.: Site layout for parallel parking given in [663] (translated)

If charging pillars are not protected from being rammed by cars by the curb, as assumed in the layouts shown above, it can be necessary to install *additional protective pollards, wheel stops, or steel frames between the parking space and the charging facility.*

The special *accessibility requirements of persons in wheelchairs* do not seem to play a role in German regulations and documents on micro planning of charging stations [12] [585] [14], but are treated in documents from the UK [10] and the USA [671] [177]. General requirements for disabled persons' parking spaces in Germany are given in [669]. The recommended layouts for disabled persons' parking spaces are shown in Fig. 9.5 on the left. An aisle of at least 1 m width needs to be free next to the parking space with a normal width of 2.50 m (also compare [672]). Operating elements should be located 0.85–1.05 m above ground (see Fig. 9.5 on the right) and have a sideward clearance of at least least 0.5 m to an obstacle [672]. In contrast to this, the general rule of application for charging facilities DIN VDE 0100-722 allows the lower side of sockets to be located at a height of 0.5–1.5 m above ground, which does not seem to take accessibility into account.

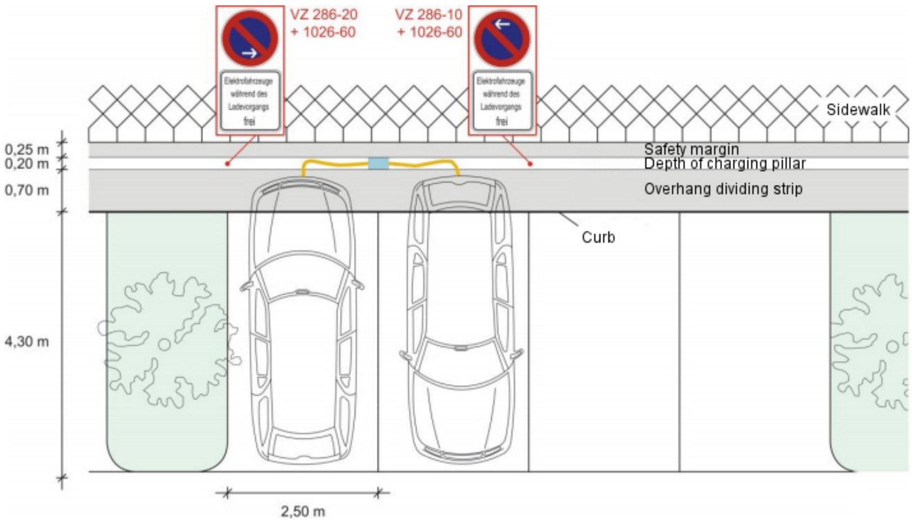


Figure 9.3.: Site layout for bay parking given in [663] (translated)

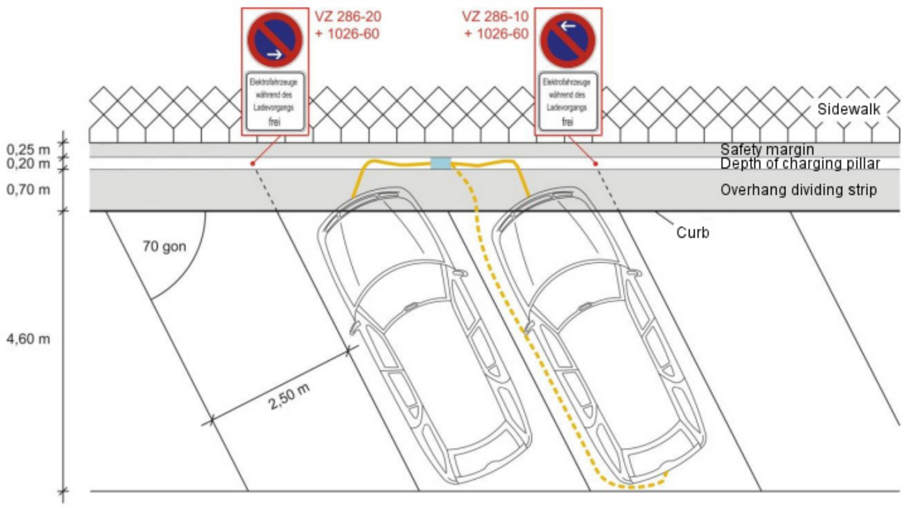


Figure 9.4.: Site layout for angle parking given in [663] (translated)

The report [10] recommends installing the charging pillar at a 45 ° angle to the curb for better accessibility by both disabled and non-disabled persons.

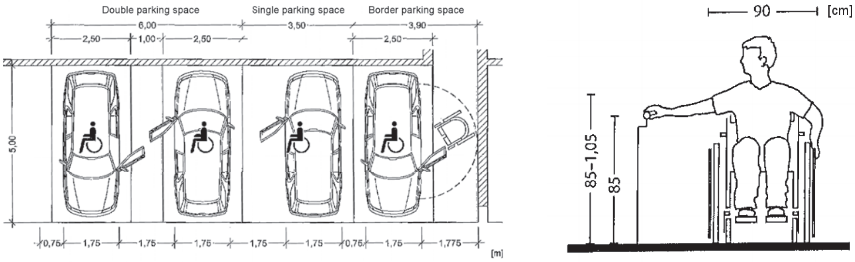


Figure 9.5.: Parking spaces for disabled persons as recommended by [669] (left) (translated) and height of control elements [670] (right) (unit added)

9.1.3. Parking regulations and signage

Charging stations in public are usually also equipped with associated signs. These signs state the parking regulations that are in place at the parking spaces.

The official German signs for the *reservation of parking spaces for EVs* can be seen in Fig. 9.7. They are combined with the standard parking space signs that are shown in Fig. 9.6. The general parking signs are put on top and the specific EV parking signs below on the same post. These signs for EVs were issued in 2011 in [156]. In order to minimize visual clutter in the streetscape it is advisable to mount such signs on already existing lamp or sign posts [10]. In Germany there seems to be *no standard for the ground marking of parking spaces* associated with EV charging stations yet.

It is commonly assumed that previously existing German regulations already allowed special parking rules for specific types of vehicles [157] [158] [159]. The electric mobility law (Elektromobilitätsgesetz) issued in 2015 [160] paves the way for public authorities to pass regulations with special parking permissions or no/lower parking fees for EVs. If such parking regulations are put in place, it has to be assured that meter maids and local police also enforce these regulations, for instance by feeing and/or towing conventional cars parked at parking spaces reserved for EVs.

Figure 9.6.: Signs 314 and 315 for parking spaces, and sign 286 for stopping restriction [156]

Figure 9.7.: Additional signs 1026-60, 1026-61, 1050-32, and 1050-33 for parking spaces for EVs [157]

In general it has to be kept in mind that the implemented parking regulations for EV charging stations have side effects. If EVs are exempted from paying parking fees, the municipality loses revenues. If parking spaces at charging stations are exclusively reserved for EVs, fewer remain available for conventional vehicles. Situations can occur where parking spaces are in short supply but those reserved for EVs remain unoccupied for much of the time. Also, EV drivers may take advantage of parking spaces reserved for EV charging to simply park their vehicle and not charge at all [349] [350], or only charge for short durations, while the vehicle remains parked for several hours [309]. Signs 1026-60 and 1050-32 (see Fig. 9.7) address this issue by allowing EVs to park *only during charging*.

A further *sign for leading drivers to charging stations* was officially issued in 2014 [161] (see Fig. 9.8). The sign is meant to be used along motorways to announce the availability of charging stations at service areas. In exceptional cases the sign can also be used with additional signs leading the drivers to a remotely located charging station (see Fig. 9.9). An application that suggests itself is to also use the sign to announce the availability of charging stations at the entrances of parking garages.

9.1.4. Weather protection and lighting

At EV charging stations people handle high voltage electrical equipment. The (perceived) need for *protection from rainwater* is therefore bigger than at other urban infrastructure such as parking meters. Charging stations and the associated parking spaces can be placed under roofs. Such a solution does not seem feasible for normal curbside parking spaces, however. It should be assured that no big puddles gather at the parking spaces, as people will be reluctant to operate charging facilities while standing in water [177]. In areas where floods may occur it has to be assured that the installations are flood resistant.

Figure 9.8.: Sign 365-65 for leading EV drivers to a charging station [162]

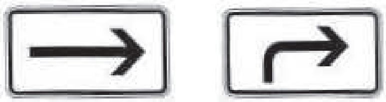


Figure 9.9.: Additional signs 1000-20 (pointing left: 1000-10) and 1000-21 (pointing left: 1000-11) which can be used to complement sign 365-65 [163]

It should be assured that the charging station is *well-lit at night*. This serves ease of use, as well as safety for EV drivers, and discourages vandalism of EVs and charging facilities. Lighting can be activated by motion detectors [177]. Safety and deterrence of vandalism can also be enhanced by placing charging stations in areas frequented by many people or in sight of other facilities [177].

9.1.5. Impacts on other traffic participants

Charging stations need to be implemented in ways that *minimize the danger for other traffic participants*. Impacts on other traffic participants can arise from the components of the station, the EV driver when plugging in his vehicle, the charging cable [39], or the EV when it leaves or enters the charging station. During ground works and electric installation the site might be needed to be cordoned off, in order to avoid danger to passing traffic, bicycles, and pedestrians.

In Germany the responsibility for assuring the safety of traffic (Verkehrssicherungs-pflichten) lies with the originator of a danger, thus the constructor of a charging station. When they are constructed on public parking spaces, the public authority responsible for public streets is also responsible for traffic safety at charging stations [12] [400].

EVs driving to or leaving a charging station should not interfere with passing traffic in dangerous ways. Thus, stations should not be placed too close to junctions [10]. Blinking lights, bright lights [400], or advertisement at charging stations can lead to distractions of passing traffic. It should be assured that the EVs' charging cables do not pose a tripping hazard for pedestrians or bicyclists (see Fig. 9.10 for a bad example). This also goes for additionally set up pollards or wheel stops. Charging stations also should not be blocking emergency vehicles, delivery vehicles, street cleaning, and snow clearing vehicles.

Figure 9.10.: Bad example of a spatial configuration where the charging cable crosses the sidewalk [673]

The reduction of available parking spaces for conventional cars or an obtrusive visual appearance of the charging station (see next section below) might lead to a NIMBY (Not In MY Backyard) reaction from drivers of conventional cars, taxi drivers, local residents, and shop owners (also see Sec. 7.1.2).

9.1.6. Urban design: visual impact on the surroundings

While the previously discussed points focused on technical and functional aspects of charging stations, the aspect of urban design is more a question of outward visual appearance. The appearance of charging stations can mainly be influenced by the model of charging facility that is chosen and its customization with color/stickers etc. It is also possible to choose different models of charging facilities or different customization for different contexts within the same city.

Building regulations set some general constraints concerning the visual impact on the urban surroundings. Applicable construction codes contain a general prohibition of deformation (Verunstaltungsverbot). The construction code of the federal state of Baden-Württemberg states: “Built facilities are to be brought into harmony with their surroundings, so that they do not deform or interfere with the intended design of the appearance of streets, cities, or landscapes. Historic and natural monuments and the characteristics of surroundings that are worth maintaining have to be taken into consideration.” (LBO §11 (1) [674]) The clause explicitly also holds for advertisement facilities and vending machines which are visible from the street. The exact meaning of deformation and interference remains a matter of interpretation.

Avoiding negative visual impacts is also part of the regulations on the protection of historic monuments. The law on the protection of historic monuments of the federal state of Baden-Württemberg states: “A historic monument may only be altered in its appearance with a permission of the responsible department for the protection of historic monuments” (DSchG §8 (1) [675]). Not only buildings themselves but also their surroundings or entire building complexes may be protected (DSchG §2 (3) [675]). A plausible interpretation of proximity that might lead to a negative visual impact is that the historic monument and the charging stations both become visible at once [400]. A negative impact can occur if there is an inconsistency in style between the historic monument and the charging station [400]. The easiest way to avoid any negative impacts is to not place charging stations in the proximity of such sites. A pragmatic approach that has been taken for the implementation of the Vélib bicycle sharing stations in Paris was to not place them within the big street axes and public places, and instead locate them in smaller side streets [676]. A possibility to place charging stations in proximity to historic monuments unobtrusively is to integrate them into other street furniture such as pollards (examples see Sec. 2.1.4).

Similar to the protection of historic monuments, the protection of natural monuments and green areas also needs to be taken into account when planning the locations of charging stations. Natural objects, such as large trees, and their surroundings can be declared to be natural monuments, with similar implications as for historic monuments and possible further protective measures (NatSChG §31 (1) [677]). Within urban areas few applicable regulative constraints seem to exist. In general the setting up of charging stations should not interfere with the protection of nature, the recreational value of green areas, and landscape appearance. If an interference occurs the responsible department for environmental protection needs to be involved (NatSchG §9 (1) [677]). Here again, the simplest measure is to locate charging stations at a distance to natural monuments and larger green areas.

Beyond the legal requirements discussed above, cities' urban planners usually go further in their consideration of the visual appearance of urban furniture. In many cities the appearance of the streetscape is part of the "brand" of a city [678]. Some cities have issued catalogs of standard street furniture to be used in order to convey a consistent visual appearance. Such a catalog for the Swiss city of Bern can for example be seen in [679]. It contains street furniture to be used homogenously throughout the city, as well as variants to be used in different city quarters, for instance different street lamps in the historic street center and in more modern areas. A common concern of urban planners is to avoid the visual clutter that results from placing more and more urban furniture on public streets. The design of the charging station and associated elements to be used within a city should therefore be coordinated with the cities urban planning department. In some situations it can make sense to use charging facilities which are unobtrusively integrated into other street furniture (examples see Sec. 2.1.4).

If advertisement is displayed at the charging stations, this can lead to a bigger visual impact on the urban surroundings. When making use of public parking grounds, it therefore has to be clarified with the responsible urban planners beforehand, to which extent the display of advertisement is admissible. An agreement can for instance be in the form of the maximally allowed surface that can be used for advertisement. It may be demanded that lights or moving displays are not visible from the street. The city administration may explicitly allow the infrastructure operator to display large scale advertisement in order to improve the profitability of the infrastructure (see Sec. 5.2.3.5).

Negative impacts on the surroundings can also occur if charging stations are damaged or vandalized. This leads to a run-down appearance of the charging stations and of their surroundings, which can encourage further vandalism. Fig. 9.11 shows a strongly vandalized fast charging station at a motorway rest area. The regular maintenance of charging stations thus also involves the removing of graffiti and stickers.

Figure 9.11.: Vandalized fast charging station at a motorway rest area [680]

Concerning the visual impact on the urban surroundings, there is a general conflict of interest between urban planners on the one hand and charging station operators and EV drivers on the other hand. While cities' urban planners usually prefer charging stations to blend in unobtrusively, charging station operators and EV drivers usually prefer them to be well visible from a distance (compare Sec. 7.2.5).

9.1.7. Further aspects to consider for charging stations in publicly accessible parking garages

In the previous sections aspects were discussed which primarily play a role when locating charging stations on public parking spaces. Within this section aspects will be treated which need to be considered when locating charging stations in publicly accessible parking garages.

Existing recommendations on the planning of parking garages already contain a few elements on the planning of EV charging stations. In the guideline [669] it is recommended to place them near the entrance of the parking garage and equip them with well visible signs leading to them, as well as signs keeping normal vehicles from parking at them.

Regulations on *ventilation and fire safety in parking garages* [681] have to be taken into account when planning charging stations. Lithium-ion batteries do not emit gases during charging. But excess heat is created during the charging process by the electric cables and by the cooling of the battery. The circulation of sufficient cool air should therefore be taken into account. However, there seem to be no requirements beyond those for parking garages in general, where ventilation is required to avoid the accumulation of exhaust fumes [681].

There is little additional risk of fire when charging EVs. The fire protection requirements for parking garages in general have to be fulfilled [681]. Burning lithium-ion batteries can be smothered using high amounts of water. Because there is no danger of flammable liquids spreading out, containing a fire from a burning EV might even be easier than one from a burning gasoline of diesel vehicle [682]. When cables with voltages over 1 000 V are laid through parking garages, these cables have to be deactivatable by firefighters from outside the building. The fire alarm system has to deactivate these cables automatically [681].

Further aspects for the planning of charging stations in (underground) parking garages in Germany are treated in the guideline [32]. The guideline recommends charging stations to be located near the cable spreading room, in order to keep the length of cables short. The cost of cabling can also be kept low by installing all charging points close together. Electric cables should be installed in ceiling ducts on cable racks which allow for good cooling of the warm electric cables [32]. The cables should be installed in a way as to be invisible or at least unobstrusive [32]. The electric cables should not be installed in floor ducts with grate covering, where they might come in contact with water, cleaning fluids, or other liquids [32].

Many modern charging facilities require an internet connection to a service center. This connection can be made via network cable, wireless connection, or by implementing a wireless local area network (WLAN) in the building [32].

Wall-mounted wallboxes are recommendable in such settings instead of charging pillars. Such wallboxes tend to cost less. A further advantage of wallboxes is that they do not require an additional crash protection and do not shorten the length of the parking places when they are installed at one end [32]. It is recommended to install wallboxes at a height of 1–1.5 m [32].

When several charging points are to be installed, the hardware costs can be further lowered by making use of a satellite architecture, where authentification, payment and other functionalities are concentrated in a central terminal [32]. This point also holds for charging stations at public curbsides.

When charging pillars are installed at the end of parking spaces, crash protection should be implemented, for instance in the form of metal pillars or by placing the charging pillars on concrete bases [32]. It should be noted that charging pillars shorten the length of the parking place. Some types of charging stations even need to respect a distance from the wall, because they need to be serviced from the back side.

Within parking garages no legal constraints seem to exist concerning the visual appearance of the charging stations. Still, the design of the charging facilities, ground markings, and signs should harmonize with the design of the parking garage (walls, markings, signage etc.) [32].

9.2. Obtaining permits from municipal departments and establishing contracts with technical infrastructure providers

The setting up of charging stations is a small scale building project, for which no official construction permit (Baugenehmigung) from the municipality's construction department is required (verfahrenfreies Vorhaben) [12] [585]. It is alike to setting up vending machines or small advertisement elements [400]. Still, when implementing publicly accessible charging stations, a large number of contracts with technical infrastructure providers and different permits from municipal departments needs to be acquired. The issues which were discussed above, such as impact on other traffic participants, protection of historic monuments and green areas, and impacts on the visual appearance of public streets need to be clarified with the responsible municipal departments.

The process of obtaining the necessary permits from municipal departments can be very time consuming. From Dortmund it is reported that the process of involving all concerned municipal departments and further stakeholders took one entire year. After initial preparations the actual permitting process for public charging stations took 4–6 weeks [683]. A recommendation given after experiences made during the implementation of public charging stations in Berlin is that local city districts, responsible for permitting and implementation, should be involved early on in the decision making process [663]. Many difficulties with the permitting procedure from municipal departments seem to be due to the fact that no standard procedure for the issuing of permits for charging stations exists within the administration yet.

Thus, large efforts are required to receive consent from all concerned municipal departments when installing charging stations on public parking spaces. This is an argument for rather installing charging stations on publicly accessible private ground. When installing charging stations within parking garages or on dedicated parking spaces of buildings much less consent from public authorities is required (see last column in Tab. 9.1).

The following Tab. 9.1 lists the different contracts, permits, and consent required from different organizations. The table first lists contracts that have to be established with technical infrastructure providers and subcontractors, then the permits that need to be acquired from municipal departments. A link exists here to stakeholder cooperation for the implementaton of public charging infrastructure as discussed in Chap. 7. The different contracts shown here are similar to the fulfillment of roles as shown in Sec. 7.2.2. In this context the municipality which provides the public parking spaces demands the compliance to the diverse regulations of urban planning for the commercial use of public space.

The procedure of achieving consent from all involved organizations can also be interpreted as achieving a balance of interest, mainly between the municipality's departments and local citizens on the one side, and the company that sets up the public infrastructure and EV drivers on the other side (for interests of different stakeholder categories see Sec. 7.1 and possible conflicts of interest Sec. 7.2.5).

Within the German federal system, local organizational structure in municipalities can vary. In the third column, the table lists the general background information that can be useful in preparing the permitting/contracting procedure. It has to be clarified beforehand with the responsible organizations exactly which forms and documents are required for the permitting procedure. The diverse agreements between a municipality and an EV infrastructure operator can be bundled in one contract (an example contract is shown in [585]).

Though not obligatory, it can make sense to also involve local citizens and EV drivers into the micro planning process. Locations for charging stations can be proposed by them. If a charging station is installed on the public street in front of a building, local residents and shop owners can be informed of the construction work and the rationale for setting up public charging stations can be explained via flyers (for further points on citizen participation see Sec. 7.4).

Table 9.1.: Overview of different contracts and permits for setting up public charging stations

Contract or permit	Concerned organization	Useful background data	Main points to consider	Also required on private ground?
Electricity network connection contract	Distribution system operator	Utility lines cadastre, technical specification of charging facility, required connection power	Keeping connection distance short to minimize ground work costs, possible impacts on power lines, transformers	Yes, but already existing connection of building/ complex can be used
Electricity provision contract	Electricity provider	—	Possibly use of electricity from renewable sources	Yes, but already existing electricity provision for building/ complex can be used
Telecom-munication contract	Telecom-munications provider	Technical specification of charging facility	Local avail-ability of wirebound or wireless connection	Yes, but already existing telecommuni-cation contract of building/ complex can be used (using WLAN)
Electric installation contract	Electric installer	Technical specification and installa-tion instructions of charging facility	Possibly also contract for regular tests and main-tenance of charging stations	Yes

Continued on next page

Table 9.1 – *Continued from previous page*

Contract or permit	**Concerned organization**	**Useful background data**	**Main points to consider**	**Also required on private ground?**
Ground work contract	Construction company	Cadastral data, utility lines cadastre	(See permit for ground works in public space below)	Yes, but ground works may not be necessary when installing wallboxes or pillars mounted on sockets
Contract for the special use of public parking spaces	Municipality's road construction department	Existing special use fee regulations	Fee for the special use, supporting regulations such as reservation of parking spaces for EVs, signs to be put up, possibly further requirements of the municipality to allow the commercial use of public space (see points below)	Yes, permission from private ground owner also required
Confirmation of not endangering the flow of traffic	Municipality's road construction department	Street maps Aerial photos	Possible interferences with passing traffic, bicyclists, pedestrians	No

Continued on next page

Table 9.1 – *Continued from previous page*

Contract or permit	**Concerned organization**	**Useful background data**	**Main points to consider**	**Also required on private ground?**
Confirmation of compliance to local urban design standards	Municipality's urban design department	Design of charging stations and auxiliary elements, local guidelines for urban design and street furniture (if existent), street photos, visit on site	Conflict between unobtrusiveness and good visibility	No
Confirmation of compliance to the protection of historic monuments	Municipality's department for the protection of historic monuments	List/map of protected historic monuments, cadastral data, aerial photos, street maps, street photos, visit on site	Keeping distance to historic monuments	Usually no
Confirmation of compliance to the protection of natural monuments and green areas	Municipality's environmental protection department	List/map of natural monuments and green areas, cadastral data, aerial photos, street maps, street photos, visit on site	Keeping distance to natural documents and green areas	Usually no

Continued on next page

Table 9.1 – *Continued from previous page*

Contract or permit	**Concerned organization**	**Useful background data**	**Main points to consider**	**Also required on private ground?**
Permit to perform ground construction work in public space	Municipality's civil/road construction department	Cadastral data, aerial photos, street maps, street photos, utility line cadastre	Cordoning off of construction site, possibly notification of utilities to switch of connection lines	No

9.3. Operational methods for micro planning

The previous sections have given an overview of the diverse aspects that should be taken into account when planning charging stations at the street scale, and the diverse contracts and permits that need to be acquired. For planning a large number of charging stations, a structured operational method is needed. Because many of the involved aspects are qualitative and subjective in nature, for instance the visual impact on the streetscape, such methods cannot be fully formalized. Also, specific constraints and permitting procedures can vary among different municipalities. The methods should therefore be adapted to the situation.

Elements of such operational methods have been presented in a few documents. These semi-structured methods define document templates which are then filled out for individual locations. Though used for the planning of bicycle sharing stations, the template shown in [684] provides several useful elements (see Fig. 9.12). The template shows a street map view of the surroundings (upper right), a map of the insertion into the streetscape (lower right), a photo of the site with markings showing where the facility is to be located (lower left), and further key characteristics such as the number of parking spaces occupied, and characteristics of the urban surroundings (nearby metro stations, nearby facilities, number of trips to the zone), and a field for further commentaries.

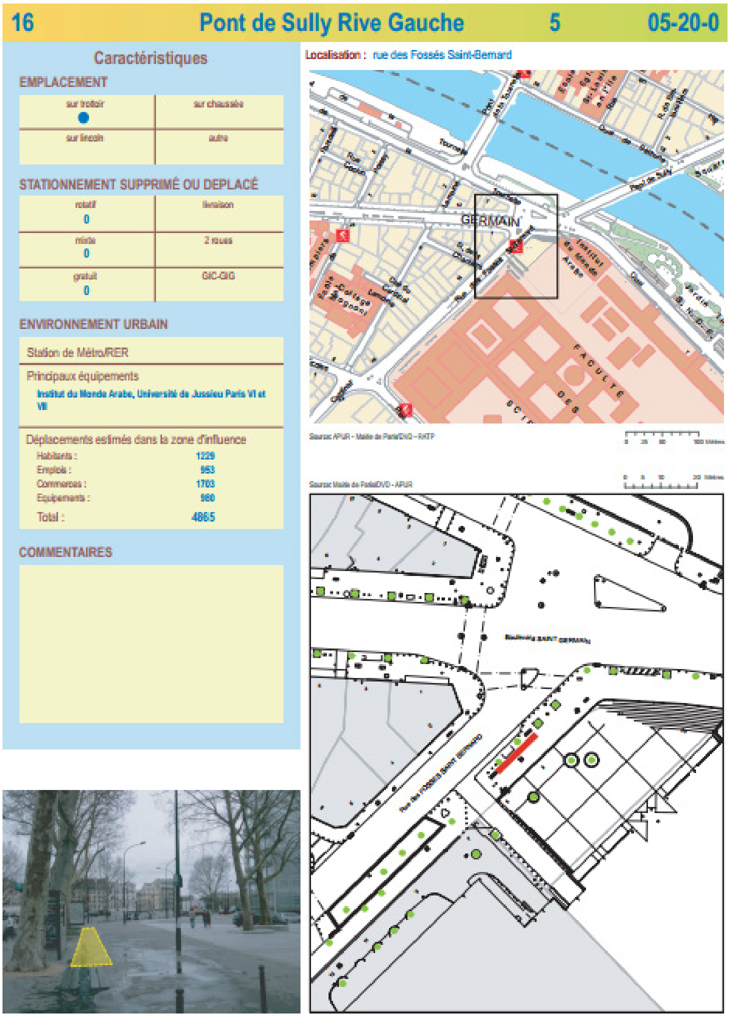


Figure 9.12.: Template used for the planning of bicycle sharing stations in Paris shown in [684]

A similar but less complete method was apparently used for planning charging stations in the German federal state of Saarland [14]. The corresponding template is shown in Fig. 9.13. An overview of the site is given (upper left), as well as photos on the street scale (upper right). Additional information is given in the three categories area-related information, visual information, and further information (below). Candidate locations for charging stations are represented in this way, in order to serve as the starting point for discussions with further stakeholders. In order to rate their suitability, the locations are then evaluated according to excluding and constraining criteria (availability of electricity and mobile phone connection etc.), descriptive criteria (location in the streetscape etc.), and comparing criteria (potential demand, expenditure for implementation, existing parking pressure etc.).

Figure 9.13.: Template used for the planning of EV charging stations in the Saarland shown in [14]

The template presented in [685] describes already implemented charging stations and has a similar overall structure (see Fig. 9.14). A map shows the location of the charging station and that of other stations in the region (upper right), as well as a street photograph (lower right). On the right side the location is described according to several criteria: user convenience, access and accessibility, safety and personal security, connections with public transport, maintenance issues etc.

Sample 'test-bed': London Road, St Albans

'Street level': emerging issues, lessons learnt, what works well in different contexts

EV user convenience, access and accessibility?

The Source East chargepoint (two sockets: one standard 13A/ 3kw, one fast 32A/ 7kw) is installed on-street in a parking space on a main commercial thoroughfare in the centre of St Albans, near to Peacock Junction. The EV space is in front of a Blockbuster video hire shop and a food takeaway. Parking fees are high on this street and time restricted 2 hrs, 8.30-18.30 maximum 2 hours £2.40.

Safety and personal security?

The positioning appears safe and secure for users. The street is well lit and there seems to be considerable pedestrian movement as well as vehicles.

Connections with other transport, especially public transport nodes?

The location is close to bus services.

Maintenance and upkeep of the charging infrastructure and streetscape?

The Council are responsible for maintenance.

Visibility of the charging points in this locality, and how does this fit with the promotional and communication strategies above?

The charging pointis in a prominent position, but as yet there is little indication that the bay is for EV users. Indeed at the time of observation, it was occupied by another vehicle.

Funding, measurable outputs and outcomes?

The chargepoint was installed with 50% funding from Evalue8 and 50% from Local Sustainable Transport Fund (LSTF) in a potentially high profile location, but would benefit from clear signage to encourage EV users, and discourage others from using it.

Destination St Albans District Council - ©2013 Google Maps

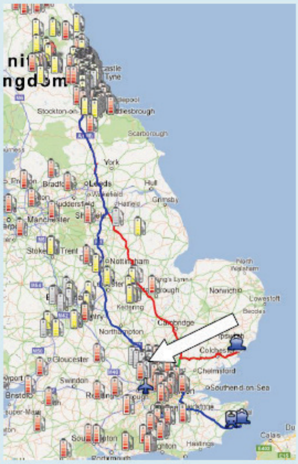


Figure 9.14.: Template to describe EV charging stations in the UK shown in [685]

The scoring table presented in [14] is more strongly formalized than the previously shown document templates (see Fig. 9.15). A candidate location is first checked for the fulfillment of general requirements. These have to be checked with "yes". Such requirements are the availability of the parking space, the fulfillment of technical prerequisites, the respect of historic monuments etc. Then the site is rated for suitability. Criteria are listed from the operator's point of view (low expenditure for ground works, for electric installation, for permitting procedures, representativity, extendability) and from the users' perspective (accessibility, attractiveness, connection to public transport, low parking pressure). Each criterion can be given a score of 1–5. The overall score is the weighted sum of the subscores, made up 50 % of the operator's and 50 % of the users' criteria.

Standort:			Standort-Nr.	
Lagebeschreibung (Lagetypus)				
I Grundsätzliche Standorteignung (Ausschlusskriterien)			ja	nein
Hinderungsgründe in Hinblick auf ...				
A.1	die Verfügbarkeit der Fläche			
A.2	die bauliche und technische Eignung der Fläche (z. B. Größe, Zugang, erforderliche Leitungslänge)			
A.3	städtebauliche Belange			
Rechtliche Hinderungsgründe in Hinblick auf ...				
A.4	den Status der Fläche (in der Bauleitplanung)			
A.5	spezielle Normen (z. B. Denkmalschutz, Naturschutz, Grünflächen)			
II Bewertung der Standorteignung				
	... aus Anbieterperspektive 50%	50%	Bewertung (1 bis 5)	Ergebnis
B.1	geringer baulicher Aufwand	10%		
B.2	geringer elektronischer Aufwand	10%		
B.3	geringer Aufwand Verwaltungsverfahren	5%		
B.4	Attraktivität/Repräsentativität der Lage, Wahrnehmbarkeit für die Öffentlichkeit	20%		
B.5	Erweiterbarkeit	5%		
	... aus Nutzerperspektive 50%	50%	Bwertung (1 bis 5)	Ergebnis
C.1	Erreichbarkeit, Erkennbarkeit, Zugänglichkeit	10%		
C.2	Attraktivität als Ladeort/Zentralität oder Standortwünsche konkerter Nutzer	25%		
C.3	Verknüpfung zum ÖV und anderen Formen des Umweltverbundes	10%		
C.4	geringer „Parkdruck" durch andere Fahrzeuge	5%		
Gesamtpunktzahl (Minimum 1,00; Maximum 5,00)				0,00

Figure 9.15.: Scoring table used for planning EV charging stations in Hamburg shown in [14]

9.3.1. A generic framework for devising and executing operational methods

In the following a generic framework for operational methods of location planning on the street scale is presented. The specific approach should be adjusted to meet the requirements of the situation. The approach is based on work the author has done together with colleague Anne-Sophie Fulda at EIFER in [645] and the methods discussed above. The framework aims at determining good locations, as well as obtaining the necessary permits for the installation at these sites.

As a starting point for the location planning on the street scale a list/map of candidate locations for EV charging stations on the macro scale is needed. The list/map can be in the form of points of interest or number of charging stations to be placed in city zones. Methods for the location planing on the macro scale were shown in the previous Chap. 8. Locations can also be determined via ad hoc brainstorming methods, for instance by asking local public authorities to propose locations [686] or alternatives to predefined locations [578]. Local EV drivers and citizens can likewise be asked to propose locations.

Then, the following procedure can be followed for further planning on the street scale:

1. **Meet with all involved permitting/contracting organizations:** the aim of these meetings is to determine which information, documents, and existing forms these organizations require to issue a permit or establish a contract. It should also be clarified which conditions need to be fulfilled in order for a permit to be issued. The discussion should also reveal which information/data is required for the planners to prepare the applications (compare Tab. 9.1). Interests of the EV infrastructure provider also should be explicitly determined.

2. **Clarify planning questions generic for all sites:** many spatial planning questions are not site-specific but generic for all sites within a city. Usually one type of charging facility and additional elements such as pollards and signs are used. The charging facility may or may not display advertisement. The general approach to take for weather protection and lighting can also be planned generically. Spatial configurations for different kinds of parking spaces and number of charging spaces can be planned beforehand (see Sec. 9.1.2). The general site plans can be validated by the concerned organizations, for instance the urban planning department for the general visual impact, the department for street construction and maintenance for traffic safety issues, and the distribution system operator for issues concerning connection to the distribution grid. The reservation of parking spaces for EVs and possible special use fees also can be settled globally or for groups of charging stations, for instance those in the urban center and those in the periphery.

3. **Develop a document template for planning on the street scale**: a planning template is then constructed which can directly be used for the permitting procedures, but also considers further aspects from the

infrastructure providers' point of view. It makes sense to separate the different siting criteria into *prerequisites that must be fulfilled* and *quality criteria which determine the suitability* of the location. Aspects which can be considered as prerequisites are the availability of the parking space, the agreement with land use regulations, the feasibility of electricity and telecommunication connection, the respect of basic requirements of fire safety, and the protection of historic monuments and green areas. The fulfillment of these requirements can be represented via a check box in the template. Quality criteria for a site can be a good integration into the urban surroundings, good accessibility from main roads, accessibility 24 hours a day and 7 days a week, good visibility for marketing purposes (possible conflict with blending in), low electric connection costs and ground work costs, ease of obtaining permits for the use of the parking space, low parking pressure at the site, access to public transport, and further criteria. The quality criteria can be quantified via scores and combined using weights (see the example in Fig. 9.15). If this is done, the scoring model should be very simple. In order to give a visual impression of the site, different kinds of maps (aerial photo, street map, cadastral map, utility line cadastre) can be integrated into the template, as well as street photos of the site (see the example templates above). The constructed template can contain all relevant information on 1 or 2 pages. Parts of the template can be dedicated to the permission procedures for specific organizations.

4. **Determine specific sites on the street scale and fill out document templates:** starting from an initial list of locations on the macro scale near specific points of interest or a number of locations in zones, specific sites/parking spaces on the street scale are determined. This can be done based on aerial photography, street maps, street photos (for instance those provided by Google Streetmap [687]), personal knowledge of the area, or visits on site. The decisions are made intuitively with prerequisites and quality criteria kept in mind. Instead of filling out entire document templates, it can make sense to fill out elements iteratively, and validate intermediate results with the involved organizations. If a prerequisite is not fulfilled it has to be checked whether an alternative site can be found nearby.

5. **Submit filled out templates for permitting and implementation:** finally, the filled out templates are handed in to all concerned organizations for permitting and setting up contracts. The order in which the documents

are handed in to the different organizations should be chosen well. Permits should be acquired from those organizations first, where objections and requests for changes in location seem the most probable. Thus, it is reasonable to obtain consent from municipal departments first, before clarifying details of implementation with the technical service providers. Permits where no objections and changes are to be expected, for instance the connection to the distribution grid and the setting up of a telecommunications contract, can be treated in parallel. Though no official consent from them is required, it can make sense to inform local residents and shop owners when a public charging station is installed in front of their buildings.

9.4. Summary: planning of EV charging infrastructure on the street scale

This chapter has treated the diverse aspects that need to be considered when planning charging stations on the street level. For a location to be suitable, the technical prerequisites must be fulfilled. The parking space(s) must be available and the implementation of EV charging stations not be in conflict with existing land use regulations (i.e. not in residential-only areas). The connection to the electricity distribution grid has to be feasible and should be as economic as possible. If charging facilities communicate with a back end system, a wire-bound or wireless telecommunication connection must be possible at the site. Basic fire safety also has to be assured.

When planning the spatial configurations of charging stations, it has to be taken into account that the socket can be located at different locations on different EV models. Usually it is located at the back right of the EV. Possible configurations of parking space and charging stations have been shown for parallel parking, bay parking, and angle parking. These can be adapted, depending on the number of charging points per charging pillar. Though it does not seem to be obligatory in Germany, charging stations should be planned to also be usable by disabled persons, as far as possible in the given situation.

In Germany standardized signs exist for reserving parking places for EVs, in general or only during the charging process, and for leading EV drivers to charging stations. When reserving free parking spaces for EVs, the possible side effects have to be taken into account, for instance the loss of parking revenues or the higher parking pressure for the surrounding parking spaces for conventional vehicles.

Weather protection is difficult to implement for on-street parking sites. At a minimum it should be assured that large puddles do not gather at the site and that the installation is flood resistant if the area is prone to floods. The site may be lit at night by an existing street light or by a dedicated light equipped with a motion detector.

Dangerous impacts on other traffic participants have to be avoided. The charging station and auxiliary equipment, the charging cable, the driver while plugging in the cable, as well as construction workers and machines during the installation should not interfere dangerously with other cars, bicyclists, and pedestrians.

Negative visual impacts on the urban surroundings should be minimized. Regulations on the protection of historic monuments and green areas have to be respected. Many cities also have explicit or implicit rules of how street furniture should be integrated within the existing streetscape. The display of large scale advertisement at the charging station leads to a higher visual impact, but generates more revenues for the charging infrastructure operator. Vandalized charging stations also lead to a bad visual image of the site and its surroundings.

When planning charging stations within publicly accessible parking garages, many of the aspects listed above, such as protection of historic monuments, do not play a role. Overall it seems easier to implement charging stations in parking garages than at public curbsides. However, fire safety and ventilation play a bigger role in parking garages than at open-air parking places. It should be assured that the heat developed during the charging process is dissipated.

The process of obtaining permits and establishing contracts is elaborate when setting up charging stations in public space. Contracts need to be set up with a wide array of technical infrastructure providers. Different permits or confirmations need to be acquired from different municipal departments. One of the reasons why the process of obtaining permits from municipal departments can be quite time consuming is that no standard administrative procedure for the permission of the setting up of charging stations exists yet.

Based on siting requirements and requirements of the permitting procedure, operational methods for the planning of charging stations on the street scale can be devised. The diverse aspects are qualitative in nature, therefore methods cannot be fully formalized. Because specific requirements can vary from application to application, only a general framework for operational methods was presented here. This framework defines five steps. First, meetings with the involved permitting/contracting organizations are held, in order to determine which information they need for their administrative procedures. In a second step the questions which are generic for all sites, such as the model of charging facility to be used, the parking regulations to implement etc., are clarified. Then, a document template is defined that encompasses all required information for permitting procedures and site planning. It makes sense to divide criteria into prerequisites that have to be fulfilled and quality criteria which determine the suitability of a site. Visual elements, such as streetmaps, aerial photography, and street photographs, are also useful in order to concretize the site planning. Next, specific sites are intuitively chosen, making use of aerial photography, street photographs, and visits on site. Filling out the document templates, it is checked whether they fulfill the prerequisites and have a high level of suitability. It can make sense to fill out only parts of the template and get intermediate feedback from the involved organizations before considering further aspects. Finally, the filled out templates are handed in for permissions and setting up of contracts. The order in which this is done should be chosen carefully. It can be reasonable to involve those organizations first, were the most objections/requests for changes are to be expected. Where the establishment of contracts is a mere formality, the procedure can be initiated for several organizations in parallel.

Overall this chapter has shown that two main points should be taken into account when planning charging stations on the street scale: the diverse siting aspects and the requirements of permitting procedures. Planning methods can be devised that take the specifics of the situation at hand into account and integrate these two aspects into one semi-formal operational planning procedure.

10. Long-term geographic planning and development of EV charging infrastructure

Chap. 8 treats the planning of a charging infrastructure for EVs as a static location planning problem: with (almost) no charging points previously existing, where should a given type and number of charging points best be placed? This is a reasonable approach when planning the very first charging points for a city or to develop a long-term vision for a charging infrastructure. However, like other infrastructure, a charging infrastructure for EVs is not implemented all at one time and then operated and maintained in this fixed status. Such a charging infrastructure develops over time. Development over time can take on different quantitative and qualitative forms:

- *Quantitative development*:
  - *Densification*: more charging points are installed in an area which already contains charging points. Charging points can be added in new locations or further charging points be added to already existing charging stations
  - *Spatial expansion*: charging points are installed in areas where no charging points have previously been installed. For instance, first, charging points are installed in a city center, later also in the surrounding city quarters and satellite towns.
  - *Replacement:* broken charging points are replaced by technologically equivalent new charging points at the same locations.

    - ◇ *Removal*: charging points are removed and not replaced by new ones, because they are little used, defect, or technologically outdated (also see point below).

- ○ *Qualitative development*:

    - ◇ *Upgrading*: charging points are being replaced (or retrofitted) by charging points supporting more advanced charging technologies, for instance higher charging powers or more advanced ICT capabilities. Technological breakthroughs might lead to disruptive replacements, for instance if conductive charging points (i.e. using sockets and plugs) are replaced by charging points using inductive technology, possibly at the same locations. Slow and normal charging points at locations where people park for longer durations might be replaced by fewer fast charging points at different locations (therefore involving a removal of charging points) where a lot of transit traffic passes. Technological *downgrading*, for instance from using a dedicated EV socket to using a normal household plug, is possible theoretically, but does not seem reasonable.

Simulation models can reasonably replicate the aspects of densification, expansion, and possibly replacement if a lifetime of charging facilities is modeled. But the removal of charging points due to lack of use is hard to replicate in a model. This case occurs when (model-based) predictions of use do not correspond to the later observed real-world use, something that should be avoided as much as possible. Upgrading of charging points in order to support more advanced technologies is also hard to replicate in a model, as disruptive breakthroughs in technology and norms are difficult to predict.

In the following section available publications on the topic of long-term development of charging infrastructure will be discussed. Then, the connection between static location planning (as treated in Chap. 8) and dynamic development (as treated in this chapter) will be discussed. The biggest part of the chapter then presents a model of the development of a charging infrastructure in the Region Stuttgart. The model is presented in concise form here, as it has already been published in the articles [355] and [688]. The theory behind the model and three generated scenarios are shown. In the final section of this chapter the presented results are summarized and overall conclusions are drawn.

10.1. Literature survey on the long-term spatial development of charging infrastructure

The existing publications on the topic are surveyed within this section. Considering the very high number of publications that treat the location planning for EV charging infrastructure (see Sec. 8.1), it is surprising how relatively few publications include a temporal aspect, with the buildup of charging infrastructure seen as a dynamic process in space *and time*.

Several reports present long-term spatial rollout programs for EV infrastructure for specific regions. Within the EV Project in the USA, infrastructure rollout plans were generated for the state of Arizona [689] and several other regions. A temporal development for Germany with some spatial elements is shown in [690]. The presentation [691] shows a dynamic infrastructure development for the city of Zürich in Switzerland. These three methods have in common that they take the development of the numbers of EVs as an input and generate a spatial development of charging infrastructure based on geographic data. However, none of these reports explain how the calculations were done in detail. The method presented in this chapter has a similar pragmatic character as these methods (with the details of the method of calculation shown).

In the scientific literature some authors have extended optimization models of EV charging station location choice to also include a temporal element. In [692] a temporal element is included in a mixed integer linear programming formulation for location choice of battery switching stations. One of the underlying ideas is to integrate a discount factor in order to discourage building charging stations too early. An application of the introduced optimization model is not shown in the report [692].

The article [600] also includes a temporal element within a mixed integer programming formulation. The optimization model locates fast charging or battery switching stations within a motorway network. For each of six time periods, three new stations are added. The model is applied to the motorway network of South Korea. The authors state that the problem is computationally very challenging and therefore also introduce heuristic solutions techniques that reduce the dynamic problem to static location planning problems which are solved for each time period in sequence (also see below for a discussion on static and dynamic planning). The authors make the connection to the area of *dynamic facility location* [693] (see [600] for further references in this direction).

Another strand of research focuses on simulating the temporal development of EV ownership. Because the decision of people to buy an EV also depends on the availability of public charging infrastructure, and providers only set up charging infrastructure if EVs use it, these two developments can be modeled in combination. This so-called chicken-and-egg problem is discussed in Sec. 4.1.2 within this document. Previously published models of alternative fuel vehicle and infrastructure development which include spatial aspects [694] [286] (and others) cannot be easily transferred to EVs and their infrastructure. This is because the recharging of electric vehicles takes place differently from that of other alternative fuel vehicles, such as hydrogen vehicles or natural-gas-powered vehicles. EVs can be recharged at homes using normal household electricity outlets and are thus not entirely dependent on a public charging infrastructure. The charging procedure usually takes place over longer durations, while parking during an activity. Because of their lower driving ranges, EVs also need to be recharged more often than other types of vehicles (compare [695]). Transferring previous models for alternative fuel vehicles and their infrastructure to EVs can result in questionable model elements such as ultra-fast charging with 120 kW [696] or EVs only charging at public charging infrastructure and never at home [697].

New models for the co-development of EVs and their infrastructure have been published in [698] [699]. However, these only model development in an aggregated form and do not contain a spatial element.

Overall, such models which model a co-development of EV ownership and infrastructure seem suitable to analyze complex interactions of policy measures. But such models seem too complex when the task is to simply generate realistic scenarios for time-spatial EV infrastructure development.

10.2. Connections between static and dynamic location planning

Publications that treat the development of a charging infrastructure for EVs in space *and time* have been discussed in the previous section. It seems that there are relatively few such publications in relation to the large number of publications that treat the static location planning problem (see Sec. 8.1). However, some static location planning methods can be extended to also model development over time. In the following the connections between static and dynamic location planning will be discussed.

The dynamic location planning problem for EV infrastructure can be reduced to solving a sequence of static location problems. For instance, it can be calculated which charging station should be placed next, taking the previously located charging stations into account. This is done for the placement of battery exchange stations in [602]. The approach corresponds to a greedy algorithm.

Instead of placing only single charging stations, batches of several charging stations can also be located in each step. This is used as a heuristic method to solve the dynamic location planning method in the article [600]. The article also uses a heuristic that solves the problem to optimality for the last timestep and then calculates backwards in time, removing charging stations at each timestep. In their application this leads to better results than calculating forward in time [600].

If priorities are calculated for potential locations [591] [592], these can also be interpreted as an implicit time sequence: place a charging stations first at the location with the highest priority, then at the location with the second highest priority, and so on. This also corresponds to a simple greedy algorithm. However, here the next best locations are not even calculated sequentially but determined all at once.

A straightforward application of static location planning methods to modeling and optimizing a temporal development can lead to problems if the algorithm is not *scaleable*. Scaleable means in this context that an increase in demand leads to an addition of locations of charging points, but never a removal of locations. Or, in more formal terms:

Definition: a charging point location scheme L is *scalable* if:

$$L(n) \subset L(n+m)$$

With:

$L(\,)$: locations selected for the placements of charging stations

n, m: measure of demand used for the location scheme (number of charging points/stations/EVs ...)

Traditional location planning formulations such as the p-median and p-center problem are *not* scalable in the above sense. The optimal solution for the placement of $n+1$ medians/centers generally cannot be obtained by adding one new location to the solution for the placement of n medians/centers. If that were the case, such problems could always be solved to optimality by a sequential calculation of next locations, starting from the placement of a single median/center.

After these theoretical remarks it will be demonstrated how the static location planning methods presented in Chap. 8 can in principle also be used to generate temporal plans for infrastructure development. The method of decision support for the placement of charging points in a city or region shown in Sec. 8.3 is scalable in the above defined sense. If a calculation is done with higher numbers of charging points, further locations and numbers of charging points are added in comparison to a calculation done with a lower number of charging points.

This was not a matter of conscious design at the time of the development of the method. Rather, this is a side effect of the simple allocation algorithm of the method. With its proportional distribution, the algorithm can be figuratively thought of as performing a "flooding" of locations. Once a location has been selected (i.e. is under the water level), increasing the overall number of charging points (i.e. raising the water level) keeps all of the previously calculated charging points and adds further ones.

The development of a charging infrastructure in time can easily be modeled by the method by doing several calculations and increasing the number of charging points. Fig. 10.1 shows how this works in principle. Calculations are done for 5 000, 10 000, and 20 000 charging points. For each of these calculations the parameterization of the method is done as for scenario 3 in Sec. 8.3.2.6. It would also be possible to change the parameterizations for the calculations. In order to obtain consistent scalable results, however, it would then be necessary to ensure that the absolute number of charging points allocated to one category of locations is never reduced from one calculation to the next.

The method of prioritization for the placement of charging stations presented in Sec. 8.4 can also be used to model a temporal development or operational rollout plan of the charging infrastructure. The priorities are then interpreted as a temporal sequence. As an example the results of scenario 1, shown in Sec. 8.4.2.3, are used. It is assumed that charging stations are first installed at the 30 supermarkets with the highest priority scores, then at the next 30, and then again at the next 30 in the third time step. The resulting development can be seen in Fig. 10.2.

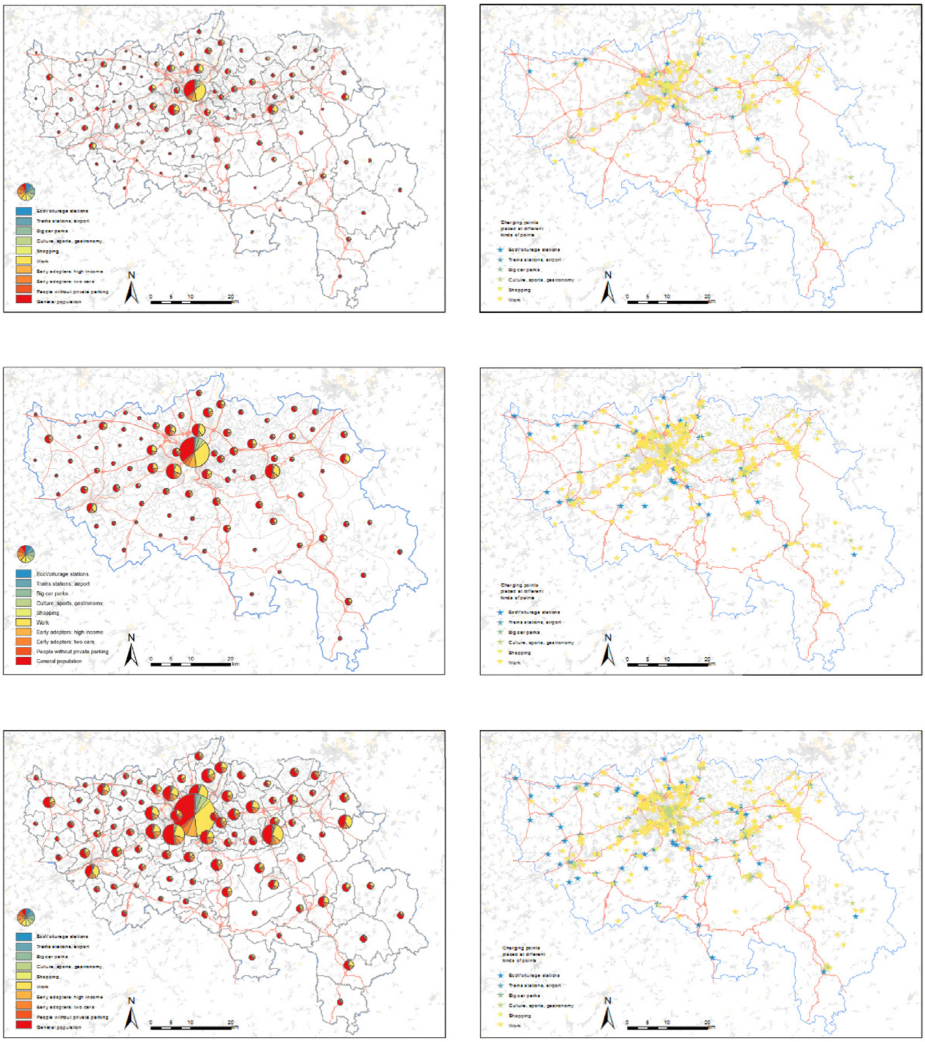


Figure 10.1.: Demonstration of feasibility: modeling a temporal development based on the method of decision support applied to Liège: placement of 5 000 (above), 10 000 (middle), and 20 000 (below) charging points in areas (left) and at selected points (right)

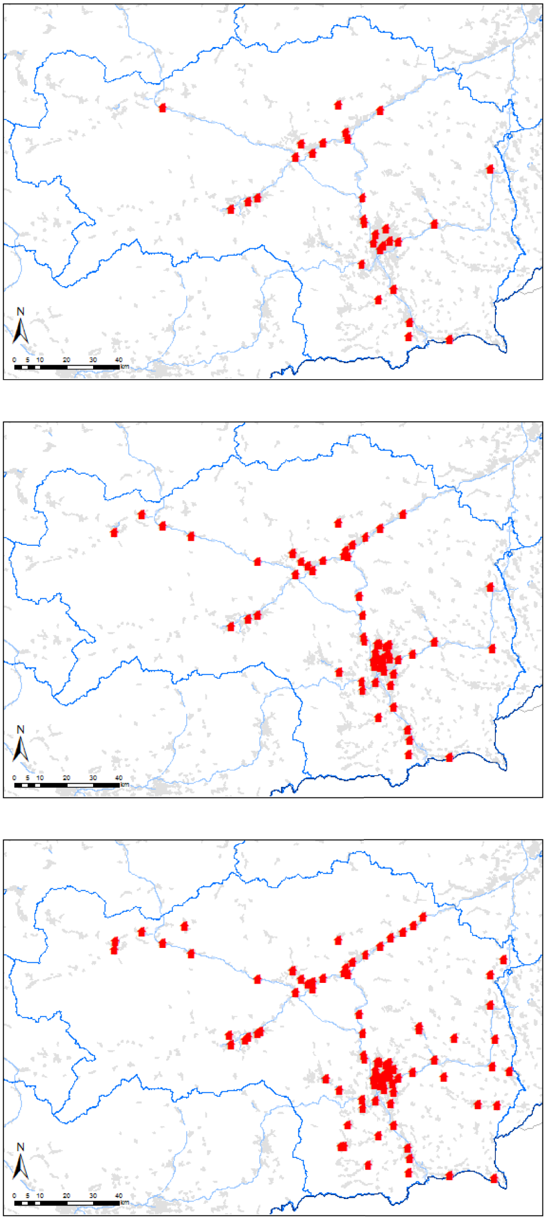


Figure 10.2.: Demonstration of feasibility: modeling a temporal development based on the model of prioritization of supermarket locations in Styria: placement of 30 (above), 60 (middle), and 90 (below) charging stations

10.3. Modeling the development of a regional charging infrastructure in the Region Stuttgart for the years 2010 to 2020

In the previous sections the available publications on the time-spatial development of charging infrastructure have been surveyed. Then the connections between static and dynamic location planning have been discussed. It has been demonstrated how the two static location planning methods presented in Chap. 8 can in principle also be used to model a dynamic development of infrastructure.

Within the following sections a third model will be presented that has specifically been constructed to simulate a long-term development of a charging infrastructure for EVs in a region. The research question for the development of this model was: *if the target of 1 million EVs in Germany by 2020 is met, how should a corresponding charging infrastructure for EVs be implemented in the Region Stuttgart in the years to 2020?* The development was considered from the year 2010 on (the work was done in 2010/2011), at a time when there were almost no EVs and charging points existing in the region.

The work has already been published in the article [355]. The part on the diffusion of EVs has been published together with the EIFER colleague Dr. Susanne Linder in [688]. The work dates from the years 2010/2011 and already seems partially outdated at the time of this writing in mid 2015. The work is only shown in concise form here, in order to show how long-term development of charging infrastructure can be modeled. Readers interested in more details are invited to read the complete articles [355] and [688]. This research was done within the project IKONE funded by the BMVBS (Bundesministerium für Verkehr, Bau und Stadtentwicklung).

The general principle of the model is to first simulate the diffusion of EVs, i.e. the development of the ownership of EVs, in the municipalities of the region. Based on the number and spatial distribution of EVs for each year, the corresponding number and distribution of charging points for this year is then calculated. The numbers of charging points and EVs are set in relation to each other making use of quotas. The locations of charging points are determined based on data on mobility between municipalities.

10.3.1. Introductory remarks: the Region Stuttgart, basic assumptions

The model has been developed for the Region Stuttgart in the federal state of Baden-Württemberg in Germany. The geographic location of the region in the southwest of Germany can be seen in Fig. 10.3. About 2.67 million people, which is about 25 % of the population of Baden-Württemberg, live in the region. The region has an area of 3 654 km^2 and consists of 179 municipalities [700]. The city of Stuttgart lies at the center of the region. It has 23 city districts, which are used in the following model to subdivide the large city area. About 1.1 million employees work in the Region Stuttgart. The most important industry sectors are the construction of vehicles and machines and electric engineering [701].

Figure 10.3.: Location of the Region Stuttgart within the German federal state of Baden-Württemberg

The model and the generated scenarios are based on several assumptions about the development of the numbers of EVs and the implementation of the charging infrastructure in the region:

- *Development of EV ownership*: it is assumed that the target stated by the German government of 1 million EVs in Germany by the year 2020 [1] will be reached. Assuming a nationally homogeneous EV/registered car ratio, this would correspond to about 35 000 EVs in the Region Stuttgart in the year 2020 (on 01.01.2010 there were 41 737 627 cars registered in Germany [702] and 1 429 706 in the Region Stuttgart [703]). In the year

2010 the number of EVs in the region is assumed to be so small as to be negligible (i.e. 0, at that time there were only 1 236 EV registered in entire Germany [702]). The number of charging points is also assumed to be negligible for the year 2010 (i.e. 0). The spatial development of the ownership of EVs is modeled independently of the spatial development of infrastructure, therefore it is implicitly assumed that a “suitable” public infrastructure is developed in parallel that neither hinders nor supports the development of EV ownership.

- *Charging technology*: it is assumed that only conductive charging via plug is used. Inductive charging or battery switching is not considered. This implicitly assumes that no big technological breakthroughs (ultra fast charging or similar) occur in the modeled ten year period. It is assumed that charging points that are being installed remain in place beyond the considered time period, i.e. they are not removed or replaced within the considered 10 year period.
- *Organization form for the public charging infrastructure*: it is assumed that planning and installation of the charging infrastructure takes place in a centralized, coordinated fashion. This would for instance be the case if the Energie Baden-Württemberg (EnBW), the biggest electric utility in the region, would play a key role in the implementation of this infrastructure. The model implicitly assumes that EV drivers can access all installed public charging points, i.e. no mutually exclusive public charging point networks are being implemented in parallel.
- *Demanding sufficient utilization*: the model assumes that the provider of the charging infrastructure demands a minimal level of utilization of the charging infrastructure. This can be the case if the charging infrastructure has to be refinanced by user fees alone. Apart from special subsidies within model projects, there are no general public subsidies for the installation and operation of charging stations of publicly accessible charging points in place in Germany (see Sec. 6.2.2). Within the authors' original article [355] the order of magnitude of sufficient utilization was determined by economic analysis for the refinancing of charging points (also see Chap. 5 within this document). For the scenarios, calculations are done for demanded levels of utilization of 1, 2, and 3 hours of average daily use.

In the introduction to this chapter different quantitative and qualitative forms of growth have been categorized. The model presented here replicates some forms of quantitative growth only. *Densification* can be seen, as more charging points are placed in communes which already contain charging points. *Spatial extension* can implicitly be seen, as charging points are placed in big centrally located zones first, and charging points are later also placed in more peripheral communes. As already explained in the basic assumptions above, some forms of quantitative and qualitative development are not replicated in the model. Within the relatively short timespan of ten years, no *removal* and *replacement* of charging points is assumed to take place. It is also assumed that no technical *upgrading* is done within this time period.

10.3.2. Simulating the diffusion of EVs in the Region Stuttgart

In a first step the development of the ownership of EVs in the 178 municipalities of the Region Stuttgart and 23 urban districts of the city of Stuttgart is simulated. The spatial diffusion model was implemented in the simulation environment AnyLogic. The model was developed together with EIFER colleague Dr. Susanne Linder and already published in the article [688]. In this context, one scenario result generated by the model is used as an input dataset for the infrastructure development model. Readers interested in more technical details of the EV diffusion model are invited to read the complete article [688].

The EV diffusion model is based on the established bass model for the diffusion of innovations [704] and its formulation as a system dynamics model in [705]. The bass diffusion model simulates the diffusion of an innovation as the interaction of two effects. These are the persuasion by advertisement (*innovation*) and positive word-of-mouth from people who are already using the innovation (*imitation*).

The model simulates EV ownership for several different sociodemographic groups. Based on the general theory on early adopters of technologies [706] and specific properties of EVs, four groups were identified as being probable early adopters of EVs. *Urban trend-setters* are young persons between 18 and 35 years old who live in single or couple households and have a high level of education and income. These kinds of persons can be expected to have a higher interest in new technologies and be more able to adapt to innovations than the average population. *Multiple-car families* are family households owning two or more cars and living in (semi-) detached houses. Family members have a high level of income and education. For this early adopter type it is assumed that one conventional car is replaced by an EV which is then mainly used for short everyday trips. *Dynamic senior citizens* are 60 to 75 years old, live in (semi-) detached houses, and own high capital. Old persons today are more mobile than they were in the past, thus this group may also belong to the early adopters of EVs. *Innovative fleet managers* want to convey an innovative and environmentally friendly image. They can be assumed to mostly work in the domains of electric utilities, municipal services, social services, city logistics, passenger transportation, telecommunications, and other infrastructure services. These early adopter categories as well as the general population and general fleet managers were located in the region making use of statistical data on demographics, households, education level, vehicle stock, building stock, and enterprises. Demographic developments (aging of the population, movements) are not considered.

In the model the diffusion by word-of-mouth was simulated to also take place between different sociodemographic groups and different municipalities in the EV diffusion model (see [688] for details).

Different scenarios of the diffusion of EVs have been presented and discussed in [688]. One specific scenario is used here as the basis for scenarios for the development of the associated charging infrastructure. The used scenario is shown in Fig. 10.4. In the scenario there are 35 001 EVs in the Region Stuttgart by 2020. Of those, 4 279 (12 %) are owned by urban trend-setters, 3 751 (11 %) by multiple-car families, 3 455 (10 %) by dynamic senior citizens, 11 575 (33 %) by other households, 7 748 (22 %) by innovative fleet businesses, and 4 193 (12 %) by other fleet businesses. It can be seen in the figure that different adopter types live in different areas of the region. Urban trend-setters mainly live in the central districts of Stuttgart, while multiple-car families live in more peripheral municipalities. Operators of fleet vehicles can mainly be found in municipalities with large industrial zones.

Some aspects would probably be simulated differently in the light of research results available at the time of this writing in mid 2015. It seems improbable that the target of 1 million EVs in Germany by 2020 will be reached. The importance of the sociodemographic group of the urban trendsetter seems to have been overrated, while the early adopter groups of the multiple-car family and dynamic senior citizen seem to be confirmed by data published in 2015 on early adopters of EVs in Germany [345].

An alternative, simpler method for generating time-spatial scenarios of the development of EV ownership would be to do simulations based on the current number (and possibly segments) of registered vehicles in the municipalities, instead of identifying specific demographic groups.

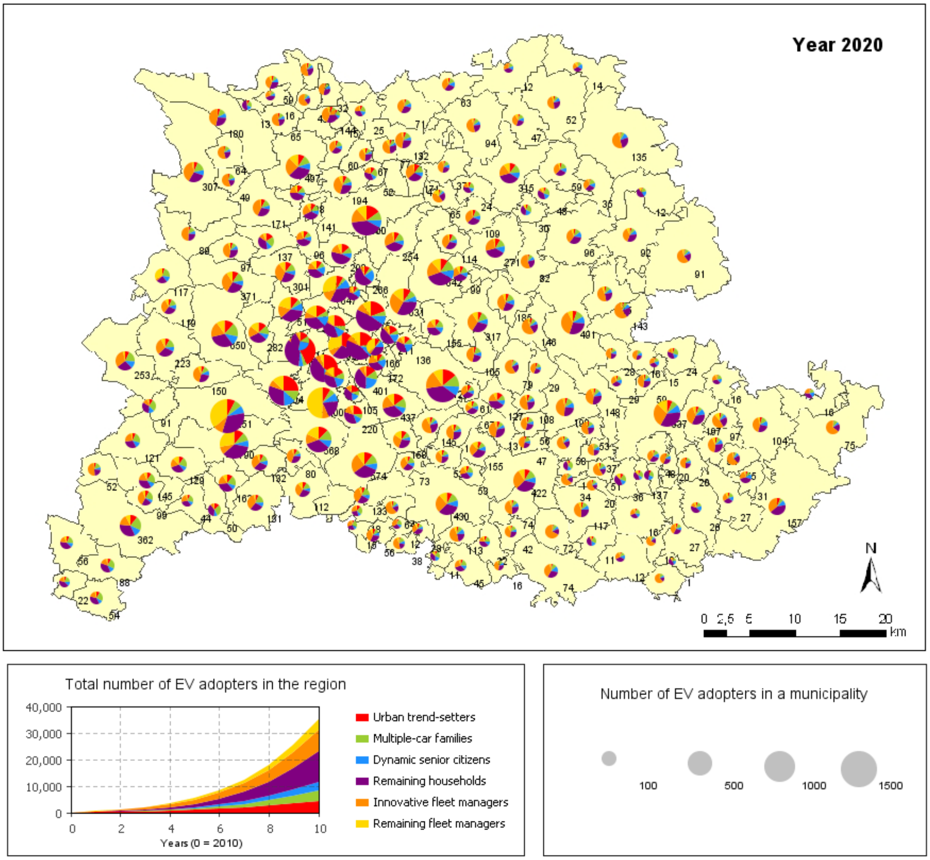


Figure 10.4.: Basic scenario of the development of EV ownership in the Region Stuttgart from 2010 to 2020

For the infrastructure development model discussed below, calculations are based on the total numbers of EVs owned in a commune, differentiated only by private use and business fleet use, but not by specific adopter types.

10.3.3. Modeling the distribution of charging points in a region

Based on the development of EV ownership in the communes/city districts of the region, the development of a corresponding charging infrastructure is simulated. For each year the corresponding number and locations of charging points are calculated based on the number and locations of EVs owned in the region in that year. The simulation contains two elements. First, the absolute number of charging points at homes, at businesses, and in public is calculated that is associated with the given number of EVs in a commune. Then this absolute number of charging points is spatially distributed among the communes/city districts making use of mobility data which quantifies the mobility between the communes/city districts.

Some quotas of charging points per EV are directly estimated. The number of charging points at homes is discussed first. In Germany a large share of car owners have their own garage. The percentage is as high as 71 % in small municipalities with less than 500 residents and still makes up 43 % in big municipalities with more than 500 000 residents [707]. It is probable that almost all people who will buy EVs in the next years will also have a private garage in which they install their charging equipment (also see the analysis in [688]). Thus quotas of *0.9–1.0 charging points at homes per privately owned vehicle* seem realistic. It is assumed here that EVs used in business fleets require no additional charging possibilities at private homes of employees, thus the quota is 0.0.

The provision of charging points at workplaces is also estimated directly. It is expected that some big companies will install charging points for their employees. In some states, such as France, providing charging possibilities in office buildings is already obligatory [363]. In Germany this is not expected to be the case in the near future. Quotas can be expected to lie in a broad range of *0.1–0.6 charging points at working locations per privately owned EV*. EVs which are used within company fleets have to be provided with a charging possibility at the company's car park. Therefore quotas close to *1.0 charging point per EV used in business fleets* seem reasonable.

The associated numbers of *public* charging points are difficult to estimate directly. In this context the term public charging points stands for all publicly accessible charging points, including semi-public points located at supermarkets, cinemas, and similar venues. A formula has been developed which allows to determine such quotas based on technical and behavioral parameters. The following formula establishes an energy balance. The formula states that a percentage of the amount of energy consumed by EVs corresponds to the amount of energy recharged at the charging points (thus assuming a closed system). This formula has already been shown and discussed in Sec. 4.3 within this document. The almost same approach to quantifying a required number of charging has been published earlier by other authors in the report [322].

The *amount of energy that is recharged at public charging points (CPs) in a region* can be described as:

$$i = 1, 2 : \quad V \cdot e \cdot d \cdot R_i = C_i \cdot p_i \cdot 24[h] \cdot U_i$$

With the variables:

i:	=1,2 different types of public CPs: normal and fast charging
V:	number of EVs in the region
$e\,[\frac{kWh}{km}]$:	average energy consumption of an EV (including losses during recharging)
$d\,[km]$:	average daily driven distance of an EV
R_i [%]:	percentage of energy charged at public CPs of type i
C_i:	number of public CPs of type i in the region
$p_i\,[kW]$:	charging power of public CPs of type i
U_i [%]:	level of utilization of public CPs of type i

The formula can be transformed in order to obtain direct *quotas of charging points per EVs*, given the other variables:

$$i = 1, 2 : \quad \frac{C_i}{V} = \frac{e \cdot d}{p_i \cdot 24[h]} \cdot \frac{R_i}{U_i}$$

The technical variables e, d, and p_i can be set directly. Higher levels of uncertainty exist for the amount of energy recharged publicly R_i and the demanded level of utilization of public charging points U_i. These values are varied for the different scenarios shown in the following.

The above discussed quotas and presented formula allow to associate a number of charging points at homes, at workplaces, and in public to a given number of EVs used privately and within business fleets. Now it will be shown how this number of associated charging points is distributed in space, among the different communes and city districts. These geographic entities will be referred to as *zones* in the following. The spatial location of charging points only takes place on the level of zones within this model, specific locations/points within zones are not considered.

Charging points at homes are located in the zone where the owner of the privately used EV lives. As already mentioned, it is assumed that EVs used in business fleets do not have associated charging points at homes.

Charging points at places of work are placed in the zone where the business is located for EVs used in business fleets. For privately used EVs the working charging points of a zone are distributed according to commuter data. The *number of charging points in the working context for private EV drivers allocated to a municipality* is calculated by:

$$C_j^w = \sum_{\text{zones } i} \left(\frac{x_{ij}}{\sum_{\text{zones } k} x_{ik}} \cdot W_i \right)$$

With the variables:

C_j^w: number of charging points at working places allocated to zone j

x_{ij}: number of commuters from zone i to zone j

W_i: number of charging points at working locations associated with EVs of zone i (according to quotas)

The formula can be interpreted as a distribution according to probabilities. The probability that an EV owned in zone i is provided with a charging point at a working place in municipality j is assumed to correspond to the number of commuters driving from i to j divided by the total number of commuters of a zone, including commuters within the same zone.

Commuter data was available only for communes, not on the level of detail of the city districts of Stuttgart [708]. Commuter flows for the city districts were therefore approximated making use of employee data on the level of the city districts. The number of incoming commuters to the commune of Stuttgart was disaggregated to the 23 city districts, proportionally to the number of employees working in each city district [709]. The commuters leaving the commune of Stuttgart were proportionally disaggregated among the city districts, based on the number of employees at the location of residence in the city districts [710]. The commuter data is not differentiated according to the transport mode used, as this information is not contained in the data [708].

For *charging points in the public context* a similar spatial distribution method is used. Because no more detailed inter-communal mobility data was available, the commuter data was also used to quantify the general mobility flows between the zones. Because shopping- and recreation-motivated mobility is different from work-motivated mobility [200], this is expected to introduce some distortions into the spatial distribution. However, using the empirically collected commuter data was considered to be a better alternative than to generate synthetic trip data for the region. Two spatial allocation schemes have been implemented for charging points in the public context: the first scheme locates charging points according to commuter data as above:

$$C_j^p = \sum_{\text{zones } i} \left(\frac{x_{ij}}{\sum_{\text{zones } k} x_{ik}} \cdot P_i \right)$$

With the variables:

- C_j^p: number of charging points at public locations allocated to zone j
- x_{ij}: number of commuters from zone i to zone j
- P_i: number of charging points at public locations associated with EVs of zone i (according to quotas)

The second location scheme only considers commuter flows between different zones. It thus assumes that EV drivers only use public charging points when they are moving outside of the zone in which they live or in which their business depot lies in the case of business fleet vehicles.

$$C_j^p = \sum_{\text{zones } i, i \neq j} \left(\frac{x_{ij}}{\sum_{\text{zones } k, k \neq i} x_{ik}} \cdot P_i \right)$$

With the variables:

- C_j^p: number of charging points at public locations allocated to zone j
- x_{ij}: number of commuters from zone i to zone j
- P_i: number of charging points at public locations associated with EVs of zone i (according to quotas)

Commuters also drive into the Region Stuttgart from outside of the region. To take the demand for charging points at working and public locations into account associated with these cars the following approach is taken. The outside region is represented as a (not spatially located) single zone. The development of EV ownership in this zone is assumed to progress as in the average of all zones in the region (concerning the number of EVs per household). No maximal limit has been set for the commuting distance, as an analysis of the data has shown that only a very low percentage of the commuters travel (euclidian) distances over 75 km. According to the commuter data a low percentage of the charging points associated to EVs registered outside of the region are thus located in zones in the Region Stuttgart. The number of charging points located in the outside zone is not calculated.

10.3.4. Scenario 1: baseline case

For all following scenarios the temporal and spatial development of EV ownership is taken to be as presented in Sec. 10.3.2. For the first baseline scenario Tab. 10.1 shows the parameters, resulting in quotas for different types of charging stations.

The energy consumption of privately used EVs was set to correspond to the average value measured under realistic circumstances in [220]. The energy consumption of business vehicles was set to correspond to the values stated for the transporter which was used in the mobility project IKONE in the Region Stuttgart. The average daily driven distance of private vehicles was taken from the statistical source [356], that of business fleet vehicles from [711].

The levels of demanded levels of utilization of 8.33 % and 12.5 % correspond to 2 and 3 hours of daily use. EVs used in business fleets are assumed to use normal 22 kW charging points much less than privately used EVs (2.5 % vs. 7.5 % of consumed energy recharged publicly). It is assumed that when business fleet EVs are recharged, they mainly charge at fast charging point to be able to continue their trips as soon as possible. EVs are assumed to only use public charging points when they are moving outside of the zone in which they live or in which their business depot lies respectively.

The results of the simulation for the year 2020 are shown in Fig. 10.5. For the 35 001 EVs in the region and those driving in from outside there are a total of 38 691 charging points. Of those, 21 852 (corresponding to 56 %) are located at homes of private EV users and 16 268 (42 %) at businesses, both for employees's EVs and those used in business fleets. There are only 478 (1.2%) normal public charging points with a power of 22 kW and 94 (0.2 %) fast public charging points with a power of 44 kW. With a total of 1.4 %, the share of public charging points is so small as to be hardly visible in Fig. 10.5. Charging points at homes and businesses can be seen to be mainly located in the bigger communes and city districts of the region.

Table 10.1.: Parameters used for the baseline scenario

EV user type	**Energy consumption** e $[kWh/km]$	**Daily distance driven** $d\,[km]$	**Percentage energy charged** R_i [%]	**Charging point type** $p_i\,[kW]$	**Demanded utilization** U_i [%]	**Resulting quota:** C_i/V
Private EV users	0.228	36.1	2.5	44 kW public fast charging	12.50	**0.0016**
	0.228	36.1	7.5	22 kW public charging	8.33	**0.0140**
	—	—	—	at working locations	—	**0.2000**
	—	—	—	at homes	—	**0.9500**
Business fleet EV users	0.460	64.2	2.5	44 kW public fast charging	12.50	**0.0056**
	0.460	64.2	2.5	22 kW public charging	8.33	**0.0168**
	—	—	—	at working locations	—	**1.0000**
	—	—	—	at homes	—	**0.0000**

Comparing this percentage distribution of charging points in different usage contexts to the one used for scenario 3 for Liège in Sec. 8.3.2.6 shows considerable differences. There, a total of 10 % of charging points were modeled to be publicly accessible, among them also charging points at curbsides for local employees, and at curbsides in areas where many people live that do not have private parking spaces. The number of 10 % was based on the European Union's clean fuel strategy published in 2013 [51]. Apparently an indirect estimation via ratios, and making use of commuter data, leads to an even lower percentage of public charging infrastructure.

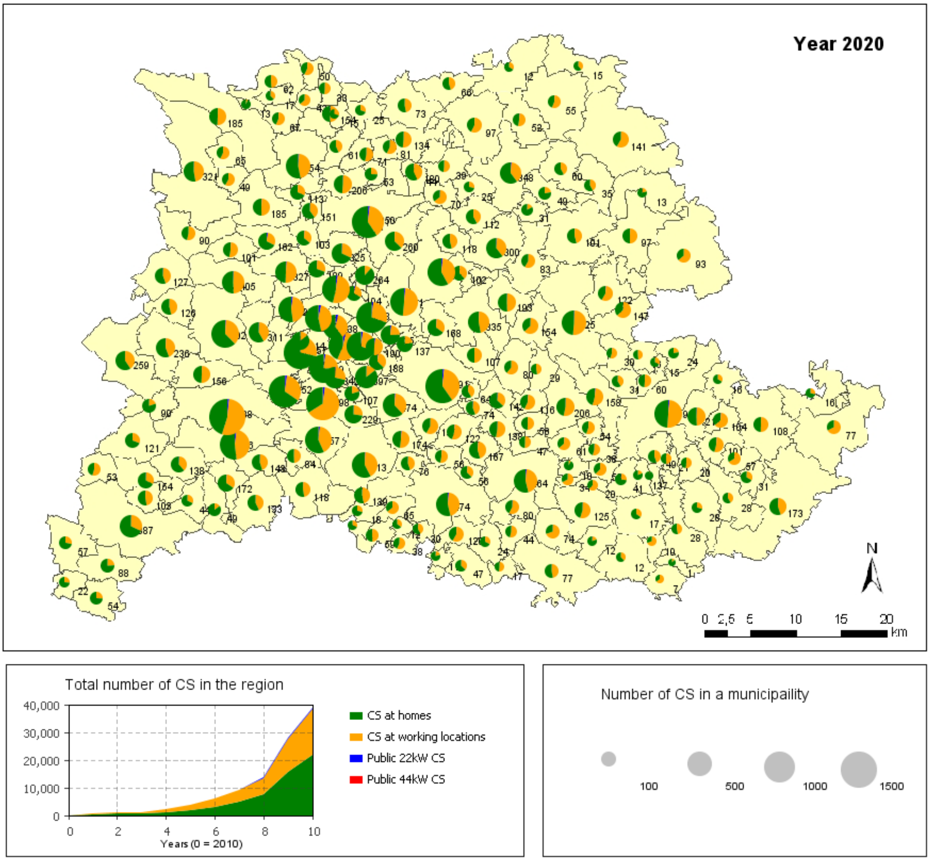


Figure 10.5.: Baseline scenario of the development of the number of charging points for EVs in the *residential, working, and public context* in the Region Stuttgart from the years 2010 to 2020

Fig. 10.6 shows the spatial distribution of only those charging points located in the public context. It can be seen that charging points are mainly placed in the bigger city districts of Stuttgart and bigger communes, while no public charging points are being set up in more peripheral communes.

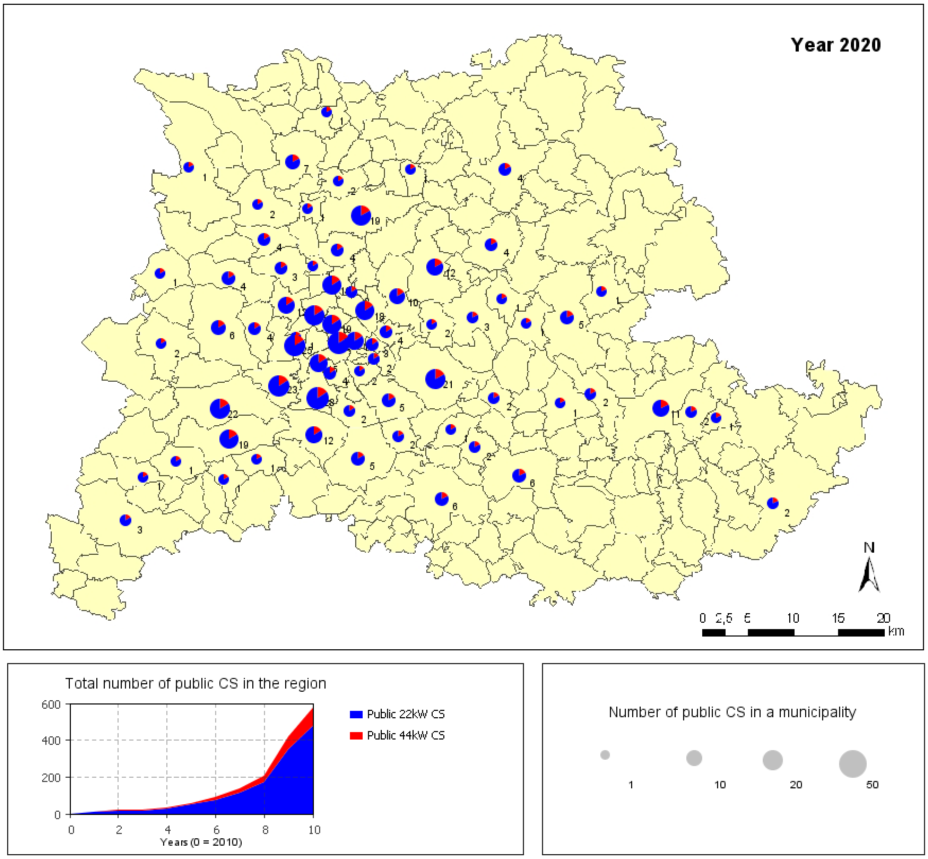


Figure 10.6.: Baseline scenario of the development of the number of *public* charging points in the Region Stuttgart from the years 2010 to 2020

Looking at the development of the number of charging points over time, displayed in the lower left corners of Fig. 10.5 and Fig. 10.6, it can be seen how the exponential growth of the number of EVs within the considered time horizon is also manifested in the growth of the corresponding charging infrastructure. The diffusion of technologies, as the bass diffusion model replicates it, takes on an exponential growth in the first years (also see the development of the number of EVs as shown in Fig. 10.4).

The total number of public charging points that this scenario calculates for 35 001 EVs in the year 2020 is quite low, with 478 normal and 94 fast charging points, even though parameters have been chosen which were considered to lie in a middle range. The following scenarios therefore simulate cases with higher quotas of charging points per EV.

10.3.5. Scenario 2: higher quotas

In this and the following scenario only the public charging infrastructure is simulated. The technical parameters are left as before, but more optimistic values for the demanded minimal level of utilization U_i and the percentage of energy publicly recharged R_i are assumed. The percentage of energy publicly recharged R_i is raised for all cases. The used utilization rates U_i of 4.16 % and 8.33 % correspond to 1 and 2 hours of average daily use. This parameter change results in higher quotas of charging points per EV (shown in the rightmost column in Tab. 10.2). Concerning the spatial allocation of public charging points, EVs are assumed to only use public charging points when they are moving outside of the zone in which they live or in which their business depot lies.

Table 10.2.: Parameters used for the higher quotas scenario

EV user type	**Energy consumption** e $[kWh/km]$	**Daily distance driven** d $[km]$	**Percentage energy charged** R_i [%]	**Charging point type** p_i $[kW]$	**Demanded utilization** U_i [%]	**Resulting quota:** C_i/V
Private EV users	0.228	36.1	3.0	44 kW public fast charging	8.33	**0.0028**
	0.228	36.1	12.0	22 kW public charging	4.16	**0.0449**
Business fleet EV users	0.460	64.2	5.0	44 kW public fast charging	8.33	**0.0168**
	0.460	64.2	5.0	22 kW public charging	4.16	**0.0672**

The results of the simulation for 2020 can be seen in Fig. 10.7. With the higher quotas there are 1 918 public charging points for 35 001 EVs within the region and those driving in from the outside. Of these charging points, 1 678 are equipped with 22 kW charging power and 240 are fast charging points equipped with 44 kW charging power.

Though the total number of public charging points is higher in this scenario, the overall spatial distribution stays unchanged. The biggest part of charging points is located in the biggest urban centers of the region. But since the overall number of charging points is higher, it also becomes worthwhile to install public charging points in smaller peripheral communes.

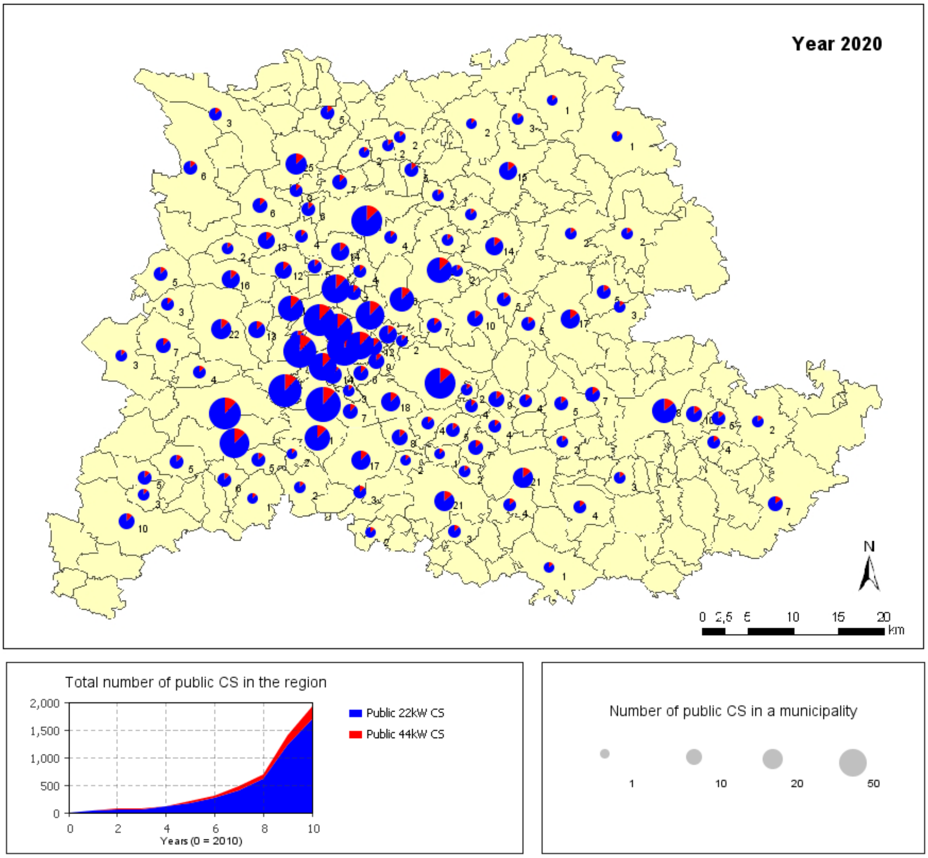


Figure 10.7.: Scenario with higher quotas of the development of the number of public charging points in the Region Stuttgart from the years 2010 to 2020

10.3.6. Scenario 3: higher quotas and use of public charging points in zone of ownership

As already explained in Sec. 10.3.3, two different spatial allocation schemes for public charging points have been implemented. The scheme used in the two scenarios above assumes the use of public charging points to only occur when EVs are moving outside of the zone in which they live or in which their business is located, in the case of business fleet vehicles. In this third scenario public charging is simulated to also occur within the zone where the EV is registered. Such an use could for instance occur when EV drivers do not dispose of a private charging possibility and would rely on using public charging points on the street or regularly charge at public fast charging points. All other technical and behavioral parameters, and thus the resulting quotas, have been left as in scenario 2.

The result of the simulation for the year 2020 is shown in Fig. 10.8. The total number of charging points is slightly higher than in the previous case. A total of 1 971 public charging points are installed for the 35 001 EVs in the region and those driving in from the outside. Of these charging points, 1 724 are normal charging points with 22 kW power, and 274 are fast charging points with 44 kW charging power. That the total number of charging points slightly increases might be due to the fact that those EV drivers that commute out of the region now require more charging points at their home/business depot zone lying within the region.

The overall spatial pattern is similar to those of the scenarios before. Charging points are mainly located in the biggest urban centers. However, when comparing the results of this scenario to the previous scenario 2, it is noticeable that more charging points are located in the big cities and districts surrounding the central city of Stuttgart, in which many people live and many businesses are located in industrial zones (compare the results of diffusion of EVs as shown in Fig. 10.4).

10.3.7. Merits and disadvantages of the method

The method for simulating the time-spatial development of a charging infrastructure, shown above, allows to develop realistic scenarios for future development. Once the development of EV ownership in the zones of a region is given, the development of the infrastructure can be modeled using only little additional data.

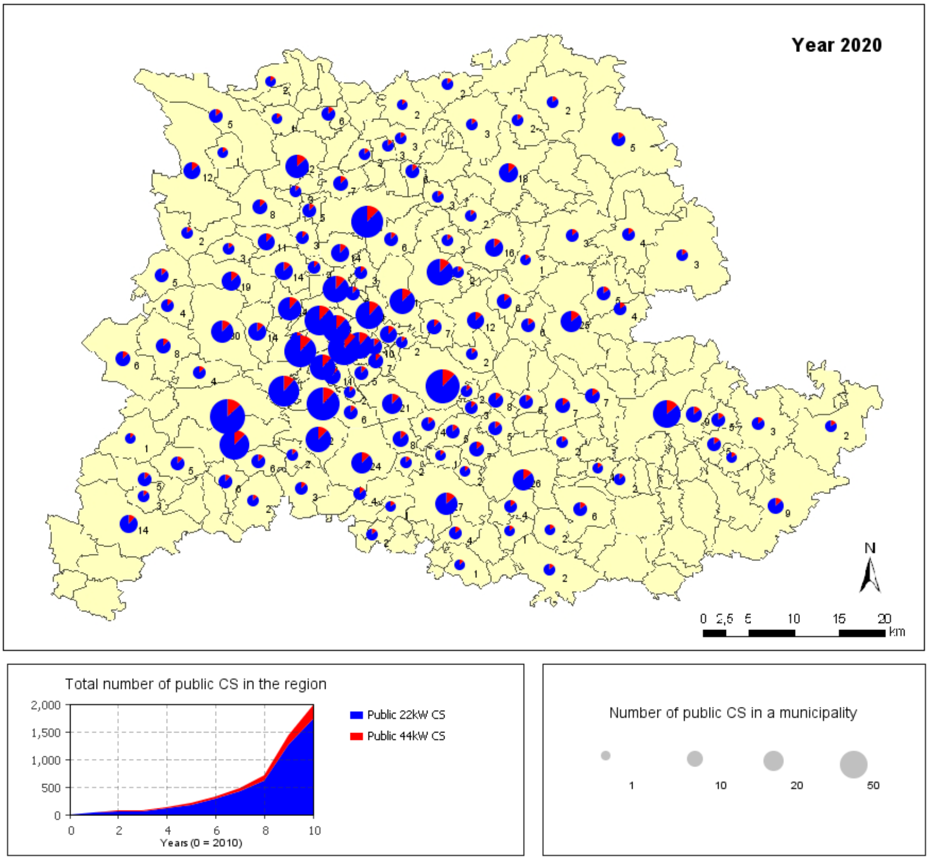


Figure 10.8.: Scenario with different spatial use and with higher quotas of the development of the number of public charging points in the Region Stuttgart from the years 2010 to 2020

Using the introduced formula, only a handful of technical and behavioral parameters are needed to calculate quotas of public charging points per EV. The spatial distribution of charging points is calculated based on commuter data. This kind of data is widely available for different regions.

The work was done in the years 2010/2011. At the time of this writing in mid 2015, some aspects would probably be parameterized/modeled differently in the light of research results published in the meantime. For instance, it seems improbable that the target of 1 million EVs on German roads by the year 2020 will be reached. More reliable empirical information is now available on the early adopters of EVs ([345] and others). While the early adopter groups of multiple-car family and dynamic senior citizen still seem relevant, the importance of the urban trend-setters seems to have been overrated. Also, the demand for public charging points by vehicles used in business fleets seems to have been overrated (compare for instance [712]).

An approach to make such results as presented here less dependent on specific years stated (here: 2010 to 2020), would be to generically express the development of infrastructure in dependence of the number of registered vehicles in the region (1 000, 5 000, 10 000, ..., 35 000).

The overall simulation method can be refined in several aspects. Only pure EVs were considered here, not PHEVs, and REEVs. Different kinds of vehicles could be modeled via different diffusion processes or parameters, such as average energy consumption per km and percentage of energy publicly recharged, could be set as to reflect a mixed fleets of EVs, PHEVs, and REEVs.

The quotas of different charging points per EV were left static over the entire 10 year time period. Quotas could also be dynamically changing over time. For instance, the number of public charging points per EV could be higher in the early years of development than in a later consolidated phase of market development, due for instance to lower demands of utilization in the early phase.

The overall approach of using a spatial probability distribution to calculate where an EV owned in a given commune might be publicly recharged seems promising. Instead of basing the distribution on commuter data only, more encompassing origin-destination trip data for different motives (work, but also shopping, recreation etc.) and specifically for the transport mode car from a transport household survey could be used. To refine such a model, it could also be interesting to consider the traveled distances. It seems more probable that an EV is publicly charged when longer distances have been traveled. However for very long distances over 100 km, it seems improbable that an EV will be used for the trip.

10.4. Conclusion: long-term planning and development of charging infrastructure

This final section will shortly summarize the results presented within this chapter. In the introduction of this chapter different aspects of the temporal development of EV charging infrastructure have been discussed. Quantitative development can take on the form of densification, spatial expansion, replacement, and removal of charging points. Qualitative development can take place in the form of technical upgrading of charging points.

The literature survey on the publications on the time-spatial development of charging infrastructure has shown that much less publications on this topic exist than on that of static location planning for EV infrastructure. A temporal aspect has been included in a few optimization models. Several publications treat the time-spatial development of EV infrastructure and its interdependency with the development of EV ownership.

The connections that exist between static and dynamic location planning methods have been discussed. A dynamic location planning problem can be reduced to a sequence of static location problems, by always placing only one more, or a batch of additional charging points, taking the previously located charging points into account. If a location planning method makes use of calculated priorities, these can be interpreted as a time sequence: place a charging point at the location with the highest priority first, than at the location with the second highest priority, and so on.

The concept of scalability of a charging point location scheme has been introduced. Informally stated, this means that an increase of the number of charging points to be located always leads to the addition of new locations, never to a removal of locations. If a charging point location scheme is scalable, it can be used to model the development of a charging infrastructure in a consistent way, by simply increasing the number of charging points for different time periods. This was practically demonstrated using the method of decision support for the (static) location planning of EV charging points of Chap. 8. The interpretation of priorities as a time sequence has also been practically demonstrated, using the prioritization method shown in Chap. 8.

The main part of the chapter presented a model and practical application of the development of charging infrastructure in the Region Stuttgart in the years 2010 to 2020. The scenarios were meant to show how a charging infrastructure for EVs should be developed in the region if the national target of 1 million EVs in Germany by the year 2020 is reached.

First, it was shown how the development of EV ownership was simulated. For this, the early adopter categories of the urban trend-setters, the multiple-car family, the dynamic senior citizen, and innovative fleet manager were identified. These groups, as well as the general population and other businesses with vehicle fleets, were located in space making use of sociodemographic data. The diffusion of EVs in these groups was simulated using the bass diffusion model implemented in system dynamics. One specific diffusion scenario was chosen for which corresponding infrastructure developments were simulated. The number of charging points corresponding to a number of EVs are first calculated making use of a newly introduced formula. The charging points are then distributed in space making use of data on commuter flows.

Three specific scenarios have been presented. For the first scenario moderate parameters were used for calculating the quotas of public charging points per EV. The calculations showed a total of 38 691 charging points for 35 001 EVs in the Region Stuttgart in the year 2020. The large majority of those charging points was located at homes (56 %) and businesses (42 %), only 1.2 % were public charging points. Of those, 478 were 22 KW and 94 were 44 kW charging points. The public charging points were spatially concentrated on the biggest cities and city districts of the region. The second scenario was calculated with more optimistic parameters, resulting in higher quotas of public charging points per EV. Still, only 1 918 public charging points were calculated to be required, of those 1 678 with 22 kW and 240 with 44 kW. The third scenario was simulated with a different spatial use of public charging points. If EVs are assumed to also use public charging infrastructure in the zone in which they are registered, more charging points are allocated to cities and city districts surrounding Stuttgart. Overall the scenarios have shown that the required number of charging points is quite low, when sufficient levels of utilization of 1, 2, or 3 hours are demanded by the operator. The scenarios have also shown a strong concentration of the infrastructure on the biggest cities and city districts of Stuttgart.

An advantage of the simulation method is that it requires only little additional data to simulate the development of an EV infrastructure, if the development of EV ownership is given as an input. However, the model could also be refined in several aspects, taking different EV variants into account, and using more refined inter-zonal mobility data.

Overall the results presented in this chapter have shown how the temporal development of a charging infrastructure can be modeled if the development of EVs is given as an input. For this, it is required to determine a corresponding number of charging points and their spatial distribution. The model and its application has shown that the number of charging points per EV should be lower than those commonly proposed and that charging points should mainly be set up in central city locations.

11. Summary and outlook: characteristics of a charging infrastructure for EVs and further need for research

This thesis discusses the planning of the charging infrastructure for EVs from many different angles. Within this concluding chapter the main findings are recapitulated again. Then, it is concluded in which areas further research is required.

11.1. Recapitulation of main findings

An overview of the current technologies for charging EVs in Chap. 2 discusses three main technologies: charging by cable, via induction, and battery switching. Charging via cable currently is and is likely to remain the most widespread form. Norming of the corresponding charging plugs has well advanced with the Type 2 plug being considered the European standard for AC and the CSS Type 2 plug for fast DC charging. Charging facilities which charge by cable can be integrated into other street furniture, such as lamp posts and pay and display machines. However, inductive charging and battery switching will remain interesting for niche applications, for instance for recharging fleet vehicles such as taxis or buses.

The discussion of technology also shows the ICT that is needed for the operation by the provider and use of the charging stations by users. The ICT components should be thought of as an integral part of the infrastructure. For operators it is especially important to develop roaming solutions which allow their users to also charge at stations of other providers. It is also important to provide EV drivers with navigational websites and smart phone applications to enable them to find the installed charging stations.

Interactions of the charging of EVs with the electricity system are discussed in Chap. 3. Numerous interactions exist on the levels of generation, storage, transmission, distribution, and local use of electricity. An evaluation of the order of scale of occurring effects shows that the planning of charging infrastructure should focus on taking effects on the level of the distribution system and the local building into account. The charging of an EV leads to a significant increase in local power demand, but even high numbers of EVs of 1 million would not lead to large effects on the national scale. It should be assured that the charging of EVs does not lead to an overloading of local buildings connections, distribution power lines, and transformers.

Impacts can be mitigated by implementing controlled charging, which alters the power and timing of charging in order for it to occur at times of low electricity demand. This might not be feasible for public charging stations, however, where EV drivers expect their cars to be recharged as fast as possible. The concept of vehicle-to-grid (V2G), which envisions to use the EVs' batteries as intermediate electricity storage, has generated a lot of interest in science and in public media. However, as there are still many unresolved issues, it seems unlikely that it will be implemented in the bigger scale in the near future.

Chap. 3 also discusses the electric installation of charging facilities. German norms and codes of practice developed in the last few years seem to specify all relevant aspects. It is only a bit problematic at the moment that these requirements are spread out over diverse documents.

The demand for public charging infrastructure is discussed from several angles in Chap. 4. The point is made that demand should not be thought of as a fixed quantity, rather, according to microeconomic theory, realized demand should be thought of as an interaction between the consumers' (EV drivers') interests, the providers' (charging infrastructure operators') interests, the quantity of the service, and the price of the service. Based on this reasoning, the demand for charging infrastructure was approached from three perspectives: from the EV drivers' point of view, from the provider's point of view, and when seen as a public service not underlying free market conditions.

A complication in the demand and supply for EV infrastructure is the so-called chicken-and-egg dilemma, i.e. the interdependency between the purchase of EVs and the installing of charging stations by infrastructure companies. However, several developments lead to mitigating this dilemma, such as PHEVs which do not require public charging infrastructure or state subsidies within pilot trials for charging stations which then are not dependent on high levels of utilization.

Demand for public charging infrastructure by EV drivers has to do with several technological and psychological factors. The majority of current EVs have driving ranges around 100–150 km, whereas gasoline-powered vehicle can drive 400–1 200 km before refueling. This implies that EVs have to be charged more often. The large majority of car drivers in Germany park their car on the own estate, where they could thus also recharge an EV. Studies which evaluate the mobility data of current cars indicate that a significant percentage (13.1 %–50 %) of them could be replaced by EVs if charging took place only at home. The phenomenon of range anxiety, i.e. the fear of stranding with an EV with an empty battery, however, leads EV drivers to perceive a big need for public charging infrastructure. Potential buyers of EVs also state that they see the availability of public charging infrastructure as a prerequisite for buying an EV, but their willingness to pay for such a service is limited. Pilot trials of EVs and their infrastructure have consistently shown that the utilization of public charging stations is low and most charging is done at homes and workplaces.

From the charging infrastructure operators' perspective it makes sense to install charging points only when their utilization is high enough. The introduced formula allows to quantify the quota of charging points per EVs based on technical parameters and a demanded level of minimal utilization. The thus calculated quotas are considerably lower than the 0.1 publicly accessible charging points per EV proposed by the EU and the quota of 0.16 proposed by the German National Platform on electric mobility.

Demand can also be defined from the point of view of a minimal level of service for a public infrastructure, not taking free market conditions into account. The number of required charging points can for instance be defined per registered EV, per parking space, per area, or per km of motorway.

The extensive discussion of the demand for public charging infrastructure, recapitulated above, reveals that both EV drivers and political organizations seem to overstate the need for public charging infrastructure. Rationally acting infrastructure providers would not install the demanded high number of charging points, as they would then be under-utilized.

The economics of public charging infrastructure is considered in Chap. 5. Looking at the regulatory frame conditions, it is found that charging infrastructure can be thought of as a conventional private good, and a natural monopoly does not seem to occur. These points indicate that the service should be provided by private companies in a free market.

The profitability is evaluated for selected business models. It is assumed that EV drivers pay per kWh of electricity charged at a 22.2 kW charging station providing one charging point. An evaluation of the basic business case shows that revenues are not even significant to cover operating costs of the infrastructure in many scenarios. Profitability can be slightly improved if the operator does not have to pay parking rent and investment and operating costs are lowered by installing technologically simpler charging facilities. Both measures combined lead to a significant improvement. Cross-financing public infrastructure from revenues generated from EVs charging at home does not seem to be feasible in most scenarios. Additional revenues generated from advertisement displayed at the charging station can have a big positive impact. This seems to be the most promising strategy for implementing self-sustaining charging infrastructure. In fact, the strategy of financing public infrastructure with revenues from advertisement is already successfully applied to public transport shelters and public toilets. The provision of public charging infrastructure could be made economically feasible by state subsidies. A reasonable scheme for this would be to pay a subsidy per kWh charged at a station. A calculation is also done for a 50 kW DC charging station. In this case it was also found that high levels of utilization above 2:00 h per day of the station are needed for it to be profitable.

In a free market model EV drivers should pay for the costs of public infrastructure. When considering the economics of EV ownership and charging costs together, it is found that occasional public charging has no large impact on the total cost of ownership of an EV.

Taking a closer look at the business model of gasoline stations it is found that these do not generate their main revenues from selling gasoline, but from selling products in the associated shops. This indirect approach could also serve to finance publicly accessible charging stations at supermarkets, cinemas, and similar locations.

Chap. 6 treats the politics and externalities concerning charging infrastructure. If the free market does not provide a service, as seems to be the case for public EV charging infrastructure which is not profitable, the state can intervene and introduce subsidies or regulations. This can be warranted if such an infrastructure creates enough positive externalities, i.e. indirect benefits for society. The expected benefits from EVs and their infrastructure are evaluated in the light of currently available studies. It is found that many benefits can only be realized under specific conditions. EVs can help reduce greenhouse gas emissions if the electricity used to charge them is generated from renewable or other low-emitting sources. Concerning other forms of pollution, the overall impact does not seem to be clear. EVs can lead to less pollution during their operation, but higher pollution during their manufacturing than ICE vehicles. EVs lead to less noise emissions at low speeds. The EU regulation which will make sound-generating vehicle alerting systems obligatory for EVs counteracts this advantage. Replacing ICE vehicles by EVs leads to a diversification of resource imports. Dependency on petroleum imports is replaced by dependency on other energy resources and resources required for the manufacturing of EVs and renewable energy power plants. The manufacturing of EVs and their parts provides the opportunity for job creation in the German automobile industry. Because batteries makes up a big part of the value of EVs, it is important that they are manufactured in Germany. EVs can be integrated into intermodal transport schemes and carsharing systems. It has to be considered, however, that they still compete with conventional vehicles, which tend to be more economic in most cases at the moment. EVs can serve as a testbed to develop smart grid and demand management applications. The above mentioned points can be interpreted as a call for action to German policy makers and the industry: actions should be taken so that the frame conditions are set which allow EVs to realize their full benefits.

Current European and German policies concerning EVs and their infrastructure are also discussed in Chap. 6. The most important regulation from the European Union in this domain is the Directive 2014/94/EU on the deployment of alternative fuels infrastructure [43] which sets the goal of 1 publicly accessible charging points for 10 EVs in EU member states in the longer term. It it not clear how Germany will set this into action. Current German policy seems to focus on providing research funds for EVs and their infrastructure, but only small subsidies for private buyers of EVs. Regulations have been introduced which allow to reserve parking places for EVs and exempt EVs from paying parking fees. But the provision of public charging infrastructure is seen as a responsibility of the industry.

Prospective German policies for the realization of public charging infrastructure are also discussed. Building owners could be forced to install charging stations via changes in the construction code. Local authorities could officially be assigned the responsibility of providing this infrastructure for the public. The economic feasibility of public charging infrastructure could be improved by indirect and direct subsidies.

Chap. 7 shows that the interaction of different stakeholders is important for the implementation of a local charging infrastructure for EVs. This is the case because the control over the different required resources, such as parking spaces, the electricity distribution grid, and electricity provision lies in the hand of different organizations. First, the interests and possible actions of diverse stakeholder categories were shown. Then, the relations between the different stakeholder categories were considered. It was found that new relationships have to be established especially between the electricity and transport sectors. Local authorities and municipal utilities are in a good position to act as coordinators between these sectors. Looking at the different roles required for the implementation of a local infrastructure, it was also found that municipal utilities are in a good position as they could solely fill out most of the roles. Different organizations act on different spatial levels, from the street level to the national level. Stakeholders acting on large spatial scales may therefore have to partner with a high number of stakeholders acting only in their respective localities. When stakeholders are mapped according to their power and interest, the most important players identified are EV infrastructure companies, distribution system operators, electricity providers and municipal utilities. It can be worthwhile to enable EV drivers to participate in local planning as these have a high interest but usually no power in this matter. Following the extensive stakeholder analysis it was shown how stakeholder cooperation can be realized in practice. Possibilities of establishing a stakeholder dialog, organizing citizen participation, and formalizing cooperation were shown.

The location planning of charging stations on the regional scale is treated in Chap. 8. A very high number of methods for this spatial planning task have already been published. The available publications treat a wide array of different cases and make use of different methodological approaches. It is not clear yet how the spatial planning of EV charging infrastructure will fit into the current framework for the spatial planning of infrastructure in Germany. The planning might be integrated into existing spatial planning documents in the long term.

Two specific methods for spatial planning are shown. The first method is based on a top-down distribution of charging points among different location categories. Candidate locations are given as points or areas and characterized by respective indicators of importance. The algorithm is implemented as a tool in GIS, in which input parameters determining the spatial distribution can be changed. A questionnaire filled out during discussions with local representatives serves to determine qualitative scenarios of the implementation of local charging infrastructure in harmony with local policies. These qualitative scenarios are translated into quantitative parameterizations of the method by the researcher. An application of the method to the Province of Liège in Belgium with three generated scenarios is shown. Previously, the author had already applied the method to six different cases in Germany and France. The advantage of the spatial planning method is its simplicity and adaptability. Discussing plausible scenarios of local infrastructure implementation with local representatives leads to a raising of awareness. A disadvantage of the method is the high amount of geographical data that is required as an input.

The second spatial planning method shown in Chap. 8 calculates priorities of supermarkets for the placement of charging stations. Priority scores are calculated by a weighted sum of different aspects describing the suitability of the markets. These are characteristics of the supermarkets themselves, the characteristics of the people living and working in proximity to the market, and the distance from the next motorway exit. To determine which surrounding area is considered for each supermarket, catchment areas of supermarkets are modeled. Different weighting of the considered aspects are used to explore different scenarios for infrastructure implementation. The algorithm is implemented as a tool in GIS to allow for easy generation of scenarios. A specific application of this method is shown for the prioritization of supermarkets in the Austrian federal state of Styria. The scenarios show three possible strategies: placement of charging stations at big supermarkets for interregional demand, at smaller supermarkets for local supply, or at supermarkets in areas where many potential early adopters of EVs live and work. An advantage of the method is that it allows to explore different implementation strategies instead of determining one supposedly "optimal" location planning. The method could be further improved by refining the modeling of catchment areas and by taking correlations which exist in the underlying data into account.

After having treated the location planning of charging stations on the regional scale, Chap. 9 then treats the location planning on the street scale. Many different aspects have to be taken into account for this planning task. The technical prerequisites, such as the feasibility of the connection to the electricity and telecommunication networks and basic fire safety, have to be fulfilled. The spatial configuration of parking space and charging facility has to allow the EV drivers to connect the cable as easily as possible. If the parking spaces are to be reserved exclusively for EVs, the corresponding official signs have to be set up. Basic weather protection should also be assured, for instance no standing puddles should gather at charging stations. Dangerous impacts on flowing traffic, bicyclist, and pedestrians have to be minimized at charging stations. From urban planners' perspective it is important that the visual appearance of charging stations harmonize with the appearance of the streetscape. If charging stations are placed in publicly accessible parking garages, the requirements are less strict, however, ventilation and fire safety play a more important role there.

The permitting procedures for installing charging stations at public parking spaces in German municipalities are elaborate. A high number of different permits and consent has to be acquired from different municipal departments. Also, diverse contracts have to established with technical infrastructure providers for electricity and telecommunication.

It is shown how operational methods can be devised, which take relevant planning aspects, and requirements of permitting procedures into account. First, meetings with involved permitting and contracting organizations are held. Then, questions which are generic for all sites are clarified. In the next steps, document templates are specified which consider relevant aspects for location planning and are also used for the permitting procedures. These document templates are then filled out and handed in to the permitting organizations.

When charging stations have been implemented in a city or region, a second phase begins: the infrastructure has to be maintained and operated. This is treated in App. A. Among the diverse involved activities are the regular electrotechnical servicing and testing, the repair, cleaning, retrofitting, and upgrading of charging facilities. A control center with a hotline should be operated. New users have to be registered and users be informed about the status of the infrastructure.

An evaluation of personal reports of German EV drivers concerning the currently existing infrastructure shows the main shortcomings of operation and maintenance. Operators should especially assure that broken charging facilities are repaired fast, that databases on charging points are kept up to date, and that the reservation of parking places for EV charging is enforced locally.

A further step beyond the implementation of initial charging stations, their operation, and maintenance, is the long-term development of the infrastructure, which is treated in Chap. 10. Quantitative development can take on the form of densification, spatial extension, replacement and removal of charging stations. Qualitative development concerns the technical upgrading of charging facilities. Static location planning methods such as those shown in Chap. 8 can be used to model a dynamic development if they are scaleable, i.e. a calculation with higher numbers of charging points adds new locations but does not remove previous ones.

A specific model of the time-spatial development of an EV charging infrastructure in the Region Stuttgart for the years 2010–2020 is shown. The model assumes that the target of 1 million EVs in Germany by the year 2020 is met. The model first breaks the global development of EV ownership down to time-spatial developments in individual municipalities and city districts. This is done based on sociodemographic data and assumptions on the characteristics of early adopters of EVs. The numbers of public charging points required by these EVs are then calculated making use of the quota formula introduced in Chap. 4 of this thesis. The charging points are allocated to the municipalities based on inter-municipal commuter data. Three scenarios of infrastructure development are shown. These indicate that the demand for public charging is concentrated in the biggest urban centers of the region and the overall number of public charging points is quite low if a minimal level of utilization is demanded for them. The model shows how the long-term development of a charging infrastructure can be modeled with relatively little data if scenarios for EV development are available as an input. The presented model could be refined in several aspects, notably concerning the modeling of traffic flow between municipalities.

After having read the above summary, the reader is invited to take a look again at the global visions on EV charging infrastructure planning shown in the introductory Chap. 1. The metaphor of a network of knowledge (see Fig. 1.1) can help to understand the information connecting the different chapters. The procedural view (see Fig. 1.2) helps to understand which methods and knowledge is required at which stage of an infrastructure planning and implementation process.

11.2. Outlook: further required research

The original research and extensive literature survey presented in this thesis can help to understand the diverse connections that exist among the many different aspects that play a role in planning a charging infrastructure for EVs. This document also presents a selection of practical methods to be used for the planning task by urban and infrastructure planners.

The broad scope of this thesis allows to identify the areas where a lot of research has already taken place and those areas where many questions still remain open. The interaction of the charging of EVs with the electricity systems has been treated in many research projects. Hundreds of articles have been published on the regional location planning of charging stations. Documents emanating from the German model regions have shown how planning on the street scale and the acquisition of permits takes place.

The actual demand for public charging infrastructure is still surprisingly little understood. The extensive discussion of demand presented in this thesis can hopefully help to arrive at a more differentiated understanding of demand. But further research still seems necessary to arrive at a thorough quantitative understanding.

The importance of stakeholder cooperation for the implementation of local charging infrastructure is frequently underlined by practitioners, but does not seem to be treated in many scientific publications.

Researchers and practitioners currently still seem to be preoccupied with the implementation of an initial infrastructure and are little concerned about the operation, maintenance, and long-term development of this infrastructure. There seem to be no established best practices for the operation and maintenance yet, and this topic does not seem to be treated by researchers.

The main challenges the development of electric mobility in Germany currently faces are economic in nature. Users seem reluctant to buy EVs as they are more costly over their lifetime than conventional vehicles. Under normal circumstances it does not seem possible to operate public charging stations profitably. This thesis proposes to finance the infrastructure via advertisement or indirectly via profits from other services. The German state could directly intervene in the market for EVs and public charging points, as electric mobility can, under specific circumstances, lead to many benefits for society. Subsidies for EVs and charging points would have to be compared to other investments in the transport and environmental sectors in cost-benefit analyses to ensure that such interventions are warranted. The EU directive on clean fuel infrastructure will require of German authorities to take on a more active role in the implementation of publicly accessible charging infrastructure for EVs.

A. Notes on the operation and maintenance of an EV charging infrastructure

Introductory remarks: the following notes contain basic information on the operation of an EV charging infrastructure. The author considers the material to not be complete enough to warrant an own chapter. Because the aspect of operation is seen as a part of an integrated vision on the planning of charging infrastructure (see the introduction in Chap. 1), the material is nevertheless included here as an appendix. The chapter was intended to be inserted between the chapter on planing on the street level (Chap. 9) and the chapter on the long term planning of the infrastructure (Chap. 10).

When the first charging stations for electric vehicles have been installed in a city or region, a second phase begins: the infrastructure has to be operated and maintained. This chapter treats the actions that should take place in this phase.

Publicly available information on this topic seems to be scarce. Many publications shortly mention this aspect. But at the time of this writing the author is only aware of two publications that treat the topic as an integral part of EV infrastructure planning, which are [10] and [32]. In the longer term concepts from general *infrastructure asset management* (see for instance [713]) could be applied to EV infrastructure.

In the following section it will first be discussed which activities are usually part of operation and maintenance. Then an overview of different user reports will show which typical problems occur during the use of currently existing charging infrastructure and how these could be avoided. Finally, the main points will be summed up again in the concluding section.

A.1. Operation and maintenance of EV infrastructure

The maintenance and operation can be done by the overall provider of the infrastructure or it can be outsourced to electric installers, companies specialized in charging infrastructure operation, or in some cases to the manufacturer of the charging facilities. If tasks of operation and maintenance are outsourced, a service level agreement should be made with the providing company. An example of such an agreement with an infrastructure operator is shown in [10], and specific service levels agreements of a charging facility manufacturer and operator are listed in [714].

The typical tasks involved in operation and maintenance are discussed in the following. Like other electric equipment, charging facilities must be *electrotechnically serviced and tested* regularly. In Germany the norm DIN VDE 105-100 describes the general procedures for this [715]. The control must be performed by an electrically qualified person. The control consists of three parts: visual control, control of physical properties, and measurements. Results of this testing procedure must be documented in a protocol. The norm does not explicitly state intervals for such controls. These depend on factors such as the type of the electric equipment, frequency of use, failure rates, and the specific environment. Recommendations for such intervals lie in the range of 6 months to 4 years for different types of electric equipment [715]. More frequent checks of 2–4 times a year can be reasonable for charging points [10]. Technical specifications of charging station manufacturers and requirements from (fire) insurance firms also need to be taken into account for service intervals and procedures [715]. When a charging station has been tested successfully it can receive a seal of approval "Tested according to DIN VDE 105-100", as well as the current date and the date of the next inspection.

Broken charging facilities must be *repaired or replaced* by electric installers. Fast repairs require a stock of spare parts and replacement charging facilities to always be available. The charging infrastructure operator can be informed of broken charging stations by EV drivers providing feedback by phone or email. Some charging facility models permit remote fault detection and diagnostics [133] [714].

Maintenance of charging facilities also involves *cleaning activities*. Street dirt may have to be washed from the charging facilities regularly. If charging facilities are covered with graffiti or stickers, these have to be removed, as this leads to a bad image of the infrastructure as well as a run-down appearance of the surroundings (compare Sec. 9.1.6).

In the long term the maintenance of charging facilities can also include *retrofitting and upgrading* of charging facilities, for instance to adapt them to more advanced norms, advanced ICT, and higher charging powers. If broken or old charging facilities are removed, they have to be *disposed of properly, or be recycled.*

The operation of a local charging infrastructure may involve the *operation of a central control center* (see Sec. 2.2.1). Such a control center can monitor the state of charging facilities in real time. It can make sense for the control center to also provide a service hotline for EV drivers to call in case of questions or problems. In this case the phone number should be noted well visible on the charging facilities. The operation of such a control center and hotline might be too expensive for small municipal utilities with only a dozen of charging stations. In that case it might be more economic if several local infrastructure providers cooperate and maintain one common control center and hotline.

Operation also involves *registering new users* and handing the RFID cards or other required means of authorization out to them. New users should receive introductory information on how to use the public charging infrastructure [10] [32]. *Billing users* regularly can be part of operational work. There also should be a defined process for canceling users. Roaming contracts may be set up with other providers of charging points, to allow clients to also charge at different providers' points (see Sec. 2.2.1).

EV drivers need to be *informed* of the current state of the charging infrastructure. The operator has to assure that information on the charging stations is up-to-date and available to users, for instance per website or as an application for smartphones. Information in popular external charging point databases such as LEMnet [661] also should be kept up-to-date by the operator. In some cases charging infrastructure operators even provide real-time information on the state (occupancy, in working order) of charging facilities, and possibly provide means to reserve them.

The operation of the charging infrastrucutre may involve regular statistical evaluation and reporting of its use [10].

The operation of charging infrastructure may also involve further *auxiliary services*. For instance, EV drivers stranded with an empty battery may be provided with a towing service, or a mobile fast recharging unit be dispatched to help them (see Fig. 2.15).

If *advertisement* is displayed at the charging stations, this involves further activities such as acquisition of clients and regular changing of the shown advertisement.

A.2. Problems encountered during the use of current charging stations and deduced recommendations

Several personal reports of German users list problems encountered during the use of public charging infrastructure [514] [518] [515] [516] [517] [716] [717] [519] [718] [719] [720]. This selection of articles which appeared in the press, particularly in the EF user journal “Emobile plus solar”, surely show a biased view on the use of the infrastructure, as articles about a successful and easy use of charging stations don’t make good stories to be published. The articles [520] [721], written by a driver of an REEV, report more positive experiences of the use of charging infrastructure during long range tours of 332 and 1 410 km respectively. In the following, first an overview of the encountered problems will be given, then it will be deduced what charging infrastructure operators should do to avoid these problems. The problems encountered can be sorted into three categories: technical problems, problems due to lack of information and communication, and problems with public accessibility of charging stations.

Technical problems encountered are:

- Charging facilities are defect [514] [515] [516] [520] [718] [721] [720].
- The authorization at charging facilities does not work [717] [520] [721].
- A different charging plug format is used at the facility than those supported by the EV [514] [516] [517] [718].

- Technical problems occur when charging several vehicles at one charging station at once [720].
- The charging process cannot be aborted [720].
- The emergency stop is activated, which is only noticed after some time [722].

Problems encountered due to *lack of information and communication* are:

- Installed charging facilities have not (yet?) been connected to the operator's control system or are missing in the operator's database [515] [718].
- Information about usable charging stations is missing in navigation applications [519].
- Operators do not openly communicate that they maintain public charging stations via their own websites or operator independent platforms [514].
- Geographic positions of charging stations in databases are wrong [721].
- It is not communicated that existing charging stations are currently defect [718].
- Information, such as the number of a service hotline [516] [720] or usage instructions [719], is missing at the charging stations.
- Employees of service hotlines do not know all necessary information for using the charging facilties [515] [717].
- Employees of local sites do not know how the charging facilities can be used/activated [514].
- Signs for leading to charging stations are missing [518] [717].

Problems encountered with the *public accessibility* of charging stations are:

- ICE vehicles or (non-charging) electric car sharing vehicles block the charging stations' parking places [518] [515] [516] [716] [520] [718] [720].
- Charging station parking places are used for storing material [717].
- Users need to be registered as a client of a charging network and cannot spontaneously charge at a public charging station [517].

- Charging stations can only be used by the electricity clients of the municipal utility operating or local citizens and not by other clients [514] [519].
- Identification cards for charging stations need several days to be handed out and/or activated, and this service cannot be performed on the weekend [515].
- Charging stations are only accessible or activable during opening hours of the site and not in the evening or on weekends when long-distance EV drivers actually need them [514] [515] [520] [720] [722].
- EV drivers need to carry several RFID cards, tokens, keys, smartphones apps etc. with them, in order to be able to use charging stations of different providers [722].

Users also complain about the *high prices* of charging at public stations [717] [519] [520] [719]. It is notably seen as unfair when the fees is calculated based on the charging duration, but the used power is very low or is varied [720]. High prices for public charging are a problem which cannot be solved easily (see the analyses of profitability of publicly accessible charging stations in Sec. 5.2.3).

Many of the listed problems seem to be caused by the way in which publicly accessible charging infrastructure has been implemented in Germany in the last years. Many different organizations have developed different regional charging infrastructures, which are often called “island solutions”. Problems with use seem to especially occur when EV drivers are doing longer trips outside of their hometowns and thus need to charge at other operators’ charging stations. The implementation of public charging stations was partially funded within research projects, apparently often without considering their long-term further operation and maintenance. Also, the importance of ICT for the control and use of the charging stations seems to have been underestimated. Sec. 2.2 of this thesis makes the point that associated ICT should be thought of as an integral part of the infrastructure.

The above list of problems shows what should *not* happen. Stated positively it can be deduced how operators of infrastructure should act. Some of these points already need to be considered during the setting up of charging stations in the implementation phase.

Operators of charging infrastructure *should*:

- Repair defect charging stations as soon as possible. Defects can be detected by giving users the possibility of feedback, via hotline or website, and by doing regular tests of the charging facilities.
- Retrofit old charging stations to take new norms into account. Because several types of plugs are currently still used in parallel, it can make sense to support multiple formats, for instance Schuko and Type 2 at AC charging stations, and CCS and CHAdeMO at DC fast charging stations.
- Keep the databases used internally (hotline, control center) and externally (charging station websites) up-to-date concerning new and deconstructed charging stations, supported plug formats, times of accessibility, and charging costs. Keeping the internal database up-to-date could go hand in hand with regular electric maintenance of the charging stations.
- Provide all necessary information on the charging station itself (phone number of hotline, instructions for use) and update it when necessary.
- Set up signs for remote charging stations which are hard to find.
- Provide a brochure explaining how the charging station should be used, for internal reference by call center personnel, for the personnel of local sites, and for EV drivers
- Enforce parking regulations for charging stations, by having ICE vehicles or non-charging EVs towed and/or ticketed. This should be enforced by the local traffic wardens or after notification by a user. Local personnel of a site also might have to be made aware of keeping the charging station parking space free.
- Implement streamlined processes for handing out authorization cards, which allow new users to gain access within minutes at all times. “Emergency” access cards can be handed to local personnel, available upon request by EV drivers. Processes could also be implemented that require no identification at all, for instance by paying directly per coins or per EC card. Joining EV charging roaming networks greatly facilitates the users’ access to other providers’ charging points.

A.3. Summary: operation and maintenance of EV charging infrastructure

This chapter has given a basic overview of the activities involved in the operation and maintenance of charging infrastructure. Such tasks are the regular electrotechnical servicing and testing of charging facilities, the repair and replacement of broken facilities, cleaning, retrofitting and updating, operation of a control center and a service hotline, registering new users, keeping users informed, and possibly providing further auxiliary services, such as mobile emergency recharging.

The evaluation of several user reports published in the press has shown the main problems that EV drivers encounter while using the currently installed public charging infrastructure in Germany. Technical problems, lack of information, and problems with public accessibility of charging stations are occurring repeatedly.

The most important recommendations deduced from this overview are that charging infrastructure operators should put more efforts in keeping installed charging points in working order, keeping their charging point databases and other internal and external data up-to-date, and ensuring that the reservation of parking spaces for EVs is enforced locally.

Overall this chapter has shown that many diverse activities are involved in the operation and maintenance of charging infrastructure. More research is required in this domain in order to establish a body of required knowledge and identify pragmatic methods.

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Planning the charging infrastructure for electric vehicles (EVs) is a new task for urban and traffic planners, civil engineers, and infrastructure planners of electric utilities. This task is very challenging because of the many different aspects that need to be taken into account. Aspects treated within this work are technologies for the charging of EVs, the associated norms, interactions with the electricity system, specifics of electrical installation, the demand for public charging infrastructure, economics of public infrastructure operation and of EV ownership, public policy in Germany and the European Union, external (mainly ecological) effects, stakeholder co-operation, spatial planning on the regional and street level, operation and maintenance, and long term spatial planning. This work aims to be the first to provide such an encompassing vision. The specific situation treated is that in Germany in the year 2015. The book can be used as a handbook by practitioners, providing practical methods and required background information. It can also be used as a scientifically founded reference work by researchers requiring information on particular aspects of EV charging infrastructure.

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