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Empirical carbon dioxide emissions of electric vehicles in a French-German commuter fleet test

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Abstract

According to many governments electric vehicles are seen as an efficient mean to mitigate carbon dioxide emissions in the transport sector. However, the energy charged causes carbon dioxide emissions in the energy sector. This study demonstrates results from measuring time-dependent electricity consumption of electric vehicles during driving and charging. The electric vehicles were used in a French-German commuter scenario between March and August 2013. The electric vehicles ran a total distance of 38,365 km. 639 individual charging events were recorded. Vehicle specific data on electricity consumption are matched to disaggregated electricity generation data with time-dependent national electricity generation mixes and corresponding carbon dioxide emissions with an hourly time resolution. Carbon dioxide emission reduction potentials of different charging strategies are identified. As carbon dioxide emission intensities change over time according to the electric power systems, specific smart charging services are a convincing strategy to reduce electric vehicle specific carbon dioxide emissions. Our results indicate that charging in France causes only about ten percent of the carbon dioxide emissions compared to Germany, where the carbon intensity is more diverse.

1 Introduction

Electric vehicles (EV) are considered as an eco-innovation that has the potential to reduce environmental problems caused by the transportation sector (Jochem et al., 2016; Lane and Potter, 2007; Rezvani et al., 2015). The potential for CO2 emission reductions depends on the CO2 emissions generated for charging the EV compared to the emissions from conventional Internal Combmagnitude in different countries (Doucette and McCulloch, 2011; Faria et al., 2013; Nordel of et al., 2014). For example CO2 emission intensities of electricity generation largely differ between France and Germany (Fig. 1) due to severe differences in the underlying electricity generation mixes (ENTSOE-E, 2014). Heavy fluctuations of electricity fed-in by photovoltaic and wind turbines can be observed in Germany whereas the high share of nuclear power effect corresponding CO2 emission intensities in France. Quantifying CO2 emission reduction potentials of EV are of particular interest with regards to European greenhouse gas emissions reduction targets. However, this task remains challenging like ongoing discussions on the appropriateness of standardized driving cycles to measure CO2 emissions of EV and ICEV show.

The objective of this paper is to contribute to this discussion by quantifying CO2 emission reduction potentials of EV used for commuting in the French-German cross-border context based on time-dependent empirical EV energy consumption data as well as data on CO2 emissions of the national power plant portfolios.

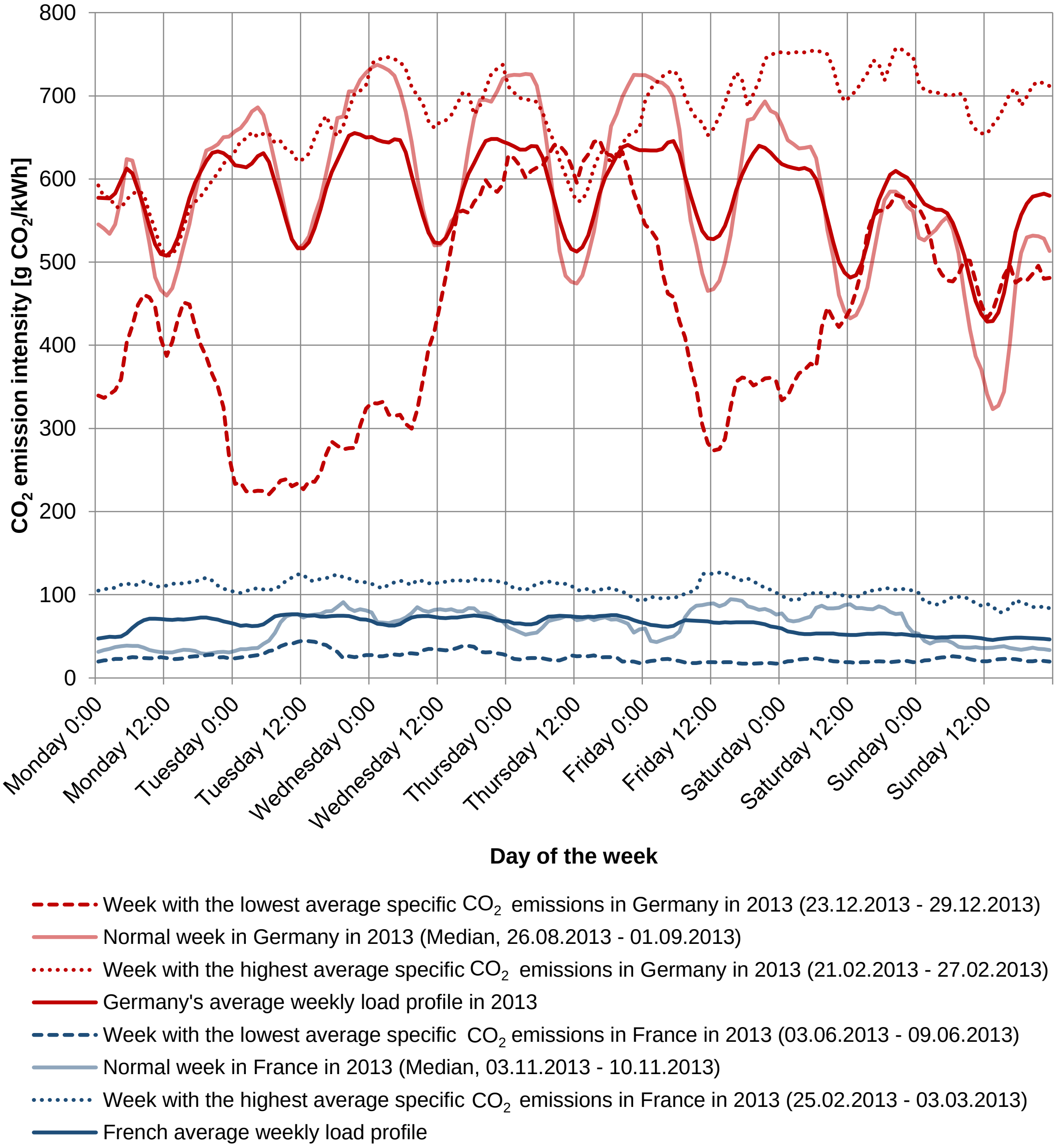

Fig. 1. CO2 emission intensities of electricity generation in France and Germany in 2013. (Sources: EEX Transparency, 2015; RTE, 2014)

2 Literature review on EV specific CO_2 emissions

Literature discussing CO2 emission reduction potentials of EV deployment usually compares the calculated values to other potentially substituted vehicle technologies. Most do so by comparing them to an identical or similar ICEV model (Doucette and McCulloch, 2011; Faria et al., 2013). Others set them in reference to regulatory limits (e.g. Euro VI) or fleet targets for ICEV (Donateo et al., 2014, 2015; Jochem et al., 2015). Some illustrate the potential by calculating the point of ecological break-even in dependence of driven mileage (Bickert et al., 2015). Yet others expand the basis for comparison to other new technologies such as hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), or fuel cell electric vehicles (FCEV) (Campanari et al., 2009; Ma et al., 2012; McCarthy and Yang, 2010; Sharma et al., 2012).

Most outcomes of previous studies indicate some kind of reduction potential. A significant dependence on the carbon intensity of electricity generation can be found. A high share of lowcarbon energies in the energy mix, such as renewables or nuclear power, significantly favors the EV emission values (Faria et al., 2013). To lower the CO2 emissions, especially for a carbon intensive energy mix such as Germany, a change towards renewable energies is needed (Bickert et al., 2015) or the implementation of specific low carbon charging strategies, such as load shifting (Jochem et al., 2015; Robinson et al., 2013).

However, these results are not consistent as they highly depend on the method and setting of the research. Table A1 in the Appendix provides an exemplary overview of different studies focusing on emissions of EV. The results of these studies are divers, because they differ in the following dimensions: region, system boundaries, specific energy consumption, definition of emission intensity (i.e. time resolution, average or marginal), and type of pollutants.
The system boundaries have two main sub-dimensions: the product life cycle and process chain of energy production. A life cycle assessment (LCA) of EV usually considers all emissions of their production process and all upstream materials used, the emission caused by operation, and the emissions caused by their recycling and disposal (e.g. Bickert et al., 2015; Hawkins et al., 2013; Muneer et al., 2015). Other studies focus only on the emissions caused during operation neglecting the upstream and downstream.

The second dimension considers the extent to that the value chain of the energy carrier (i.e. fuel or electricity) is considered. For EV the literature distinguishes between four different perspectives: tank-to-wheel (TTW), grid-to-wheel (GTW), plant-to-wheel (PTW) and well-to-wheel (WTW) (Fig. 2).

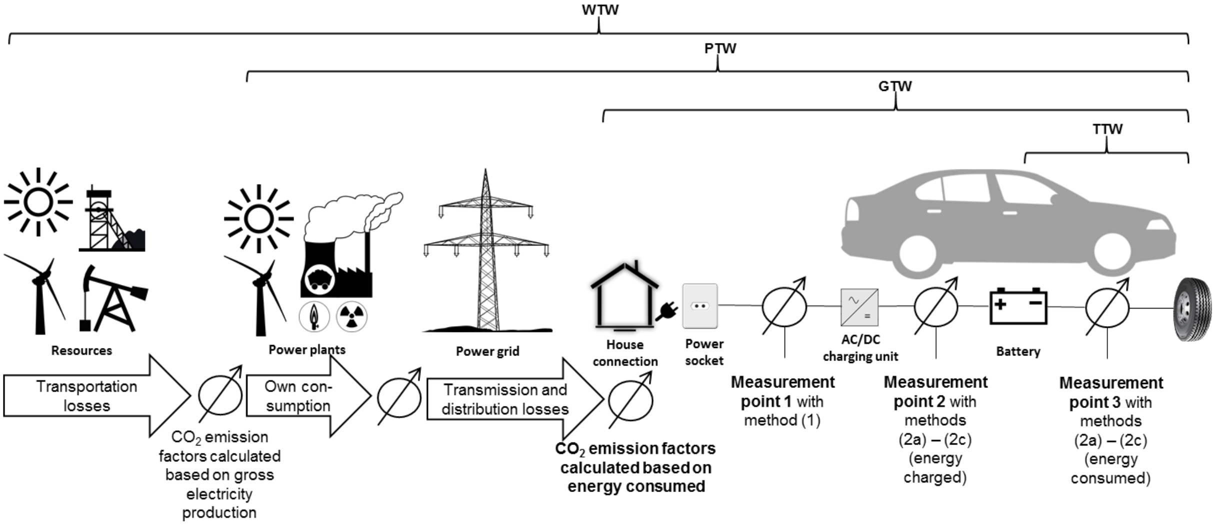

Fig. 2: Energy measurement points and methods in the energy supply chain for charging EV

TTW as the most limited only considers the efficiency of the energy conversion stored in the battery. Additionally to the TTW perspective, GTW considers efficiency losses from the grid into the battery. PTW additionally considers the losses in the process of energy generation, transport and conversion. WTW as the most holistic approach considers all the energy consumption (and emissions) from resource depletion, electricity generation, transport, conversion, and vehicle usage. While energy conversion for generating electricity to run EV takes place in power plants (PTW) with the major parts of efficiency losses, fuel combustion, corresponding energy conversion and efficiency losses for ICEV occur in internal combustion engines (TTW). Therefore concerning the emissions caused by energy supply TTW for ICEV is adequately represented by PTW of EV.

In this context it is also important to distinguish whether empirically measured energy consumption values are taken or values based on standardized driving cycles, such as the New European Driving Cycle (NEDC), as basis for emission assessment. Like the consumption values of ICEV depending on the conditions of deployment (driving profiles, driver behavior, and the auxiliaries, etc.) the real energy consumption values can significantly differ from the ones based on standardized driving cycles (Donateo et al., 2014; Muneer et al., 2015; Rangaraju et al., 2015). Nevertheless, most studies do not consider real driving profiles.

The considered time resolution and time duration of the investigation varies significantly between studies and shows a significant impact on the results. Some only take average values for one year of a specific energy mix (e.g. Campanari et al., 2009; Doucette and McCulloch, 2011) others take smaller distinctions looking at different seasons, monthly averages or even use disaggregated data with a 30 min time resolution (e.g. Donateo et al., 2014; Rangaraju et al., 2015; Robinson et al., 2013). Some studies do not focus on the average emissions of the energy mix, but focus only on the marginal emissions that are caused by the additional demand of EV, which are mostly carbon-intensive plants (Jochem et al., 2015; Ma et al., 2012; McCarthy and Yang, 2010), which consequently leads to higher CO2 emission values. Due to different energy mixes depending on various factors such as local resources, climate, and energy policy, it is important to clearly distinguish regional boundaries inwhich the emissions are investigated. Especially the different energymixes and their volatility can have a significant impact on the EV emissions Doucette and McCulloch, 2011; Faria et al., 2013; Ma et al., 2012). For example average CO2 emissions from electricity generation in 2013 in the neighboring countries, Germany and France, illustrate these differences evidently: 486 g/kWh in Germany and 64 g/kWh in France (IEA, 2015).

The importance of clearly distinguishing between the different approaches to assess emissions from EV is illustrated by Jochem et al. (2015) for the example of Germany. EV specific PTW CO2 emissions are measured based on four methods including (i) the annual average electricity generation mix, (ii) the time-dependent average electricity generation mix, (iii) the marginal electricity generation mix and (iv) balancing zero emissions (e.g. by the European Emission Trading System). As vehicle driving and parking is not equally distributed over the day in general (Kaschub et al., 2011; Ketelaer et al., 2014) and the European carbon pricing mechanism seems to be inefficient (Koch et al., 2014), quantifying EV specific CO2 emissions with methods (ii) or (iii) considering time dependent energy mixes seems appropriate, when charging under a high volatile energy emission factor (cf. Fig. 1).

There seems to be a research gap in the current literature concerning charging-dependent PTW CO2 emissions of EV based on empirical, disaggregated, time-dependent data series of the energy mix charged in real world usage scenarios in order to derive CO2 reduction potentials for different countries. Due to the various potential ways to set the system boundaries and measure the energy consumption, there is no direct comparability of the different studies and their proposed reduction potentials among themselves. The studies that are comparing the CO2 emissions of EV in different countries do so, due to the lack of empirical data, mainly based on standardized driving cycles or exemplary recorded trips. In order to fill this gap in the literature a long-term fleet test of EV deployed in a common and real cross-border mobility profile between two countries with distinctively different energy mixes is required.

Therefore, we present a French-German commuter fleet test as a case study. The driving profiles of commuters are characterized by a deterministic, repetitive, and therefore predictable mobility demand on fixed routes. Hence, commuting is widely considered an ideal application for substituting ICEV with EV (e.g. Tomi_c and Kempton, 2007). According to the Association of European Border Regions (2012) the French-German Pamina region is notably characterized by a high degree of cross-border labor mobility with large-scale cross-border cooperation. About 16,000 workers daily cross the French-German border in the Pamina region for commuting purposes, which underlines the validity presented results.

In order to achieve the paper's objective of quantifying the time dependent real CO2 emission reduction potentials of EV in the French-German cross-border context we raise the following research questions:

(i) How much energy was charged and consumed by the EV on the individual trips during the fleet test and how much does this amount depend on the chosen measurement points or assessment method (e.g. GTW, TTW, NEDC)?
(ii) What are the CO2 emissions caused by the EV considering the time-dependent national PTW CO2 emissions and the different assessment methods?
(iii) How high are the real CO2 emission reduction potentials of different EV use cases based on the previous results?

3 Methods and data

Section 3.1 describes the French-German e-mobility commuter case study. Section 3.2 presents the methods applied (Section 3.2.1) and data used (Section 3.2.2) to measure EV specific energy charged and consumed. Section 3.3 provides an overview on the methods applied (Section 3.3.1) and data used (Section 3.3.2) to measure charging-dependent CO2 emissions of EV.

3.1 Case study description

The fleet test to answer the proposed research questions was a French German cross-border e-mobility project carried out between 2013 and 2015 (Stella et al., 2015). EV were used by cross-border shift workers to commute between their homes in Alsace (France) and their workplace in Karlsruhe (Germany) in fixed car-pooling groups (Table 1). Hence, the time of use changed according to their rolling shift schedule: the workers arrived 30 min before the start of their eight hour shift at 6 am, 2 pm, or 10 pm respectively. After their shift they immediately started their journey back home, which usually lasted between one and 1.5 h. The average commuting distance of 75 km one-way was too long to travel two ways on one battery charge. Therefore, the EV were directly recharged during the eight hours of work as well as at home, usually immediately after arrival.
Out of the six EV used by the shift workers during the project data of three e-Wolf Delta 2 is analyzed in this study.

3.2 Measuring EV specific energy charged and consumed

Different methods to quantify the energy charged and consumed by EV are applied. The first approach calculates the energy charged during the charging events based on an exemplary charging curve (Fig. 3) measured at measurement point 1 (Fig. 2) during a charging event. The second approach quantifies the energy charged (measurement point 2, Fig. 2) and consumed (measurement point 3, Fig. 2) based on data from EV on-board data loggers. The third approach calculates the energy consumed during the charging events based on standard energy consumption (NEDC). Furthermore, information on the case study are provided including important meta-information of the data used.

Table 1: Characteristics of shift worker commuting in the project.

User group	Employees in shift production
User per EV	Fixed group of 5-7 people
Usage frequency	7 days per week before and after shift changeovers
Average one-way distance	75 km
Average annual mileage	36,000 km
Average speed	55 – 60 km/h
Type of EV	3 e-Wolf Delta 2
Charging locations	At home and at work
Charging infrastructure	12 standard outlets (230 V, max. 16 A, max. 3.7 kW)

3.2.1 Assessment methods

To calculate the time-dependent CO2 emissions, it is essential not only to know the total amount of energy charged, but also the changes of charging power during the charging process. The amount of energy charged during one charging event or discharged during a journey can be calculated via the integral of the product of current and voltage over time. As recording frequency of the onboard data logger measuring the charging power, the voltage and current was rather low, three different approaches are used to approximate the energy charged and consumed by the EV.

One possibility to calculate the energy charged during the charging processes relies on one exemplary charging curve recorded for the conventional AC charging process from 0% to 100% state of charge (SOC) (1). Voltage and current were measured at measurement point 1 within the energy supply chain presented in Fig. 2. This approach is used to quantify the GTWcharging energy of the three EV under investigation. Fig. 3 indicates that the charging power was set by the on-board charging unit of the EV, which lay at a maximum of 2.544 kW significantly lower than the allowed 3.6 kW for the European domestic Schuko socket outlets (CEE 7/7). For the charging process two different phases can be distinguished: almost directly after the start and for the main part of the process the effective charging power remained almost constant at 2.544 kW; after around 8.75 h the charging power started to decrease stepwise until it reaches zero at 10.75 h. This simply reflects the constant current constant voltage charging regime used by almost all lithium ion battery chargers. This regime starts with constant current until a preset cell voltage level is reached. At this time, the charger switches to constant voltage charging, which requires a current derating until a predefined minimum current level, where the charging process is finished (Kaschub et al., 2013).

Our approach of modelling EV charging processes is based on Kaschub et al. (2013), but is using a battery voltage limit of 685 V as an indicator for the point of power reduction. Until this voltage level, the battery is charged at constant power (i.e. 2.544 kW) (Formula 1). Then an approximated linear charging power reduction begins (Formula 2 and Fig. 3).

$$w_{q,1,constant} = 2.544 \cdot \Delta t_{q,1,constant}\ [kWh] \qquad \text{(Formula 1)}$$

$$w_{q,1,reduction} = \frac{1}{2} \cdot 2.544 \cdot \Delta t_{q,1,reduction}\ [kWh] \qquad \text{(Formula 2)}$$

The energy needed during charging event q in this approach is calculated by:

$$w_{q,1} = w_{q,1,constant} + w_{q,1,reduction} \qquad \text{(Formula 3)}$$

For each individual charging process the energy charged was calculated based on these considerations.

A second possibility to calculate the energy charged during the charging processes is based on the data recorded by the EV onboard data logger (2a). It calculates the energy consumed and recuperated during the journeys as well as the energy charged and the timely distribution by multiplying the battery voltage, the battery current and the interval from the actual data point to the previous (Formula 4).

$$w_{q,2a} = \sum_{\substack{t_{Logger} \\ \in T_{Logger,q}}} U_{t_{Logger}} \cdot I_{t_{Logger}} \cdot \Delta t_{\,Logger} \qquad \text{(Formula 4)}$$

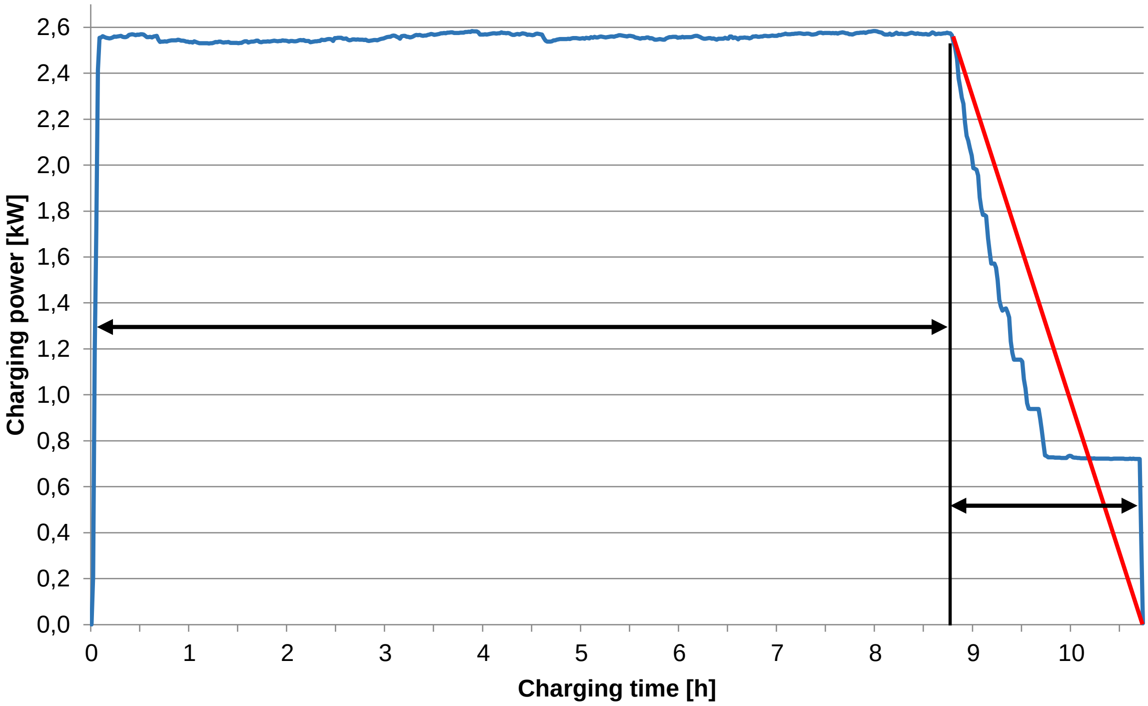

Fig. 3: Recorded charging curve of project EV (e-Wolf Delta 2) at domestic power outlet

This approach is used to measure the energy charged at battery entrance without considering the losses of the AC/DC charging unit (measurement point 2, Fig. 2) and the energy consumed at the battery outlet (measurement point 3, Fig. 2).

The frequency of only one data point every 20 s while driving and five to ten minutes while charging still lead to a significant degree of inaccuracy. So additionally this study compares two rolling means for the values of battery voltage and current taking into account three (2b) and five measured values (2c). As the switch between charging and driving is promptly, equalizing over a high number of values is not sensible. Therefore, the first rolling mean only includes the preceding and the following data point (2b); the second rolling mean includes the two predecessors and followers of each data point (2c).

The third possibility to calculate the energy charged during the charging processes is widely applied in literature and takes the standard energy consumption based on the NEDC (3). The NEDC does not consider the losses during charging processes, although this has been suggested by UNECE (2005). For our vehicle the manufacturer states 187 Wh/km as specific energy consumption (Table 2). Accordingly the energy consumption on the journeys was estimated under the assumption that this was the exact energy consumption for each journey and therefore had to be recharged after the arrival.

As the energy charged calculated by (1) is based on data measured directly at the socket outlet (GTW), no additional losses for transmitting energy from the power socket to the wheel need to be considered. On the other hand (2a), (2b), (2c), and (3) are all based on the energy charged and consumed at battery level. Therefore, the charging efficiency from the grid to the battery additionally needs to be taken into account.

3.2.2 Data used

The EV used in the project, i.e. the e-Wolf Delta 2 (an EV reconstruction based on the chassis of Nissan NV200), and the installed charging infrastructure were chosen according to the technological, user, and research requirements. For the accompanying research it was important to gain detailed access to the vehicle and its battery data. Technical data of the e-Wolf Delta 2 are presented in Table 2.

Table 2: Technological data of the EV (e-Wolf Delta 2)

Technical Data	e-Wolf Delta 2
Number of seats	7
HV-Battery capacity	24.2 kWh
HV-Battery voltage (max.)	720 V
Number of cells	168
Cell technology	Li-ion NMC
Battery weight	250 kg
Energy consumption (NEDC)	187 Wh/km
Maximum range (NEDC)	154 km
Performance	60 kW
Peak performance	90 kW
Heating	Bio-Diesel
Vehicle mass (empty)	1,666 kg
AC charging power	2.5 kW (nominal)
AC plug type	Type 2 (EN 62196 - 2)
AC charging mode	Mode 1 (IEC 61851)
Data logger	On-board CAN and GPS Logger

Only conventional charging (Mode 1, according IEC 61851) was used. Therefore, standard outlets (230 V) with a maximum current of 16 A were installed at the workers' homes as well as at the plant. To allow a detailed assessment of the energy consumption and charging processes the e-Wolf Delta 2 were equipped with special data loggers (VIKMOTE VX 20, Vikingegaarden). Details on the data collected are presented in Stella et al. (2015).

The charging events were identified and distinguished based on the data recorded by the EV data logger. Whenever the ignition was switched off, indicated by a LV-circuit of zero, and a current speed of zero the start of a charging event was set.

Over the timeframe of this study, from March to August 2014, the three EV travelled about 38,365 km, 18,612 in France and 19,753 in Germany. 639 charging events were recorded, 299 in France and 340 in Germany. 565 transnational commuting trips were identified, 283 to France and 282 to Germany.

As expected, in Germany the charging events usually started before the shifts of the commuters started at 6:00, 14:00 and 22:00.

In France the charging events mostly started between one and two hours after work when the commuters had returned back home (Fig. 4). The active charging hours are well distributed over the days with peaks before shift changeovers in Germany and after shift changeovers in France.

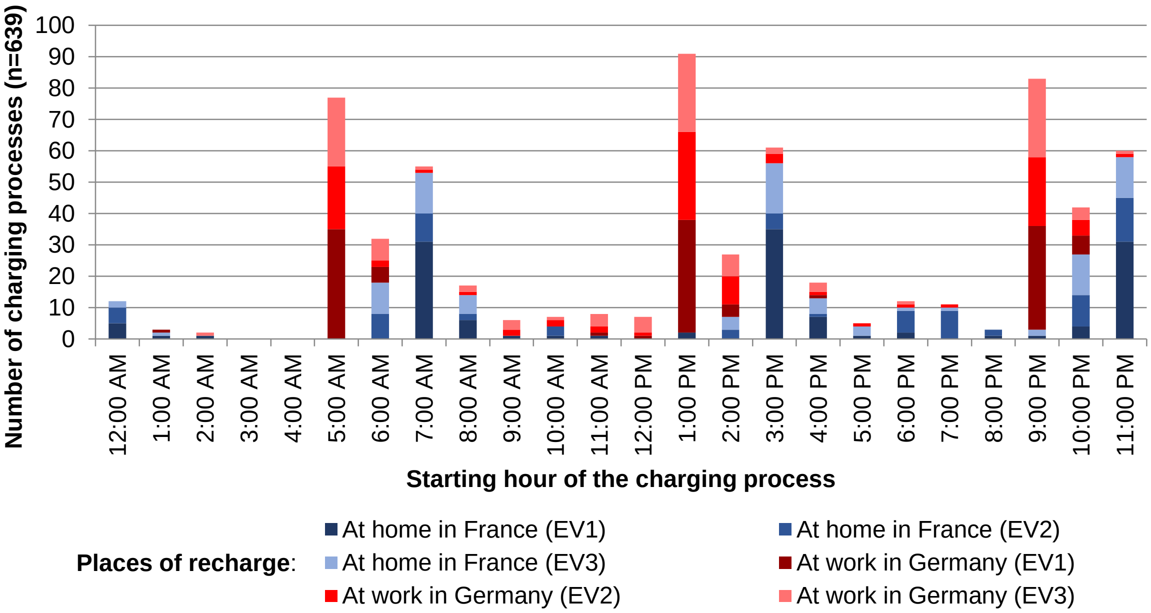

Fig. 4: Timely distribution of starting hours of the charging events.

3.3 Measuring charging-dependent CO_2 emissions

As CO2 emission intensities of electricity generation show large seasonal as well as hourly variations (Fig. 1), particularly in Germany, usage of a time-dependent mix to assess CO2 emissions of EV is appropriate (Jochem et al., 2015). Therefore (ii) the time dependent average electricity generation mix or (iii) the marginal electricity generation mix could be used. Since the EV were used for commuting and usually showed a very low SOC at arrival they had to be directly charged after they were plugged in to ensure that sufficient energy could be charged during the available time. This represents a highly inelastic manner and is very similar to other electrical appliances. Consequently it seems not to be justified to take the EV as the marginal consumer. Hence, using (iii) the marginal electricity generation mix seems not to be appropriate for our evaluation. Consequently we focus on the (ii) hourly average CO2 emission mix of the electricity generated.

3.3.1 Method

The energy charged w_q during a charging event q with duration of Tq (cf. Formula 3 and Formula 4) is mapped to the time dependent and country specific CO2 emission factors of electricity generated (fi;t) in order to quantify the CO2 emissions of a charging event cq;i (Formula 5).

$$c_{q,i} = \frac{\sum_{t\in T_q} f_{i,t}\cdot \Delta t}{T_q}\cdot w_q, \qquad \forall i,\forall q$$

(Formula 5)

The time-dependent CO₂ emission factors of country i during hour t ($f_{i,t}$) are calculated based on the time- dependent shares of the energy generated by sources j of power generation in hour t ($e_{i,j,t}$) multiplied with the appropriate specific CO₂ emission factors of the different energy sources $k_{i,j}$ (cf. Formula 6).

$$f_{i,t} = \sum_{j \in J} e_{i,j,t} \cdot k_{i,j}, \qquad \forall i, \forall t \qquad \text{(Formula 6)}$$

$e_{i,j',t} = \frac{E_{i,j',t}}{\sum_{j \in J} E_{i,j,t}}$ represents the share of electricity generated in country i by one energy source j' during hour t with $E_{i,j,t}$ representing the electricity generated by energy source j in country i during hour t with

$t \in T = \{1; \dots; T\}$: Hourly time intervals from March 2013 – August 2013.

$i \in I = \{France; Germany\} = \{F; G\}$: Countries considered.

$j, j' \in J = \{Lignite;\ Hard\ coal; Natural\ gas; Oil;\ Nuclear; Pump\ storage; Run - of - river\ hydro;\ Wind; Photovoltaics;\ Bioenergy, Waste\ and\ others\}$: Power plant technologies.

Additionally, knowing all $c_{q,i}$ as well as the overall distances travelled by the EV during the period considered, the average specific CO2 emissions of the project EV as well as country specific average CO2 emissions for exclusively charging in one of the countries can be calculated.

3.3.2 Data

The emission factors in Table 3 represent the emission factors of the energy at power outlet level. As only PTWCO2 emissions and not the life cycle emissions, i.e. no WTW perspective, are considered within this study, specific emission factors for nuclear power, hydro power, wind, and photovoltaics are zero (Table 3). For the German case the total CO2 emission values from electricity generation divided by the total electricity consumption in the year 2012 including losses for transmission and distribution are used to calculate ki,j (Icha, 2014). For France only data on electricity generation by source is available (RTE, 2015). In order to include CO2 emissions for efficiency losses of electricity transmission and distribution the values are calculated based on 6% losses provided by themajor French distribution system operator (ERDF, 2009) and the 2.5% losses provided by the French transmission grid operator (RTE, 2016). Corresponding efficiency losses are in line with other studies, e.g. Donateo et al. (2015) calculated with about 7% losses and Robinson et al. (2013) with 9.1% losses.

In order to calculate French electricity consumption based on gross electricity generation in accordance to Icha (2014), power plant's selfconsumption of 24 TWh in 2013 (INSEE, 2014) as well as electricity produced from pump storage of 7 TWh in 2013 (INSEE, 2014) are taken into account. Corresponding efficiency losses consequently amount to 13.3%.[1] These efficiency losses are comparable to those in Germany, which amounted to about 11.6% in 2012 (Icha, 2014). In order to calculate the specific CO2 emissions of France based on electricity consumption $k_{F,j}^{CONS}$ we multiplied the specific CO2 emissions based on gross electricity generation $k_{F,j}^{PROD}$ with $\vartheta = 1.153$[2] (Table 3). The additional losses are included in the GTW energy consumption assessment. The datasets concerning

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[1] $100\% - (100\% - 2.5\%)(100\% - 6\%)(\frac{575\ TWh - 7\ TWh - 24\ TWh}{575\ TWh}) = 13.3\%$

[2] $\vartheta = 1/(1-13.3\%) = 1.153$

hourly electricity generation by different energy sources for the year 2013 originate from RTE for France (RTE, 2015) and from the EEX Transparency Platform for Germany (EEX Transparency, 2015).

Table 3: Specific emission factors depending on the sources of energy in France (RTE, 2015) and Germany (Icha, 2014)

Energy source (j)		**Specific emission factors $k_{i,j}$ $(\frac{g\,CO_2}{kWh})$**		
		France (F)		**Germany (G)**
		$k_{F,j}^{PROD}$	$k_{F,j}^{CONS} = k_{F,j}^{PROD} \cdot \vartheta$	$k_{G,j}^{CONS}$
Lignite		956	1102.5	1,159.7
Hard coal				904.8
Gas	Combustion turbine	593	683.9	376.8
	Co-generation	350	403.6	
	CCG	359	414.0	
	Other gases	552	636.6	
Oil	Combustion turbine	777	896.1	571.4
	Co-generation	459	529.4	
	Other fuels	783	903.0	
Nuclear		0	0	0
Pump storage hydro		0	0	0
Run-of-river hydro		0	0	0
Wind		0	0	0
Photovoltaics		0	0	0
Bioenergy waste and others		983	1,133.7	328.1

Legend:
Combustion turbine: Also known as gas turbine
Co-generation: Generates electricity and useful heat at the same time
CCG: Combined Cycle Gas – Combination of thermodynamic cycles to improve turbine efficiency
Other gases: E.g. steam turbines or gas engines
Other fuels: E.g. steam turbines and diesel engines
Bioenergy, waste and others: Specific CO_2 emissions of biomass, biogas and waste are assumed to be at the same level in France. For Germany specific CO_2 emissions of biomass are assumed to be zero. Waste and other energy sources are at different levels This leads in the differences observed for specific CO_2 emissions of bioenergy, waste and others between France and Germany.
PROD: Calculations based on gross electricity generation
CONS: Calculations including efficiency losses

4 Results

In Section 4.1 the energy charged and consumed by the considered EV are presented. In Section 4.2 the results concerning corresponding charging-dependent CO2 emissions are given.

4.1 EV specific energy charged and consumed

The battery efficiency and the charging efficiency of the EV deployed were calculated by comparing the measured energy values at three different points as presented in Fig. 2. The energy losses in the battery depend on various factors, e.g. the cell chemistry, the assembly and connection between the cells, and the cell temperature. To calculate an average value of the battery efficiency for all three EV the ratio of the total amount of energy consumed at battery level (measurement point 3, Fig. 2) and total amount of energy charged at battery level (measurement point 2, Fig. 2) was calculated for (2a), (2b), and (2c). The corresponding results are presented in Table A2 in the Appendix. Since the measured battery efficiency of the second EV (EV2) were greater than one and showed other additional irregularities (later in the project it was discovered that one cell of the battery pack was damaged), the values were excluded for calculating charging efficiency.

The empiric average charging efficiency between the sockets and the batteries of EV1 and EV3 amounted to 0.924. Comparing GTW and NEDC energy of the three project EV, on average norm consumption (18.7 kWh/100 km) was exceeded by 42% (Table 4). Considering the charging processes only taking place in France (Germany), on average norm consumption was exceeded by about 49% (36%). Neglecting the losses in the AC/DC charging unit (measurement point 2, Fig. 2) efficiency losses compared to NEDC amount to about 32%, i.e. 39% for the charging processes taking place in France and 26% for the charging processes taking place in Germany. Additionally neglecting the losses in the battery (measurement point 3, Fig. 2) results in efficiency losses of about 30% compared to NEDC, i.e. 34% for the trips from Germany to France and 26% for the trips from France to Germany.

Table 4: Total energy charged and consumed by the project EV

Activity	**Parking and charging**						**Driving, consuming and recuperating**					
Assessment method	**Method (1)**			**Average of the methods (2a), (2b) & (2c)**			**Average of the methods (2a), (2b) & (2c)**			**Method 3 (NEDC)**		
	Measurement point 1			**Measurement point 2**			**Measurement point 3**			**-**		
Place of recharge / Trip destination	**Total**	**F**	**G**	**Total**	**F**	**G**	**Total**	**F**	**G**	**Total**	**F**	**G**
Total energy [kWh]	10,195.6	5,182.7	5,012.9	9,456.7	4,818.9	4,637.7	9,320.7	4,674.6	4,646.1	7,174.3	3,480.4	3,693.8
Overall surplus of total energy compared to calculations based on NEDC [%]	42.1%	48.9%	35.7%	31.8%	38.5%	25.6%	29.9%	34.3%	25.8%	-		
Average trip specific energy per kilometer [kWh/km]	0.267	0.279	0.254	0.248	0.259	0.237	0.244	0.251	0.236			
Standard deviation of trip specific energy per kilometer [kWh/km]	0.044	0.048	0.034	0.043	0.044	0.038	0.024	0.023	0.023			
t-Test results	t(563)=7.26, p<.001, d=0.61			t(563)=6.55, p<.001, d=0.55			t(563)=8.21, p<.001, d=0.69					
Levene-test results	F(1;564)=.092, p=.76			F(1;564)=.182, p=.67			F(1;564)=.559, p=.46					

Next to the overall surplus compared to NEDC values the results show that the energy consumption is on average significantly higher on the home trips from Germany to France (Table 4 and Fig. 5). These findings are supported by highly significant independent sample t-test results (Student, 1908) with medium effects (Cohen's d ranges between 0.55 and 0.69, Table 4). These results are of particular interest, as they indicate that external factors influenced electricity consumption of the EV on their home trips significantly. However, no significant differences between the variations of energy consumption on the trips to work and back home could be observed. According to Table 4 standard deviations of trip specific energy charged and consumed per kilometer do not differ significantly. This is supported by insignificant Leveneetest results (Levene, 1960) which are also presented in Table 4.

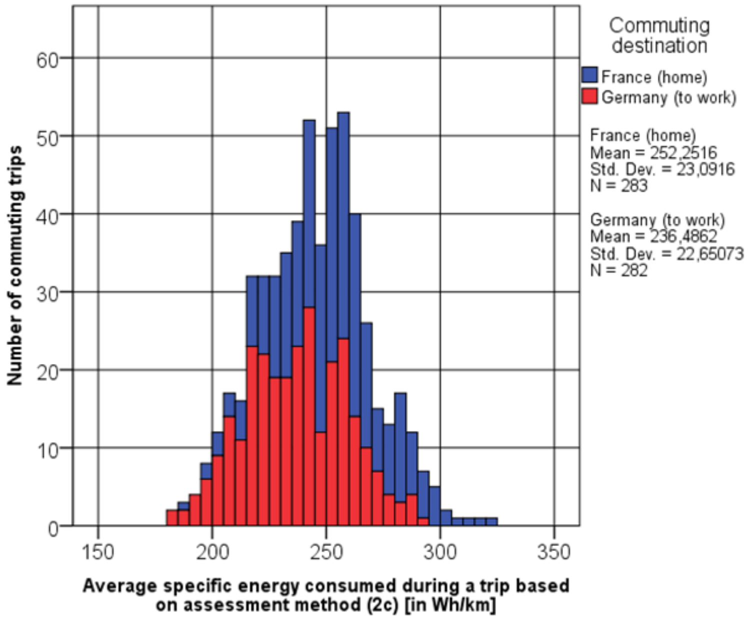

Fig. 5: Distributions of the specific energy consumed (measurement point 3, Figure 2) during the bi-national commuting trips by the 3 project EV

4.2 Charging-dependent CO_2 emissions

The average CO2 emissions during the charging processes of the project EV in France and Germany are presented in Fig. 6.According to these results average CO2 emission factors of the charging events vary considerably, particularly in Germany. The standard deviations of average CO2 emissions during the charging processes ($SD_{c_{q,F}}$ and $SD_{c_{q,G}}$) and Levene's test (Levene,1960) showthat the variations of the distributions differ at a highly significant level ($SD_{c_{q,F}}$=30.6; $SD_{c_{q,F}}$=91.2; F[1,637]=201.9, p<.001). Obvious differences observed concerning arithmetic averages $M_{c_{q,F}}$ and $M_{c_{q,G}}$ are supported by highly significant t-test (Student, 1908) results with strong effect sizes (Cohen, 1988) (t[423.2] ¼ 97.3, p < .001, d ¼ 7.5). These findings are further supported by aggregated results presented in Table 5.

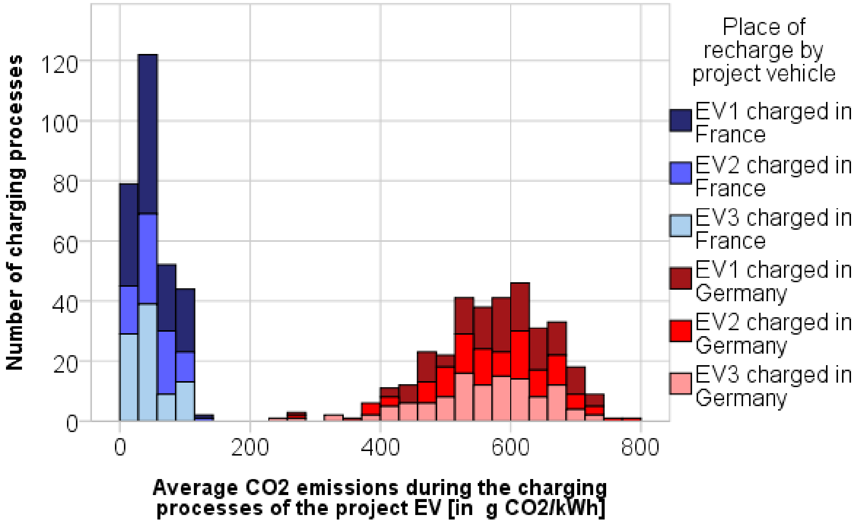

Fig. 6: Distribution of the average CO2 emissions during the charging processes of the project

On average PTWCO2 emissions of charging the project EV from March until August 2013 exceeded CO2 emissions calculated based on norm consumption by about 37% (measurement point 1, Fig. 2). Not taking into account efficiency losses in the battery and for charging still results in a surplus of PTW CO2 emissions of about 27% (measurement points 2 and 3, Fig. 2).

Table 5: Total and average CO2 emissions of project EV

Activity	**Parking and charging**						**Driving, consuming and recuperating**					
Assessment method	**Method (1)**			**Average of the methods (2a), (2b) & (2c)**			**Average of the methods (2a), (2b) & (2c)**			**Method 3 (NEDC)**		
	Measurement point 1			**Measurement point 2**			**Measurement point 3**			**-**		
Place of recharge / Trip destination	**Total**	**F**	**G**	**Total**	**F**	**G**	**Total**	**F**	**G**	**Total**	**F**	**G**
Total CO_2 emissions [kg]	3,209.6	304.8	2,904.8	2,976.9	283.7	2,693.2	2,957.0	275.1	2,681.8	2,338.0	205.3	2,132.8
Overall average time-dependent specific CO_2 emissions (in g CO_2/km)	83.7	16.4	147.1	77.6	15.2	136.3	77.1	14.8	135.8	60.9	11.0	108.0
Overall surplus of average time-dependent specific CO_2 emissions compared to calculations based on NDEC [%]	37.3%	48.5%	36.2%	27.3%	38.2%	26.3%	26.5%	34.0%	25.7%	0%		

Two major reasons for the discrepancies between real CO2 emissions and CO2 emissions calculated based on NEDC can be distinguished in (i) differences between the specific NEDC consumption and real consumption and (ii) differences between TTW and GTW. As NEDC consumption is also measured at measurement point 3 (Fig. 2) the first reasons for the discrepancies between the CO2 emissions calculated based on NDEC and real consumption can be quantified. This amounts to about 27% for all trips considered, to about 34% for the trips from Germany to France and to about 26% for the trips from France to Germany (Table 5). However, this analysis neglects the losses occurring in the converter and the battery. Additionally incorporating the losses between measurement point 1 and measurement point 3 (Fig. 2) permits accounting for GTW consumption in order to quantify the empirical, time dependent PTW CO2 emissions, as efficiency losses between electricity generation and measurement point 1 (Fig. 2) are considered in the specific emission factors used.

Empirical specific GTW energy charged amount to about 0.27 kWh/km (Table 4, measurement point 1) and results in average specific transnational PTW CO2 emissions of about 83.7 g CO2/km. Specific CO2 emissions derived from norm consumption are on average only at a level of 60.9 g CO2/km (Table 5). During the evaluation period of six months about 3.2 tons of CO2 were emitted. As the major part of the electricity generated in France is based on “carbon-free” nuclear power, specific PTWCO2 emissions are substantially lower for the EV (16.4 g CO2/km in France compared to 147.1 g CO2/km for Germany). A detailed EV specific overview on charging-dependent CO2 emissions is provided in Table A3.

5 Discussion

Section 5.1 discusses the results concerning EV specific energy consumption, Section 5.2 the results concerning CO2 emissions and Section 5.3 corresponding potentials to reduce CO2 emissions.

5.1 Energy consumption

When putting the emission values into a broader context concerning the energy charged two distinctive outcomes have to be discussed: firstly, the higher energy consumption in comparison to the NEDC values and secondly, the higher average energy consumed on the commuters' way home. The higher energy need of about 42% is not the result of a single factor, but can rather be explained by a combination of different factors.

First of all, the charging efficiency is considered in the GTW energy calculated based on method (1) (Table A2), which the NEDC does not take into account. The calculated average value of 0.924 is supported by the technical data of the e-Wolf Delta 2 components, e.g. the on-board AC/DC charging unit itself has an efficiency of up to 0.95, according to the manufacturer; and the calculated battery efficiency lies between 0.976 and 0.984. It is slightly higher than the charging efficiency that has been stated in previous studies with a value around 0.9 (e.g. Campanari et al., 2009; Eaves and Eaves, 2004; Van Vliet et al., 2011), which might be due to other battery types, onboard AC/DC charging units or other electrical components (Thomas, 2009). Additionally, our period of investigation was mainly during summertime, when due to the mild temperatures less energy is lost due to the battery's internal resistance, than in winter. When we compare our results to a recent commercial German vehicle test of EV (ADAC, 2015) with 11 EV, results of our empiric additional energy consumption compared to the NEDC values are comparable. The commercial test provides deviations from þ17.1% up to þ49.7%, with an average of þ34.7% (standard deviation 11%). This test also includes the new Nissan eNV200, which is very similar to the project vehicles Delta 2 (the car bodies are identical). The project vehicles consume (based on the GTW approach) on average 17% (26.6 kWh/100 km) more than the Nissan eNV200 in the commercial test. Furthermore the results provided by Hacker et al. (2009) indicated an additional empirical energy demand measured by the

GTW approach of 25% up to 70% compared to NEDC values. Additionally to efficiency losses during the charging process, two further influencing factors leading to an increased energy demand were identified: route profiles and average payload. In this specific usage scenario the EV travel high distances on motorways and (flat) country roads (share of motorways 49.5% and country roads 46.4%) and have only a very low share of inner-city usage (4.1%) e which is not optimal for EV. This leads to comparably energy intensive high speed profiles with average speeds between 55 km/h and 60 km/h (Stella et al., 2015), where a higher amount of energy is lost to drag, whereas the driving cycle used by ADAC (2015) only covers a short motorway phase. The last, but probably most severe argument is the payload. As commuters use the EV to carpool in order to travel as cheap as possible to work, usually 5 to 7 people travel in one EV. The difference in specific higher energy consumption (~7% surplus) between the trips from France to Germany and back from Germany to France is arguably the result of three conditions: (i) the shift workers might try to get home as quick as possible after work resulting in higher average speeds or higher driving dynamics. Furthermore, (ii) the users' homes are located at higher altitudes. Finally (iii) the average wind direction in this area is south-west, which is opposing the usual commuting direction when driving home and therefore increasing the drag losses.

Additionally, the data quality and uncertainties in the energy consumption measurement should be addressed. In terms of generalization it should be kept in mind that only the energy charged of three EV was measured. Even more limiting is the fact that EV2 showed some irregular behavior in its data due to damaged individual battery cells. Also the precision of the measurement of the energy consumed and recuperated is limited due to the 20 s time resolution of data points taken during a trip. As the recuperation phases are often shorter, these phases might be underrepresented due to the sampling frequency. Within this work the ratio of energy recuperated and energy consumed lies between 10% and 15%. This should be considered as lower bound. Furthermore, the assessment of energy charged in the GTW approach with method (1) at measurement point 1 (Fig. 2) is based on one exemplary charging curve. Charging behavior might vary considerably based on different parameters, particularly outdoor temperatures.

5.2 CO_2 emissions

The calculated EV emissions based on the French and German energy mix reveal significant differences between the two countries. Therefore, different reduction potentials are derived from the comparisons to comparable ICEV. Assuming that the project vehicles would only be charged in Germany results in average time-dependent PTW CO_2 emissions of about 147.1 g CO_2/km. This is about 36% above the CO_2 emissions calculated based on the norm consumption of the EV (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Although the CO_2 emissions calculated by ADAC (2015) are based on a WTW assessment, the average PTW CO_2 emissions according to our results still exceed the CO_2 emissions calculated for Nissan eNV200 by about 15%. Comparing CO_2 emissions according to norm consumption of a conventional Nissan NV200 also having an identical chassis (128 g CO_2/km) with the CO_2 emissions calculated based on the norm energy consumption of the project EV (11 g CO_2/km in France and 108 g CO_2/km in Germany) leads to the conclusion that EV usage in France (Germany) is more environmentally friendly than usage of comparable ICEV. CO_2 emission reduction potentials in France (Germany) consequently amount to 91.4%[3] (15.6%[4]). However, additional efficiency losses in the batteries and the AC/DC charging unit (charging efficiency, section 3.1) increases the amount of energy needed for charging. This consequently also increases of CO_2 emissions and results in reduction potentials compared to ICEV of about 90.7%[5] in France and 8.7%[6]

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[3] (128 gCO_2/km – 11 gCO_2/km) / 128 gCO_2/km

[4] (128 gCO_2/km – 108 gCO_2/km) / 128 gCO_2/km

[5] (128 gCO_2/km – (11 gCO_2/km / 0.924)) / 128 gCO_2/km

[6] (128 gCO_2/km – (108 gCO_2/km / 0.924)) / 128 gCO_2/km

in Germany. PTW CO_2 emissions for charging EV in France are consequently about 10 times lower than CO_2 emissions of comparable ICEV and about 10 times lower than charging in Germany. These results underline the effects of the different electricity generation mixes in France and Germany on operational, charging and time dependent CO_2 emissions of EV.

It needs to be critically mentioned, that the disaggregated data on electricity generation used for the calculations differs between France and Germany. Notably electricity generation by source is classified differently and specific CO_2 emissions in the two countries differ (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Nevertheless, almost all of the specific CO_2 emissions provided for operating the power plants are within the range of Turconi et al. (2013). Furthermore, differences between official German statistics on annual electricity generation by source and the averages calculated based on the hourly disaggregated data provided by the EEX Transparency Platform (EEX Transparency, 2015) were observed. In comparison to the AGEB (2015) share of lignite is heavily and electricity generated by wind and photovoltaic is slightly overrepresented, while on the other hand gas, biomass, and waste are heavily underrepresented. Furthermore, we did not consider electricity exchange between countries (which is currently increasing). In the border region this electricity exchange is strongly influencing the regional electricity generation mix. For other uncertainties, such as regional specific grid losses or power generation mixes (such as local electricity use from photovoltaics), there is to our knowledge currently no reliable data available and therefore could not be used. Depending on the region the time-dependent local energy mix could potentially vary significantly from the national one (UBA, 2016). Further limitations include that only CO2 emissions were considered. Other environmental indicators were neglected in this analysis.

5.3 CO_2 emissions reduction potentials and strategies

Focusing on our results, we observed that if EV would have been charged exclusively in Germany, specific CO2 emissions according to NEDC of the EV would have still been slightly lower than for a comparable ICEV (Section 5.2). Consequently, according to our findings the upcoming European fleet target of 95 g CO2/km in 2022 would not be achieved by the project EV when real power plant emissions would be considered. For Italy, Donateo et al. (2014) are more optimistic about the potentials of EV to reach the fleet targets.

However, as the German electricity generation is in a considerable decarbonization process, the 95 g CO2/km target might be achieved in 2022 e even with our calculation method. The time-dependent CO2 emissions assessed for 2013 and the CO2 emissions calculated based on national average CO2 emissions are about at the same level. This is surprising, as time-dependent CO2 emissions fluctuate heavily during the day, particularly in Germany. However, this can be explained by the usage scenario within this particular project, as the commuters are shift workers with a 24 h rotating shift schedule. The EV were in constant deployment and charged rather slow (Mode 1). Consequently, charging times are well distributed over the hours of a day (Fig. 7). For commuters not working in a rotating shift schedule the outcome would be different.

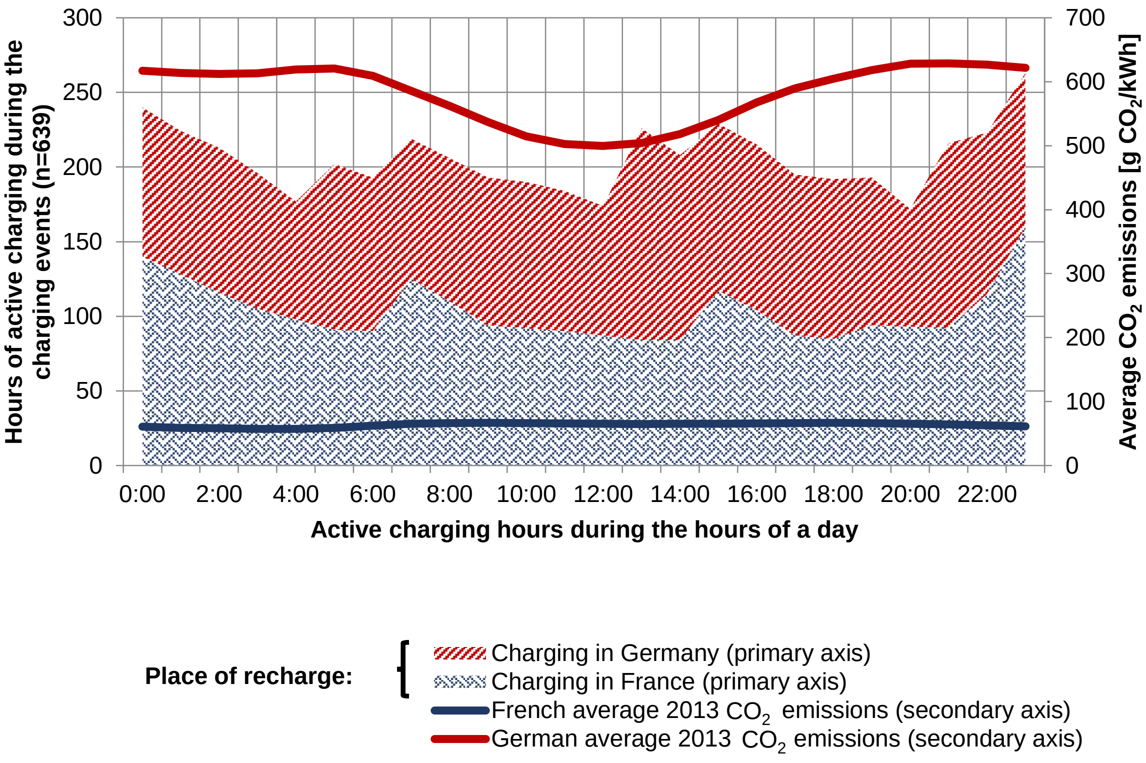

Fig. 7:Cumulated active charging hours of the project vehicles

Our results implicate that CO2 emission reduction potentials of EV could be used by charging them during windy and sunny hours in Germany. From an environmental perspective, the time the charging processes take place is much more important in Germany than in France, as time-dependent CO2 emissions in France remain relatively stable on a low level (Fig. 1). The findings are supportive to Faria et al. (2013) who showed that CO2 emission reduction potentials of EV are high for France. Additionally Faria et al. (2013) showed that the reduction potential in Portugal varies significantly depending on the month and time of day. Therefore, particularly for Germany, we suggest introducing controlled Mode 3 (IEC 61851) charging with comparably higher charging powers up to 44 kW and the possibility to shift load into periods with comparably low time-dependent CO2 emissions. This however would require smart services controlling the charging events so the batteries are fully charged at the end of the shifts. In this context the potentially harmful effects of higher charging powers on battery health as well grid constraints need to be considered.

Table 6: Estimates on CO2 emission reduction potentials and strategies

Use cases	**Number of commuters**	**Strategies to reduce CO_2 emissions**	**CO_2 emission reduction potential per electric kilometer travelled**
French-German transnational commuters in the Pamina region	~16,000 (Association of European Border Regions, 2012)	Shifting charging activities to France, if possible. If commuters need to charge in Germany, shifting load into periods with high shares of fluctuating renewable energy sources.	Assuming that energy consumption is equal on the way to work and back and the EV are charged as often in Germany as in France, CO_2 emissions can be almost halved. Load shifting, so EV are charged as much as possible in France, would permit to further reduce CO_2 emissions of EV charging.
German commuters using EV instead of cars	66% of the German workforce, i.e. ~27 million (Wingerter, 2014)	Load shifting into periods with high shares of fluctuating renewable energy sources.	The high volatility of CO_2 emission intensities of the German electricity generation mix results in highly volatile CO_2 emission reduction potentials. According to **Fehler! Verweisquelle konnte nicht gefunden werden.** load shifting into afternoon hours could decrease CO_2 emission intensities of EV charging by about 100 gCO_2/kWh on average.
French commuters using EV instead of cars	About 73% of the French commuters use cars, i.e. 18.6 million (INSEE, 2009)	Emissions are always at comparably low levels, so charging when convenient is possible. Alternatively usage of self-generated renewable energy could be an option.	About 10 times less CO_2 emissions are generated if EV are used instead of ICEV.

An overview on strategies and potentials for reducing CO2 emissions by substituting ICEV with EV for different commuting use cases in the French-German context is presented in Table 6. Based on our findings the strategy suggestions for the different use cases vary: for transnational EV users commuting between France and Germany we recommend charging their EV in France as much as possible in order to reduce the specific CO2 emissions. For commuters only commuting within Germany we recommend shifting the load into periods with high shares of renewables, i.e. particularly into afternoon hours, when the sun is shining, or into windy periods. As CO2 emissions in France are generally on a low and stable level, our results permit to conclude that charging when convenient has no negative impact on CO2 emissions. Further reduction is only possible when self-generated renewable energies are available. In this case the charging schedule should be adapted accordingly.

6 Conclusions

The energy needed for charging three well-loaded electric vehicles in a French-German fleet test resulted in an average specific consumption surplus above the official values of about 42% on average. Considering time-dependent average French (characterized by a high share of nuclear power) and German (characterized by a high share of fluctuating renewables) electricity generation mixes, time-dependent carbon dioxide emissions for charging electric vehicles are roughly ten times lower in France than in Germany. Recommendations derived from the case study results of focusing on commuting with electric vehicles in a region with a high degree of cross-border labor mobility include that time dependent plant to wheel carbon dioxide emissions for charging electric vehicles should be considered in future driving test procedures.

Furthermore, the findings of this study underline the postulation that hypothetical energy consumptions of the standardized driving cycles should be validated by long-term real world consumption analysis. Assuming that electric vehicles are not charged equally distributed over the day in general, time dependent carbon dioxide emissions should be calculated and considered in the currently developed Worldwide Harmonized Light Vehicles Test Procedures. The better specific real world consumption and corresponding carbon dioxide emissions are incorporated in upcoming test procedures, the more attractive it becomes for car manufacturers to build low consuming electric vehicles and provide attractive services supportive to charging electric vehicles, when carbon dioxide emissions are low.

7 Future work

In order to assess charging dependent carbon dioxide emissions precisely, future research could address this problem by comparing the energy consumption of different types of electric vehicles operating on the same routes. For this, the data on energy consumption of the vehicles during driving and charging phases should be recorded in higher sampling rates. This would allow better estimates on energy consumption of electric vehicles. Furthermore, to compare the empirical carbon dioxide emissions of electric vehicles and internal combustion engine vehicles, measuring real fuel consumption of comparable conventional cars operating on the same routes could be investigated. The data on time-dependent carbon dioxide emissions within the two countries could be analyzed in a more detailed manner in order to develop environmentally friendly charging strategies for the two countries. Analyses focusing on the research question how charging processes of electric vehicles used in France and Germany could be scheduled in a carbon dioxide minimizing manner could also be addressed in future works by focusing on EV specific time-dependent marginal carbon dioxide emissions due to the fact that EV are marginal consumers, when they are capable to shift their load. Furthermore, load flow calculations, taking into account the technical constraints of the electric power grid, could be supportive to map energy sources and sinks more precisely in order to derive conclusions about the real carbon dioxide emissions of consumers in different areas.

Acknowledgements

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Appendix

Table A1: Examples of previous studies discussing EV emissions

Author	**Region**	**Time of data**	**System boundaries**	**Energy consumption**	**Definition of emission intensity**	**Type of pollutants**	**Reduction potential**	**Recommended measurements and policies**
Bickert et al. (2015)	Germany	2013/4 2020 & 2030 (projected)	LCA	NEDC + 20%, 2.7 kW for auxiliaries	Lifetime emissions of different energy sources	CO_2eq	Comparison to ICEV on individual level shows that only a mileage of 2,500 – 5,500 km/a is required to reach an ecological life-cycle CO_2 break-even	Expansion of EV in Germany has to go hand in hand with increasing the share of renewable energies, therefore incentives should encourage charging with renewable energies.
Campanari et al. (2009)	Italy	2007	WTW	ECE-EUDC, US06	Average emissions Italian power mix, coal, renewables, natural gas	CO_2	In comparison to ICEV on individual level at higher one-way ranges fuel cell electric vehicles (FCEV) show high CO_2 reduction potential, EV, if not charged with renewables, have almost none	---
Chatzikomis et al. (2014)	Greece	2012	LCA	NEDC, EPA values	Average emission values of electricity mix	CO_2	The potential total environmental impact of different levels of EV diffusion in Greece depends on the energy efficiency of both technologies and the source of electricity	---
Donateo et al. (2014)	Italy	2013	PTW	Measured EV consumption from eight separate charging events	Hourly disaggregated emissions	CO_2, NO_x, CH_4, SO_x, CO, HC, VOC, metals, particles	Comparison to the EU fleet targets and Euro VI limits on individual level shows significant lower emissions for all pollutants, but HC, which is lies at the same level	---
Donateo et al. (2015)	Italy	2013	PTW, LCA	Measured charging energy from 7.700 charging events	Specific emissions from three timeslots per day	CO_2, NO_x, CH_4, CO, particles	Comparison of different EV energy mix, charging habits, vehicle types, and driving conditions to the EU fleet targets and Euro VI limits shows reduction potential for most pollutants	---
Douchette et al. (2011)	USA, France, India, China	2009	TTW	Numerical simulation based on NEDC	The grid average intensity	CO_2	Comparison of different EV types to their ICEV counterparts on individual level shows high reduction potentials for France, medium for USA, and none or even negative for India and China	Countries need to decarbonize their power generation to gain a positive effect from EV introduction.
Faria et al. (2013)	Portugal, Poland, France	2011	WTW, LCA	Measured EV consumption on two different routes	Primary average and monthly distribution of energy among the year for three different energy mixes for three hour time slots	CO_2	Comparison of different EV types to their ICEV counterparts on individual level shows high reduction potentials for France, medium for Portugal and none or even negative for Poland. The reduction potential in Portugal varies significantly depending on the month and time of day, for Poland and France it is almost constant	Two main factors are required to make EV more sustainable from an environmental perspective: eco-driving attitude, and an environmental electricity mix.
Hawkins et al. (2013)	Europe	< 2010	LCA	Industry performance tests of NEDC. Nissan LEAF: 17.3 kWh/100 km	Aggregated environmental impacts of vehicles' global warming potentials and other potential impacts.	CO_2eq, toxicity, acidification, eutrophication	EV powered by the present European electricity mix offer a 10% to 24% decrease in global warming potential (GWP) relative to conventional diesel or gasoline vehicles; but supply chain exhibit high toxicity potential.	Reducing vehicle production supply chain impacts and promoting clean electricity sources in decision making regarding electricity infrastructure.
Jochem et al. (2015a)	Germany	2030 (projected)	WTW	Assumption: 20 kWh/100 km	Hourly electricity mix further regionally disaggregated in order to account for transmission capacities of the electricity grid	CO_2	Comparison of different assessment methods and charging strategies on the total energy consumption and emission to ICEV EU emission targets for 2030 on individual level shows that taking the marginal electricity mix the emissions will be higher than the targets set by the EU	Controlled charging should be supported, consistent methodologies to address key factors affecting EV CO_2 emissions should be developed, and efficient policy instruments to guarantee emission free mobility should be implemented
Ma et al. (2012)	England, California	2015 (projected)	WTW, LCA	Standard driving cycles, auxiliaries, additional load	Annual average energy mix and marginal emission factor	CO_2eq	Comparison of ICEV and hybrid electric vehicle (HEV) to comparable ICEV assessed with average and marginal grid intensity at different driving conditions for England and California shows that depending on the driving style there is no CO_2 emission reduction potential for England and only very little for California	---
McCarthy et al. (2010)	California	2009	WTW	Simulation based on annual driving data	Marginal emission factor from an hourly dispatch model	CO_2	Comparison of emissions of individual level between EV, ICEV, PHEV, and FCV shows that EV have the lowest specific emissions, more than half of comparable ICEV	---
Muneer et al. 2015	Scotland, Slovenia	2010/1	LCA	Simulation based on driving data	UK and Scottish average annual energy mix and local renewables	CO_2eq	---	Significant investment into renewable energies is required to lower the carbon emissions from EV
Nordelöf et al. (2014)	Worldwide review	1998 - 2013	WTW, LCA, LCIA	Review: different studies are considered	Review: different studies are considered	CO_2eq, toxicity, acidification, eutrophication	Greenhouse gas emission reduction potentials of EV are heavily dependent on the fossil content of the electricity mix.	Environmental benefits from large-scale deployment of EV depends on parallel improvements of the background energy system.
Rangaraju et al. (2015)	Belgium	2011	WTW, LCA	Measured charging energy	Disaggregated hourly emissions	CO_2eq, NO_x, SO_2, particle	Comparison of EV to ICEV emissions for different pollutants on individual level shows significant savings potential for CO_2eq, NO_x, and SO_2 but nor for particle emissions, also charging strategies and electricity mix influences the savings potential	---
Robinson et al. (2013)	England	2011/2	WTW	Charging profiles of 7.704 charging events over two six month periods	Two half hourly disaggregated emission profiles for winter and summer	CO_2	Comparison of different charging processes shows the effect of carbon content of the electricity mix and season	Smart metering and/or financial incentives are recommended to increase load shifting to of peak times
Sharma et al. (2012)	Australia	2011	LCA (no disposal)	AUDC	Average energy mix	CO_2eq	Comparison of total live cycle emissions of EV, HEV, and ICEV of different types shows that EVs do not always have a comparative environmental advantage	---

Table A2: Total energy charged and consumed by the project EV assessed by different methods (1) - (3) including charging efficiency calculations

		1 (GTW)			2a			2b			2c			3 (NEDC)		
		Total	**France**	**Germany**	**Total**	**France**	**Germany**	**Total**	**France**	**Germany**	**Total**	**France**	**Germany**	**Total**	**France**	**Germany**
EV1	Overall energy charged (measurement points 1 & 2) [kWh]	4,361.6	2,329.6	2,032.0	4,124.0	2,167.7	1,956.3	4,100.0	2,156.2	1,943.8	4,079.1	2,143.9	1,935.2	-		
	Overall energy consumed (measurement point 3 / NEDC assumption) [kWh]	-			3,949.5	2,075.5	1,874.0	3,980.6	2,091.2	1,889.4	3,987.3	2,094.8	1,892.6	3,055.6	1,534.3	1,521.3
	Battery efficiency (2x)	-			0.958	0.957	0.958	0.971	0.970	0.972	0.977	0.977	0.978	-		
	Charging efficiency (excl. battery)	-			0.946	0.930	0.963	0.940	0.926	0.957	0.935	0.920	0.952	-		
	Method 1 (GTW) compared to NEDC (incl. charging efficiency)	-												1.32	1.37	1.21
	Consumption ratio including battery efficiency to NEDC	-			1.313	1.374	1.252	1.324	1.385	1.262	1.326	1.387	1.264	-		
EV2	Overall energy charged (measurement points 1 & 2) [kWh]	2,611.1	1,261.8	1,349.3	2,327.4	1,162.3	1,165.1	2,306.6	1,153.0	1,153.7	2,289.6	1,145.6	1,143.9	-		
	Overall energy consumed (measurement point 3 / NEDC assumption) [kWh]	-			2,437.2	1,158.0	1,279.2	2,451.7	1,164.0	1,287.7	2,454.1	1,165.8	1,288.3	1,940.2	896.6	1,043.6
	Battery efficiency (2x)	-			1.047	0.996	1.098	1.063	1.010	1.116	1.072	1.018	1.126	-		
	Charging efficiency (excl. battery)	-			0.891	0.921	0.864	0.883	0.914	0.855	0.877	0.908	0.848	-		
	Method 1 (GTW) compared to NEDC (incl. charging efficiency)	-												1.24	1.30	1.19
	Consumption ratio including battery efficiency to NEDC	-			1.220	1.254	1.190	1.227	1.261	1.198	1.228	1.263	1.199	-		
EV3	Overall energy charged (measurement points 1 & 2) [kWh]	3,222.9	1,591.3	1,631.6	3,070.0	1,519.4	1,550.6	3,046.1	1,508.3	1,537.8	3,027.2	1,500.5	1,526.7		-	-
	Overall energy consumed (measurement point 3 / NEDC assumption) [kWh]	-			2,889.2	1,419.3	1,470.0	2,904.9	1,426.8	1,478.1	2,907.7	1,428.4	1,479.3	2,178.5	1,049.5	1,128.9
	Battery efficiency (2x)	-			0.941	0.934	0.948	0.954	0.946	0.961	0.961	0.952	0.969	-		
	Charging efficiency (excl. battery)	-			0.953	0.955	0.950	0.945	0.948	0.942	0.939	0.943	0.936	-		
	Method 1 (GTW) compared to NEDC (incl. charging efficiency)	-												1.37	1.40	1.34
	Consumption ratio including battery efficiency to NEDC	-			1.359	1.386	1.335	1.367	1.393	1.342	1.368	1.395	1.343	-		
Total	Charging (measurement points 1 & 2) [kWh]	10,195.6	5,182.7	5,012.9	9,521.4	4,849.3	4,672.0	9,452.7	4,817.4	4,635.3	9,395.9	4,790.1	4,605.9	-		
	Consumption (measurement point 3 / NEDC assumption) [kWh]	-			9,275.8	4,652.8	4,623.1	9,337.2	4,682.0	4,655.2	9,349.1	4,689.0	4,660.1	7,174.3	3,480.4	3,693.8
Average	Charging (measurement points 1 & 2) [kWh/km]	0.266	0.278	0.254	0.248	0.261	0.237	0.246	0.259	0.235	0.245	0.257	0.233	-		
	Consumption (measurement point 3 / NEDC assumption) [kWh/km]	-			0.242	0.250	0.234	0.243	0.252	0.236	0.244	0.252	0.236	0.187	0.187	0.187
Average consumption above NDEC	Charging (measurement points 1 & 2)	42.1%	48.9%	35.7%	32.7%	39.3%	26.5%	31.8%	38.4%	25.5%	31.0%	37.6%	24.7%	-		
	Consumption surplus (measurement point 3 / NEDC assumption)	-			29.3%	33.7%	25.2%	30.1%	34.5%	26.0%	30.3%	34.7%	26.2%	0.0%	0.0%	0.0%

Table A3: Overview on CO_2 emission assessment results

		Different assessment methods used to assess the energy charged of the project EV in order to calculate CO_2 emissions of project EV														
		Method (1), measurement point 1			**Method (2a), measurement points 2 & 3**			**Method (2b), measurement points 2 & 3**			**Method (2c), measurement points 2 & 3**			**3 (NEDC)**		
		Total	**F**	**G**	**Total**	**F**	**G**	**Total**	**F**	**G**	**Total**	**F**	**G**	**Total**	**F**	**G**
CO_2 emissions of EV1 [kg]	Charging	1,318.6	138.0	1,180.5	1,265.3	127.6	1,137.7	1,258.2	127.6	1,130.6	1,251.9	126.2	1,125.6	-		
	Consumption	-			1,209.7	121.8	1,087.9	1,219.6	122.7	1,096.8	1,221.7	123.0	1,098.7	973.4	90.4	883.0
Average time-dependent specific CO_2 emissions of EV1 (in g CO_2/km)	Charging	80.7	16.8	145.1	77.4	15.6	139.8	77.0	15.6	139.0	76.6	15.4	138.4	-		
	Consumption	-			74.0	14.8	133.7	74.6	15.0	134.8	74.8	15.0	135.1	59.6	11.0	108.5
CO_2 emissions of EV2 [kg]	Charging	869.2	81.3	788.0	758.9	75.7	683.1	751.7	75.1	676.5	745.6	74.7	670.9	-		
	Consumption	-			814.9	75.5	739.4	820.4	75.9	744.5	820.9	76.0	744.9	662.2	58.7	603.5
Average time-dependent specific CO_2 emissions of EV2 (in g CO_2/km)	Charging	83.8	16.9	141.2	73.1	15.8	122.4	72.4	15.7	121.2	71.9	15.6	120.2	-		
	Consumption	-			78.5	15.7	132.5	79.1	15.8	133.4	79.1	15.9	133.5	63.8	12.2	108.1
CO_2 emissions of EV3 [kg]	Charging	1,021.8	85.5	936.3	973.8	81.9	892.0	966.0	81.3	884.7	959.4	80.9	878.5	-		
	Consumption	-			917.7	76.5	841.1	922.7	77.0	845.7	923.5	77.1	846.4	702.4	56.2	646.2
Average time-dependent specific CO_2 emissions of EV3 (in g CO_2/km)	Charging	87.7	15.2	155.1	83.6	14.6	147.7	82.9	14.5	146.5	82.4	14.4	145.5	-		
	Consumption	-			78.8	13.6	139.3	79.2	13.7	140.1	79.3	13.7	140.2	60.3	10.0	107.0
Total CO_2 emissions [kg]	Charging	3,209.6	304.8	2,904.8	2,998.0	285.2	2,712.8	2,975.9	284.1	2,691.8	2,956.9	281.8	2,675.1	-		
	Consumption	-			2,942.3	273.8	2,668.5	2,962.6	275.6	2,687.0	2,966.0	276.1	2,690.0	2,338.0	205.3	2,132.8
Surplus of CO_2 emissions ompared to calculations based on NEDC [%]	Charging	37.3%	48.5%	36.2%	28.2%	39.0%	27.2%	27.3%	38.4%	26.2%	26.5%	37.3%	25.4%	-		
	Consumption	-			25.8%	33.4%	25.1%	26.7%	34.3%	26.0%	26.9%	34.5%	26.1%	0.0%		
Average time-dependent specific CO_2 emissions (in g CO_2/km)	Charging	83.7	16.4	147.1	78.1	15.3	137.3	77.6	15.3	136.3	77.1	15.1	135.4	-		
	Consumption	-			76.7	14.7	135.1	77.2	14.8	136.0	77.3	14.8	136.2	60.9	11.0	108.0
Surplus of average time-dependent specific CO_2 emissions compared to calculations based on NDEC [%]	Charging	37.3%	48.5%	36.2%	28.2%	39.0%	27.2%	27.3%	38.4%	26.2%	26.5%	37.3%	25.4%	-		
	Consumption	-			25.8%	33.4%	25.1%	26.7%	34.3%	26.0%	26.9%	34.5%	26.1%	0.0%		

References

ADAC, 2015. EcoTest Test- und Bewertungskriterien. Available online at https://www.adac.de/_mmm/pdf/TO27473_118924.pdf, checked on 7/2/2015.

AGEB - AG Energiebilanzen e.V., 2015. Bruttostromerzeugung in Deutschland ab 1990 nach Energieträgern. Available online at http://www.ag-energiebilanzen.de/index.php?article_id=29&fileName=20150227_brd_stromerzeugung1990-2014.pdf, checked on 7/1/2015.

Association of European Border Regions, 2012. Information services for cross-border workers in European border regions. Available online at http://www.aebr.eu/files/publications/121030_Final_Report_EN_clean.pdf, checked on 3/3/2016.

Bickert, S., Kampker, A., Greger, D., 2015. Developments of CO_2-emissions and costs for small electric and combustion engine vehicles in Germany. Transportation Research Part D: Transport and Environment. 36, 138–51. http://dx.doi.org/10.1016/j.trd.2015.02.004.

Campanari, S., Manzolini, G., De la Iglesia, F.G., 2009. Energy Analysis of Electric Vehicles Using Batteries or Fuel Cells through Well-to-Wheel Driving Cycle Simulations. Journal of Power Sources. 186(2), 464–77. http://dx.doi.org/10.1016/j.jpowsour.2008.09.115.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences. Hillsdale: Lawrence Erlbaum Associates..

Chatzikomis, C. I., Spentzas, K. N., Mamalis, A.N., 2014. Environmental and economic effects of widespread introduction of electric vehicles in Greece. European Transport Research Review. 6, 365-376. http://dx.doi.org/10.1007/s12544-014-0137-1.

Donateo, T., Licci, F., D'Elia, A., Colangelo, G., Laforgia, D., Ciancarelli, F., 2015. Evaluation of emissions of CO_2 and air pollutants from electric vehicles in Italian cities. Applied Energy. 157, 675-687. http://dx.doi.org/10.1016/j.apenergy.2014.12.089.

Donateo, T., Ingrosso, F., Licci, F., Laforgia. D., 2014. A method to estimate the environmental impact of an electric city car during six months of testing in an Italian city. Journal of Power Sources. 27, 487–98. http://dx.doi.org/10.1016/j.jpowsour.2014.07.124.

Doucette, T. R., McCulloch, M. D., 2011. Modeling the CO_2 emissions from battery electric vehicles given the power generation mixes of different countries. Energy Policy. 39(2), 803–11. http://dx.doi.org/10.1016/j.enpol.2010.10.054.

Eaves, S., Eaves, J., 2004. A cost comparison of fuel-cell and battery electric vehicles. Journal of Power Sources. 130(1-2), 208–212. http://dx.doi.org/10.1016/j.jpowsour.2003.12.016.

EEX Transparency, 2015. Transparency in Energy Markets. Available online at http://www.eex-transparency.com/homepage, checked on 5/20/2015.

ENTSOE-E, 2014. Statistical Factsheet 2013. Edited by European Network of Transmission System Operators. Available online at https://www.entsoe.eu/Documents/Publications/ENTSO-E%20general%20publications/2013_ENTSO-E_Statistical_Factsheet_Updated_19_May_2014_.pdf, checked on 10/27/15.

ERDF – Électricité Réseau Distribution France, 2009. La compensation des Pertes à ERDF. Available online at http://gtpe.cre.fr/media/documents/presentation_pertes_ERDF_PONS.pdf, checked on 3/3/2016.

Faria, R., Marques, P., Moura, P., Freire, F., Delgado, J., de Almeida, A. T., 2013. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renewable and Sustainable Energy Reviews. 24, 271–87. http://dx.doi.org/10.1016/j.rser.2013.03.063.

Hacker, F., Harthan, R., Matthes, F., Zimmer, W., 2009. Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe. ETC/ACC Technical Paper 2009/4. Available online at https://fenix.tecnico.ulisboa.pt/downloadFile/3779573930397/ETCACC_TP_2009_4_electromobility.pdf, checked on 10/27/15.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., Strømman, A. H., 2013. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology. 17(1), 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x.

Icha, P., 2014. Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2013. Edited by Umweltbundesamt. Dessau-Roßlau. Available online at http://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/climate_change_23_2014_komplett.pdf, checked on 5/20/2015.

IEA – International Energy Agency, 2015. CO_2 Emissions from Fuel Combustion 2015 Edition. http://dx.doi.org/10.1787/co2-data-en.

INSEE – Institut national de la statistique et des études économiques, 2009. Les déplacements domicile-travail en 2009 : résultats nationaux. Available online at http://www.insee.fr/fr/themes/document.asp?reg_id=99&ref_id=rp2009ddt&file=rp2009ddt_nat.xml, checked on 4/8/16.

INSEE – Institut national de la statistique et des études économiques, 2014. Production brute et consommation d'électricité en 2014. Available online at http://www.insee.fr/fr/themes/tableau.asp?reg_id=0&ref_id=NATTEF11360, checked on 3/12/16.

Jochem, P., Babrowski, S., Fichtner, W., 2015a. Assessing CO_2 emissions of electric vehicles in Germany in 2030. Transportation Research Part A 78, p. 68-83. http://dx.doi.org/10.1016/j.tra.2015.05.007.

Jochem, P., Doll, C., Fichtner, W., 2015b. External Costs of Electric Vehicles, Transportation Research Part D: Transport and Environment, https://doi.org/10.1016/j.trd.2015.09.022.

Kaschub, T., Jochem, P., Fichtner, W., 2011. Integration von Elektrofahrzeugen und Erneuerbaren Energien ins Elektrizitätsnetz - eine modellbasierte regionale Systemanalyse . 7. Internationale Energiewirtschaftstagung (IEWT'11), Wien, Österreich. Available online at http://eeg.tuwien.ac.at/eeg.tuwien.ac.at_pages/events/iewt/iewt2011/uploads/fullpaper_iewt2011/P_276_Kaschub_Thomas_31-Jan-2011,_19:11.pdf, checked on 06/13/16.

Kaschub, T., Jochem, P., Fichtner, W., 2013. Interdependencies of Home Energy Storage between Electric Vehicle and Stationary Battery. World Electric Vehicle Journal, 6 (4), 1144-1150. ISSN: 2032-6653.

Ketelaer, T., Kaschub, T., Jochem, P., Fichtner, W., 2014. The potential of carbon dioxide emission reductions in German commercial transport by electric vehicles . International Journal of Environmental Science and Technology, 11 (8), 2169-2184. http://dx.doi.org/10.1007/s13762-014-0631-y.

Koch, N., Fuss, S., Grosjean, G., Edenhofer, O., 2014. Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything?—New evidence. Energy Policy, 73, 676-685. http://dx.doi.org/10.1016/j.enpol.2014.06.024.

Lane, B., Potter, S., 2007. The adoption of cleaner vehicles in the UK: exploring the consumer attitude–action gap. Journal of Cleaner Production. 15(11-12), 1085–1092. http://dx.doi.org/10.1016/j.jclepro.2006.05.026.

Levene, H. (1960). Robust tests for equality of variances. In Olkin et al. Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling. Stanford University Press. pp. 278–292.

Ma, H., Balthasar, F., Tait, N., Riera-Palou, A., Harrison, A., 2012. A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. Energy Policy. 44, 160–73. http://dx.doi.org/10.1016/j.enpol.2012.01.034.

McCarthy, R., Yang, C., 2010. Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: Impacts on vehicle greenhouse gas emissions. Journal of Power Sources. 195(7), 2099–2109. http://dx.doi.org/10.1016/j.jpowsour.2009.10.024.

Muneer, T., Milligan, R., Smith, I., Doyle, A., Pozuelo, M., Knez, M., 2015. Energetic, environmental and economic performance of electric vehicles: Experimental Evaluation. Transportation Research Part D: Transport and Environment. 35, 40–61. http://dx.doi.org/10.1016/j.trd.2014.11.015.

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., Van Mierlo, J., 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment?. Int J Life Cycle Assess. 19(11), 1866-1890. http://dx.doi.org/10.1007/s11367-014-0788-0.

Rangaraju, S., De Vroey, L., Messagie, M., Mertens, J., Van Mierlo, J., 2015. Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: A Belgian case study. Applied Energy. 148, 496–505.

Rezvani, Z., Jansson, J., Bodin, J., 2015. Advances in consumer electric vehicle adoption research: A review and research agenda. In Transportation Research Part D: Transport and Environment. 34, 122–136. http://dx.doi.org/10.1016/j.trd.2014.10.010.

Robinson, A.P., Blythe, P. T., Bell, M. C., Hübner, Y., Hill, G. A., 2013. Analysis of electric vehicle driver recharging demand profiles and subsequent impacts on the carbon content of electric vehicle trips. Energy Policy. 61, 337–48. http://dx.doi.org/10.1016/j.enpol.2013.05.074.

RTE – Réseau de Transport d’électricité, 2016. Pertes sur le Réseau Public de Transport. Available online at http://clients.rte-france.com/lang/fr/clients_producteurs/vie/vie_perte_RPT.jsp, checked on 3/3/2016.

RTE – Réseau de Transport d'électricité, 2015. CO2 Emissions per kWh of Electricity Generated in France. Available online at http://www.rte-france.com/en/eco2mix/eco2mix-co2-en and http://www.rte-france.com/fr/eco2mix/eco2mix-co2, checked on 9/18/2015.

RTE – Réseau de Transport d'électricité, 2014. Bilan électrique 2013. Available online at http://www.rte-france.com/sites/default/files/bilan_electrique_2013_3.pdf, checked on 7/1/2015.

Sharma, R., Manzie, C., Bessede, M., Crawford, R.H., Brear, M.J., 2012. Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: Life cycle CO2-e emissions. 28, 63–73. http://dx.doi.org/10.1016/j.trc.2012.12.011.

Stella, K., Wollersheim, O., Fichtner, W., Jochem, P., Schücking, M., Nastold, M., Ensslen, A., Wietschel, M., Held, M., Gnann, T., Friedmann, M., Graf, R., Wohlfarth, K., 2015. Über 300.000 Kilometer unter Strom : Physikalisch-technische, ökonomische, ökologische und sozialwissenschaftliche Begleitforschung des Schaufensterprojektes RheinMobil: Grenzüberschreitende, perspektivisch wirtschaftliche elektrische Pendler- und Dienstwagenverkehre im deutsch-französischen Kontext. Karlsruhe. http://dx.doi.org/10.5445/IR/1000048691.

Student, 1908. The Probable Error of a Mean. Biometrika 6(1), p. 1–25. https://dx.doi.org/10.1093%2Fbiomet%2F6.1.1

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy. 34(15), 6005–20. http://dx.doi.org/10.1016/j.ijhydene.2009.06.003.

Tomić, J., Kempton, W., 2007. Using fleets of electric-drive vehicles for grid support. Journal of Power Sources. 168(2), 459–468. http://dx.doi.org/10.1016/j.jpowsour.2007.03.010

UNECE, 2005. E/ECE/TRANS/505 Rev.2/Add.100/Rev.2 page 60 Annex 7 2.4.3. Available online at http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r101r2e.pdf, checked on 18/9/2015.

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renewable and Sustainable Energy Reviews. 28, 555–565. http://dx.doi.org/10.1016/j.rser.2013.08.013

UBA – German Federal Environment Agency, 2016. Strom- und Wärmeversorgung in Zahlen. Available online at https://www.umweltbundesamt.de/themen/klima-energie/energieversorgung/strom-waermeversorgung-in-zahlen, checked on 11/06/2016.

Van Vliet, O., Brouwer, A. S., Kuramochi, T., van den Broek, M., Faaij, A., 2011. Energy use, cost and CO_2 emissions of electric cars. Journal of Power Sources. 196(4), 2298–2310. http://dx.doi.org/10.1016/j.jpowsour.2010.09.119.

Wingerter, C., 2014. Berufspendler: Infrastruktur wichtiger als Benzinpreis. STATmagazin: Arbeitsmarkt, 5/2014. Available online at https://www.destatis.de/DE/Publikationen/STATmagazin/Arbeitsmarkt/2014_05/2014_05PDF.pdf?__blob=publicationFile, checked on 04/08/2015.