# Assessing CO2 Emissions of Electric Vehicles in Germany in 2030

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# Assessing $CO_2$ emissions of electric vehicles in Germany in 2030

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ABSTRACT

Electric vehicles are often said to reduce carbon dioxide ($CO_2$) emissions. However, the results of current comparisons with conventional vehicles are not always in favor of electric vehicles. We outline that this is not only due to the different assumptions in the time of charging and the country-specific electricity generation mix, but also due to the applied assessment method. We, therefore, discuss four assessment methods (average annual electricity mix, average time-dependent electricity mix, marginal electricity mix, and balancing zero emissions) and analyze the corresponding $CO_2$ emissions for Germany in 2030 using an optimizing energy system model (PERSEUS-NET-TS). Furthermore, we distinguish between an uncontrolled (i.e. direct) charging and an optimized controlled charging strategy. For Germany, the different assessment methods lead to substantial discrepancies in $CO_2$ emissions for 2030 ranging from no emissions to about 0.55 kg/kWh$_{el}$ (110 g/km). These emissions partly exceed the emissions from internal combustion engine vehicles. Furthermore, depending on the underlying power plant portfolio and the controlling objective, controlled charging might help to reduce $CO_2$ emissions and relieve the electricity grid. We therefore recommend to support controlled charging, to develop consistent methodologies to address key factors affecting $CO_2$ emissions by electric vehicles, and to implement efficient policy instruments which guarantee emission free mobility with electric vehicles agreed upon by researchers and policy makers.



## 1. Introduction

Climate change and the necessity to reduce anthropogenic greenhouse gas (GHG) emissions are widely acknowledged. On the European level, all sectors except for the transport sector have already reduced their emissions compared to the levels of 1990. The transport sector having a share of about 20% in total emissions on the global (IEA, 2012b) and European (Eurostat, 2013) scales is still increasing its greenhouse gas emissions, which consist mainly of $CO_2$ emissions (Eurostat, 2013). After the adoption of several less successful political instruments, the European Commission introduced the European Regulation No. 443/2009 and 333/2014 on Emission Standards of Light-duty Vehicles in order to reduce specific $CO_2$ emissions in road passenger transport. For vehicle manufacturers, the ambitious target of 95 g $CO_2$ emissions per kilometer for the whole new vehicle fleet of passenger vehicles (M1 vehicle segment) in 2020 has been defined. In order to meet the reduction target for GHG emissions from transport in 2050 of at least −60% compared to 1990 values (EC, 2011), the specific target in 2030 should amount to about 70 g $CO_2$ per km. This requires a significant increase in emission reduction efforts for the

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new vehicle fleet. During the last 10 years, specific emissions of newly registered vehicles in the EU-15 states were reduced by 2.4% per year on the average. In 2012, the specific emissions of newly registered conventional passenger cars in the European Union (EU-27) were 132.2 g $CO_2$/km (EEA, 2013). In order to reach the targets defined, annual reduction must be increased to about 6% per year from 2016 until 2020. The standard is binding for manufacturers. Otherwise, they have to pay penalties of 95 € per each exceeding gram and sold car. In countries with a saturated car market and vehicle density is rather constant (e.g. Germany), this measure is quite successful. In other markets, where the motorization rate is still increasing (mainly in Eastern Europe), the overall $CO_2$ emissions in transport are still rising. An attractive leverage for the automotive industry to reduce the specific emissions seems to be the increase of battery electric vehicle (BEV) sales. According to the European regulation, BEV are considered zero-emission vehicles (0 g $CO_2$/km). In the beginning, each BEV counted for 3.5 (until 2013)[1] vehicles in the fleet. In reality, however, the hypothesis that "BEV are an efficient means to significantly reduce greenhouse gases" is subject to three uncertainties. (1) The market penetration is unclear; (2) the underlying actual energy mix used to generate electricity for the charging process strongly influences the specific $CO_2$ emissions per km; and (3) the additional electricity demand could lead to new bottlenecks in the electricity grid, thus causing an additional need for investments which might lead to additional emissions. Our paper focuses on the second uncertainty relating to electricity generation.

Many analyses have already been issued on measuring the environmental impact of BEV (cf. Hacker et al., 2009). They started in the 1980s (e.g. Hamilton, 1980; DeLuchi et al., 1989) and increased considerably in recent years. All of them usually analyze electricity generation on a highly aggregated level (e.g. Torchio and Santarelli, 2010; Anable et al., 2012; Bickert and Kuckshinrichs, 2011; Thomas, 2012; Thiel et al., 2014; Brand et al., 2013; Millo et al., 2014; van Vliet et al., 2011; Hackney and de Neufville, 2001; Zhang et al., 2013). Another focus is on the comparison of internal combustion engine vehicles (ICEV) and BEV based on a lifecycle analysis (Hawkins et al., 2012a, 2012b; Messagie et al., 2010; Lane, 2006; Lucas et al., 2012; Ma et al., 2012). For Germany, e.g. Helms et al. (2013), Zimmer et al. (2011), and Peters et al. (2012) provided first analyses. However, a concrete analysis of the electricity generation needed to satisfy the additional electricity demand from BEV and a comparison of different assessment approaches have been lacking so far.

The national power plant portfolio and, hence, the specific power plants used to generate electricity for the BEV charging process are relevant to determining the corresponding $CO_2$ emissions of electric mileage. This is rather challenging, as the electricity in the grid always is a mix from different power plants. Direct allocation of electricity is hardly possible.

In order to assess the corresponding time-dependent $CO_2$ emissions appropriately and allocate them precisely to BEV usage, four different assessment approaches are presented in the following (cf. Section 2.2): (1) the annual average electricity mix, (2) the time-dependent average electricity mix, (3) the marginal electricity mix, or (4) balancing with other $CO_2$ emission reductions in order to achieve zero $CO_2$ emissions per kWh. Whereas the assessment of the average mixes (1 and 2) is straightforward, marginal electricity generation (3) can either be determined by considering the marginal power plant in the electricity market (i.e. Merit Order) or by running an energy system model once with and another time without the "extra" electricity demand for BEV (cf. Hadley and Tsvetkova, 2009; Jochem et al., 2013). Our analysis of these four assessment methods is based on the example of Germany, as it has rather high specific $CO_2$ emissions per kWh – which are strongly fluctuating due to a high share (about 13%) of wind and photovoltaic electricity generation (BMWi, 2014). In hours with a high market share of fossil fuels the specific $CO_2$ emissions amounts to about 800 g per kWh and in windy hours with a high sun radiation the value decreases to about 100 g per kWh. The low specific emissions from electricity generated from renewable energy sources (RES) (Weisser, 2007) are neglected for the following analyses. With the help of the energy model PERSEUS-NET-TS, we analyze the $CO_2$ emissions caused by this additional demand based on the four assessment methods. PERSEUS-NET-TS is a dispatch and investment model based on linear optimization (Eßer-Frey, 2012; Babrowski et al., 2014b). Driven by the exogenously given electricity demand, the model minimizes the system-relevant expenditures. The electricity needed at a certain point of time can either be generated in existing generation units or in newly commissioned ones. Additionally, we evaluate 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. Technical feasibility of controlled charging is subject to the ISO 15118 standard and is already implemented for most BEV. The concept guarantees stability of the future electricity grid with a high share of BEV (Hahn et al., 2013; Babrowski et al., 2014a). The PERSEUS-NET-TS model considers this by a flexible charging strategy for all BEV in terms of charging time (according to the empiric mobility patterns) and charging power. The corresponding results provide further details about the main factors ensuring a sustainable mobility in the future.

The paper is structured as follows: First, we focus on market penetration and characteristics of BEV (Section 2). Then, we develop four different approaches to assessing $CO_2$ emissions from BEV (Section 3.1) before we introduce the PERSEUS-NET-TS model and implement the additional BEV load and the changes needed to depict a controlled charging strategy (Section 3.2). Subsequently, we use the PERSEUS-NET-TS model to evaluate the different approaches to assessing $CO_2$ emissions by BEV (Section 4). Finally, we discuss our results in the context of the European emission target and give a conclusion (Sections 5 and 6).

[1] In 2014, the factor declines to 2.5, in 2015 to 1.5 and in 2016 and beyond, the factor equals 1.

## 2. Electric vehicles

### 2.1. Market penetration of electric vehicles

Even though the BEV was invented about the same time as the ICEV and it appeared to be rather successful at first (Abt, 1998), its market share remained zero during the last decades. Only recently the registrations of BEV increased significantly (IEA, 2013). In addition to the political pressure to reduce $CO_2$ emissions and find alternatives for limited fuels, the fast technological development in the area of batteries contributed to this recent development. Worldwide sales of BEV almost doubled in 2012 – in some countries, the increase was much higher, but still at a very low level. With market shares of 1–5‰ in almost all industrial countries (IEA, 2013), BEV are still lagging behind the high expectations (i.e. the ambitious political targets, IEA, 2011) and the medium-term national goals for 2020 and 2030. Only in countries with substantial subsidies does a first breakthrough become visible (e.g. Røstvik, 2013). A prognosis of the market penetration of BEV in the coming years seems to be difficult, since the market success of BEV depends on the 'unpredictable' customer acceptance and other developments (e.g. Axsen et al., 2013). Hence, even extremely diverging scenarios cannot be disproved today. Suggested values of market shares range from negligible to larger two-digit percentages (cf. Kay et al., 2013).

Due to the currently low market penetration of BEV, their impact on the energy system is marginal and their $CO_2$ emissions are negligible. Therefore, we analyze the market in 2030 with 6 million electric vehicles (EV) (15% market share), which is the target defined by the German government (German Federal Government, 2011) and which seems to be a viable number for 2030 (Kay et al., 2013). Based on an average yearly mileage of 12,000 km (German Mobility Panel, 2013) and an empiric average gross fuel efficiency of 20 kWh/100 km (cf. van Vliet et al., 2011; Thiel et al., 2010; Plötz et al., 2014; Metz and Doetsch, 2012; Liu, 2012; Smith, 2010) the resulting additional electricity demand from EV will be about 14.4 TWh (3% of national electricity demand). In this context EV are defined in the following as all EV with a plug (sometimes also abbreviated by PEV), i.e. BEV, plug-in hybrid electric vehicles (PHEV) as well as range-extended electric vehicles (REEV). Hybrid electric vehicles (HEV) without or with a marginal purely electric driving range only or fuel cell electric vehicles are neglected here.

The mobility patterns of German car users over an exemplary weekday are unevenly distributed. Most cars are parking for more than 90% of the day and during rush-hour in the morning and in the evening we observe a peak of about 10% of mobile passenger cars (German Mobility Panel, 2013). We, therefore, assume most charging events to be observed after these peaks if a charging station is available at the destination. This daytime and vehicle specific information on parking location, daily mileage as well as parking and driving time is taken from the Mobility in Germany study on mobility patterns (BMVBS, 2008) and spatially integrated in our assessment model below (cf. Section 3.2). This allows us to consistently examine the $CO_2$ emissions from the German energy system in 2030 induced by EV. For the market penetration over time we assume in our model, that in 2020 the target of one million EV by the German government is not reached (cf. Plötz et al., 2014). We assume half a million EV for 2020 (1.2 TWh additional demand by 2020) instead and interpolated 2025 accordingly (about 7 TWh). We consider regional differences in EV market penetration according to the local residential structure and the number of registered vehicles based on Heinrichs (2013).

### 2.2. Electric vehicle charging strategies

Electricity generation has to match electricity demand at all times. Traditionally, this means that a certain electricity demand is given for each hour and that the generation has to be adjusted accordingly. However, increasing integration of volatile electricity generation by RES, such as wind and solar energy, has changed this situation. Supply does not always follow the demand anymore. Instead, storage systems and demand response measures are needed to increase the flexibility of demand. Controlled charging of EV is such a demand response measure. Through a controlled charging strategy, the additional EV demand can be shifted to times when load is low or electricity generation by RES is high. With uncontrolled charging, this is not possible. The electricity has to be charged according to a fixed charging curve, leading to commissioning of additional generation capacity to satisfy the demand.

From an energy economic point of view, the point in time of the charging process has a significant impact on the system and on the corresponding $CO_2$ emissions. Different charging strategies lead to significant differences in the corresponding load curves (electricity demand over time) of EV (cf. Zhang et al., 2011; Babrowski et al., 2014a). Three different charging strategies are distinguished:

- Unidirectional uncontrolled charging: The charging process begins right after connecting the vehicle to the grid.
- Unidirectional controlled charging: The charging process can be postponed (and the load might be adjusted) by a local or global entity in order to improve the condition of the underlying energy system. This strategy equals the control of night storage heaters in Germany via a grid signal by the distribution grid operators.
- Bidirectional controlled charging: The charging process can be controlled within given limits, including the possibility to feed electricity from the EV back into the grid (the so-called vehicle-to-grid – V2G – approach), where EV can be aggregated to virtual power plants (cf. Hahn et al., 2013).

In the beginning when the market penetration of EV is low, the uncontrolled charging strategy seems to be adequate. With an increasing market share, the controlled charging strategy becomes more appropriate from an energy economic perspective. In electricity markets with a high share of volatile RES (i.e. wind and solar energy) or due to local restrictions, even the V2G approach seems to be eligible in the far future (e.g. Lund and Kempton, 2008). In principle, the controlled charging approaches might support the energy sector in reducing pollutants. At the local level, this has already been demonstrated by an increase in the share of direct electricity consumption in private households (e.g. by photovoltaic (Kaschub et al., 2013) or combined heat and power (CHP) generation (Jochem et al., 2015)). At the national level, especially V2G seems to improve the potential of RES integration (Lund and Kempton, 2008). Due to increasing charging cycles, however, battery degradation is accelerated (Hoke et al., 2011) and the acceptance of V2G by vehicle users might be reduced. The predicted longer lifetime of batteries in the future might overcome these concerns and will provide a high load shifting potential for private households, which is mainly based on the high degrees of freedom for the charging process: Adding an EV (with average mileage) to an average German private household increases the load peak considerably and more or less doubles its energy demand (Jochem et al., 2012). The degree of freedom for load shifts between the arrival of the EV and its departure is tremendous: Many current EV can charge at 11 kW and have an average parking time at home of about 13 h per night (German Mobility Panel, 2013). With an average mileage per day of about 40 km and the specific average electricity consumption of about 0.2 kWh/km, however, only about 8 kWh have to be charged per night. At 11 kW, an average charging time of only approx. 45 min results within these 13 h (or longer charging at lower charging rate). Without an EV, the load shift potential of a private household is limited to some appliances (e.g. washing machine, refrigerator, dishwasher, etc.), if they were controlled automatically. Those appliances could optimally lead to a shiftable load of up to 2 kW for some minutes with a corresponding energy content of up to 2 kWh per night (cf. Paetz et al., 2013).

However, the high power compared to a usual household load curve and the high simultaneousness of arrival times in the evening hours (German Mobility Panel, 2013) for home charging may have a severe impact on some grid regions (e.g. Waraich et al., 2013). These challenges are similar to those induced by photovoltaic systems – with reciprocal current flows, however. The usual peak for an average German household is somewhat below 3 kW. A demand for more than 20 kW is very seldom – even though the maximum technical connection power for a detached house generally is above 43 kW. Exceptions are households with electric night-storage heaters, which also have a high simultaneousness and a high peak demand in accordance with the night tariff (RWI and Forsa, 2011).

Hereinafter, only the unidirectional uncontrolled and controlled charging strategies are analyzed, as the V2G strategy requires additional technology, which currently seems to be unprofitable on the German electricity market (Dallinger et al., 2011). For controlled charging, the scheduling only refers to the optimization of the power plant fleet and the transmission grid and neglects shortages in the distribution grids, which might be significant (Green et al., 2011; Pollok et al., 2011; Waraich et al., 2013).

## 3. Methodology

### 3.1. Assessing $CO_2$ emissions from electric vehicles

There has not yet been any broadly accepted approach for assessing the $CO_2$ emissions from power plants which are caused by the additional electricity demand from EV during their usage phase. For a comprehensive evaluation, the whole electricity generation system should be considered. In the following section, four different assessment approaches are defined:

1. *Annual average mix:* A straightforward method is to assess the emissions based on the national annual average electricity mix. This means that the emissions caused to satisfy the total demand are divided by the total demand in order to obtain the grams of $CO_2$ emitted to generate one kWh of electricity. Subsequently, this figure is multiplied by the annual electricity demand from EV to calculate the emissions caused by EV.
2. *Time-dependent average mix:* In contrast to the annual average mix, the time-dependent average mix takes into consideration how much energy is charged at a certain hour. In case of the uncontrolled charging strategy, for example, the EV load peaks in the evening when people return home, while at night time most charging processes have already been completed. Consequently, the weighting of the electricity mix in the evening hours exceeds that of the electricity mix of the night hours when using the time-dependent average mix.
3. *Marginal electricity mix:* The additional electricity demand of EV inevitably leads to an increase in electricity generation. By comparing electricity generation with that additional demand for electricity and without that additional demand, the marginal electricity mix can be determined (ex-post by spatial market data or ex-ante by energy system models). This marginal electricity mix is based on different power plants with different specific emission factors. These factors are again multiplied by the annual electricity demand from EV.
4. *Balancing zero emissions:* When a political measure leads to a reduction of emissions in the same order of magnitude than the induced EV emissions in another sector, it might be argued that the additional electricity demand of EV does not induce any additional $CO_2$ emission. This argument is currently used in Europe with respect to the existing Emission Trading System (EU ETS) cap for GHG emissions in the electricity sector. As the cap for the European electricity generation

is constant and was settled before EV have been identified to become a potential market success and therefore refers only to the conventional electricity demand, we might argue that the additional electricity demand by EV can be interpreted to be $CO_2$ emission-free. Hence, the increase in $CO_2$ emissions through the charging process has to be reduced somewhere else within the EU ETS. In the future, however, when the EV's additional electricity demand might be considered in political discussions of the EU ETS cap for the fourth EU ETS trading period after 2020, this argument will fail. Due to flexible mechanisms within the EU ETS and the Kyoto protocol, in-depth investigations will be required.

All four approaches might lead to different results concerning the $CO_2$ emissions of EV. This is especially true for countries with a power plant portfolio having heterogeneous specific $CO_2$ efficiencies. In order to evaluate the differences of the approaches, we calculate (in Section 4) the $CO_2$ emissions of EV in Germany for 2030 based on the annual average mix, the time-dependent average mix, and the marginal mix. For the calculation, we use the PERSEUS-NET-TS model that will be explained in the next section.

### 3.2. The PERSEUS-NET-TS energy system model

The following section describes the PERSEUS-NET-TS model. Due to the complex nature of the model only the target function and the most important restrictions will be discussed. A more detailed explanation of the model is given in Babrowski et al. (in press).

#### 3.2.1. General description

The PERSEUS-NET-TS energy system model (Babrowski et al., 2014b) is an optimizing bottom-up model of the German electricity system. The model minimizes the system-relevant expenditures needed to satisfy the exogenously given electricity demand. It is part of the PERSEUS (Program package for Emission Reduction Strategies in Energy Use and Supply) model family (Rosen, 2008; Fichtner, 1999) and a myopic version of PERSEUS-NET (Eßer-Frey, 2012). The model is written in GAMS and uses the CPLEX solver for its linear optimization. It includes a nodal pricing approach based on a direct current (DC) approximation of the active power flows in the transmission network. Most (over 500) 360 kV and 220 kV lines of the transmission network are modeled according to the current expansion plans with their specific capacities and limits (UCTE, 2008; BMJ, 2009; BNA, 2012b). Additionally, 440 administrative districts (Kreise) are modeled with their specific power plants (BNA, 2012a) and electricity demand (cf. Eßer-Frey, 2012). While bigger 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.

With a time frame until 2030, PERSEUS-NET-TS calculates the redevelopment plans for coal, lignite, and gas power plants throughout Germany. At the same time, the power plant dispatch of the resulting generation system is calculated for the considered time structure of each period ($t \in T$). Taking 2012 as the base year, at least every fifth year is calculated until 2030 as one period. Furthermore, each year is represented by the hourly mapping of three days of a type (a weekday, Saturday and Sunday) per season. Thus, 288 h ($s \in S$) are considered for each year. The driving force of the model is the exogenously given hourly electricity demand at each grid node, which has to be satisfied while minimizing the global expenditures of each period. This can either be done by electricity generation of power plants specifically assigned to that grid node or by electricity transport to the grid node from neighboring grid nodes. If there is not enough generation capacity available, new thermal capacities can be commissioned.

The expenditures in the objective function (cf. Eq. (1)) are composed of three parts. Firstly, costs related to energy carriers ($ec \in EC$), such as coal, lignite, natural gas, or biomass, are considered. These mainly consist of fuel supply costs, which are depicted as energy carrier flows ($FL_{imp,prod',ec,t,s}$) from outside of the system boundaries ($imp \in IMP$) to the grid nodes ($prod \in PROD$) multiplied by the specific delivery costs ($Cfuel_{imp,prod',ec}$) in which possible $CO_2$ costs are already included. Secondly, costs related to the electricity generation processes ($proc \in GENPROC$), i.e. variable costs ($Cvar_{proc,t}$) of the electricity generation ($PS_{proc,t,s}$). Additionally, load variation costs are included for thermal generation processes, such as lignite, coal, and combined cycle plants ($Cloadchange_{proc,s-1,s,t}$). Thirdly, costs related to the provision of generation units ($unit \in UNIT$) are determined. Fixed costs ($Cap_{unit,t} * Cfix_{unit,t}$) for all generation units are considered as well as investments in new power plants ($NewCap_{unit,t} \cdot Cinv_{unit,t}$).

$$\min \left[ \sum_{s \in S} \sum_{imp \in IMP} \sum_{ec \in EC} \sum_{prod \in PROD} (FL_{imp,prod,ec,t,s} \cdot Cfuel_{imp,prod,ec}) + \sum_{s \in S} \sum_{proc \in GENPROC} (PS_{proc,t,s} \cdot Cvar_{proc,t} + (Cloadchange_{proc,s-1,s,t})) \right.$$
$$\left. + \sum_{unit \in UNIT} ((Cap_{unit,t} \cdot Cfix_{unit,t}) + (NewCap_{unit,t} \cdot Cinv_{unit,t})) \right] \forall t \in T \subset \{2012, 2015, 2020, 2025, 2030, 2035, 2040\} \quad (1)$$

The exogenously given demand at each grid node is based on a calculation by Eßer-Frey (2012) and mainly takes into account the regional GDP and forecasts of the population growth. The electricity ($electr \in EC$) demand at each grid node for each considered hour is depicted as an electricity flow ($FL_{prod,exp,electr,t,s}$) leaving the system ($exp \in EXP$).

The model balances the material and energy flows for each grid node in each period and time slot. Imports from outside of the system ($FL_{imp,prod,ec,t,s}$) or neighboring grid nodes ($FL_{prod',prod,ec,t,s}$) plus the generation ($PS_{proc,t,s} \cdot \lambda_{proc,ec}$) through processes

(*GENPROC*) corresponding to the grid node equal the outflows ($FL_{prod,exp,ec,t,s}$, $FL_{prod,prod',ec,t,s}$) and use ($PS_{proc,t,s} * \lambda_{proc,ec}$) in demand processes (*DEMPROC*) of this grid node. Here, $\lambda_{proc,ec}$ stands for the share of a certain energy carrier in the total input of the considered process. The efficiencies of the flows and the use process ($\eta_{prod,exp,ec,t}$, $\eta_{prod,prod',ec,t}$, $\eta_{prod,ec}$) are also considered. While energy carriers such as coal, lignite, natural gas or oil can be imported from outside of the system, this is not possible for electricity. Electricity has to be generated with the considered German generation units.

$$\sum_{imp \in IMP} FL_{imp,prod,ec,t,s} + \sum_{prod' \in PROD} FL_{prod',prod,ec,t,s} + \sum_{proc \in GENPROC} PS_{proc,t,s} \cdot \lambda_{proc,ec} = \sum_{exp \in EXP} \frac{FL_{prod,exp,ec,t,s}}{\eta_{prod,exp,ec,t}} + \sum_{prod' \in PROD} \frac{FL_{prod,prod',ec,t,s}}{\eta_{prod,prod',ec,t}} + \sum_{proc \in DEMPROC} PS_{proc,t,s} \cdot \frac{\lambda_{proc,ec}}{\eta_{prod,ec}} \quad \forall t \in T;\ \forall s \in S;\ \forall prod \in PROD;\ \forall ec \in EC \tag{2}$$

The power flow between grid nodes is subject to the restrictions of the DC approach of the German transmission network. If there is no sufficient transmission capacity between certain grid nodes, there might be a surplus of generated electricity on one side of the bottleneck and a shortage on the other side, leading to the use of more expensive plants and, thus, to different nodal prices. Consequently, the nodal prices also give endogenous incentives for the allocation of newly commissioned capacities. If it is not possible or efficient to generate the electricity needed in the existing generation units, new generation units may be endogenously commissioned. While the possibility of commissioning new gas plants is given for every grid node, options for new lignite and coal plants are restricted to grid nodes at which such plants exist today already. Other allocations are unlikely due to acceptance issues or the lack of water for cooling. The economic and technological parameters of the new extension options are based on the German pilot study (BMU, 2011) (please see Table A.1 in the Appendix A). Power plants are automatically decommissioned 40 years after they are built. Electricity generation in the power plants at each considered hour is restricted by the installed capacity and unit availability. Additionally, the generation is limited by the maximum full-load hours per year as well as by the maximum available power (Eßer-Frey, 2012). Furthermore, load variation costs are considered for thermal units, such as uranium, coal or combined-cycle plants. Restrictions concerning reserve capacity, electricity storage systems, and the feed-in of electricity generated from RES complete the optimization model.

The development of power plants using RES at each grid node is given. The reason is that these plants are constructed neither due to economic reasons alone, nor because of a strategically good allocation in terms of the electricity demand, but rather because of regulations, politics, and regional potentials. Based on the development sketched in the German pilot study 2011 (BMU, 2011), the distribution of generating capacity is calculated considering regional potentials (Eßer-Frey, 2012). In the model version developed for this analysis, electricity generation from RES is in accordance with historical feed-in curves given by Tennet (2011) and can be reduced in case of a surplus or bottleneck.

Fuel costs for thermal units as well as $CO_2$ certificate prices are based on the World Energy Outlook 2012 (IEA, 2012a) (please see Table A.2 in the Appendix A). Regarding the development of conventional demand, a slight decline to 493 TWh (506 TWh) in 2030 (2020) is assumed (Eßer-Frey, 2012) (please see Table A.3 in the Appendix A).

### *3.2.2. Integration of the additional electricity demand from EV*

To determine the additional $CO_2$ emissions resulting from EV, the time-dependent additional electricity used by EV (*EVuse*) has to be incorporated in the PERSEUS-NET-TS structure. For the case of an uncontrolled charging, no separate equation is needed. The additional electricity demand is fixed for each considered hour. It is set as an export flow ($FL_{prod,exp,EVuse,t,s}$) and subsequently balanced (using Eq. (2)). In that case, charging follows a charging curve that has been determined by evaluating trip data of a German mobility study MID (BMVBS et al., 2008). It is assumed that EV can either be charged at home or at the workplace and that they are charged as soon as possible with full power. The starting and ending time of the trips are considered as well as the trip length and purpose (Babrowski et al., 2014a). On a working day, the resulting charging curve is determined by the trips to and from work. There is a morning peak at around 8 a.m. when about 8% of the daily electricity demand from EV is charged and an evening peak at around 6 p.m. with about 10% of the total daily electricity demand from EV (cf. Fig. 1). On the weekend days a peak occurs around noon (about 9% of the daily electricity demand from EV). These charging curves have been extracted by Babrowski et al. (2014a) and are scaled to one. Subsequently they are multiplied with the daily electricity demand from EV to obtain the load at each considered hour. According the mobility data we assume that the overall driving distances and thus the daily electricity demand from EV is the same for a working and a weekend day.

For controlled charging, on the other hand, further adjustments are needed. The electricity needed can be shifted within limits throughout the day (Eq. (3)). The electricity for EV required in a given time slot ($PS_{proc,t,s}$) has to be between a lower and an upper limit (cf. Fig. 2). The lower limit is based on the assumption that at least 10% of the drivers start charging directly after arrival, because their daily trip length exceeds the maximum distance that can be traveled with one battery charge (100 km/day). Due to acceptance issues, this lower limit might even be too low and more likely is a technical limitation rather than a realistic one (Franke et al., 2012). The upper limit is also extracted from the MID data and considers the availability of vehicles at a charging station at each hour ($EVupper_s$). As during night time almost all cars are parked at home, all EV with drivers willing to allow an automatic delay in charging may be charged (90%). This share is multiplied by the daily electricity demand of EV ($D_{prod,EVuse,t,day}$) to obtain the absolute upper limit.

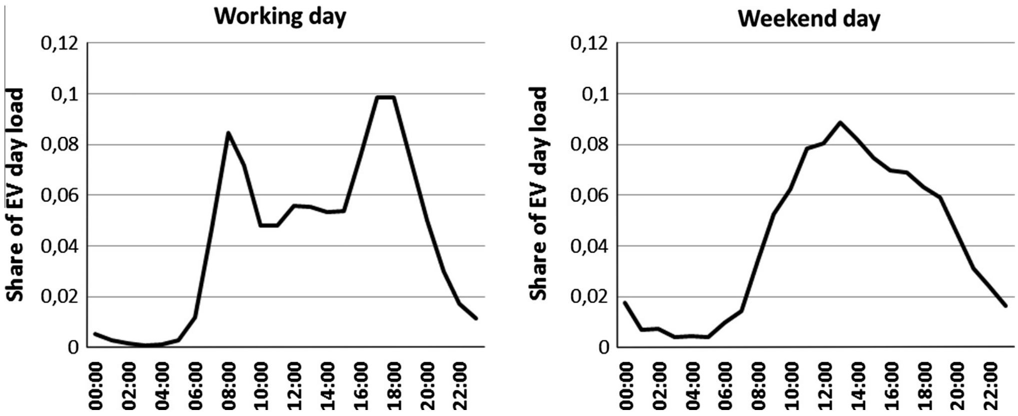


**Fig. 1.** EV charging curve (data source: Babrowski et al., 2014a).

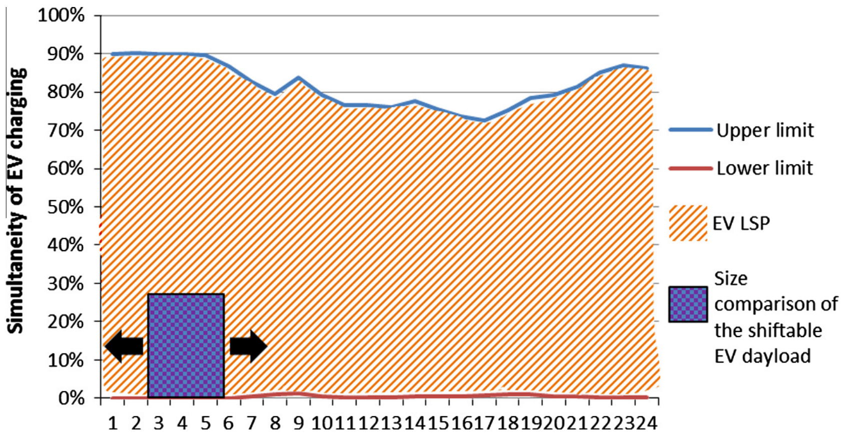


**Fig. 2.** Load shift potential (LSP) of EV (date source: Babrowski et al., 2014a).

$$EVupper_s \cdot D_{prod,EVuse,t,day} \geqslant PS_{proc,t,s} \geqslant 10\% \cdot FL_{prod,exp,EVuse,t,s} \quad \forall proc \in EVDEMPROC_{prod}; \forall prod \in DEMPROD;\ \forall EVuse \in EC;\ \forall t \in T;\ \forall s \in S \tag{3}$$

Every day, the electricity needed by EV has to be charged. Using Eq. (4), it is specified that the cumulated amount of electricity charged until a specific hour meets the exogenously given share of the yearly demand for EV ($DL_{prod,EVuse,t}$) that has to be charged until this specific time slot ($EVcum_{t,s'}$). As there is a value given for the last time slot every day ($s'$), the amount that has to be charged on that day is set (cf. Heinrichs, 2013).

$$\sum_{s=1}^{s'} PS_{proc,t,s} = EVcum_{t,s'} \cdot DL_{prod,EVuse,t} \quad \forall proc \in EVDEMPROC_{prod};\ \forall prod \in DEMPROD;\ \forall t \in T;\ \forall s' \in S \tag{4}$$

In order to analyze the (marginal or average) electricity mix used to satisfy the additional electricity demand by EV, the PERSEUS-NET-TS model is run three times: Without the additional demand of EV in order to have a reference electricity mix and two times with the additional demand for EV. In this case, calculations are made for an uncontrolled charging strategy according to the given charging patterns and for a controlled charging strategy.

## 4. Results and discussion

### *4.1. Generation, demand, and electricity mix*

By 2030, there will be a total installed capacity of about 193 GW when no additional electricity demand from EV is considered. For the case of an uncontrolled charging, this total installed capacity is 195 GW and, hence, slightly higher. With controlled charging no additional capacity is needed in comparison to the case that no additional electricity demand from EV is considered. In all cases 142 GW of the installed capacity will be based on RES by then and, hence, is given exogenously (policy target). Because of the comparably long lifetime of the power plants, most of the thermal units of 2030 already exist in the base year 2012 and are therefore also given. Due to this and the assumption of a slightly decreasing conventional electricity demand, the estimated total commissioned capacity is comparatively low in the German energy system until 2030.

For the case that no additional electricity demand from EV is considered only about 4.5 GW of electricity generation units are endogenously commissioned (cf. Fig. 3). According to the PERSEUS-NET-TS model, uncontrolled charging (i.e. 14.4 TWh additional electricity demand for EV in 2030) will lead to the commissioning of about 1 GW more lignite generation units and almost 1 GW more gas units than without this additional demand. The overall commissioned capacity is about 40% higher for uncontrolled charging (6.4 GW) than for the system without EV. With controlled charging, even less generation units (gas units and storage systems) will be commissioned (4.3 GW) than without this flexible extra demand. Instead, full-load hours of the generation system will increase. This is especially true for coal and biomass units. In case of controlled charging, flexibility of the EV load is used for so-called "valley filling" in conventional demand during the night (cf. Fig. 4), which leads to a slightly decreasing usage of storage systems. Additionally, due to the high share of solar electricity generation, the EV load is used to raise the peak load during the day in order to integrate the generation at noon, while at the same time preventing the base load capacities, such as lignite units, from reducing their generation (cf. Fig. 5). Accordingly, the peak load of the German system in 2030 will amount to 83 GW for the controlled charging strategy, 79 GW for the uncontrolled charging strategy, and 78 GW without electricity demand for EV (cf. Fig. 4). In other countries with less solar electricity generation, controlled charging might rather be used to increase the load of base load power plants and, hence, lead to the same peak load as without EV.

### 4.2. Annual average mix

As depicted above, one approach to determine the emissions caused by driving EV is to use the average annual electricity mix for the generation of the total electricity demand (cf. Section 2.2). As the additional load for EV only corresponds to 3% of the total load, differences between the two charging strategies are small for the annual average electricity mix (cf. Fig. 6). According to PERSEUS-NET-TS, about 60% of the generation will be based on RES by 2030. As today's share of RES in Germany is about 24% (BMWi, 2014), this value is optimistic and even higher than the 50% target for 2030 outlined in the current German legislation. However, as the commissioning of power plants based on RES is exogenously given in PERSEUS-NET-TS and according to the German pilot study, this is not surprising. An increased use of lignite and storage systems for uncontrolled charging is opposed to an increased use of existing coal and biomass plants with controlled charging. For both charging strategies, the emissions amount to about 0.29 kg $CO_2/kWh_{el}$. This is also true for the average annual mix calculated without the additional demand from EV. Assuming an empiric consumption of 20 kWh/100 km, this would lead to emissions of 58 g $CO_2$/km for EV.

For 2020, the annual electricity mix in PERSEUS-NET-TS already includes about 47% electricity generation from RES and the emissions amount to about 0.38 kg $CO_2/kWh_{el}$ which corresponds to 76 g $CO_2$/km for Germany.

The annual average electricity mix approach is highly suitable for country comparisons. In some countries, these values are – even today – much lower due to their different electricity generation (cf. Table 1). In Sweden, for example, where most of the electricity is generated by hydropower plants, EV only emit 6 g $CO_2$/km based on the annual mix of 2010. In France, where most of the electricity is generated by nuclear power, emissions are only about 16 g $CO_2$/km. Other countries, such as Poland, have a highly $CO_2$-intensive generation system. When neglecting the EU ETS, EV in these countries are unlikely to reduce $CO_2$ emissions in the medium term, as the specific emissions of EV are even higher than those of conventional vehicles (cf. Table 1). As stated above, the specific emissions of newly registered conventional passenger cars in 2012 in the European Union were 132.2 g $CO_2$/km (EEA, 2013). For 2030, a target in European legislation of about 70 g $CO_2$/km is being discussed (Thiel et al., 2014). This target leads to challenges in the energy sector of some countries to reduce their specific $CO_2$ emissions in order to make EV a successful means of $CO_2$ mitigation – at least when taking the average electricity mix into account.

### 4.3. Time-dependent average mix

The second approach to consider the $CO_2$ emissions of EV is by comparing the time-dependent average electricity mix values which are obtained by relating the electricity mix of each hour to the electricity demand by EV. If all EV would be charged between 3 a.m. and 4 a.m., for example, only the average electricity mix of that hour would determine the EV emissions. According to the PERSEUS-NET-TS model, the time-dependent average mix for EV charging in Germany is about the same as the average annual electricity mix. Consequently, the emissions based on that mix are also 0.29 kg $CO_2/kWh_{el}$. For controlled charging, this is different. The time-dependent average electricity mix consists of about 67% of electricity from RES and therefore has the lowest $CO_2$ intensity of 0.25 $CO_2/kWh_{el}$ only (50 g $CO_2$/km for EV) (cf. Fig. 7). However, the fact that the electricity mix used to satisfy both conventional and EV demand is more $CO_2$-intensive than it would be without the additional load is neglected here. It also has to be noted that the marginal power plant in PERSEUS-NET-TS often (depending on the considered hour) is a biomass power plant in our analysis. This is due to the exogenous commissioning of RES plants. Otherwise, controlled charging would not necessarily lead to lower $CO_2$ emissions, as the marginal power plant could mostly be a lignite plant (cf. e.g. Holland and Mansur, 2008).

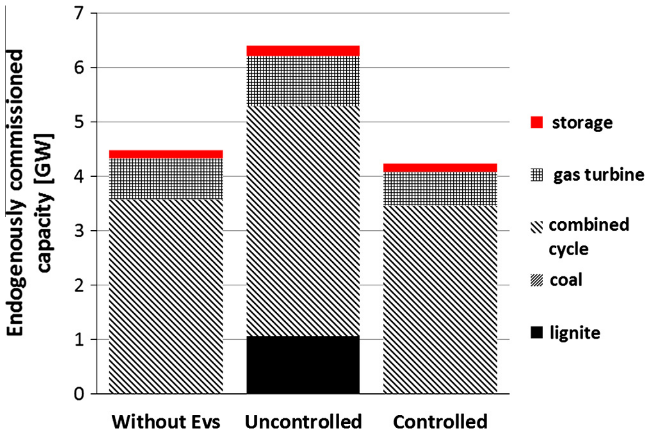


**Fig. 3.** Endogenously commissioned thermal power plants and storage systems in 2030.

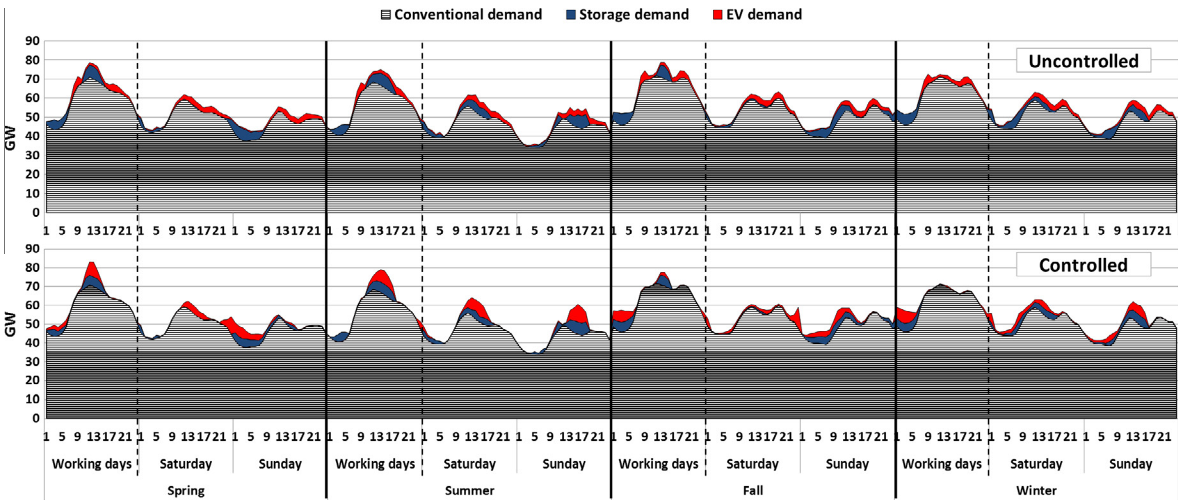


**Fig. 4.** Time-dependent electricity demand for uncontrolled and controlled charging in 2030.

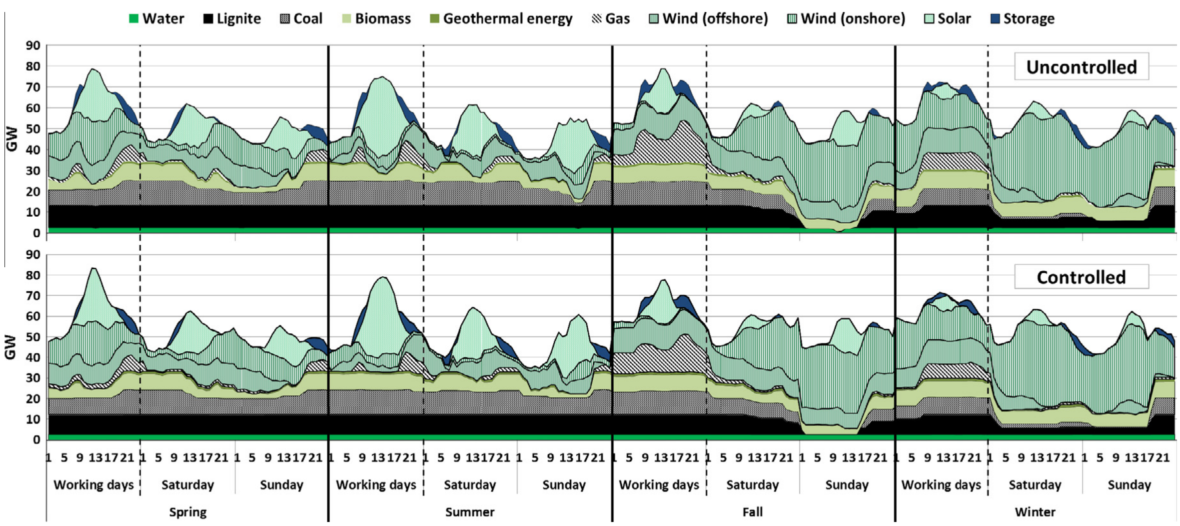


**Fig. 5.** Time-dependent electricity mix for uncontrolled and controlled charging in 2030.

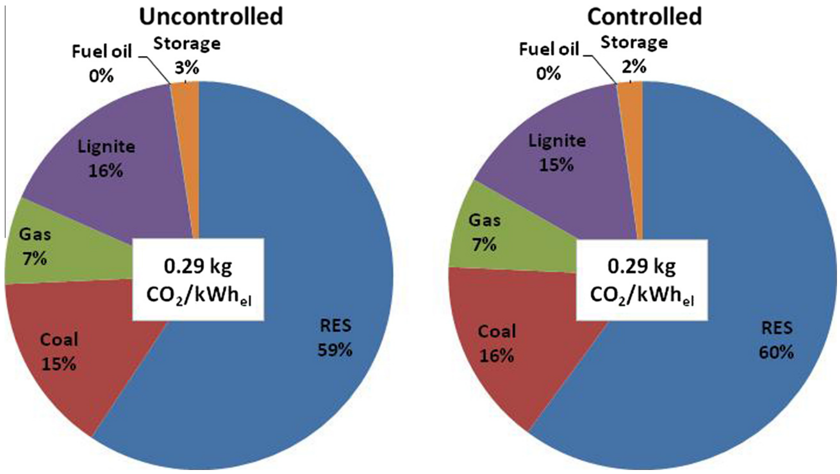


**Fig. 6.** Annual average electricity mix in Germany in 2030.

**Table 1**
Specific $CO_2$ emissions by EV in different European countries in 2010 (g $CO_2$/km). *Source:* IEA (2012b), Assumption: electricity consumption of EV is 0.2 kWh/km.

| Country | Average $CO_2$ emissions in | |
|---|---|---|
| | kg $CO_2$/kWh$_{el}$ | g $CO_2$/km |
| Austria | 0.19 | 38 |
| Belgium | 0.22 | 44 |
| Denmark | 0.36 | 72 |
| Finland | 0.23 | 46 |
| France | 0.08 | 16 |
| Germany | 0.46 | 92 |
| Greece | 0.72 | **144**[a] |
| Ireland | 0.46 | 92 |
| Italy | 0.41 | 82 |
| Netherlands | 0.42 | 84 |
| Poland | 0.78 | **156**[a] |
| Portugal | 0.26 | 52 |
| Spain | 0.24 | 48 |
| Sweden | 0.03 | 6 |
| UK | 0.46 | 92 |
| EU-27 | 0.43 | 86 |

[a] Values above the current European regulation 443/2009 (130 g $CO_2$/km).

### *4.4. Marginal electricity mix*

The electricity mix to cover only the additional electricity demand of EV is defined as the marginal electricity mix. As described above (Section 2.2), this mix is obtained by subtracting the electricity generated by PERSEUS-NET-TS without the extra EV load from the results including the extra EV load. This yields to the marginal mix used to satisfy the extra load of 14.4 TWh for EV in 2030 for both charging strategies (cf. Fig. 8). For the uncontrolled charging strategy, the marginal mix from our model consists of about 57% of electricity generated by lignite units. The rise in electricity generation from lignite is also reflected by the hourly marginal mix (cf. Fig. 9). The additionally installed 1 GW lignite capacity generates surplus electricity in almost all hours considered. Another 22% come from gas units, so that about 80% of the extra demand is covered by thermal units. Only 18% come from RES. The use of storage systems also increases. According to PERSEUS-NET-TS, this leads to marginal $CO_2$ emissions of 0.55 kg $CO_2$/kWh$_{el}$. This even is above the emission level of today's average annual electricity mix in Germany (see above). For EV, emissions would amount to 110 g $CO_2$/km. As a result, neither the target of 95 g $CO_2$/km in 2020, nor the target in 2030 would be reached by EV in case of uncontrolled charging. This is different for controlled charging. About 39% of the electricity for the controlled charging strategy will be generated from RES – mainly from biomass. Only about 31% are generated from lignite or coal. The corresponding marginal emissions amount to 0.38 kg $CO_2$/kWh$_{el}$ and 76 g $CO_2$/km, respectively. The flexibility of controlled charging also leads to a reduction of electricity supplied by storage systems.

The hourly marginal mix displayed in Fig. 9 shows at which hour how much of the electricity needed for EV is generated by which technology. For the uncontrolled charging strategy, it can be seen that the additionally commissioned capacity of

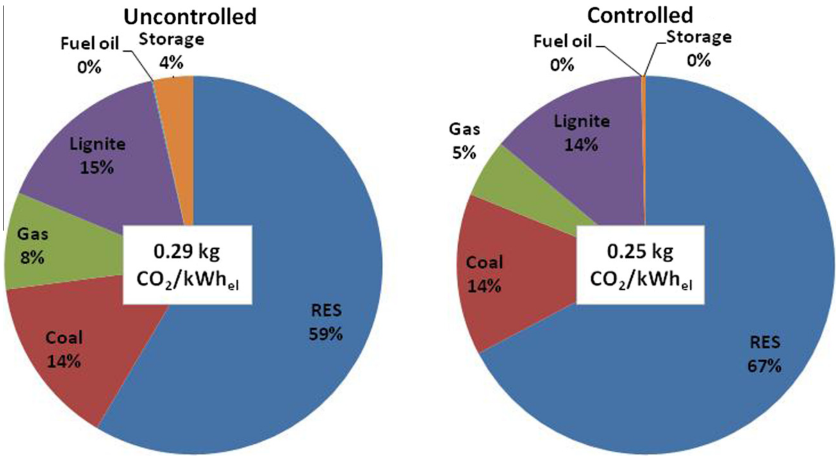


**Fig. 7.** Time-dependent average electricity mix for EV charging in Germany in 2030.

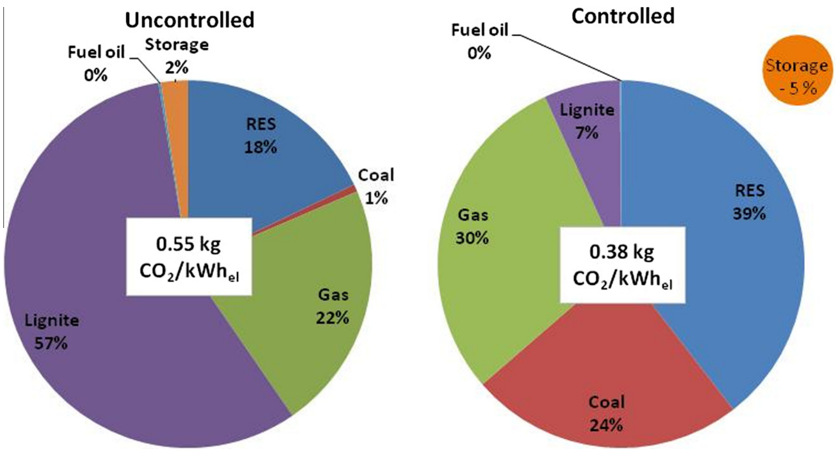


**Fig. 8.** Marginal mix for uncontrolled and controlled charging of EV in Germany in 2030.

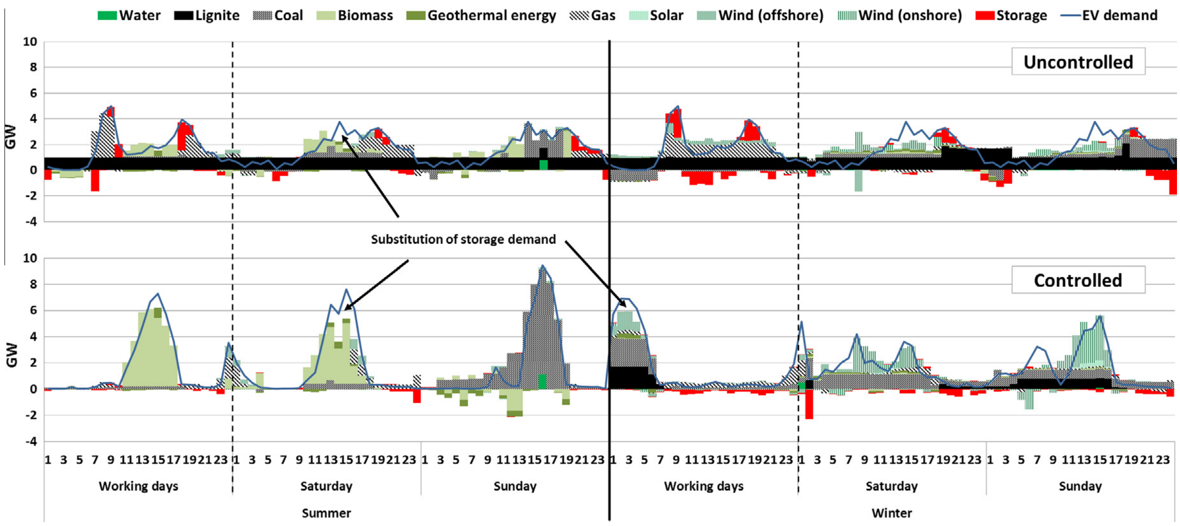


**Fig. 9.** Hourly marginal mix for uncontrolled and controlled charging of EV in Germany in 2030.

one GW of lignite is almost nonstop in operation. On the working days, the required electricity is also provided by gas and storage units. In times of a low electricity demand by EV, the additional generation by lignite units replaces the generation of electricity from other fuels. With the controlled charging strategy, charging on working days takes place either during the night hours or on days with a high solar feed-in during the midday hours. For the weekend days, the structure is not that clear, but the demand is also shifted to times when generation units have not been used to their full extent before.

## 5. Discussion

In most national legislations, EV are considered zero emission vehicles. For Europe, this approach seems appropriate when the electricity demand from EV is interpreted as additional and not explicitly considered in the discussions of the emission allowance cap for 2030 by the EU ETS (cf. assessment approach *balancing zero emissions* in Section 3.1). For other countries and for a technology-specific evaluation, however, the assessment of the corresponding $CO_2$ emissions from power plants is necessary in order to allow comparisons to $CO_2$ emissions from ICEV. Furthermore, lower emission values help to argue for policy instruments supporting higher EV market penetrations and convince users during their vehicle purchase decision.

In this article, we presented four approaches to assessing $CO_2$ emissions associated with the additional load by EV. From a scientific point of view, we cannot state which approach is the most appropriate. This certainly depends on the underlying objective of the comparison. The use of the annual electricity mix is the most practical way to assess $CO_2$ emissions of EV. At least ex-post, the emissions can be determined with certainty by using the corresponding real annual average electricity mix. It is highly convenient for country comparisons and easy to understand for different stakeholders. In 2010, for example, average emissions in Germany were 0.46 kg/kWh$_{el}$ (IEA, 2012b), which would have led to emissions of 92 g $CO_2$/km for our average EV. The time-dependent average mix is a first step toward real induced emissions. However, the corresponding effort for calculation is significantly higher, even ex-post. Another negative aspect of using the time-dependent electricity mix is that it neglects the influence of the additional EV load on the mix used to satisfy other (flexible) demand, which will be especially relevant, if considerable market shares of EV become reality. With the third approach, the marginal electricity mix, on the other hand, the uncertainty is even higher. Even ex-post, the electricity mix that would have resulted without the additional EV load would have to be determined through the use of an energy system model or comprehensive spatial market data. Furthermore, charging processes of EV have to be accounted for precisely. Nevertheless, the marginal mix seems to account best for the emissions caused by using EV – at least in theory – and it allows for a most precise analysis of the impact on the energy system.

A comparison of the $CO_2$ emissions resulting from the different approaches shows that EV do not necessarily decrease $CO_2$ emissions by 2030. The corresponding results for our German case study differ significantly (cf. Table 2). Even though the underlying scenario is rather optimistic, with an assumed generation from RES of 60%, the emission values for an average EV based on the *annual average mix* amount to about 58 g $CO_2$/km. While this is still well below the European target for ICEV of about 70 g $CO_2$/km under discussion for 2030, things change when the *marginal electricity mix* is considered. At least with the uncontrolled charging strategy, the emissions exceed the target considerably and reach 110 g $CO_2$/km. Those emissions can already be reached by efficient conventional combustion engines today (EEA, 2013). In case of controlled charging, *marginal emissions* amount to 76 g $CO_2$/km only, which might be below the European target to be specified for 2030. However, it has to be noted that the flexibility is used to increase the full load hours of existing power plants – which increase their profitability. For PERSEUS-NET-TS, this often is a biomass plant, but this depends on the underlying power plant portfolio. In reality, it may also be a lignite plant. Hence, depending on the marginal power plant, the charging strategy has a significant influence on the ecological compatibility of EV driving. The controlled charging strategy also is associated with lower emission values when the time-dependent average mix is used as a basis. The *balancing zero emissions* approach leads consequently to the lowest $CO_2$ emissions.

For the low EV penetration assumed for 2020, only the value for the annual German electricity mix is calculated, which amounts to 76 g $CO_2$/km (47% electricity generation by RES). Hence, the average EV is going to be well below the European targeted 95 g $CO_2$/km for ICEV. Controlled charging would also help integrate the additional demand from EV in other countries. In some countries with a high share of solar power, e.g. Spain, charging would probably take place during the midday hours. In Sweden, for example, charging would most likely be shifted to the night time in order to fill the load valleys.

Apart from the direct $CO_2$ emissions during the usage phase of the EV, the emissions during the whole lifecycle should be taken into consideration. While the emissions caused by the disposal of the vehicles are rather uncertain, the $CO_2$ emissions during vehicle construction have already been analyzed by various studies, most of which indicate significantly higher emissions for EV. Recently, this finding was somewhat relativized by Hawkins et al. (2012a) and Dunn et al. (2013). Obviously, it depends on the local electricity mix used for the production process. Furthermore, it is pointed out that EV using clean electricity during their whole lifetime can compensate for the higher emissions during their production phase. Whereas currently the production of EV results in about 10 tons of $CO_2$ and the production of ICEV in about 6 tons, the overall $CO_2$ emissions during the whole product lifecycle of both technologies amount to about 20 tons of $CO_2$. Furthermore, the high emissions during the production phase of EV are going to decrease in the near future (e.g. Sanfélix et al., 2015; Kay et al., 2013; Helmers and Marx, 2012; Held and Baumann, 2011). An increasing efficiency of EV during the usage phase might, additionally, strengthen this reduction of $CO_2$ emissions in the future.

**Table 2**
$CO_2$ emissions for EV in Germany in 2030 based on the three different assessment approaches.

| | Uncontrolled charging strategy | | Controlled charging strategy | |
|---|---|---|---|---|
| | kg $CO_2/kWh_{el}$ | g $CO_2$/km | kg $CO_2/kWh_{el}$ | g $CO_2$/km |
| Annual average mix | 0.29 | 58 | 0.29 | 58 |
| Marginal mix | 0.55 | 110 | 0.38 | 76 |
| Time-dependent average mix | 0.29 | 58 | 0.25 | 50 |

## 6. Conclusion

Assessing $CO_2$ emissions of electric vehicles (EV) is a challenging task. We illustrate that different assessment methods may lead to conflicting results. For this reason, four different assessment approaches are presented in order to contribute to the ongoing discussion and to reveal the underlying differences. These assessment approaches are the *annual average mix* ($CO_2$ emissions from the national annual average electricity mix), the *time-dependent average mix* (weighted $CO_2$ emissions from the average electricity generation mix related to the times of EV charging), the *marginal electricity mix* (increase in $CO_2$ emissions due to the additional electricity generation), and *balancing zero emissions* (considering political measures that ensure that $CO_2$ emissions by EV are balanced elsewhere, e.g. by the EU ETS). Especially in countries with a heterogeneous power plant portfolio, the assessment approaches applied have a significant influence on the resulting emissions. The differences are mainly based on the time-dependent operation of power plants.

For illustration purposes, we calculate the corresponding emissions for Germany in 2030, when EV might have a significant market share. We apply an optimizing energy system model (PERSEUS-NET-TS) and distinguish between an uncontrolled (i.e. direct) charging and an optimized controlled charging strategy. Besides the *balancing zero emissions* approach, the emissions resulting from our analysis amount to 0.25 kg $CO_2/kWh_{el}$ and 50 g $CO_2$/km for the *time-dependent average electricity mix* and the controlled charging strategy, respectively, and to 0.55 kg $CO_2/kWh_{el}$ and 110 g/km for the *marginal electricity mix* and uncontrolled charging. The other assessment approaches lead to specific emissions between these two extremes. When interpreting those values, however, we have to consider the underlying assumptions (e.g. the share of electricity generation by renewable energy sources). Hence, for some countries, the EV will not necessarily help to significantly reduce $CO_2$ emissions of individual road transport by 2030, especially when the national power plant portfolio consists of many thermal plants and because emission of conventional vehicles will also be reduced to about 80 g $CO_2$/km until that time. Therefore, we recommend developing political measures to reduce $CO_2$ emissions from electricity generation and incentivize controlled charging in order to ensure $CO_2$-free driving of EV in 2030. Besides this, an increased share of EV might also contribute to decreasing local emissions and the high oil dependency of many countries.

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**Table A.1**
Configuration of thermal expansion options (based on BMU (2011)).

| | | Gas turbine | Combined cycle gas turbine | Coal unit | Lignite unit |
|---|---|---|---|---|---|
| Investigation | [€/kW] | 400 | 700 | 1300 | 1500 |
| Fixed costs | [€/(kW a)] | 14 | 14 | 95 | 102 |
| Variable costs | [ct/kWh] | 0.3 | 0.3 | 0.15 | 0.2 |
| Efficiency | [%] | 46 | 61.1 | 50.9 | 49.1 |
| Economic lifetime | [a] | 25 | 25 | 25 | 25 |

**Table A.2**
Price development of energy carriers and $CO_2$ certificates (based on IEA (2012a)).

| | 2012 | 2020 | 2030 | Source |
|---|---|---|---|---|
| *[ct/kWh]* | | | | |
| Coal | 1.1 | 1.0 | 1.0 | IEA (2012a) |
| Lignite | 0.4 | 0.4 | 0.4 | Eßer-Frey (2012) |
| Gas | 2.4 | 2.8 | 3.0 | IEA (2012a) |
| Oil | 4.9 | 5.4 | 5.6 | IEA (2012a) |
| *[€/ton]* | | | | |
| $CO_2$ certificates | 9 | 21.5 | 28.8 | IEA (2012a) |

**Table A.3**
Assumption for the demand development (based on Eßer-Frey (2012)).

| [TWh] | 2012 | 2020 | 2030 |
|---|---|---|---|
| Conventional | 503 | 506 | 493 |
| Electric mobility | 0 | 1 | 14 |
| Total | 503 | 507 | 510 |

## Appendix A

See Tables A.1–A.3.

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