Electric Vehicles with Range Extenders: Evaluating the Contribution to the Sustainable Development of Metropolitan Regions

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Abstract: Electric vehicles play a key role in strategic development plans of urban regions in Europe because they are seen as a promising technology to promote environmental quality, livability, and sustainability. Studies on electric mobility mostly concentrate on battery electric cars and disregard hybrid technologies which could address the weakness of range limitations. Therefore, this paper studies the impact of extended range electric vehicle (EREV) solutions on travel behavior, energy demand, environment, and overall sustainable development in the greater Stuttgart region in Germany. An integrated large-scale simulation approach merging different models is applied for future scenarios in 2025. The results show that with EREVs (1) most travel patterns can be fulfilled, (2) the impact on electricity generation is marginal, and (3) there is a high potential to reduce local emissions in areas with high traffic density. Overall, electric mobility is evaluated as one component toward sustainable development in the study area. This study demonstrates the complexity of the topic and highlights the importance of addressing this issue with a multidisciplinary approach. **DOI: 10.1061/(ASCE)UP.1943-5444.0000408.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, http://creativecommons.org/licenses/by/4.0/.*

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Introduction and Background

Role of BEVs and EREVs in Sustainable Electric Mobility

Electric mobility is becoming a reality in Europe, Asia, and the United States as many countries announced a set of measures and decisions aiming at replacing fossil fuel–powered vehicles with cleaner technologies, mostly based on electric or hybrid drivetrains. Studies show that one main hurdle for a comprehensive market breakthrough of electric vehicles (EVs) is still the range of battery electric vehicles (BEVs) (Bühler et al. 2014; Ziegler 2012; Ensslen et al. 2016). In recent years the range has been continuously enlarged by using advanced battery technology, and in the future this trend will continue (Nykvist and Nilsson 2015). However, even from this perspective, BEV performance remains below the performance of conventional combustion vehicles in some aspects and still will not meet the expectations of all vehicle users (Bunzeck et al. 2011; Franke and Krems 2013). Furthermore, the officially announced range values are often too optimistic (i.e., based on standard driving cycles) (Franke et al. 2015). These factors can contribute to a psychological barrier of BEV range (Franke et al. 2012) and ultimately lead many potential customers to decide against BEV purchase.

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One possible solution for the range limitation of BEVs is to add an electricity generator, called a range extender (RE), that can be activated to perform longer trips (i.e., an additional energy source or a backup energy source when the battery is completely empty). An extended range electric vehicle (EREV) has three driving modes: it can be driven (1) using only the battery, (2) using both the battery and the RE (the RE is used as a complementary power source), and (3) using the RE only (degraded mode if battery is depleted). Depending on the RE specifications, the vehicle may not have its full performance in degraded mode because the RE is typically a heavily downsized engine which is not designed to provide the full power for the vehicle alone.

From the user perspective, the vehicle should optimally fulfill all mobility requirements and decrease both the total usage costs and the environmental impact. For inhabitants of urban areas, the range of a typical BEV seems to be sufficient, because most daily distances are short (Pearre et al. 2011; Streit et al. 2015). However, in a metropolitan region, long-distance trips (e.g., regularly in the case of commuters traveling from/to the city center or occasionally in the case of weekend or holiday trips) must be considered, which would require stops for recharging or switching to alternative travel modes. In general, users can rather be assumed to make their car purchase decisions based on their perceived maximum daily trip distances—even if it is only occasionally above a daily BEV range (Stark et al. 2015). Hence, for mobility profiles with many days of short distances and few days of long distances, EREVs might be a solution with a high potential. This applies from the users' perspective, and also from a cost perspective because on many days the range needs will typically be much lower than the range that BEVs offer (Axsen et al. 2016; Jakobsson et al. 2016; Ensslen et al. 2016). The EREV design can take into account this fact in order to reduce the cost and environmental footprint caused by battery manufacturing. At the same time, the battery size should be sufficient in order to perform a significant part of the mobility using the all-electric mode to reduce fossil fuel consumption and pollutant emissions.

Furthermore, to ensure sustainable development of a metropolitan region, the efficiency of its power system should not be affected in a negative way. A growing number of charging events affects the load on the electricity grid respectively. The location and time of day when vehicles are plugged to the grid are therefore critical factors.

Considering this, the evaluation of impacts on mobility, the grid, and the environment resulting from EREV implementation in a metropolitan region is of high relevance. This study evaluates the overall contribution of EREVs to sustainable development of a region. Because of the complexity of this topic, the authors chose an interdisciplinary simulation–based approach.

Interdisciplinary Simulation Approach for Modeling Effects of an EREV Fleet

The effects of an EREV fleet can only be assessed comprehensively, when considered in a scale, i.e., the representation of different users or user types, the use in different spatial settings (urban, suburban, and rural) and the use of adequate samples. This can be achieved either (1) by a real-world demonstration (e.g., field trial) with empirical measurements and a subsequent extrapolation of results, or (2) with the help of a simulation approach. Although the demonstration approach is often applied to study relevant effects of introducing EVs (Ensslen et al. 2016; Weiss et al. 2016), this approach is typically limited to certain kinds of research questions and, above all, is a resource-intensive research approach. Hence, for a truly comprehensive assessment, an integrated large-scale simulation approach is advised, which comprises car use behaviors as well as the resulting effects on the transportation system and the energy demand. For such a simulation, certain preconditions have to be fulfilled: (1) an adequately large region with different spatial types has to be examined; (2) an integrative model concept including all relevant evaluation dimensions, well-defined interfaces, and the relevant input data (e.g., behavior, land use characteristics, and data for environmental assessments) is needed; and (3) dynamics over longer periods have to be incorporated to represent the variability in travel behavior and charging behavior and thus in electric energy demand. These objectives can only be achieved in an interdisciplinary research approach.

Study Objective

The main objective of this research was to evaluates a predefined EREV concept for a metropolitan area when taking into account a wide range of constraints—car usage and energy consumption, the electricity system, environment effects—and to analyze whether EREVs may contribute to future sustainable development in a metropolitan area. To achieve this objective, the authors designed an integrated large-scale simulation, which comprises different models and allows assessing future development scenarios. The approach was applied to a study area in Germany.

Structure

The Research Methodology section describes the modeling approach, the developed scenarios and the planning area which were used to address the research objectives. The Results section presents the analyses conducted and the results. First, the impact on car use behaviors and electricity demand is analyzed. Then the results regarding the impact on the energy system are presented. The results regarding the impact on the environment are given next. An overall assessment of the EREV concept completes the results section. The conclusion discusses the results and the transferability of these results, and critiques the limitations of this research.

Research Methodology

Modeling Approach

Complex and transdisciplinary research questions require the use of different models (Fig. 1). These models are autonomous in their application and every model has a specific focus. Results of single models are used as input for consecutive models. This section describes the combined models and relevant interfaces. This paper does not address in detail the VEHLIB vehicle model (Derollepot et al. 2014).

The Smart Electric Mobility (SEM) model was developed to allow forecasts of the development of the future car market dependent on indicators describing the sociodemographic framework, political economic framework, sociogeographic framework, sociopolitical framework, travel behavior, transport-policy framework, and technological framework (Stark et al. 2014). This model represents a further development and adaptation of an individual-based car-purchase model that was developed at the Institute for Transport Studies at the University of Natural Resources and Life Sciences, Vienna (Link et al. 2012a, b). Outputs are market penetration rates in the future new car market. The derived total shares of EREVs and BEVs of the car fleet (and car segment shares of the EREV fleet) are input data for the microscopic travel demand model (mobiTopp).

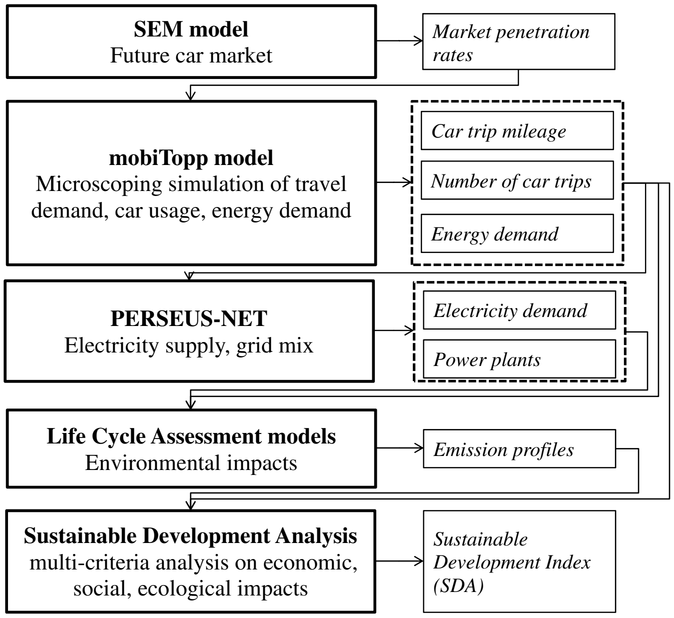

Fig. 1. Modeling approach: overview of models and their output

The mobiTopp model (Mallig et al. 2013) was developed at the Karlsruhe Institute of Technology. The model simulates the travel behavior of all persons living in the planning area over a period of 1 week. The model consists of two stages: the long-term stage and the short-term stage. Both stages consist of several modules, each of them individually exchangeable. The long-term stage contains the population synthesis and models the aspects that are stable over a longer period, such as workplace and car ownership. The short-term stage models the activity-travel behavior in terms of destination and mode choice. Because traffic assignment is not included in mobiTopp, external tools are used for this purpose and the resulting travel times are fed back into mobiTopp.

The central part of the long-term stage is population synthesis. Based on demographic statistics at the person and household level for each zone, a distribution for the households of the synthetic population is created using an iterative fitting approach (Beckman et al. 1996). Based on this distribution, households are drawn randomly from the data of a household travel survey. The next step is activity schedule generation. Currently, a module is used that assigns each agent the activity schedule of the corresponding person of the survey; however, a module for synthetic activity-schedule generation is under development. In addition, fixed destinations for work or education are assigned. A binary logit model is used to model the possession of a transit pass. A car ownership model is used to model the segment of the car owned and the type of engine (Weiss et al. 2015).

The short-term stage models the activity-travel behavior of each agent using a temporal resolution of 1 min. An agent is either traveling or conducting an activity. When an activity is finished, the agent selects the next activity from its agenda. If the next activity is an activity with a fixed location, i.e., home, work, or education, no destination choice is necessary. In the case of an activity with a flexible location, a destination choice is made using a discrete-choice model. After that, a mode choice is made using a multinomial logit model. The available choice set in the mode-choice model depends on the previous actions of the agent and of the actions of the other agents of its household. If the agent is not at home and the previous mode used was cycling or car driving, the choice set consists only of this mode. If the agent is not at home and the previous mode was car passenger, walking, or public transit, the choice set consists of these three modes. If the agent is at home, the choice set consists in principle of all modes; however, the mode car as driver is only available if the agent holds a driving license and there is a car available. After the mode choice, the agent starts traveling. If an agent travels by car, the cars' current mileage and fuel level are adjusted (Mallig et al. 2016). When a trip is finished, the agent starts with its next activity.

A mobiTopp run results in several log files. The trip file contains the trips of all persons made during the week with their attributes, such as purpose, source, destination, mode used, start time, and duration. The car trip file contains additional information for the trips made by car, i.e., current mileage, fuel level, and battery level. Based on these results of mobiTopp, the electricity demand and the resulting impact on the electricity system can be assessed using an extended version of the bottom-up energy system model.

The energy system model PERSEUS-NET for unit commitment and commissioning of power plants is based on a linear optimization approach (Heinrichs 2013; Eßer-Frey 2012; Babrowski 2015). Driven by the exogenously given electricity demand, the model minimizes the system-relevant expenditures. The electricity needed at a certain time can either be generated in existing generation units or in newly commissioned units. The electricity demand by EVs is based on representative usage patterns of German private passenger vehicles (BMVBS et al. 2008) and adjusted according to the results from the mobiTopp model. Additionally, the model allows considering the concept of controlled charging, i.e., automated and optimized scheduling of the charging process in time and charging power according to the needs of the power plant portfolio. It includes a nodal pricing approach based on a direct current (DC) approximation of the active power flows in the transmission network. Most (more than 500) 360 and 220 kV lines of the German transmission network are modeled according to the current expansion plans, with their specific capacities and limits (UCTE 2008; BGBI 2009; BNA 2012). Additionally, 440 administrative districts are modeled with their specific power plants (BNA 2012) and electricity demand (Eßer-Frey 2012). Whereas larger power plants are directly connected to the nodes of the transmission grid, the demand and decentralized small power plants are connected to the two grid nodes closest to the center of the district. This paper used the power plant commissioning and unit commitment in Germany for the future scenarios in 2025 output by the PERSEUS-NET model. The power plant–specific electricity generation for covering the electricity demand by EREVs in 2025 was then transferred to the environmental impact analysis.

Environmental impacts were assessed using parameterized lifecycle assessment (LCA) models for small and compact–class EREVs, small-class BEVs, and compact conventional gasoline and diesel vehicles, which were developed at University of Stuttgart (Baumann and Brethauer 2015). The models consider all relevant resource and energy inputs taken from the environment as well as the emissions to the environment during the lifecycle of the vehicle production and use phase, and can be adjusted to boundary conditions of different European countries. All LCA models were created within *GaBi* software using the *GaBi* database for background data, e.g., for raw material exploitation and electricity and fuel supply. Vehicle specifications which are relevant for vehicle production (e.g., dimensions of drivetrain components) and use phase (e.g., electricity and fuel consumption and exhaust emission data, driving cycles) were adopted from results of the vehicle model (Derollepot et al. 2014) and from the Handbook Emission Factors for Road Transportation (Hausberger et al. 2014). The results and parameter settings of the LCA models were used to calculate the spatial distributed environmental impacts during the use

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Table 1. Overview of the Scenario Specifications

	Scenario				
				High	
Characteristic	Without	Low	Likely	High A	High B
Share of EREVs/BEVs in the car fleet	0%/0%	5%/1%	7%/1%	12%/2%	
Percentage of car segments of EREV fleet	—	26% small, 67% middle, 7% large			
Recharging locations	—	At home		At home and at work	
Charging performance	—	3.7 kW			
Charging strategy	—	—	—	Uncontrolled	Controlled

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phase of the vehicles in the planning area. The spatial distributed environmental impacts of the use phase were analyzed based on car usage patterns of the mobiTopp model and electricity grid mixes calculated with the PERSEUS-NET model. The work with geographic data and the graphical illustration of the results was conducted with the geographic information system (GIS) Software *ArcGIS*.

For the overall assessment, a sustainable development analysis (SDA) was conducted. This is a methodology to analyze the contribution of the proposed solutions for the sustainable development in the planning area based on sociological, economic, and ecological indicators. Following the principle of a multicriteria analysis, indicators and their contribution toward a sustainable development have to be defined (part-index) using values between 0 (indicating the worst case for a sustainable development in the planning area) and 1 (existing sustainable development in the planning area) (Stark et al. 2014). A synthesis of all part indexes of the indicators leads to the assessment of the overall contribution for a sustainable development (sustainable development index). The indicators were selected with regard to data produced as output of the other models and were enriched by further statistical data (accident rates, employment rates, and so on) for the planning area. Interfaces to the other models were yearly travel mileages per propulsion systems (mobiTopp), vehicle costs (SEM model), and environmental indicators (LCA models).

All models were compiled to allow an integrated large-scale simulation for a specific area. This kind of approach can be regarded as state of the art in order to assess new technologies in the field of transport.

Description of Scenarios

The authors focused on simulation of car ownership, car usage, electricity supply, and transportation-related emissions in the year 2025. The year 2025 was chosen because the share of EREV can be assumed to be rather marginal before (IEA 2016). Four different scenarios were set (Table 1).

These scenarios differed in various specifications, such as the penetration rate with EVs (BEVs, EREVs) and the recharging places. The scenarios designations Low, Likely, and High refer to the market penetration of EREVs in the year 2025; the scenario Without was used as reference scenario simulating the situation without EVs in the planning area.

The share of electric cars in the fleet was derived from the SEM model. This implies, however, that the car fleet of the planning area is representative of the car fleet structure of Germany as a whole. Within the car fleet, conventional combustion vehicles, BEVs, and EREVs were distinguished. Further assumptions had to be made about (1) the distribution of charging facilities within the planning area and (2) the charging strategy (uncontrolled and controlled charging). For the Low and Likely scenarios it was assumed that charging can only take place at home with a charging performance of 3.7 kW (at a typical household socket); for the High scenario, workplaces also are potential charging locations, and both uncontrolled (scenario High A) and controlled (scenario High B) charging is possible.

Two technical specifications of the EREVs were taken as input for the modeling procedure. The specifications were based on an optimization design procedure for the drivetrain according to the use specifications from European travel surveys. The drivetrain optimization considered a performance-based and a price-based optimization. Using validated simulation software, the method took into account the range requirements of the car use profile, its energy consumption, realistic driving cycles, and battery aging (Derollepot et al. 2014).

Planning Area

The greater Stuttgart region in southern Germany was chosen as the planning area for the assessment of the EREV technology. This planning area has an adequate size in terms of population, car fleet, and extent. The region covers the German city of Stuttgart and the five surrounding administrative districts Ludwigsburg, Rems-Murr, Goeppingen, Boeblingen, and Esslingen (Fig. 2).

The planning area is situated in the province of Baden-Wuerttemberg in southwest Germany and has a total land area of 3,070.86 km^2. It covers various land-use types, such as urban (e.g., Stuttgart city center), suburban (e.g., midsized cities Ludwigsburg and Esslingen), and rural regions (e.g., small villages in the Swabian Alb). The greater Stuttgart region has a population of approximately 2.7 million inhabitants; all persons aged 6 and above (2.5 million mobiTopp agents) were modeled, along with 1.3 million registered private cars. The population is distributed in the administrative districts as follows: 23% live in the city of Stuttgart, 20% live in the administrative district of Ludwigsburg, 16% live in Rems-Murr, 8% live in Goeppingen, 14% live in Boeblingen, and 19% live in Esslingen. Trips of people who live outside the planning area were not modeled. However, trips made by the mobiTopp agents to and from destinations outside the planning area (outer planning area) were modeled.

Most of the agents' trips take part within the planning area, which was divided into 1,012 model zones. The outer planning area covers 159 zones (for example, cities Karlsruhe, Munich, or Zurich) with potential destinations for the inhabitants of the greater Stuttgart region. The projected year is 2025.

Results

Impact on Car Use Behaviors and Electricity Demand

The simulation results of the model show that the new car market share of EREVs will clearly increase between 2010 and 2025. Contrarily, conventional car types (diesel and gasoline driven cars)

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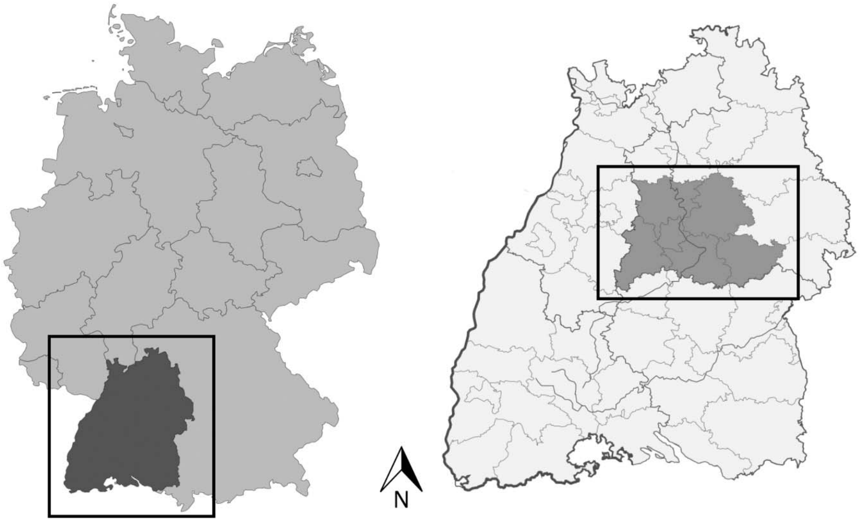
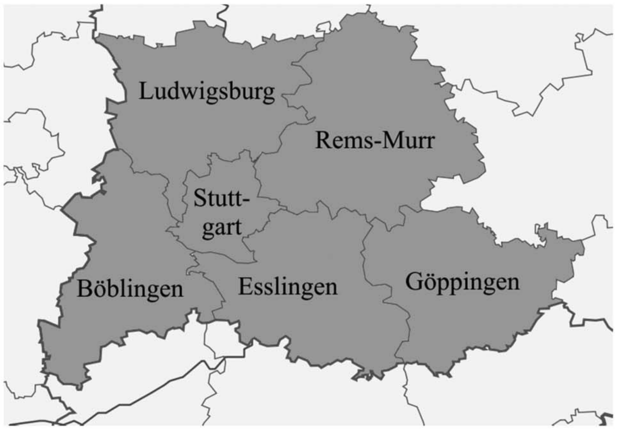


Germany

Province Baden-Wuerttemberg



Greater Stuttgart Region

Fig. 2. Location of planning area greater Stuttgart region (city of Stuttgart and five surrounding administrative districts)

lose market share (Table 2). The EREV rates (new car market share year 2025) are 11–34% for Germany depending on the scenario, and the share of EREVs is much higher than that of BEVs (Klementschitz et al. 2013).

The model results from the microscopic travel demand model mobiTopp showed that average car trip mileages and the number of car trips during 1 week were almost equal for EREVs and for conventional cars; consequently, the average weekly mileages for both propulsion systems are similar (Fig. 3).

An intrapersonal analysis between scenarios (i.e., whether the same households change their car usage behavior when they own an EREV or BEV instead of a conventional car) indicated that, within the model, former conventional car owners did not change their car usage behavior when owning an EREV; former conventional car owners who owned a BEV decreased their car usage intensity in the considered scenario. These findings imply that EREV owners could fulfill almost all of their mobility needs in the same way in which they would have with a conventional car.

Table 2. New Car Market Share in Germany, Year 2025, By Scenario (%)

	Scenario		
Type of drive	Low	Likely	High
Conventional cars (gasoline and diesel)	87	80	60
BEVs	1	2	6
EREVs	11	17	34

Concerning the results of energy demand from car usage, the model results show that more than two-thirds of the weekly EREV mileage is covered in battery mode. Additional recharging places at workplaces in the High scenario led to even higher mileages in battery mode. Furthermore, the energy demand from electric vehicles was uneven throughout the day (Fig. 4), peaking every day between 6 and 7 p.m.

The average car usage intensity varied for different socioeconomic groups; e.g., the car mileage of employed persons was higher than the car mileage of retired persons. Consequently, the potential of reducing CO_2 emission by EREV differs between sociodemographic groups.

Another interesting aspect is the spatial distribution of the electricity consumption used for vehicle charging. For this analysis the zones were classified into three classes based on the ratio of workplaces to inhabitants in the zone (Table 3).

Zones with a ratio of workplaces to inhabitants less than 0.25:1 were classified as residential use, zones with a ratio of workplaces to inhabitants greater than 1.5:1 were classified as office/industrial

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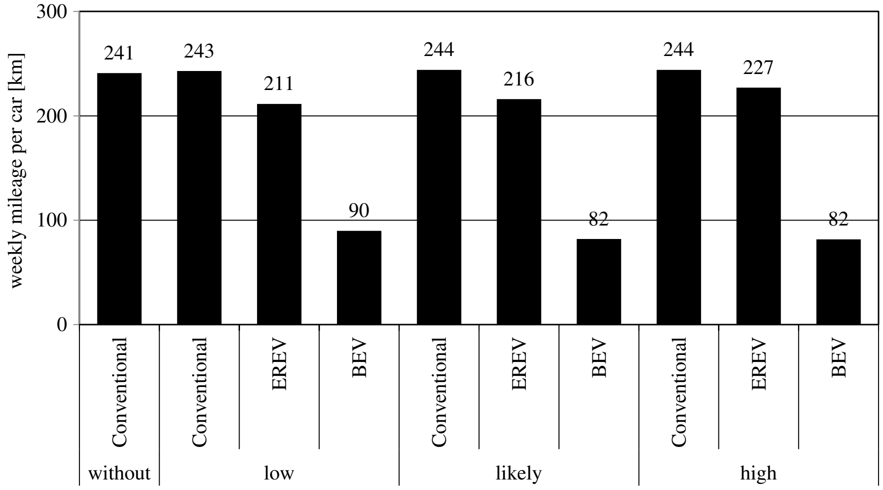

Fig. 3. Average weekly car mileages in the planning area, differentiated by propulsion systems and scenarios

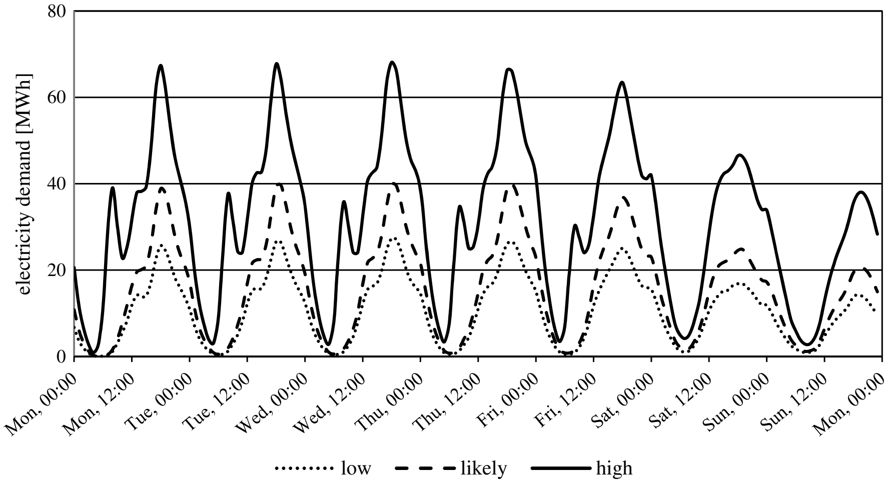

Fig. 4. Electricity demand in the planning area by day and time of day for the three scenarios

Table 3. Land Use Characteristics of the Different Zone Types in mobiTopp

Characteristic	Residential use	Mixed use	Office/industrial use
Workplaces per inhabitants	≤0.25	0.25–1.5	>1.5
Number of zones	485	400	127
Inhabitants per zone (mean)	2,478	3,587	290
Workplaces per zone (mean)	353	1,947	2,684

use, and the remaining zones were classified as mixed use. This analysis considered only the High scenario, because charging at the workplace was possible for this scenario only. The results of this analysis (Fig. 5) show quite distinct power consumption profiles for zones with residential use and zones with office/industrial use. For workdays, the zones with office/industrial use had a peak in the morning and a stable demand between noon and early evening. The electric power demand in the zones with residential use rose from 6 a.m. reached its peak after 6 p.m., and fell significantly until 6 a.m. the next day. The electric power consumption profile for the zones with mixed use resembled a superposition of the profiles for zones with residential use and office/industrial use.

Impact on Energy System

The impact on the electricity system depends on the charging processes of EVs, i.e., timing, amount of energy, and the current system load. In turn, this is dependent on the chosen scenario assumptions relating to market penetration, allocation of charging facilities, and charging strategies. This section analyzes the impacts from the additional electricity demand by EVs on the future power system (i.e., development of power plant capacities as well as their operation, which allows determination of the electricity mix over time) by applying and extending the PERSEUS-NET model (Babrowski 2015; Jochem et al. 2015).

As mentioned previously, the possibility of charging only at home led to the highest concentration in time of the additional load at approximately 6 p.m., when people return from work. However, because this was assumed only for comparably low penetration rates of EVs in the Low and Likely scenarios, with little additional electricity demand (<2%), the influence on electricity generation was low. For the High scenario, approximately 3.6% of the total demand was due to EVs by 2025 and charging at home and at work was possible. Hence when no control of the charging time occurred (scenario High_A), the load from EVs peaked first in the morning at approximately 8 a.m. when people have driven to work and again

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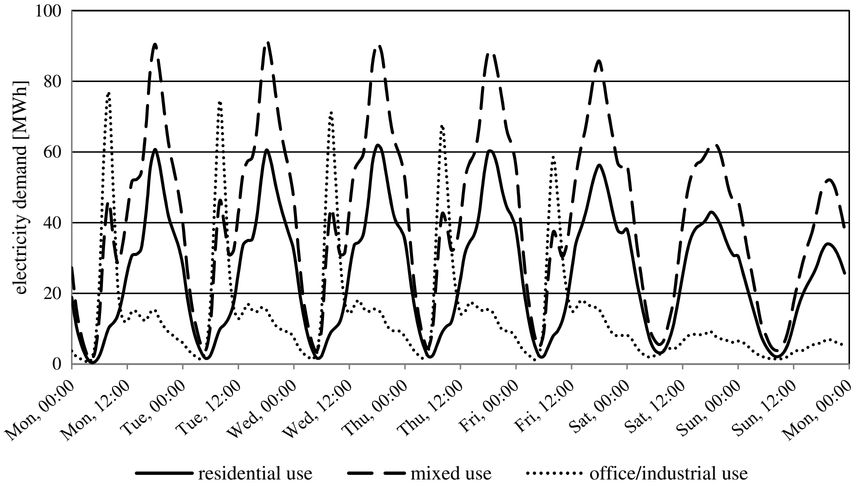

Fig. 5. Electricity demand in the planning area by day and time of day for scenario three differentiated by land use

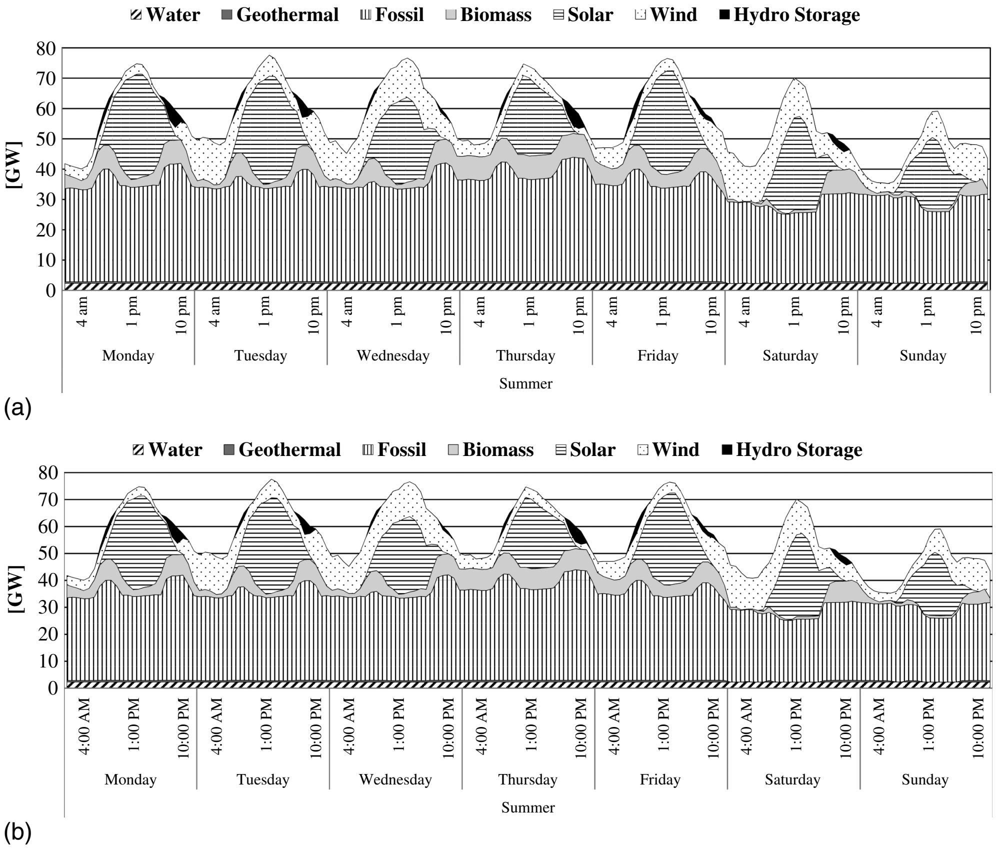

Fig. 6. Time-dependent electricity mix for scenario High B (controlled charging) in summer 2025

in the evening at approximately 6 p.m. after they have arrived at home. In scenario High_B (controlled charging), most of this electricity can be shifted over the course of the day. This is based on the high load-shift potential of EVs (Babrowski et al. 2014) that can be used in the power system to increase the full load hours of base-load power plants as well as of renewable generation units (Fig. 6).

Hence the gross effect on the greenhouse gas emissions in the German electricity system in 2025 is somewhat ambiguous. Whereas the additional electricity generation by renewable generation units (mainly wind and biomass) decreases the emissions, the increased full-load hours of base-load power plants (mainly lignite) increases the emissions. According to the model results, all power plants increased their electricity generation by approximately the same share except hydro pump storages, which decreased their operation by approximately 27% (i.e., load control of charging processes replaces parts of the conventional storage technologies). The corresponding CO_2 emissions from power plants amount to approximately 12.6 Mt per year.

With regard to the grid impact, the influence at the national level was rather marginal and was outweighed by other consumers such as industry (Heinrichs and Jochem 2016). However, the current

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electricity demand from EVs is not equally distributed across Germany (Heinrichs and Jochem 2016) and the impact on the regional grid might differ locally. Furthermore, the distribution grid architectures are heterogeneous, and a general conclusion about bottlenecks seems hardly possible. In principle, distribution grids are most jeopardized where a high penetration of EVs takes place, grid stability is already at its limit, and charging processes are uncontrolled at charging rates of more than 10 kW (Neaimeh et al. 2015).

Impact on Environment

Electric vehicles do not cause local emissions on short trips during their driving operation in electric mode and reduce local emissions compared with conventional vehicles on longer trips when driving with full power. An important environmental aspect of the EREV concept is therefore its potential to reduce emissions in urban areas.

The authors assessed the environmental effects of BEV and EREV trips compared with trips made with a gasoline car of the corresponding segment. For the LCA, the environmental effects of BEV and EREV usage with gasoline car usage were compared.

The Low, Likely, and High scenarios were assessed and compared with the reference scenario Without. The illustrations of the spatial distribution of the environmental impacts are based on the results of the mobiTopp and PERSEUS-NET models and cover the whole planning area (including the outer planning area). The LCA results for the use phase of the various vehicles and their driving modes are related to the single trips defined by mobiTopp and allocated to the passed zones. The zones of mobiTopp were aggregated to clusters by districts and suburbs. The emissions of each trip were divided and assigned to the intersected clusters and then summed to calculate total emissions per cluster. The lifecycle impact assessment for spatially differentiated LCA focuses on the impact categories Global Warming Potential (GWP) and Photochemical Ozone Creation Potential (POCP) because of their important role in current discussions about emission reduction by electric mobility. The GWP category includes all emissions from combustion with an impact on the global warming; POCP includes all local emissions which cause the formation of low-level ozone by sunlight. Figs. S1 and S2 graphically present the summed results in maps showing the relative savings compared with the reference scenario for each cluster. Because of the limited extent of this paper, only the results of the High scenario are shown in detail, because they show the maximum environmental impact reduction potential of EREVs within the assumed period. For the graphical illustration of the spatial distribution of LCA results, only the impacts caused by emissions from car exhausts while driving were considered; the spatial distribution of impacts during fuel and electricity production were not analyzed within LCA.

Table 4 shows the summed GWP and POCP results and their reduction compared with the reference scenario Without for the total use phase, including not only the emissions from car exhausts while driving but also the impacts caused during the production of fuel and electricity. In addition to the differentiation of the electricity grid mixes in one winter and one summer week, the two scenarios of uncontrolled (High A) and controlled (High B) battery charging also were analyzed. Additionally, one scenario with 100% wind energy was calculated to assess the maximum environmental improvement potential of EREVs.

In sum, the spatial distribution of the environmental impacts of the use phase shows a high potential of EREVs to reduce local emissions. The local emissions included in the impact category POCP showed the highest reduction potential, particularly in the urban area of the city center of Stuttgart. Extended range electric vehicles could therefore help to significantly improve the air quality in areas with high traffic density. A more detailed description of the project, further results, and discussions of the project results are in the EVREST project deliverable D5.1 (Baumann and Brethauer 2015).

Table 4. Total GWP and POCP of Use Phase Emissions Including Fuel and Electricity Supply of Scenario High and Their Reduction Compared with Reference Scenario Without

Grid mix	Scenario	GWP (kg $CO_{2\text{-eq.}}$)	GWP reduction (%)	POCP (kg ethene-equivalents)	POCP reduction (%)
Summer	A	64,063,568	−5.6	12,603	−6.8
	B	63,910,001	−5.8	12,621	−6.7
Winter	A	63,504,672	−6.4	12,554	−7.2
	B	63,362,587	−6.6	12,563	−7.1
100% wind		59,968,199	−11.6	12,073	−10.7

Further Aspects and Overall Assessment

Based on the Brundtland Report (World Commission 1987), the Rio Conference (1992) for Environment and Development of the United Nations sustainability should address the following three pillars: ecology, economy, and social society. According to this optimization principle of sustainability, indicators were defined for the sustainable development analysis. Table 5 shows the indicators as well as the definition of the upper and lower limits of the sustainability part indexes. Even though the authors are aware of the challenges of aggregated sustainability indexes (Böhringer and Jochem 2007) the overall contribution toward sustainability was calculated and equal weights were used for all indicators; each aspect (economic, ecological, and social aspect) received an equal weighting (1/3 share of each aspect).

The rest of this section briefly describes the indicators and the definitions of the upper and lower limits of the utility function (further details are given by Klementschitz and Stark 2016).

For the assessment of economic aspects, two indicators were considered: the energy consumption during operation of vehicles, and employments effects. The first indicator considered the car mileage traveled per year in the greater Stuttgart region for different types of propulsion (BEV, EREV, diesel, and gasoline) and the share of energy consumption in 2025. For the lower limit (not sustainable) of the utility function, the energy consumption rate for private cars from year 2010 with car mileage of year 2025 was used. The upper limit (100% sustainability) was defined as a 25% reduction of energy consumption. This definition is based on an extrapolation of targets in the Energy Efficiency Plan (European Commission 2011a): for 2020, a target was set of saving 20% of primary energy consumption compared with projections.

The second indicator (employment effects) was expressed as additional workplaces in the province of Baden-Wuerttemberg being a result of additional investments because of the implementation of electric mobility. The additional person-years correlate with the additional welfare by a certain factor expressed in person-year per Euro currency. The mean number of additional annual full-time workplaces was calculated by dividing the additional person-years of employment by the number of years. For correcting the unemployment rate the authors considered annual full-time workplaces as the net impact (negative crowding-out effects in other areas such as in the conventional automotive industry were neglected). Consequently, the unemployment rate declined for this area of investigation. In the scenario Without, no additional workplaces were assumed. In the other scenarios, additional investment costs led to

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Table 5. SDA Indicators and Definition of Upper/Lower Limits of the Utility Function (Data from Klementschitz and Stark 2016)

Indicator	Description	Unit	Lower limit of utility function (0% sustainable)	Upper limit of utility function (100% sustainable)
Economic aspects				
Energy consumption during operation	Per type of propulsion (BEV, EREV, diesel, and gasoline)	kWh/year	2010 energy consumption rate for private cars with car mileage 2025	−25% for 2025 (extrapolation of 20-20-20 target from EU until 2020)[a]
Employment effects	Additional workplaces due to additional investments	Unemployed persons	20% unemployment	0% unemployment
Ecological aspects				
Noise	Number of disturbed persons in planning area	Disturbed persons	All inhabitants of planning area are disturbed	No inhabitant of planning area is disturbed
Global warming	CO_2 emissions due to traffic in planning area	t/year	2010 emission rate for private cars with car mileage of 2025	−60% for 2050[b]
Primary energy from nonrenewable resources	Energy consumption (production and maintenance)	MJ/year	Scenario Without	−25% of scenario Without
Acidification potential	Including production	kg SO_2 equivalents/year	Scenario Without	−25% of scenario Without
Eutrophication potential	Including production	kg PO_4^{3-} equivalents/year	Scenario Without	−25% of scenario Without
Photochemical ozone creation potential	Including production	kg C_2H_4 equivalents/year	Scenario Without	−25% of scenario without
Social aspects				
Traffic safety	Number of fatalities in the planning area	Fatalities/year	Worst situation (Germany 1970) and trend of fatalities in Germany[c], Share of fatalities in Baden-Wuerttemberg Province[c]	No fatalities in the planning area
Traffic safety	Number of injured persons in the planning area	Injuries/year	Worst situation (Germany 1970) and trend of injured Germany[c], Share of injured in Baden-Wuerttemberg Province[c]	No injuries in the planning area
Mobility cost for driving private car	All car users (fix and running cost)	€/year	+50% of 2010 cost for private car, car mileage 2025	−50% of 2010 cost for private car, car mileage 2025

[a] European Commission (2011a).
[b] European Commission (2011b).
[c] German Federal Statistical Office (2013).

higher employment rates by 30 person-years per million Euro investment (Sammer et al. 2004, p. 25). The limits of the function were set as follows: 100% sustainable denoted full employment in the province of Baden-Wuerttemberg; the lower limit was set to 20% of unemployment.

The ecological evaluation, considered noise and the results from the LCA models for global warming, primary energy from nonrenewable resources, acidification, eutrophication, and photochemical ozone creation potentials. Noise reduction is seen as a big advantage of EVs. However, this effect strongly depends on the driving speed and the composition of the car fleet on the road. Another aspect of noise is that there could be an impact on traffic safety if oncoming vehicles are less noticed because of their silence (see indicator traffic safety). The overall impact from electrification on safety seems to be still unclear in road transportation (Jochem et al. 2016). This assessment used the number of disturbed persons due to road traffic noise; the lower limit of the utility function was defined as all of the inhabitants in the planning area are disturbed, and the upper limit was defined as no one is disturbed. For each scenario, the part indexes of sustainability were calculated using the car mileage per year of fossil fuel vehicles and the share of disturbed persons in the city of Stuttgart [>50 db(A) day-evening-night noise index over 24 h from Stadtklima Stuttgart (2010)]. For the change of persons disturbed by traffic noise, the following approach was used (Sammer and Wernsperger 1994):

$$\Delta PN[\%] = 37.5 * [\log_{10}(ckm_{\text{low/likely/high}}) - \log_{10}(ckm_{wo})] \qquad (1)$$

where ΔPN (%) = percentage change of persons disturbed by road traffic noise between scenarios Without and Low/Likely/High; $\mathrm{ckm}_{\text{low/likely/high}}$ (km) = car-kilometers of fossil fuel vehicles for scenarios Low/Likely/High; and ckm_{wo} (km) = car-kilometers of fossil fuel vehicles for scenario Without.

This approach assumed that (1) traffic noise is mainly a problem in the urban area, (2) the number of disturbed persons in 2009 is constant until 2025, (3) EREVs drive in electric mode in the urban area due to shorter trips and lower velocities (50 km/h and less), and (4) EVs cause no noise pollution higher than 50 db(A) in the city of Stuttgart.

Global warming (mainly related to CO_2 emissions) was the second indicator. CO_2 emissions from car traffic were calculated using the car mileage per type of vehicle simulated for each scenario in 2025 and the CO_2 emissions per km per type of vehicle. The lower limit of the utility function (0% sustainable) was defined as the emission rate for private cars (year 2010) with the car mileage of 2025. For the upper limit (100% sustainable), the European Unions' white paper target for 2050 was used, which includes a CO_2 reduction of 60% (European Commission 2011b).

Environmental pollution stemming from manufacturing EVs was considered by using the indicator primary energy from nonrenewable resources. It describes the energy consumption for production and maintenance. The input for the calculation was derived from the LCA models. The lower limit (0% sustainable) for the utility function assumed energy consumption if there were no EVs in the planning area (scenario Without); the upper limit (100% sustainable) assumed a reduction of 25% of this energy consumption level based on the targets of the European Energy Efficiency Plan (European Commission 2011a).

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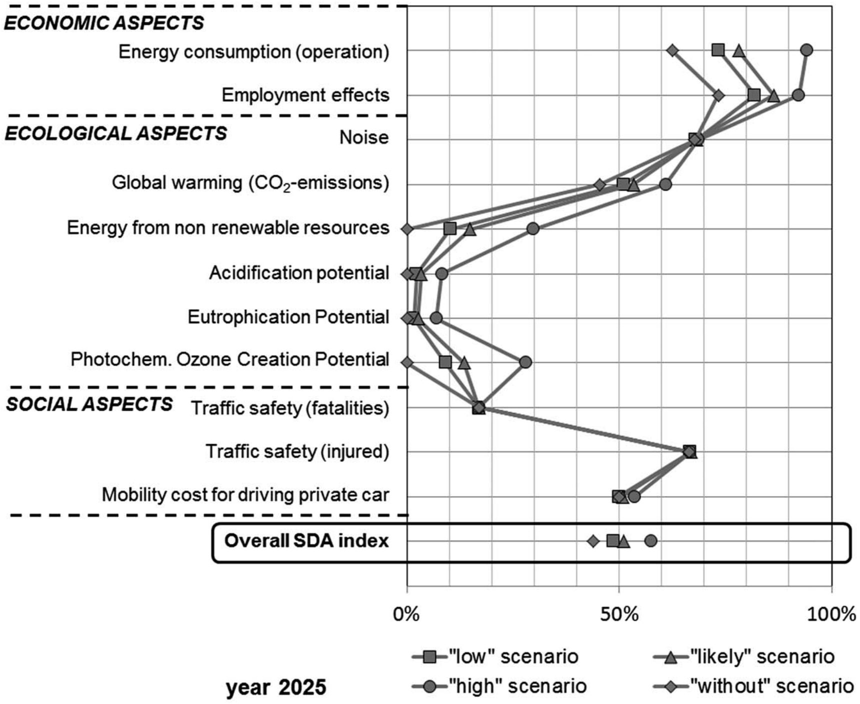

Fig. 7. Part indexes of sustainable development in the planning area and overall SDA index

The indicator acidification potential (result of LCA) describes the emissions of SO_{2-} equivalents per year considering the car mileage in 2025 including production of the vehicles. The eutrophication potential (result of LCA) describes the emissions of phosphate-equivalents per year considering the car mileage in 2025 including production of the vehicles. The definition of limits for the utility function for the acidification and eutrophication potential followed the same principle as described previously. The same procedure was used for the indicator POCP, which describes the emissions of ethene-equivalents per year considering the car mileage in 2025 in the planning area including production of the vehicles.

Social aspects used in the SDA were impacts on traffic safety and mobility costs. Two indicators with regard to traffic safety were calculated: the number of fatalities and the number of injured persons caused by road accidents. For each scenario, the number of fatalities in 2025 was calculated based on the car mileage per vehicle type and the number of fatalities per accident with fatalities. For EREVs and BEVs, no accident rates are available; therefore a slightly higher rate for EVs was assumed compared with fossil fuel cars according to the assumption of noise reductions (+10%). The use of the same accident rate for BEVs and EREVs creates a bias toward EREVs. The lower limit was set with the highest number of traffic fatalities recorded in the planning area. In this case, the authors allocated the number of fatalities in Germany in 1970 to the province of Baden-Wuerttemberg (German Federal Statistical Office 2013) and the greater Stuttgart region according to the distribution of inhabitants. The upper limit was 0 in all cases. The same approach was applied for the number of injured caused by road accidents.

Another indicator is mobility cost for driving a private car, including maintenance and operating costs, considering the composition of the car fleet per scenario in 2025.

For each indicator, the contribution toward sustainable development was calculated. Furthermore, the sustainable development index (SDI) is presented, which is the weighted mean value of all indicator values for a scenario; the SDI lies between 0 and 1 for each scenario (Fig. 7). The SDI values are, however, controversial (e.g., Böhringer and Jochem 2007).

The results show that electric mobility contributes to sustainable development in the Greater Stuttgart region. Especially in the field of economic aspects, benefits can be seen because there are large differences between the reference and future scenarios. For ecological impacts, the green reputation of electric mobility is not clearly reflected; high benefits lie in primary energy from non-renewable resources and POCP, but according to the results the differences are small for the other indicators because the production of BEVs and EREVs leads to greater environmental pollution than does producing conventional cars. In terms of social aspects, there are hardly any noticeable differences between the scenarios and only small differences for the indicator mobility costs. The overall SDA indicator for 2025 shows a positive contribution toward sustainable development. Although the Likely and Low scenarios do not show large differences, a high support of electric mobility as assumed in High scenario results in higher contributions to sustainable development in the planning area.

Outlook

Limitations of the Approach

This research aimed at an integrated evaluation of an EREV concept that addresses some of the core limitations of BEVs such as the high purchase price and the limited range. The simulation results for the greater Stuttgart region revealed that the EREV technology is feasible to act as a bridging technology. This section reflect briefly on the transferability of the results to other planning areas and countries.

First, for any transfer of results it has to be considered that there is a relatively uncertain group of variables for the development of the future scenarios, namely those describing the future

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political-economic framework, such as acquisition costs of vehicles, which are dependent on standards and other regimentations such as subsidies, the labor market, and unit costs depending on the number of vehicles produced. For example, in 2016, Norway—a leader when it comes to environmentally-friendly vehicles—held serious discussions on banning petrol-powered cars by 2025 to reach target numbers (Independent 2016); the country will at least implement progressive policies (e.g., differentiated rush-hour taxes) to encourage a transition toward electric vehicles. Of course, such measures could have a significant impact on future developments. In particular, this could have an impact on research to improve the technological performance of vehicle range and charging time on a shorter term. Hence the results are only directly transferable to those planning areas that have similar political-economic frameworks.

Second, concerning the EREV usage in the greater Stuttgart region, which was displayed in the microscopic travel demand model mobiTopp, two simplistic assumptions were made. It was supposed that the owners of EVs are the same as owners of conventional cars, meaning that an EV was bought to replace a conventional car. Consequently, it was not assumed that the car fleet in the region increased because of EV availability. Furthermore, a dense network of public charging stations was not assumed, but rather mainly recharging possibilities at home and at work. The explicit definition of a dense public recharging infrastructure might lead to even higher driving shares in the battery mode for EREVs and to a slight temporal unbundling of the energy demand from EV usage. As soon as more data are available on the development of public charging infrastructure, these results should be updated to examine relevant effects.

Because of other aspects, the transferability of the results to other regions is limited to those cities with above-average income per capita, an urban population density, and an excellent transit system. However, many areas across Europe and beyond show such comparable framework conditions. People living in rural areas and/or areas with weaker transit supply may face the need to cover higher vehicle mileage per day, which may cause additional charging needs. This would have a major impact on the electricity demand. The challenges of the distribution grid might increase significantly, especially in districts with higher income levels, and consequentially higher penetration rates of EVs.

Another aspect that has to be taken into account is the focus on the German energy system. The environmental impact in other countries might differ significantly; e.g., in Sweden, where the electricity is generated mainly from hydro, the negative impact on the environment is significantly lower.

Hence the specific results of the analyses most clearly apply to the greater Stuttgart region, and the change of several framework conditions could also change details of the evaluation. However, the general holistic evaluation framework and the overall pattern of results can be expected to be transferable also to other regions of similar structure, at least in European countries with similar general framework conditions.

Conclusions and Summary

Against the background of megatrends such as climate change, urbanization, globalization, and demographic change, any opportunity should be seized to strengthen the development of a more sustainable transportation system. This study provides a further step in quantifying the overall benefits of an extended range electric vehicle concept to sustainable development of urban areas. As a specific application in the greater Stuttgart region, the results reveal that EREVs can provide substantial benefits compared with BEVs and conventional vehicles. From an environmental point of view, EREVs present advantages even when electricity grid mixes used for charging have high shares of fossil-fuel power plants (e.g., the German grid mix). The environmental benefits increase with higher shares of renewable energy in the grid mix of the use phase. A comparison of EREVs and pure electric vehicles shows a slight benefit of EREVs in the production phase because of their smaller batteries, but this benefit is decreasing with the increasing share of renewable electricity for charging in the use phase. Nevertheless, EREVs provide a higher range of application than do pure electric vehicles, as well as a more flexible management of heat generation in winter, which cannot be represented within the results of the lifecycle assessment.

The results show clearly that EREVs could become an important player in the future car market of Europe. Nevertheless, the development clearly depends on the future framework conditions because many factors may influence the sales figures. These factors relate, among others, to technological, socioeconomic, sociodemographic, and political developments, and are difficult to predict. Therefore different research perspectives have to be integrated in order to allow for a comprehensive assessment. Future scenarios can help to gain a holistic interlinked view of a complex system. They can also clarify which strategies and goals must be pursued to reach desired developments in the long term.

Although this research is only a first step toward a consistent and global assessment of innovative transportation systems, it can provide effective information for researchers in the field of transportation planning. First, the integrated and holistic approach used in this paper seems to be an effective tool to address complex questions and allows the valuation of benefits of new technologies. The authors recommend that policy makers promote interdisciplinary collaboration and holistic research approaches for upcoming new technologies such as autonomous driving. Despite the fact that interdisciplinary strategies could be intensive and more time consuming, the complexity of transportation systems requires the knowledge and skills of different partners to work collaboratively.

Second, agents in urban planning may be able to better understand and regulate the coupled human and natural system, especially in highly urbanized areas. Society will adapt to the technology and vice versa. As a bridging technology on the way to an electricity-dominated car market, EREVs can also help to overcome skepticism with regard to new technologies from the car users' side.

The conclusions show that EREVs can contribute to sustainable development in metropolitan regions under specific framework conditions as outlined in the Limitations of the Approach section. However, serious efforts have to be targeted at integrating EREVs sustainably into the existing mobility and energy systems (charging system, intermodal linkages, and so on).

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Supplemental Data

Figs. S1 and S2 can be found in the ASCE Library (www.ascelibrary.org).

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