Electromobility in Germany: CO_2 Balance Depends on Charging Electricity

By Wolf-Peter Schill, Clemens Gerbaulet and Peter Kasten

The German government plans to significantly increase the deployment of electric vehicles. What impact would this have on the country's power system and carbon emissions? This question was addressed as part of a European research project analyzing various scenarios up to 2030. One of the key findings of the study is that total annual power consumption of the four to five million electric vehicles (depending on the scenario) would be small. However, recharging the vehicles, particularly in an uncontrolled charging mode, which involves the car being fully recharged as rapidly as possible after being connected to the electricity grid, would result in problematic peak loads in the power system. The type of additional power generation required for electric vehicles also largely depends on the charging mode. For example, a charging mode that minimizes system costs would use a particularly high share of power from hard-coal- and lignite-fired plants, which, in turn, would result in an above-average level of specific carbon emissions of the charging electricity. If the electricity and transport sectors are both considered, it becomes evident that the introduction of electromobility would result in a significant net reduction in carbon emissions only if linked with an additional expansion of renewable energy sources compared to current plans.

One of the German government's stated goals is to increase the use of electric engines in the field of motorized private transport.[1] The aim is for Germany to have a fleet of one million electric road vehicles (EVs) by 2020 and six million by 2030[2] and, parallel to this, for Germany to become both the "lead market" and "lead supplier" in the field of electric mobility by 2020.[3] In order to meet these targets, one of the steps taken by the German government was to establish the National Electric Mobility Platform (*Nationale Plattform Elektromobilität, NPE*). Following a phase of market preparation (up to 2014) and market launch (up to 2017), the plan is to reach the mass market by 2020.[4] In September 2014, the German cabinet passed a new electric mobility law to underpin the market introduction of EVs.[5]

The introduction of electric mobility is accompanied by a number of challenges: for example, the range, weight, and life of vehicle batteries all still require significant improvement. Purchasing an EV also remains a relatively expensive undertaking for customers while the range of available models is limited and the level of acceptance

1 There are other – in some cases long-established – forms of electric mobility outside the field of motorized private transport, particularly local and long-distance rail transportation. Almost 60 percent of public transport services in Germany are powered by electricity. In 2012, passengers traveled 167 billion passenger-kilometers by public transport in Germany (excluding air travel), where 105 billion passenger-kilometers were on the railways and 95 billion were powered by electricity. See Institute for Energy and Environmental Research (IFEU), *Auswertungen des Modells TREMOD 5.53* (November 15, 2014).

2 The target for 2020 was set out in August 2009 in the German government's National Development Plan for Electric Mobility and has since been confirmed on numerous occasions, including in the December 2013 Coalition Treaty between the CDU, CSU, and SPD.

3 German government, *Regierungsprogramm Elektromobilität* (2011).

4 For recent information on this, see National Electric Mobility Platform (NPE), *Fortschrittsbericht 2014 – Bilanz der Marktvorbereitung* (Berlin: Nationale Plattform Elektromobilität, December 2014).

5 The purpose of the law was to establish the legal basis for granting EVs certain privileges such as special parking spaces at public charging stations or the right to use bus lanes. German government's draft bill: Entwurf eines Gesetzes zur Bevorrechtigung der Verwendung elektrisch betriebener Fahrzeuge (Elektromobilitätsgesetz), Berlin, September 24, 2014, Bundestags-Drucksache 18/3418.

Box 1

Glossary of Terms Used

Here, electromobility refers to the following types of electric passenger vehicles:

- Pure battery electric vehicles (BEVs): these all-electric vehicles run solely on an electric motor that derives its power from battery packs which are recharged from the power grid.
- Plug-in hybrid electric vehicles (PHEVs): like battery electric vehicles, these vehicles have an electric motor and battery packs that can be recharged from the power grid. In addition, these vehicles also have a standard internal combustion engine.
- Range extender electric vehicles (REEVs): these vehicles have an auxiliary internal combustion engine which can be used to recharge the vehicle battery pack if needed.

One thing these three vehicle types have in common is that they can all draw power from the grid. In contrast, non-plug-in hybrid electric vehicles are not considered here.

A distinction is made between the following charging modes for electric vehicles:

- Fully user-driven or uncontrolled charging: the EVs start charging as soon as they are connected to the power grid and charge at their maximum rate until the batteries are completely charged.
- Fully cost-driven or optimized charging: under the assumption of perfect foresight, the vehicles recharge to a level that is sufficient to cover at least the next trip. Here, the timing of EV charging is such that system costs are minimized. In other words, the vehicle batteries are charged at a time of day when the wholesale electricity prices are particularly low.
- Partially user-driven charging: the EVs start charging as soon as they are connected to the power grid and charge with full rating until the battery state-of-charge reaches a specified level, for instance, 50 percent. The cost-driven mode can be used for the remaining 50 percent of the battery capacity.

In this case, the system costs comprise the variable costs of power plant dispatch, including fuel and CO_2 costs as well as start-up costs. Capital costs and other fixed costs are not taken into account, since this analysis is based on an existing power plant fleet.

Different scenarios are analyzed with distinctive assumptions on the number of EVs:

- A reference scenario without EVs.
- Business-as-usual (BAU): nearly four million EVs in 2030.
- Electromobility$^+$ (EM$^+$): around five million EVs in 2030.
- Renewable Energy$^+$ (RE$^+$): the same EV fleet as in EM$^+$.

The power plant fleet does not change between these scenarios; only in RE$^+$ an additional expansion of renewable power generation capacities is assumed.

among car users remains largely uncertain. Further expansion of the charging infrastructure is also needed.

At the same time, however, electric mobility has the potential to open up a wide range of opportunities in the medium and long term. For instance, EVs could enable us to use domestic renewable energy sources without having to rely on biofuels. Moreover, electric drives are generally considerably more efficient than combustion engines. They also produce only low levels of local air pollution and no CO_2 emissions. However, it is possible that these emissions might be shifted, at least to a certain extent, occurring when the electricity is generated instead. Last but not least, there is also the hope that the optimized grid integration of EVs will make a positive contribution to improving the flexibility of the power system.[6]

6 For an overview, see W.-P. Schill, "Elektromobilität in Deutschland – Chancen, Barrieren und Auswirkungen auf das Elektrizitätssystem," *Vierteljahrshefte zur Wirtschaftsforschung*, vol. 79, *Verkehr und Nachhaltigkeit* (2010): 139-159, http://dx.doi.org/10.3790/vjh.79.2.139.

European Research Project Examines Impact of Electric Mobility

A European research project studied the possible impact of future EV fleets on the German power system and CO_2 emissions in the transport sector.[7] One of the key areas of interest was the effects of electric mobility on German power plant dispatch and the resultant net CO_2 emissions, in each case on the basis of various assumptions regarding the EV charging mode.

The Institute for Applied Ecology (*Öko-Institut*) initially developed two market scenarios illustrating the expan-

7 The present *DIW Economic Bulletin* is based on the findings of the European research project "Definition of an Evaluation Framework for the Introduction of Electromobility" (DEFINE, ERA-NET Plus, Seventh Framework Programme). The project was led by the Institute for Advanced Studies (Austria). Other project partners alongside DIW Berlin were the Institute for Applied Ecology (*Öko-Institut*), the Federal Environment Agency (*Umweltbundesamt*) (Austria), Vienna University of Technology (*TU Wien*) (Austria) and the Center for Social and Economic Research (Poland), http://www.ihs.ac.at/projects/define/index.html.

sion of EVs up until 2030 and derived the corresponding time profiles for hourly vehicle usage and charging options. DIW Berlin then calculated the impact of these EV fleets on the German power system using a power plant dispatch model. The results of this calculation, in turn, provided essential input parameters for a transport sector model developed by the Öko-Institut and used to calculate the net CO_2 emissions of the electricity and transport sectors.

Scenarios for Development of Electric Mobility in Germany

The Öko-Institut developed two scenarios for electric mobility in Germany for the period up to 2030, covering pure battery electric vehicles (BEVs) as well as plug-in hybrid electric vehicles (PHEVs) and range extender electric vehicles (REEVs) (see Box 1).[8] A business-as-usual (BAU) scenario envisages a continuation of the current policy framework conditions. In contrast, the Electric Mobility+ (EM+) scenario assumes additional policy measures promoting electric mobility. These measures include higher taxes on fossil fuels, ambitious emissions standards for new vehicles, and the introduction of a feebate system based on emissions for all new vehicle registrations.[9] Representative mobility data for Germany were used to calculate vehicle use.[10] The purchasing decision between different engine technologies is simulated using a conjoint analysis of a survey of 1,500 buyers of new cars.[11]

The main factors affecting the purchase and use of EVs include acquisition costs, running costs, charging infrastructure requirements, charging times, and the frequency of longer journeys which go beyond the BEV range. Around 50 percent of car owners in core cities do not have a parking spot on their own property and would therefore constantly have to rely on a public charging infrastructure in order to use an EV. The share of car owners without a parking spot on their own property falls to 30 percent in suburbs and rural areas. On average, each vehicle makes around six journeys of longer than 150 kilometers every year. Using the Poisson probability distribution, we can assume that the probability of a BEV being driven beyond its range more than four times a year is over 70 percent.

The survey indicated a high level of acceptance of electric mobility. The market potential of EVs derived from the survey during the period under observation was approximately 50 percent of new vehicle registrations in the BAU scenario and around 60 percent in the EM+ scenario. According to the survey, the level of acceptance of PHEVs and/or REEVs is higher than for BEVs. A simulation of the future market shares of EVs uses a diffusion factor to take other obstacles into account such as the required expansion of production capacities and the currently rather limited selection of EV models. Accordingly, the market share of new EV registrations is below market potential.

In the two scenarios, the market share of new EV registrations will be approximately five to six percent in 2020, increasing to 20 to 25 percent by 2030. PHEVs and REEVs account for considerably higher market shares than BEVs. The overall EV fleet size is around 0.4 million (BAU) or 0.5 million (EM+) by 2020. According to the BAU scenario, by 2030, the EV fleet will expand to just under four million and, according to the EM+ scenario, to approximately five million cars, equating to 13 percent of the total number of passenger cars (see Figure 1).[12]

8 For a more detailed description of the scenarios, see P. Kasten and F. Hacker, *Two electromobility scenarios for Germany: Market development and their impact on CO_2 emissions of passenger cars in DEFINE* (Berlin: November 14, 2014).

9 Vehicles that produce high specific emissions are subject to a surcharge when purchased whereas financial assistance is provided for the purchase of vehicles with low specific emissions.

10 R. Follmer et al., *Mobilität in Deutschland 2008. Ergebnisbericht: Struktur – Aufkommen – Emissionen – Trends* (Bonn and Berlin: February 2010).

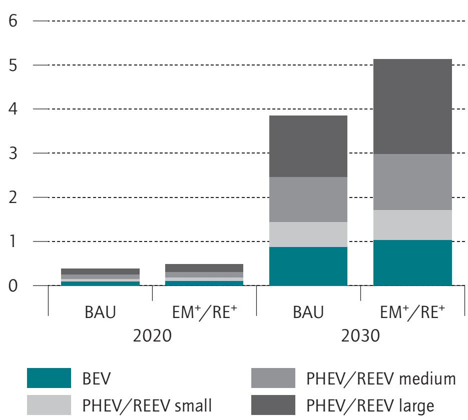
11 Survey respondents were repeatedly asked to choose between various vehicle types which differed by drive type, performance, CO_2 emissions, and purchasing and fuel costs. See K. Götz et al., *Attraktivität und Akzeptanz von Elektroautos. Arbeitspaket 1 des Projekts OPTUM: Optimierung der Umweltentlastungspotentiale von Elektrofahrzeugen* (Frankfurt/Main: October 2011).

12 The scenarios were defined in the European project group using a common methodology. Meeting the German government targets was not a constraint here. The scenarios cannot be interpreted as a method of forecasting whether or not the German government targets will be met.

Figure 1

Stock of electric vehicles in the scenarios

In million cars



BEV: Purely Battery-Electric Vehicles.
PHEV/REEV: Plug-in Hybrid Electric Vehicles and Range Extender Electric Vehicles.

Source: Kasten, P., Hacker, F. (2014), l.c.

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PHEV and REEV have the largest shares in the scenarios.

Box 2

Methods of the Analysis

In addition to surveys and other empirical studies, two numerical models were used in the analysis: a power plant dispatch model developed by DIW Berlin and a transport sector model developed by the Öko-Institut.

Power plant dispatch was simulated using a mixed-integer cost minimization model representing individual power plant units with a capacity of 100 megawatts and above.[1] This model factors in the flexibility restrictions of thermal power plants by including start-up costs, minimum load conditions, and minimum off-times. Using hourly time steps, the model is run sequentially at four-week intervals over an entire year. The key input parameters are the thermal power plant fleet, as well as the time-varying power generation possibilities of renewable resources based on historical feed-in data. Other important input parameters are the hourly profiles of energy consumption and maximum charging capacities of the EVs. Using representative mobility data, 28 different patterns of vehicle utilization and charging availability are generated and extrapolated proportionately for the fleet size of the relevant scenario. Other techno-economic parameters are derived from the DIW Berlin database and the Grid Development Plan.[2]

The analysis of power plant dispatch is limited to Germany or, more precisely, the German wholesale electricity market. In line with the scenario framework for the Grid Development Plan, it is assumed that there are no transmission constraints within Germany. In addition, no interaction with neighboring countries is assumed. As a result, the contribution of EVs to increase the flexibility of the power system tends to be overestimated. If, in contrast, extensive Europe-wide power transmission would be presumed, the utilization of lignite- and hard-coal-fired power plants in Germany should in fact be higher than calculated here, even in the reference case. Accordingly, the share of lignite-fired generation in the charging power of EVs tends to be overestimated, particularly for cost-optimized vehicle charging.

In the case of plug-in hybrid electric vehicles, the decision about the driving mode–electric or with the conventional internal combustion engine–is not modeled in detail; instead, it is generally assumed that the share of electric power in vehicle use ought to be increased to a maximum.

With regard to the network integration of EVs, controlled EV charging was analyzed (grid-to-vehicle), but not the option of feeding electricity from the vehicle battery packs back into the grid (vehicle-to-grid). Various studies indicate that vehicle-to-grid could be particularly relevant for the control reserve market segment; this is not explored here, however.

The Transport Emissions and Policy Scenarios (TEMPS) model developed by the Öko-Institut is used to quantify the energy demand and greenhouse gas emissions of the transport sector for various scenarios, depicting changes in transport demand, vehicle fleet, and fuel use. Using key mobility parameters (number of trips, trip distances, modal split of passenger and freight transport, and transport distances), transport demand scenarios for passenger and freight transport are determined and used in the model as input parameters. The technology database documents the possible technical developments of the respective mode of transport up to 2050 according to vehicle category and powertrain. The future development of vehicle efficiency is calculated using a model for new vehicle registrations and the existing vehicle fleet, meaning the effect of CO_2 emission standards or measures to promote the use of alternative technologies on the existing vehicle fleet in Germany can be analyzed.

1 A full description of the model and the data sources can be found in Schill and Gerbaulet, "Power System Impacts."

2 See 50Hertz et al., *Netzentwicklungsplan Strom*.

Power Plant Dispatch Model Used to Simulate Impact on Electricity System

The impact of the EV fleets outlined in the *Öko-Institut* scenarios on the German electricity system is analyzed using a power plant dispatch model developed by DIW Berlin (see Box 2).[13] The power generation capacities of the various technologies for 2020 and 2030 are derived from the scenario framework of the German Grid Development Plan[14] (see Figure 2).

The model minimizes power plant dispatch costs, factoring in the necessary charging requirements for EVs. The model distinguishes between two extreme charging

13 For more details on power plant dispatch modeling, see W.-P. Schill and C. Gerbaulet, "Power System Impacts of Electric Vehicles in Germany: Charging with Coal or Renewables?," *DIW Discussion Papers* 1442 (2015).

14 The middle Scenario B from the 2013 Grid Development Plan was used as a basis. 50Hertz et al., *Netzentwicklungsplan Strom. Zweiter Entwurf der Übertragungsnetzbetreiber* (July 17, 2013).

strategies (see Box 1): in the uncontrolled charging mode which is completely user-driven, EVs are fully recharged as quickly as possible immediately after being connected to the charging station. In the optimized charging mode, however, which is completely cost-driven, vehicle charging can be delayed subject to the constraints of the vehicles' hourly usage and charging profiles, which minimizes the charging costs arising in the electricity system. The model also allows simulating (semi-optimized) charging strategies which are user-driven to a certain extent and where only some of the battery capacity must be recharged as quickly as possible as soon as the vehicle is connected to the power grid.

Energy Consumption of EVs Marginal But Charging Power Can Be Critical

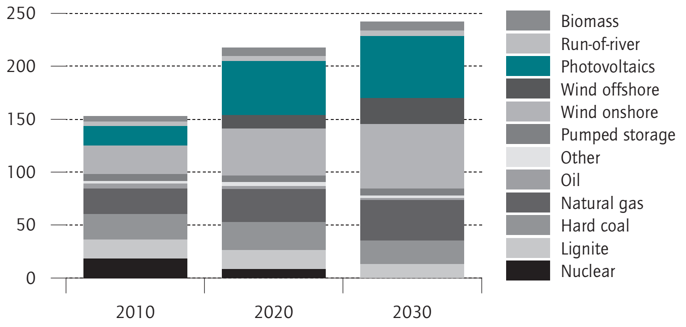
The annual energy requirements for future EV fleets are minimal compared to total power demand. In 2020, depending on the charging strategy, electric mobility requires only 0.1 to 0.2 percent of total electricity demand. By 2030, these shares increase to 1.2 to 1.6 percent or seven to nine terawatt hours (TWh).[15]

In contrast to the yearly energy consumption of EVs, their hourly charging power could, however, become very high. Charging rates fluctuate considerably from one hour to the next and there are substantial differences between the user-driven and cost-driven charging modes. Purely user-driven charging occurs primarily during the daytime and evening (see Figure 3). This may result in a significant increase in the power system's peak load which could have serious consequences for system security. According to both the BAU and the EM+ scenarios, a completely user-driven charge mode would mean that, in 2030, there would be several hours when the assumed power generation capacities (based on the Grid Development Plan) would be completely exhausted.[16]

In the cost-driven mode, on the other hand, the evening peaks of the charging profile are shifted to the nighttime when electricity demand is low and to the hours over midday when solar power generation is high. The average charging profile for the cost-optimized mode is considerably more balanced overall than for the fully user-driven mode and it consequently also results in a much less pronounced increase in demand during peak load periods.

Figure 2

Installed power generation capacities
In gigawatt



Source: Schill, W.-P., Gerbaulet, C. (2015), l.c.

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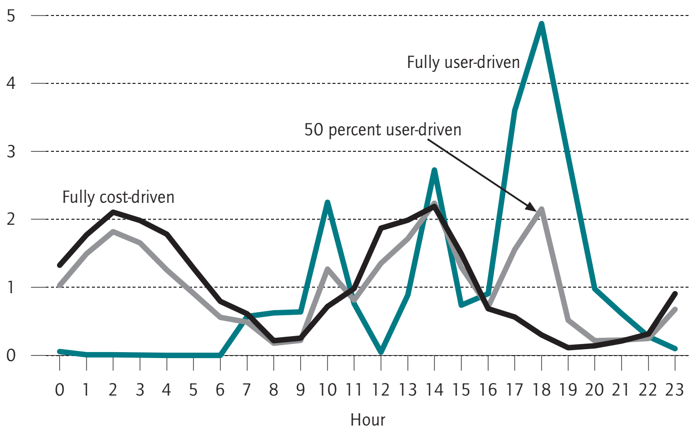
The capacities of wind power and photovoltaics stronlgy increase.

Figure 3

Average charging power over 24 hours in 2030
In gigawatt



Exemplary for the scenario EM+
Source: Schill, W.-P., Gerbaulet, C. (2015), l.c.

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Fully user-driven charging primarily takes place during evening hours.

Compared to fully uncontrolled charging, even semi-optimized charging where, for example, only half of the battery capacity must be recharged immediately after connecting to the power grid, results in a much smoother average charging profile.

Power Generation for Electric Vehicles Depends on Charging Mode

The different charging profiles are associated with corresponding changes in power plant dispatch. EVs may,

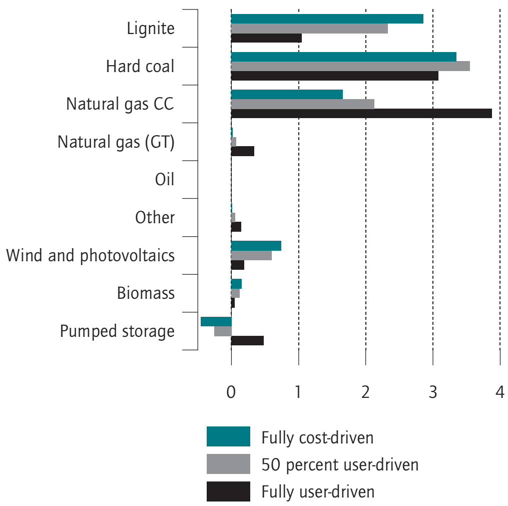
15 In comparison, in 2012, final energy consumption by Germany's electrified trains was just under nine terawatt hours for passenger transport and between three and four terawatt hours for freight transport. See IFEU, *Auswertungen des Modells.*

16 The solvability of the model in these peak hours is ensured using a stylized, very expensive peak load technology. In the real world, an according level of load shedding, the provision of a capacity reserve, or the import of electricity from abroad would be required.

Figure 4

Changes in power plant dispatch compared to a scenario without electric vehicles in 2030

In terawatt hours



Exemplary for the scenario EM+.
CC: Combined Cycle; GT: Open Gas Turbines.

Source: Schill, W.-P., Gerbaulet, C. (2015), l.c.

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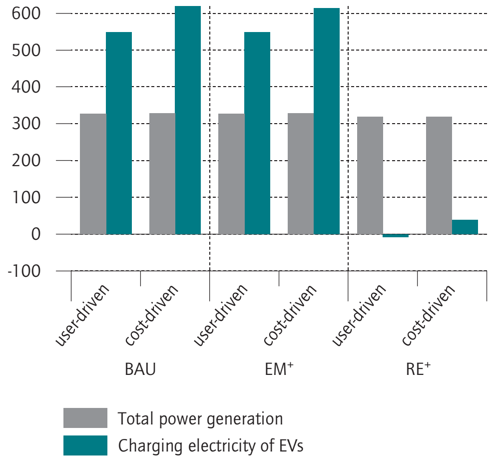
Power generation from hard coal and lignite plants increases substantially under cost-driven charging.

Figure 5

Specific CO_2 emissions of power generation in 2030

In grams per kilowatt hour



Source: Schill, W.-P., Gerbaulet, C. (2015), l.c.

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Without additional renewables, specific emissions of the charging electricity are above average.

on the one hand, increase the utilization factor of emissions-intensive power generation technologies such as lignite- and hard-coal-fired plants and, on the other, consume temporary surplus energy from intermittent renewable energy sources.

In the 2030[17] Electric Mobility+ scenario (EM+), a cost-driven charging strategy increases the utilization of hard-coal- and lignite-fired plants significantly in comparison to a reference scenario that does not include EVs (see Figure 4). In the case of fully user-driven vehicle charging, the vehicle is often charged at times when lignite-fired power plants are running to full capacity, meaning the additional power needed comes mainly from natural-gas-fired combined cycle plants as well as coal-fired-plants and, to a lesser extent, from lignite plants.

In both cases, the use of renewable sources of energy is only slightly higher, since these sources produce very little surplus energy; this means that virtually all the wind and solar power generated, as anticipated in the scenarios, can already be adopted by the energy system in the scenario with no EVs. Here, cost-optimized charging allows for a slightly larger increase in the utilization of renewables, since in this case vehicle charging can be shifted to times where there is surplus electricity from wind and solar power.

Charging Power Causes Above-Average Greenhouse Gas Emissions

The specific CO_2 emissions from the additional energy demand for EVs depend both on the power plant fleet and the charging strategy applied. If the use of EVs increases the utilization of emissions-intensive power generation plants such as lignite- and hard-coal-fired plants, the specific CO_2 emissions also increase. Conversely, if EVs can be charged with additional renewable poweremissions will decrease. In the 2020 and 2030 BAU and EM+ scenarios, additional coal-fired power generation dominates the emissions balance. This applies, in particular, to cost-driven charging. Consequently, specific emissions resulting from the increased energy demand caused by EVs ("charging power") are—irrespective of the charging mode—higher than those for the entire power mix (see Figure 5).[18]

17 The effects are most evident in this scenario. In the BAU 2030 scenario and in the 2020 scenarios, the results are similar in quality, albeit less pronounced.

18 The effects observed depend heavily on the structure of the power plant fleet and the relevance of renewable curtailment. In future, the emissions balance of cost-driven charging could be far better if emissions-intensive power plants are removed from the system and renewable curtailment becomes more significant.

In another scenario called Renewable Energy+ (RE^+), the introduction of electric mobility is directly linked to the further expansion of renewable power generating capacities beyond the scope set forth in the Grid Development Plan. These additional capacities are selected such that the total annual power generation from these sources covers the electricity demand for EVs exactly. For example, if the electricity demand for EVs were to be covered solely by additional solar PV installations, the 2030 scenario (EM^+) would require around 13 to 14 gigawatts of capacity more than the 59 gigawatts already anticipated. In this scenario, the specific emissions resulting from vehicle charging are near zero.

Additional Renewable Power Capacities Have Positive Effect on Net CO_2 Emissions from EVs

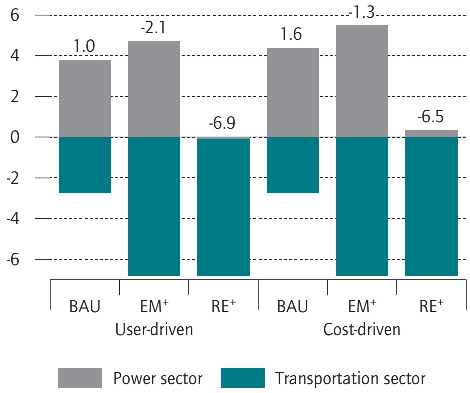
The introduction of electric mobility essentially shifts CO_2 emissions from the transport to the power sector.[19] Accordingly, electric mobility will have a beneficial net CO_2 emissions balance only if, by using electric vehicles rather than vehicles with a combustion engine, the road traffic emissions reductions exceed the increase in emissions caused by the generation of the additional electricity needed. An analysis based on the TEMPS model (see Box 2) taking account of the CO_2 emissions in the power sector shows that the net emissions balance of EVs largely depends on the assumptions made.

According to the 2030 BAU scenario, the CO_2 reductions in the traffic sector achieved by EVs are more than offset by the increase in emissions in the power sector. Depending on the charging mode, the overall CO_2 emissions are 1.0 or 1.6 million tons higher than in a scenario with no electric mobility (see Figure 6). This equates to approximately one percent of the CO_2 emissions of passenger cars in Germany today.[20] In the EM^+ scenario, in contrast, net CO_2 emissions are 1.3 or 2.1 million tons lower, or up to two percent of the passenger cars' CO_2 emissions in Germany today. It must be said, however, that these reductions are achieved because in the EM^+ scenario—unlike in the scenario with no electric mobility (or the BAU scenario)—the CO_2 limits for conventional passenger cars are assumed to be far stricter. In both scenarios, the specific CO_2 emissions resulting from the additional electricity demand for EVs will be greater in 2030 than those produced by internal combustion vehicles. This means that the expected efficiency gains or emissions reductions for conventional passenger cars are greater than the impact of the assumed expansion of renewable energy sources by 2030 on the CO_2 emissions of the charging power.

Figure 6

Net CO_2 balance of transportation and power sectors in 2030

In million tons CO_2



The graph shows the results of respective scenarios compared to a reference scenario without electric vehicles and without additional renewables.

Source: Kasten, P., Hacker, F. (2014), l.c.

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Emissions decrease in the transportation sector and increase in the power sector.

This finding no longer applies, however, if the introduction of electric mobility is accompanied by additional renewable power generating capacities (RE^+). According to these model simulations, the electric vehicles of 2030 are virtually CO_2 neutral in the power sector. Accordingly, the net CO_2 emissions balance is 6.5 to 6.9 million tons lower than in a scenario with no electric mobility (a good six percent of traffic-based emissions in Germany). This accordingly allows to fully realize the potential of electric mobility to reduce CO_2 emissions.

Policy Conclusions

The impact of electric mobility on the German power system and the CO_2 emissions balance of EVs were studied as part of a European research project. Several energy policy conclusions can be drawn from the model results.

First, the total energy consumption of future electric vehicles is essentially to be regarded as unproblematic. Yet the possible peak loads from vehicle charging can be substantial. To avoid problematic peak loads, system cost-optimized vehicle charging is far preferable to un-

19 Any changes in mileage or size range structure of the vehicle fleet are not taken into account here. It is assumed that mileage is constant in all scenarios.

20 In 2010, the direct CO_2 emissions from passenger cars in Germany amounted to 110 million tons.

controlled charging where the EVs are fully charged as rapidly as possible after being connected to the power grid. Due to limited power generating capacities, in future it may be necessary to limit purely user-driven charging by means of regulation, at the very latest when vehicle fleets reach the size assumed in the 2030 scenarios. Even improving the charging strategy from a fully user-driven to an at least partly cost-driven mode could lead to substantial improvements.

Second, the model results show that optimized vehicle charging not only facilitates the integration of renewable energy sources into the power system but can also increase the utilization of hard-coal- and lignite-fired power plants. If the government aims to politically introduce electric mobility in connection with the use of renewable energy sources, steps must be taken to ensure that renewable energy capacities are further expanded beyond the levels set down in existing scenarios. With regard to CO_2 emissions, this is particularly important as long as the installed capacities of emissions-intensive power plants are still sizable and, what is more, these plants are increasingly under-utilized in the context of the German energy transition. As to the energy system, it is of no consequence whether the additional power generated from renewable sources is consumed entirely by the EVs themselves by means of a dedicated charging strategy, or whether some of the additional power generated is used to cover other power demand.

Third, cost-optimized vehicle charging can only help reduce emissions if the external costs of these emissions are factored in to the wholesale electricity price accordingly. Otherwise, cost-optimized charging can lead to above-average specific CO_2 emissions that are even greater than those for uncontrolled charging. Failure of policy-makers to put an appropriate price on CO_2 emissions would render other emissions-oriented charging strategies necessary which may be feasible in theory but which are very unlikely to be implemented in practice.

What is important, however, is that electric mobility is not introduced with a view to short- and medium-term CO_2 emissions effects only. In fact, electric vehicles can bring about a host of other advantages such as lower local emissions from other air pollutants and reduced dependency on mineral oil in the transport sector. In particular, electric mobility offers the opportunity to use energy gained from domestic renewable sources without the utilization of biofuels. In the long-term, beyond 2030, battery-driven EVs pave the way for alternative drive concepts and fuels and open up new possibilities for near-zero-emissions vehicles powered by renewable sources of energy.

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