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# Economic and Environmental Viability of using a PV plant as an energy source for battery electric vehicles

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**Summary**

This paper focuses on investigating the usage of photovoltaics (PV) as electricity source for battery electric vehicles (BEV). The potential of PV usage is assessed based on user surveys within the InitiativE-BB and InitiativE-BW projects. A case study of a BEV used in 2015 and 2016 in conjunction with a roof-installed PV plant is analysed, charging patterns are derived and $CO_2$ emissions originating from electricity production are calculated. The effect of using PV electricity on $CO_2$ emissions and costs is quantified and a TCO comparison to conventional vehicles is performed.

The results for 2015 and 2016 show that using PV for BEV charging is beneficial in terms of costs and emissions with savings of 16 to 20% of grid energy and 15 to 18% of $CO_2$ emissions. Concerning total costs of BEV ownership the PV usage has a minor reduction effect (-10% on energy costs, -1% on TCO), as other cost components such as leasing rates take the major share.

Compared to conventionally powered cars the BEVs energy costs per km (incl. PV charging) are reduced by 49% vs. a gasoline car and by 12% vs. a diesel car in similar applications. However, the mileage-based TCO of the conventional cars are lower by 42% in the diesel case and by 6% in the gasoline case due to significantly lower leasing rates.

*Keywords: photovoltaic, charging, case-study, LCA (Life Cycle Assessment), cost*

## 1 Introduction

Electric vehicles (EV) are foreseen as one mitigation instrument in climate protection and air pollution control strategies [1]. In the context of the German energy transition strategy they are discussed to work as mobile storages to help balancing fluctuations due to increasing shares of renewable electricity sources. Vice versa, an increasing share of renewables in the German electricity mix shall improve the well-to-wheel (WTW) $CO_2$ emission balance of EVs.

To enhance market penetration of EVs in Germany the three-year research projects “InitiativE Berlin-Brandenburg” and “InitiativE Baden-Württemberg” were started in 2014. Their focus is to gain insights on

EV real world usage, charging patterns and energy consumption, $CO_2$ emission balances and economic viability.

This study focuses on investigating the usage of photovoltaics (PV) as electricity source for battery electric vehicles (BEV) within both projects for the years 2015 and 2016. The ownership rate of PV plants and a specific use case of a BEV used in conjunction with a roof-installed PV plant are analysed. Based on the charging patterns the $CO_2$ emissions originating from electricity production are calculated. Finally, life cycle $CO_2$ emissions and total costs of ownership (TCO) are derived and the effect of using PV electricity on emissions and costs is quantified.

## 2 PV usage in InitiativE research projects

The scientific approach of the InitiativE projects includes a combination of vehicle data loggers to gain driving and charging patterns and user surveys (workshops, interviews, online questionnaires) to gain additional information on EV usage, PV availability and boundary conditions.

Until the end of 2013, 18 GW of roof-mounted PV plants have been installed in Germany [2], 70% of them with a power of less than 10 kW, 25% with a power of 10 to 40 kW and 5% with more than 40 kW [3]. The majority of the installed plants are thus not sufficient to provide adequate power for charging stations with charging rates > 10 kW.

The analyses of the online questionnaires show that 30% of the company´s charging sites in the Berlin-Brandenburg (BB) region and 43% in the Baden-Württemberg (BW) region have a PV plant installed. Further 7 to 10% are planning to install a PV plant within the next 12 months (see Fig. 1). In both regions roughly 70% of the PV plant owners are able to use the produced electricity to charge their EV.

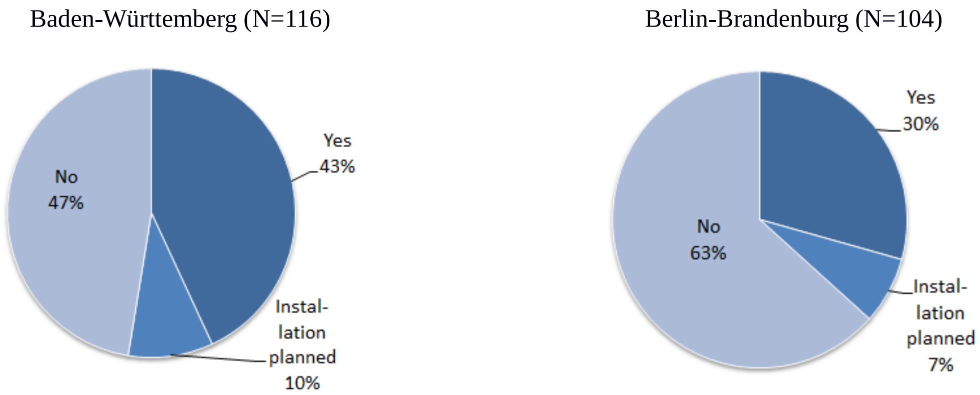


Figure 1: Photovoltaics plant availability rate at the company sites in the Baden-Württemberg region (left) and Berlin-Brandenburg region (right)

In both regions, the majority of PV plant owners are small- to medium-sized companies with less than 120 employees, half of them having up to 15 employees. The fields of business of PV owners lie in manufacturing and construction, consulting, social and administrative services as well as research and development. Companies in Berlin-Brandenburg without a PV plant have on average twice as many employees as those companies owning a PV plant. In Baden-Württemberg there were no significant differences in the average number of employees between PV owners and non-owners. In BB companies without PV tend to have more vehicles (mean=28 vehicles) in their fleet than companies with a PV (mean=12 vehicles). In BW we observed the opposite trend; companies which installed a PV plant have on average larger fleets (mean=21 vehicles) than companies without a PV plant (mean=11 vehicles).

61% (63%) of the study participants in Baden-Württemberg (Berlin-Brandenburg) have installed an own charging facility > 3.7 kW for their electric vehicle(s) (Fig. 2). 57% (59%) of the commercial users installed charging stations with a power between 11kW and 22 kW. In both regions only 4% of the participants installed a fast charging station with a power of ≥ 44 kW. In contrast to the Baden-Württemberg region, the commercial users in Berlin-Brandenburg seem less inclined to use a charging facility for their EV with 3.7 kW.

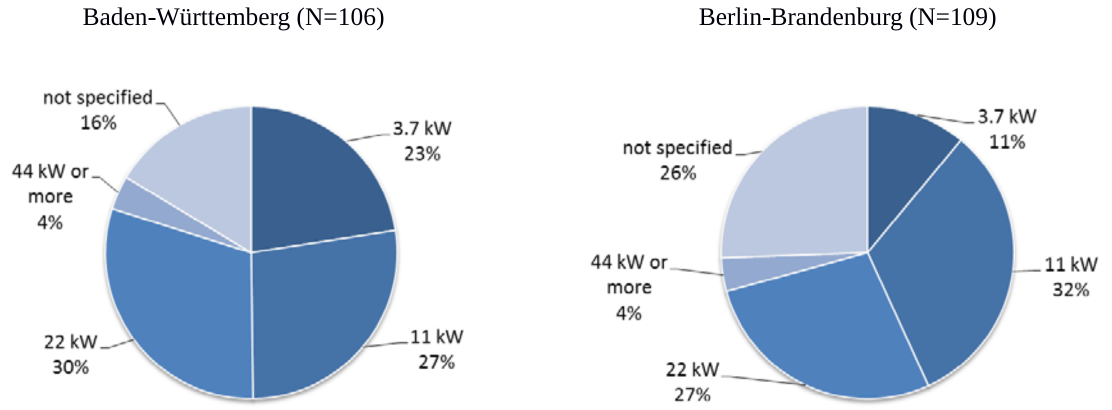


Figure 2: Charging power of the installed charging stations at all company sites in the Baden-Württemberg region (left) and Berlin-Brandenburg region (right)

In order to assess the potential of direct PV energy use within the two regions, the driving and charging characteristics of the two fleets were analysed using the statements from the questionnaires. A comparison of the typical time slots for the start of charging shows that 36% of the participants in Baden-Württemberg and 41% of the participants in Berlin-Brandenburg charge their EV after 6 pm, a time of day potentially unfavourable for direct PV energy use (Fig. 3). On the other hand, 59% of the participants in Baden-Württemberg and 49% of the participants in Berlin-Brandenburg charge their EV during daylight hours from 6/7 am to 6 pm. In Baden-Württemberg, a quarter of the users stated that they would charge their EV between 12 am and 3 pm. In Berlin-Brandenburg, only 10% of the participants charge around noon. This time period has a high potential for using PV energy to charge the EV.

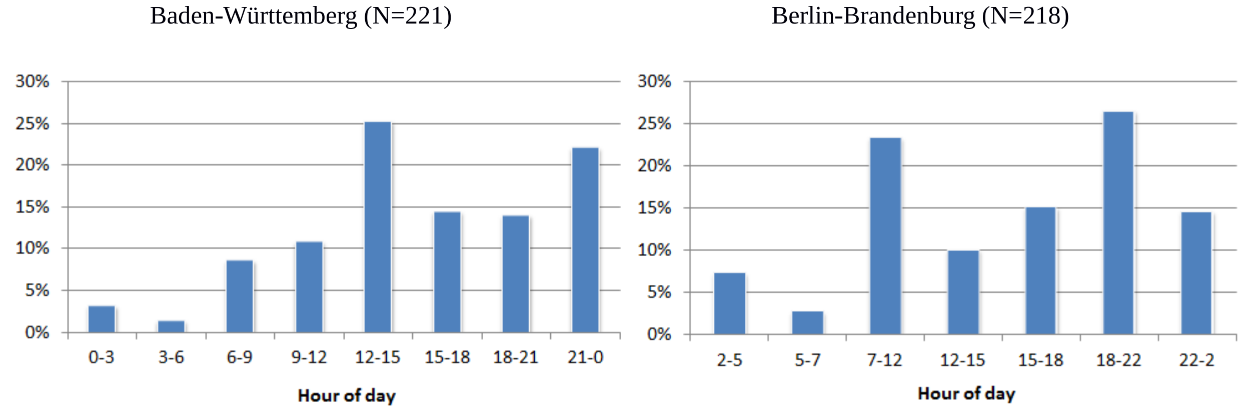


Figure 3: Typical time slots for start of charging in Baden-Württemberg (left) and Berlin-Brandenburg (right) – all commercial users, multiple answers possible

The vast majority of the commercial EV users in Baden-Württemberg (70%) charge daily at their workplace, while only 42% do so in Berlin-Brandenburg (Fig. 4). In that region, not all commercial users seem to charge on a daily basis: another 36% stated that they would charge their EV at work, but only one to three days a week. Another 10% stated that they would never charge at work (3% in Baden-Württemberg). The results suggest that for the participants in Berlin-Brandenburg charging at home or at public charging stations seems to be more common than in Baden-Württemberg.

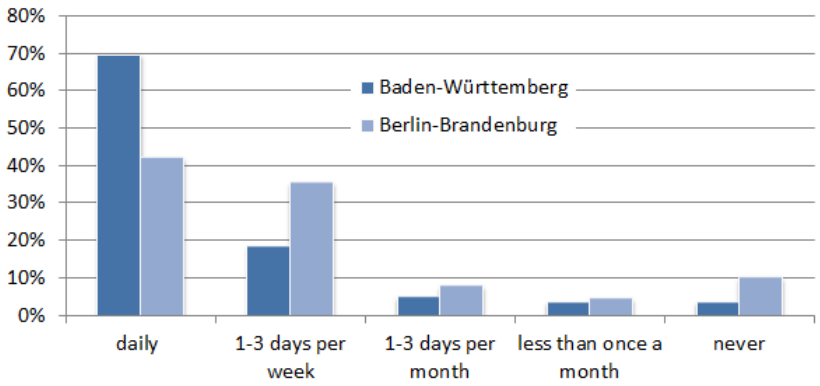


Figure 4: Charging frequencies at workplace locations per company – all commercial users

# 3 BEV use case

The BEV in this use case is a Renault Zoe Life (B-Segment) which is used by various employees of a clearing centre in Baden-Württemberg in south-west Germany. The vehicle is predominantly charged by an 11 kW charging station at the companies' premises. In 2015 the annual mileage of the vehicle was 14,543 km with an average specific energy consumption of 20 kWh/100 km including charging station losses [4]. The BEV operator's business premises include a roof mounted photovoltaic system with a power rating of 18 $kW_{peak}$ and guaranteed revenues of 12.22 Ct/kWh excl. VAT [5]. In comparison to typical PV power generation curves this specific PV system's power generation is shifted to the evening hours due to the distinct south-westerly orientation of the roof.

## 3.1 Electricity production and related $CO_2$ emissions

The German Environment Agency (Umweltbundesamt, UBA) publishes the average annual $CO_2$ emission factor for electricity consumption in the German electricity production mix and also the annual electricity production and related $CO_2$ emissions per production source [6][7]. The emission factors are the basis for update reports of German greenhouse gas emissions in the "National Inventory Report for the German Greenhouse Gas Inventory" [8] within the United Nations Framework on Climate Change.

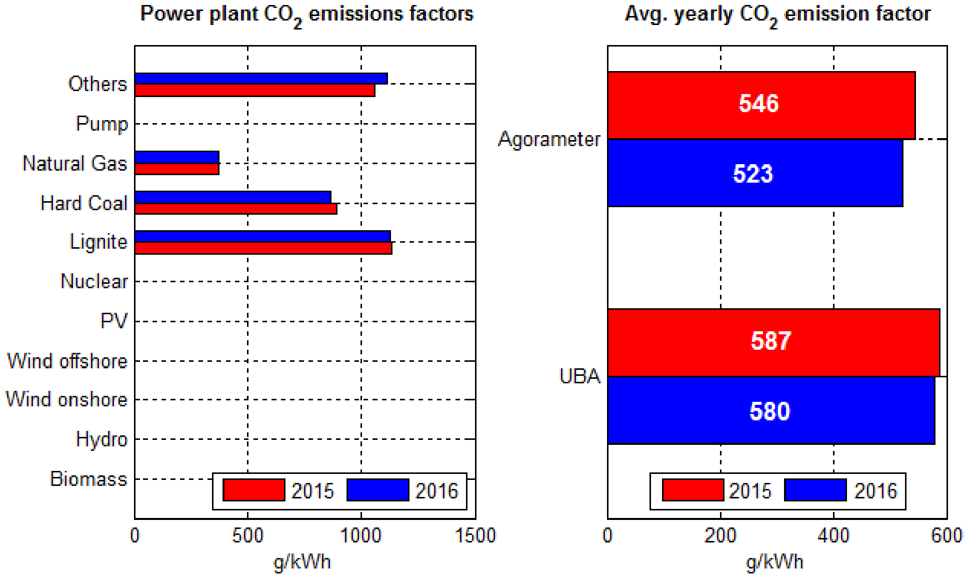


Figure 5: Annual $CO_2$ emission factors per production source [6][7] (left) and resulting annual average according to own calculations based on [6][7][9][10] (right)

Within this paper it is intended to calculate the BEV $CO_2$ emissions based on the $CO_2$ emission factors used for inventory reporting. Their main disadvantage is that they are not temporally resolved i.e. electricity consumption produces the same emissions regardless of time and actual electricity production mix. Thus, in addition to the UBA data the Agorameter database [9][10], which records the composition of electricity production sources for each hour within a year, is used. In conjunction with the annual UBA $CO_2$ emission factors per production source the hourly emission factors for electricity consumption in the German electricity mix are derived. It has to be mentioned, that the absolute values of annual electricity consumption and average annual $CO_2$ emission factors differ between UBA and Agorameter database due to different methodologies of data acquisition. However, it is assumed that relative emissions savings calculated with Agorameter data are transferable to UBA emission factors.

The average annual $CO_2$ emission factors calculated from UBA data are displayed in Fig. 5, left. The UBA methodology takes only those emissions related to the production of electricity into account. Thus so called renewables like photovoltaics, wind, hydro and biomass show a $CO_2$ emission factor of zero. Lignite and hard coal show greater emissions. “Others” summarizes production sources with a very small share of overall German electricity production like waste incineration and oil-based power plants. The comparison of the resulting average annual $CO_2$ emission factors of Agorameter database to the official UBA values is displayed in Fig. 5 (right). Apparently, the calculated Agorameter $CO_2$ emission factors are smaller than the UBA values in both years; also the decrease of $CO_2$ emissions from 2015 to 2016 is greater than in the UBA data.

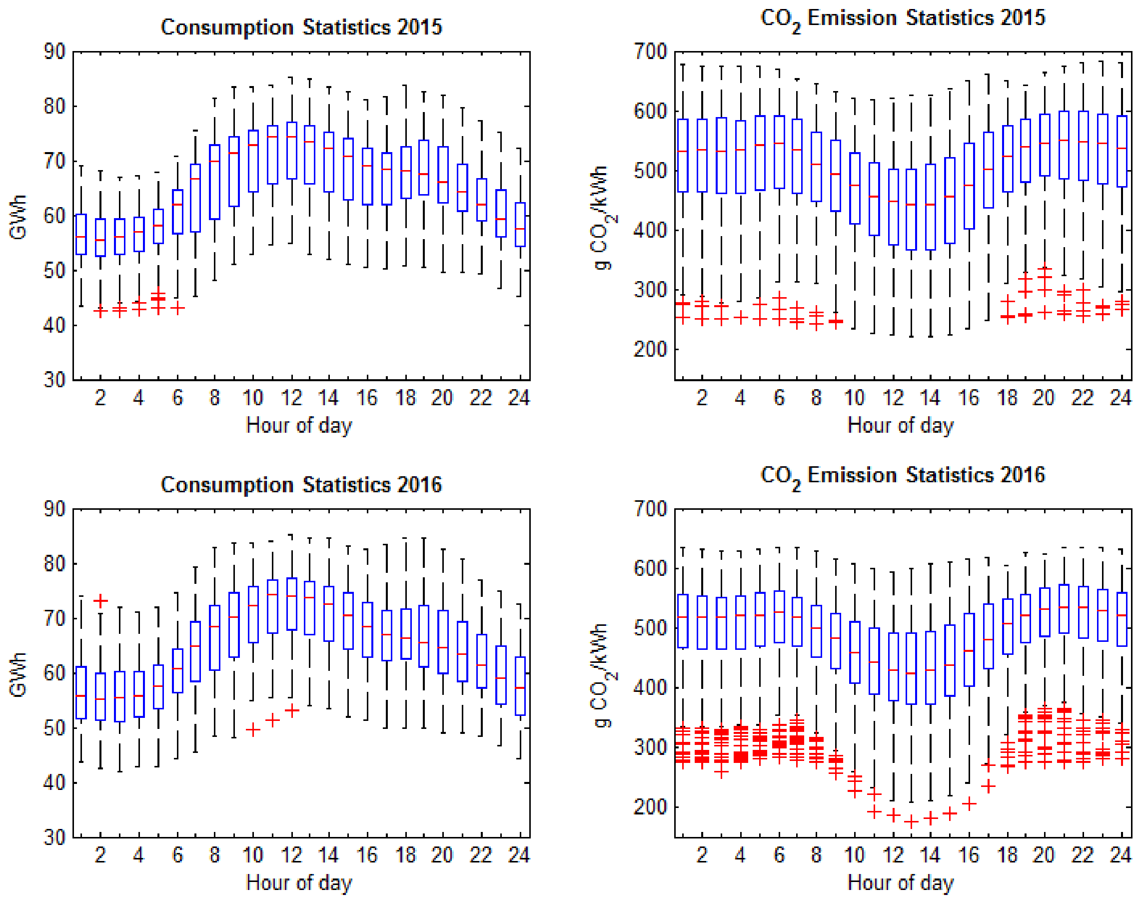


Figure 6: Statistical analysis of electricity consumption and specific $CO_2$ emissions in Germany

Fig. 6 shows the statistical analysis of Agorameter electricity consumption and the calculated $CO_2$ emission factors for 2015 and 2016. For each hour of the day the boxplots are the summarized representation of the whole year, where the box includes the 50% of samples between the first and third quartiles. The median of the sample series is displayed in red, and the whiskers and red crosses represent the range of samples and outliers. Although the ranges are wide in electricity consumption as well as in $CO_2$ emission factors, the fundamental correlations are evident; thus the discussion below refers to the median values.

In both years the lowest electricity consumption occurs between 2 am and 5 am followed by a steep growth until the consumption peak is reached around noon. Consumption decreases slightly between 1 pm and 5 pm and stabilises until 7 pm. After 7 pm it decreases steadily to the period of minimum electricity consumption between 2 am and 5 am. The $CO_2$ emissions per kWh of electrical energy derived from the conjunct Agorameter electricity production data and UBA emission factors are displayed in Fig. 6 (right). These emission factors show a peak period between 8 pm to 10 pm, remain relatively high during the night hours and have another peak around 6 am. This peak is followed by a steady decrease to the period of minimal emissions which occurs between 10 am and 3 pm.

The general rule for $CO_2$-optimised charging behaviour of a BEV with regard to the German electricity production mix is that the highest probability for low $CO_2$ emissions occurs during daytime, especially between noon and 2 pm. In a simplified consideration of the median values, charging processes exclusively in this period would reduce the specific $CO_2$ emissions by roughly 20% from 535 g $CO_2$/kWh to 425 g $CO_2$/kWh compared to charging exclusively around 9 pm.

## 3.2 BEV energy demand and charging patterns

To determine the BEV´s energy demand and charging patterns of the use case an algorithm was developed to analyse the data logged by the PV system. This algorithm and the general methodology to determine PV energy consumption and emissions are described in [11]. In 2015 a total of 529 charging events occurred at the company´s premises with an overall charging duration of 316 hours. In total 2,388 kWh were delivered to the BEV. In 2016 a total of 564 charging events occurred with a charging duration of 286 hours and a total charging energy of 2,334 kWh.

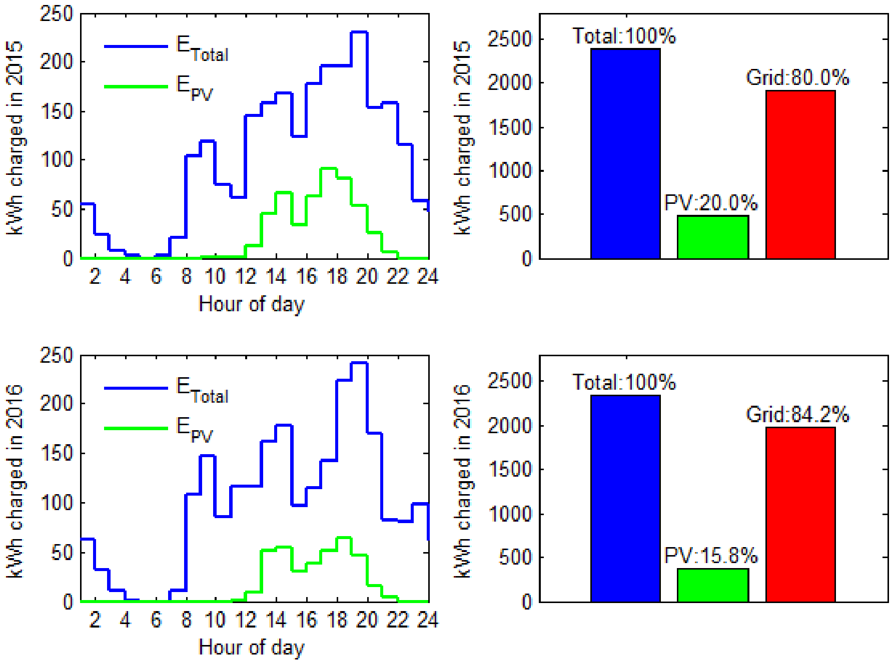


Figure 7: Hourly sum of charging energy and PV energy used for charging (left) and shares of charging energy (right) in 2015 (top) and 2016 (bottom)

Fig. 7 (left) shows the annual sums of total charging energy and PV charging energy per hour of the day in 2015 (top) and 2016 (bottom). In both years the BEV was typically charged between 8 and 10 am, between noon and 2 pm and between 6 and 9 pm; charging events between midnight and 6 am appear rather seldom. As a result the PV system provided 20.0% of the energy in 2015 and 15.8% in 2016 (Fig. 7, right) and the remaining 80.0% in 2015 respectively 84.2% in 2016 were supplied by the electricity grid. The relative and absolute utilisation of PV energy for BEV charging decreased from 2015 to 2016 due to two effects:

- In 2016 the amount of energy charged in the early morning hours was greater than in 2015, resulting in less available PV energy for these charging events. Also the amount of energy charged during midday, when the availability of PV energy is high, was smaller than in 2015. Thus, the change of charging behaviour was unfavourable in terms of PV energy used for charging the BEV.
- The total PV output of the PV system at the company's premises in 2016 was 8.5% smaller than in 2015. Thus, in 2016 the probability of using PV energy for charging the BEV was smaller than in 2015.

## 3.3 $CO_2$ emissions related to battery charging

The $CO_2$ emissions during charging are provided two ways from the previously determined charging patterns: first with the $CO_2$ emissions factors in an annual consideration based on UBA data, second with consideration of hourly resolved emission factors based on the linkage of Agorameter and UBA data. In case of pure grid charging UBA's annual $CO_2$ emission factors of 587 g $CO_2$/kWh (2015) [6] respectively 580 g $CO_2$/kWh (2016) [7] are unaffected by temporal distribution of the charging processes and remain unchanged as displayed in Fig. 8 (top). Considering the usage of PV energy for charging the average annual $CO_2$ emission factor is reduced exactly by the percentage (20% in 2015, 15.8% in 2016) of energy provided by the PV plant. This is plausible for UBA's annual emission factors because the PV energy rated with zero emissions directly substitutes a part of grid energy.

The case is different for the temporally resolved emission data based on the linkage of Agorameter and UBA displayed in Fig. 8 (bottom). Here the specific emission factors in 2015 (2016) for pure grid charging are calculated to 518 (501) g$CO_2$/kWh. Compared to the Agorameter annual average emission factors (Fig. 5) these emission factors already demonstrate emission reductions of 5.1% in 2015 respectively 4.2% in 2016 due to a favourable timing of charging processes. The effect of PV charging is evaluated by comparison of the pure grid charging emission factor with the emission factor for the combination of grid and PV charging - both temporally resolved. In both years the decrease of $CO_2$ emissions is smaller than in the previously discussed case with UBA's annual emission factors. In 2015 (2016) PV utilisation leads to 18.3% (14.5%) decrease, thus being smaller than the amount of grid energy substituted by PV energy. The conclusion is that the PV plant substitutes grid energy at times when grid energy is already relatively clean.

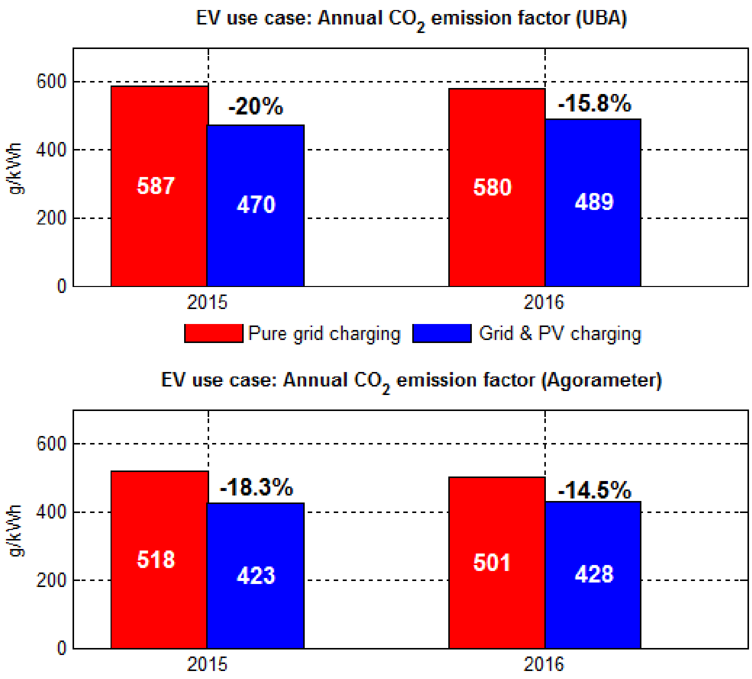


Figure 8: Annual average $CO_2$ emission factors of BEV with and without PV charging according to UBA [6][7] (top) and derived from temporally resolved electricity production mix based on Agorameter [9][10] (bottom).

The mileage based $CO_2$ emissions of the BEV in the considered use case are determined by merging the emission reductions derived from temporally resolved Agorameter data with the official average annual

$CO_2$ emission factor published by UBA. In both years the energy consumption of the BEV at charging station input accounts to 20 kWh/100 km. Assuming UBA's annual average $CO_2$ emission factor of 587 (580) g $CO_2$/kWh in 2015 (2016) this results in mileage based emissions of 117 (116) g $CO_2$/km if energy is purely supplied from grid energy. If PV plant utilisation is considered the $CO_2$ emissions are reduced by 18.3% to 96 g $CO_2$/km in 2015 and by 14.5% to 97 g $CO_2$/km in 2016.

## 3.4 $CO_2$ emissions related to BEV manufacturing

The $CO_2$ emissions produced during manufacturing of the vehicle are determined based on emission factors of the ecoinvent database [12]. The results of this approach are displayed in Table 1. In the considered use case a total of 10.8 t of $CO_2$ emissions are emitted during the BEV-manufacturing.

Table 1: Life-cycle $CO_2$ emissions related to BEV manufacturing

| | Unit | $CO_2$ |
|---|---|---|
| **Vehicle data** | | |
| Vehicle mass without battery | kg | 1,213 |
| Battery mass | kg | 435 |
| **Emission factors** | | |
| ecoinvent BEV without battery | kg/kg vehicle | 7.00 |
| ecoinvent battery | kg/kg battery | 5.41 |
| **Results: $CO_2$ emissions related to BEV manufacturing** | | |
| BEV without battery | kg | 8,491 |
| Battery | kg | 2,353 |
| **Total manufacturing emissions** | **kg** | **10,844** |

In the BEV use case the annual mileage in 2015 was 14,543 km. Assuming 12 years of BEV use results in a total mileage of roughly 175,000 km over the vehicle's lifetime. Eventually the mileage based $CO_2$-burden due to vehicle manufacturing accounts to 62 g $CO_2$/km.

## 3.5 Total $CO_2$ emissions in BEV use case 2015 and 2016

The overall mileage-based $CO_2$ emissions of the analysed BEV use case are composed of usage related emissions due to battery charging and production based emissions due to manufacturing of the BEV and its battery. Based on the respective values stated above, the mileage based $CO_2$-burden of that respective BEV amounts to 158 (159) g $CO_2$/km in 2015 (2016) including the emission benefits from PV system usage for battery charging. Without PV energy $CO_2$ emissions of 179 (178) g $CO_2$/km are derived for 2015 (2016), which is in good accordance to the value of 187 g $CO_2$/km published by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety in [13].

# 4 Total costs of ownership

For 2015, a cost-wise comparison of the BEV to a conventional diesel and a gasoline car of comparable commercial use and size were undertaken using the total costs of ownership methodology. All costs are based on the annual mileage of that respective vehicle (14,543 km for the BEV, 21,298 km for the diesel car and 9,950 km for the gasoline car) excluding VAT. The cost components analysed include costs for energy (including and excluding PV usage), leasing, maintenance and repair, insurance and taxes. In addition, costs for installing the charging station are accounted for. Here, a depreciation span of 10 years is used, following [14]. Today in Germany, purchase costs and thus leasing rates of electric vehicles are considerably higher than of conventional vehicles. To overcome this obstacle, the project's participants were granted subsidies of roughly 45% of the vehicle purchase costs in 2014 – 2016 with support of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

In Fig. 9 the respective energy costs of the BEV including and excluding PV are shown as well as energy costs of a diesel and a gasoline car. BEV energy costs including PV usage amounted to 4.34 €/100 km (0.22 €/kWh [15]), reducing the BEV's energy costs by around 10% if compared to the situation where PV usage is not taken into account (4.82 €/100 km, 0.24 €/kWh). As the diesel fuel price was relatively low in 2015

(1.03 €/l excluding VAT for that specific diesel vehicle, compared to 0.99 €/l as given in [16]) and as this diesel car was relatively fuel efficient (4.8 l/100 km), energy costs of the diesel car are almost equal to the BEV energy costs with 4.95 €/100 km. In contrast to that, the energy costs of the gasoline car are almost twice as high with 8.48 €/100 km. As energy taxes on gasoline fuel are higher than on diesel fuel in Germany, prices for gasoline fuel are higher and amounted to 1.11 €/l excluding VAT in 2015 for that respective car (1.17 €/l according to [16]). In addition, the fuel efficiency of that respective gasoline car was comparatively low (7.6 l/100 km).

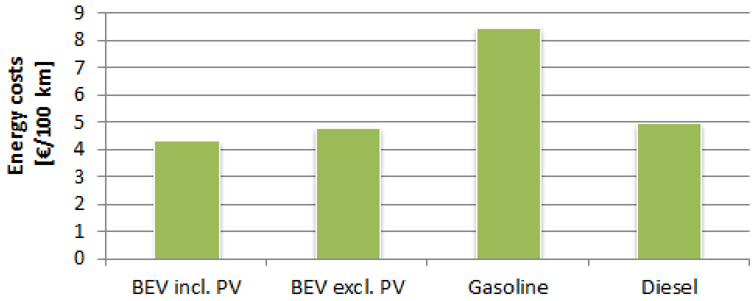


Figure 9: Energy costs per kilometre including/excluding PV charging (all figures excluding VAT)

While energy costs of BEV bear cost saving potentials, purchasing costs/leasing rates are more favourable for conventional cars. Adding up all other cost components mentioned above, the BEV’s TCO in 2015 amounted to 38.61 €/100 km including or 39.08 excluding PV charging (all figures including project-specific purchase subsidies, Fig. 10 top). The major cost components are the BEV’s leasing rates, accounting for 74/75% of the total costs (including subsidies), followed by energy costs (11/12%), vehicle insurance costs (8%), costs for installing the charging point (4%) and maintenance costs (1%). Battery electric vehicles in Germany are freed from motor vehicle taxation. The analysis shows that PV usage has a minor cost reduction effect (-10% on energy costs, -1% on TCO) as other cost components such as the leasing rates take the major share.

As mentioned before, the BEV’s leasing rates were subsidised with 45% within the research project. Under a full-cost-perspective, these costs should be included in the cost evaluation of electric vehicles. Fig. 10 bottom shows the resulting TCO when these subsidies are stated (9.63 €/100 km). Total costs of ownership then amount to 48.23 €/100 km, including PV usage.

In addition to the BEV, TCO were calculated for a diesel car and a gasoline car. These conventional cars are used for equal commercial purposes (social services) and belong to the A segment. The costs per kilometre of all vehicles were based on their respective annual mileage: 14,543 km (BEV); 21,298 km (diesel car); 9,950 km (gasoline car).

The TCO of the diesel car amounted to 22.28 €/100 km (42% lower than the BEV’s TCO including PV use and subsidies) and is thus the lowest of all drivetrains. At the same time, the diesel car had the highest annual mileage of all three cars (46% higher than the BEV and 114% higher than the gasoline car) which has a strong effect on the reduction of TCO per kilometre. Analogous to the BEV, the major cost component for the diesel car were its leasing rates (61% or 13.49 €/100 km). The second major cost element for the diesel car were its energy costs (22% of the total costs), followed by insurance costs (10%), motor vehicle taxation (3%) and maintenance (2%).

The TCO of the gasoline car amounted to 36.32 €/100 km and were thus slightly lower than the BEV’s TCO. The major cost elements are leasing rates (49% of the TCO), followed by energy costs (23%), insurance costs (21%), maintenance (3%) and taxes (1%). In the case of the gasoline car, motor vehicle taxes amounted to 26 €/a. Motor vehicle taxation in Germany is based on displacement size and $CO_2$ emissions and is differentiated between gasoline and diesel cars. Owners of diesel cars have to pay higher rates: the motor vehicle tax of the diesel car was 154 €/a. Still, these taxation rates are comparatively moderate and BEV owners do not noticeably profit from tax exemptions.

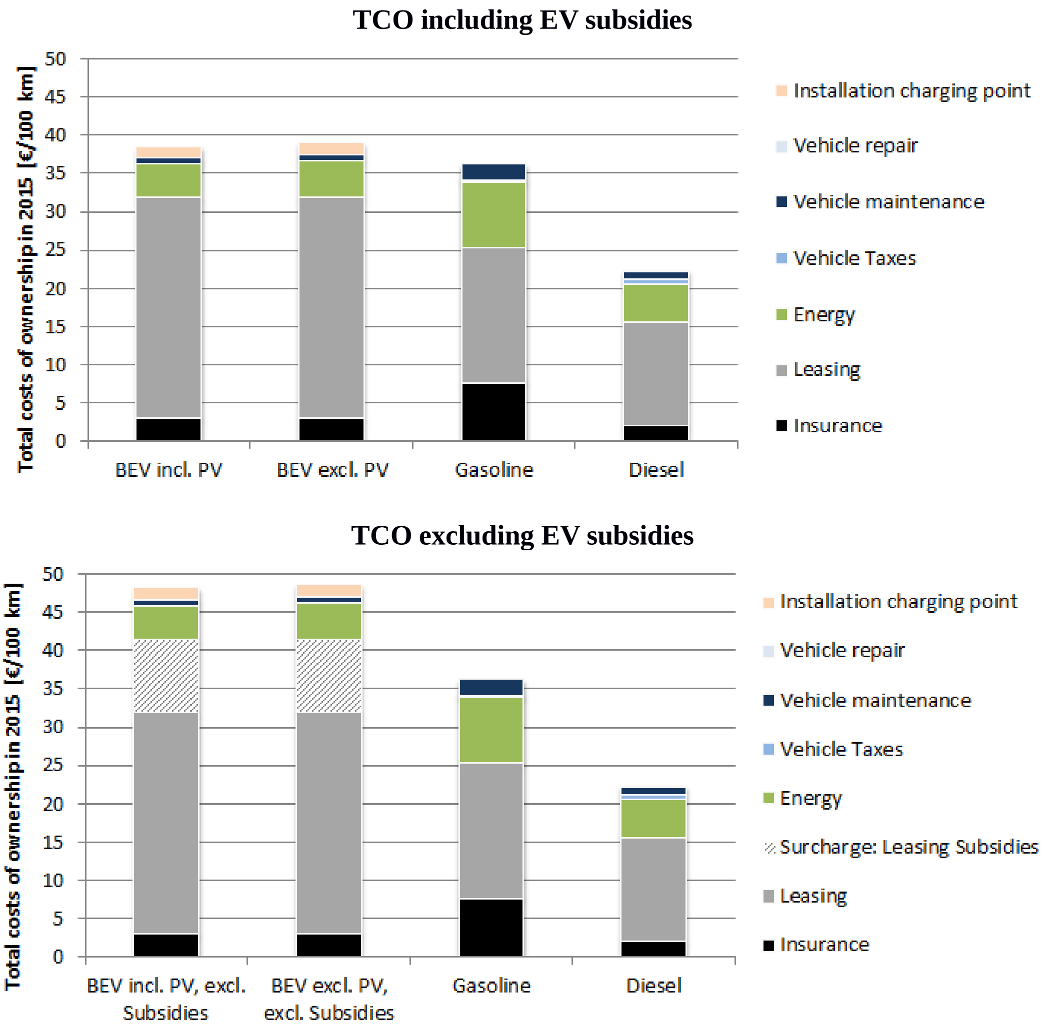


Figure 10: Total costs of ownership including/excluding PV and including/excluding subsidies; BEV vs. gasoline and diesel cars; all figures excluding VAT

Comparing the TCO of the conventional cars with those of the BEV, it is clear that BEVs in Germany today cannot compete cost-wise with conventional cars, as has also been shown in [17]. Reasons are:

- higher purchase prices of electric vehicles plus a strong OEM discount policy for conventional cars
- relatively high electricity prices and relatively moderate conventional fuel prices
- extra costs for the EV energy infrastructure
- relatively low motor vehicle taxation rates for (smaller) conventional cars.

# 5 Conclusions

The analysis within the InitiativE research projects revealed a good potential for using self-owned PV plants for BEV charging. According to the user surveys 30% of the company´s charging sites in Berlin-Brandenburg and 43% in Baden-Württemberg have a PV plant installed; the user surveys show that 50% to 60% of charging processes occur during daytime and roughly 25% in a time period around noon, when the availability of PV energy is high. However, considering that the majority of PV plants currently installed in Germany have a power rating of less than 10 kW, the effective contribution of self-owned PVs to charge EVs with adequate power of 11 kW or more is rather small.

The case study for a specific BEV in combination with an 18 $kW_{peak}$ PV plant was performed by analysing the charging processes recorded by the roof-top PV system. In 2015 (2016) the PV plant contributed 20% (16%) of the BEV’s charging energy. Compared to pure grid supply of charging energy the PV usage induces $CO_2$ emission savings of 18% (15%). Considering additional $CO_2$ emissions related to manufacturing of the BEV and its battery the mileage based $CO_2$-burden of that respective BEV amounts to 158 (159) g $CO_2$/km in 2015 (2016) including the emission benefits from PV system usage for battery charging. The $CO_2$-emissions without manufacturing but with PV usage amount to 96 g $CO_2$/km in 2015 and to 97 g $CO_2$/km in 2016. The conclusion of the case study is that usage of PV energy for BEV charging is definitely reasonable in terms of $CO_2$ emission savings.

The analysis of the BEV total costs of ownership showed that PV usage has notable effect on reduction of energy costs (-10%), but a minor effect on TCO (-1%) because other cost components such as the leasing rates take the major share. Compared to conventionally powered cars the energy costs per km of the BEV incl. PV charging are 49% less than those of a gasoline car and 12% less than those of a diesel car in similar applications. However, the mileage-based TCO of the conventional cars compared to the BEV including PV charging and subsidies are lower by 42% in the diesel case and by 6% in the gasoline case due to significantly lower leasing rates. As a conclusion it is evident that today BEVs in Germany cannot compete cost-wise with conventional cars due to the following main reasons:

- higher purchase prices of electric vehicles plus a strong OEM discount policy for conventional cars
- relatively high electricity prices and relatively moderate conventional fuel prices
- extra costs for EV energy infrastructure and
- relatively low motor taxation rates for (smaller) conventional cars.

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