Project InitiativE-BW - Real-world driving, energy demand, user experiences and emissions of electrified vehicle fleets

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1 INTRODUCTION

The research project *InitiativE-BW – Elektrische Flottenfahrzeuge für Baden-Württemberg* investigates real life operation of electrified vehicles in the German federal state of Baden-Wuerttemberg. It aims mainly at commercial applications of industrial and business customers, public authorities, service providers, car sharing fleets and, to a small extend, on individual customers. With support of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) a financial aid of 45% of the vehicle investment costs, i.e. the leasing rates, is provided for the participants of the project. The goal is to bring up to 500 electrified vehicles on the roads of the federal state within the project duration from January 2014 to December 2016.

The project addresses scientific issues in the fields of vehicle usage, energy consumption, emissions, user behaviour and life cycle analysis Thus vehicles have been equipped with data loggers; customer and user experiences are regularly assessed with structured surveys.

2 BACKGROUND OF THIS STUDY

EU Regulation 333/2014 (2014) sets per passenger car manufacturer a target of 95 g CO_2/km for the average tank-to-wheel emissions of new car fleets. Obviously, battery electric vehicles (BEV) do not cause any tank-to-wheel emissions. Nevertheless the regulation explicitly points out that green house gas emissions associated with generation and distribution of electric energy shall not erode the benefits related to improved energy use during operation of the vehicle.

From a user perspective energy costs are an important part of the total costs of ownership. Hence this paper addresses a specific use case, where the vehicle is charged by power from electricity grid as well as power provided by an on-site photovoltaic (PV) system. Based on measurements for 2015 and literature sources it discusses economic and ecologic benefits of PV power usage for BEV charging. The aim is to determine the influence on the vehicle's specific emissions in g CO_2/km using temporally resolved data of the 2015 electricity production mix and the resulting CO_2 emissions in conjunction with the charging events of the specific BEV use case.

3 THE BEV USE CASE

3.1 BEV characteristics and vehicle usage

In this paper a use case of one battery electric vehicle (BEV) in commercial operation is assessed. This BEV is a compact class Renault Zoe Life which is driven by various employees of a clearing centre in a rural area in the Upper Rhine Plain in southwest Germany.

The battery capacity is rated at 22 kWh and the vehicle is predominantly charged by an 11 kW wall box at the companies' premises. In 2015 the annual mileage of the vehicle was 14,543 km. In reference to the power supply of the wall box an average specific energy consumption of 20 kWh/100 km was determined for the same vehicle model with similar usage pattern at a different site (Kugler et al, 2016).

3.2 Photovoltaic system

The BEV operator's business premises include a roof mounted photovoltaic system. Under standard conditions (1000 W/m² solar radiation, cell temperature 25°C) the PV system has a power rating of 18.04 kW, also denoted as 18.04 kW_{peak}. According to German Renewable Energy Act (Erneuerbare Energien Gesetz, EEG) the first operating date determines the revenues earned for PV energy fed to electricity grid. The PV system was first taken into operation on 2014-07-01; based on Bundesnetzagentur (2016) this guarantees revenues of 12.22 Ct/kWh excl. VAT over 20 years of system operation. 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 (Figure 1).

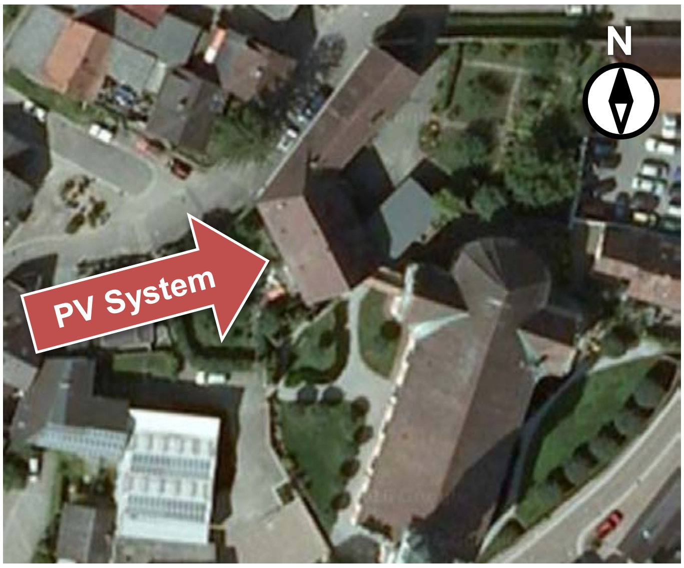

Figure 1: Location and orientation of the PV system used for BEV charging

Electric power generation of the PV system, the building's power consumption and power flows transferred to or taken from electricity grid are recorded by a data logger installed with the PV inverter. On the web-based service portal of the inverter manufacturer the data is available as average power per time interval with a maximum resolution of 15 min. The building's power also includes the charging events of the BEV. Whenever the BEV is charged via the 11 kW wall box the charge power is added to the base load consumption of the building. Thus the charging events are visible as additional consumption in the logged data.

4 IDENTIFICATION OF PV POWER USED FOR BEV CHARGING

4.1 Methodology to determine charging patterns

Charging power of a battery follows a typical pattern, which depends on the characteristic combination of battery size and charging infrastructure. Figure 2 displays a full cycle charging pattern for the combination of an 11 kW wall box and a 20 kWh battery. The figure is based on data from Beermann et al. (2010), and the continuous power is recalculated to 15-min average power to reflect the representation of the PV data logger.

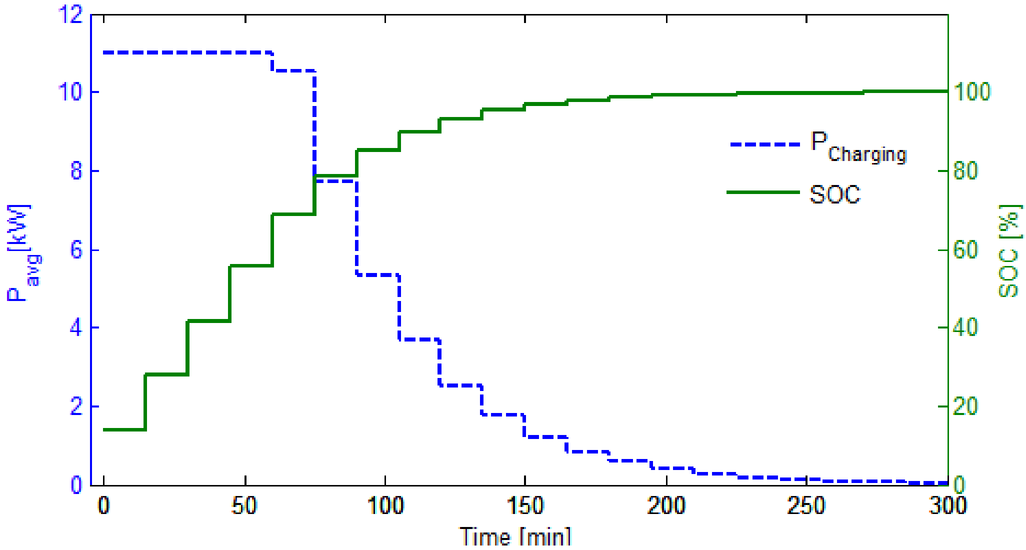

Figure 2: Charging pattern of a 20 kWh battery at 11 kW wall box, own diagram in 15 minute interval based on Beermann et al. (2010)

The basic concept for the identification of such charging patterns is shown in Figure 3, where the recorded power data for one exemplary day is displayed. The buildings power consumption data shows a steady base load power of approximately 1.5 kW at night and a higher, more varying power load during the day.

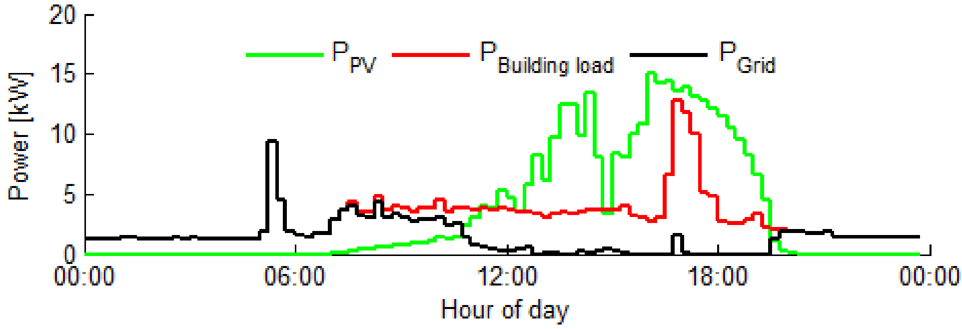

Figure 3: Power flows of PV system and building consumption

In this example power generation of the PV system starts at seven with low power and strongly increases at eleven in the morning. At half past two in the afternoon power generation drops suddenly, probably due to a cloudy sky. Between three thirty and seven in the evening the power generation matches the expected ideal PV power generation of a cloudless sky very closely. The data contains two charging events, one around five o'clock in the morning, the other around five o'clock in the afternoon. The first is completely covered by power from the electricity grid while the latter is covered predominantly by PV power. Within the latter a small grid power peak is visible, although PV power always exceeds the power consumption of the building. This is a result of using average power per 15 minute interval. Most likely generated power was temporarily insufficient to supply the charging power demand and the gap was covered by grid power for a few minutes.

The identification of charging events uses the building consumption base load needed for the electrical devices such as lighting, IT-infrastructure, heating etc. On the one hand this base load depends on the usage of the offices in the building, thus showing differences between working days and non-working days such as weekends or holidays. On the other hand seasonal changes occur due to the energy consumption of the heating system and the lighting devices. Hence an algorithm was developed to identify the typical building load for working day and non-working days for each month.

The algorithm gathers the building's power consumption for the working and non-working days of each month and assigns them to the belonging 15 min interval of a day. Then the median value of each interval is determined separately for the working and non-working days. This median is defined as the typical load of the consumers in the building for this interval. Eventually two reference load curves are derived for each month, one representing the working day power load and the other the non-working day power load of the building. Figure 4 shows the resulting reference curves for each month.

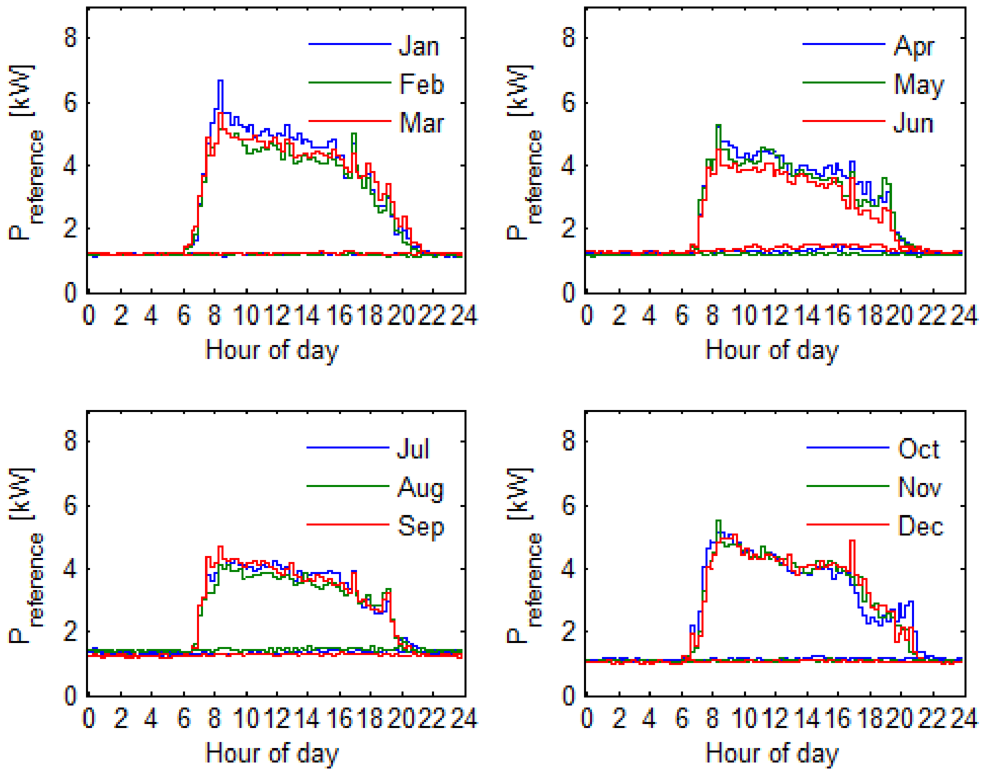

Figure 4: Monthly working and non-working day base load of the building

In a next step each day's power load is compared to the respective reference load curve. If the power load in an interval differs by more than +1.75 kW from the reference a charging event is detected and the power difference is documented as a charging event.

The monthly energy sum of the detected charging events in comparison with the monthly consumption values measured by the energy meter of the wall box showed maximum deviations of +/- 5%. A double check with the charging events of the data logger installed in the BEV underpins adequacy of the described methodology.

4.2 Results for 2015

Application of the described algorithm on the data logged by the PV system enabled detection of the charging events and the energy transferred through the wall box to the BEV. In 2015 a total of 529 charging events occurred. The overall charging duration at the companies' premises was 316 hours and 15 minutes with an average charging power of 7.55 kW and a total energy of 2,388 kWh delivered to the BEV. The PV system provided 20% of the energy (Figure 5 right side) and the remaining 80 % were supplied by the electricity grid.

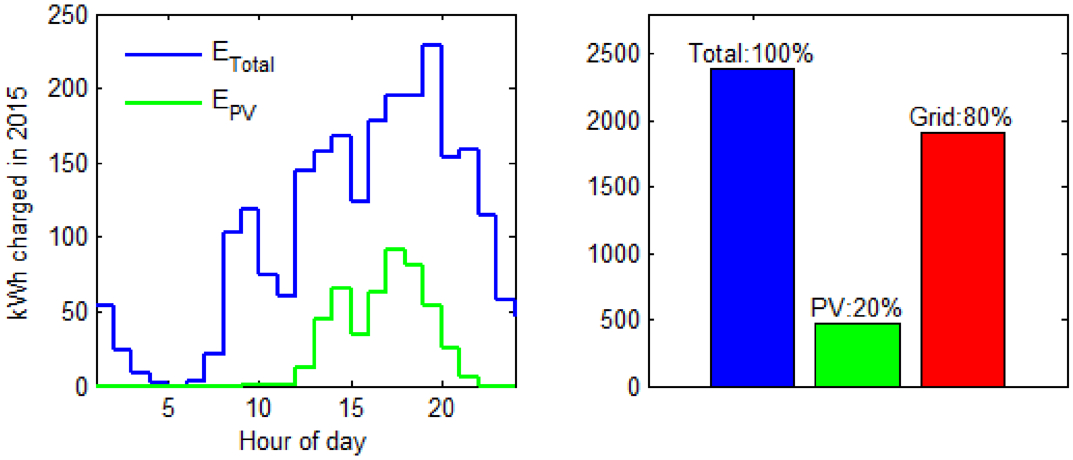

Figure 5: Hourly sum of charging energy and PV energy used for charging (left) and shares of charging energy (right) in 2015

For the correlation with the temporally resolved German electricity production mix in 2015 the charging energy demand was aggregated to intervals with a resolution of one hour. In this representation the charging events cover 795 of the years 8,760 hours. The diagram on the left in Figure 5 shows the sums of total charging energy and PV energy used for charging for each hour of the day. The BEV was typically charged between 8 and 10 in the morning and between noon and 10 in the evening. The maximum of charging energy was delivered between 7 and 8 in the evening.

5 DETERMINATION OF CO_2-EMISSIONS

5.1 Hourly CO_2 emissions of electricity production for 2015

The CO_2 emissions due to charging the BEV with energy taken from electricity grid are determined based on a database providing the German electricity production mix for the year 2015 temporally resolved in hourly intervals (Agorameter 2016) and yearly factors for the direct CO_2 emissions in 2015 for each electricity production source (Icha and Kuhs 2016). In a first step the total mass of direct CO_2 emissions related to each type of 2015 production plant was correlated with the produced amount of electric energy to define emission factors for direct CO_2 emissions in g CO_2/kWh. Table 1 displays the resulting direct CO_2 emission factors linked to each electricity source.

Table 1: Direct CO_2 emissions linked to each electricity source listed in Agorameter (2016) for the year 2015 based on Icha and Kuhs (2016)

Electricity source	Biomass	Hydro	Wind onshore	Wind offshore	PV	Nuclear
g CO_2/kWh	0	0	0	0	0	0
Electricity source	Lignite	Hard Coal	Natural Gas	Pump	Others[1]	
g CO_2/kWh	1,136	888	370	0	1,057	

Assignment of the derived emission factors to the hourly electricity production mix results in temporally resolved overall direct CO_2 emission factors. The statistics for the sample emission factors is shown in Figure 6. In these box plots the top and bottom of each box are the 25th and 75th percentiles of the samples. The red line in the middle of each box is the sample median. The lines extending above and below each box (whiskers) are drawn from the ends of the interquartile ranges to the furthest observations with a maximal length of 1.5 times the range between the 25th and 75th percentiles; data points outside the whiskers are outliers marked with a red + sign.

Although the hourly values are distributed over a wide range due to varying shares of production types throughout the year, the overall picture is evident: during the daylight hours the emissions are significantly lower than in the nights, with a minimum between 11 am and 2 pm.

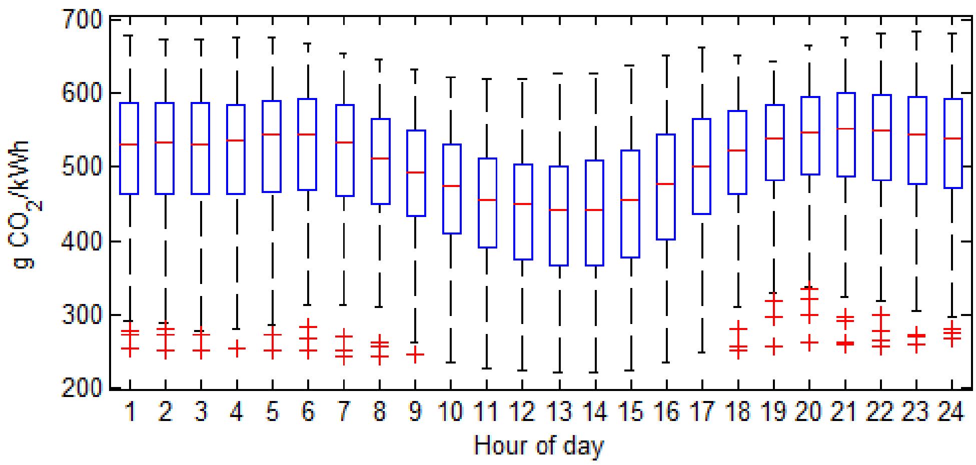

Figure 6: Statistical distribution of hourly direct CO_2 emission factors of the German electricity mix in 2015

[1] Others: Mineral oil plants, waste incineration plants and unspecified sources

5.2 CO_2 emissions related to BEV charging

The correlation of charging events for the BEV and hourly CO_2 emissions is performed for two cases:

1. The reference case assumes that the energy for all charging events is purely supplied by grid electricity.
2. The BEV use case takes the de facto grid and PV energy of the charging events into account.

In both cases the temporally resolved charging events are correlated with the temporally resolved CO_2 emission factors of the energy production mix. Table 2 summarises the numeric results of this analysis.

Table 2: Comparison of absolute CO_2 emissions and derived specific CO_2 emissions of 2015 charging events for reference case and real use case

	kg CO_2	Yearly average g CO_2/kWh
Reference case without PV		
CO_2 emissions from grid charging	1,235.8	517.5
BEV use case with PV		
CO_2 emissions from grid charging	1,010.2	528.8
Avoided CO_2 emissions by PV charging	225.6	472.4
Overall CO_2 emissions in use case	1,010.2	423.0
Use case CO_2 reduction	**18.26 %**	

The main conclusion is that in the BEV use case PV power usage for charging offers a CO_2 emission reduction of 18.26% compared to the case of pure grid charging. Although it may seem contradictory that the PV energy share of 20% exceeds the actually realised CO_2 emission reduction, this contradiction is resolved by observation of the avoided emissions due to PV charging: whenever energy is provided by the local PV system the actual German electricity production mix is also cleaner in terms of specific CO_2 emissions.

For the year 2015 the German Environmental Agency (Umweltbundesamt, UBA) publishes a CO_2 emission factor of 587 g CO_2/kWh in Icha and Kuhs (2016). Comparison of this value to the Agorameter electricity production mix in conjunction with the emission factors in Table 1 shows a deviation of 15% due to different databases and methodologies. Therefore the absolute specific CO_2 emission factor stated in Table 2 is not considered for the calculation of mileage-based CO_2 emissions of the BEV; however, the calculated relative reduction of CO_2 emissions together with the UBA value is considered adequate for this purpose. Based on the BEV's average energy consumption of 20 kWh/100km and the specific emissions of 587 g CO_2/kWh for the German electricity production mix mileage-based CO_2 emissions of 117 g CO_2/km are derived for the reference case. In the BEV use case with PV charging these specific emissions are reduced to 96 g CO_2/km.

5.3 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 (ecoinvent Center 2016). For the purpose of specific emission calculation in g CO_2/km the pure CO_2-emissions are relevant, but most sources provide data on CO_2-equivalents instead of pure CO_2 (for example Wang et al. (2014) and Dallinger et al. 2011). Consequently the EcoInvent database is used to calculate pure CO_2 emissions as well as CO_2-equivalent emissions enabling comparison of the DLR approach with literature values from Wang et al. (2014) and Dallinger et al. (2011). The results of this approach are displayed in Table 3. The calculated $CO_{2,eq}$ emissions related to vehicle and battery manufacturing of 12.1 t are within the range of 9.8 t according to Wang et al. (2014) and 14.3 t according to Dallinger et al. (2011). It is thus concluded that the calculated 10.8 t of CO_2 emissions related to BEV-manufacturing are feasible for the purpose of this study.

Table 3: Life-cycle CO_2 and $CO_{2,eq}$ emissions related to BEV manufacturing

	Unit	**CO_2**	**$CO_{2,eq}$**
Vehicle data			
Vehicle mass without battery	kg	1213	
Battery mass[2]	kg	435	
Emission factors			
Ecoinvent BEV without Battery	kg/kg vehicle	7.00	7.74
Ecoinvent Battery	kg/kg battery	5.41	6.16
Results: CO_2 emissions related to BEV manufacturing			
BEV without battery	kg	8,491	9,389
Battery	kg	2,353	2,680
Total manufacturing emissions	**kg**	**10,844**	**12,069**

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.

5.4 BEV CO_2 emissions – the 2015 case

The overall mileage-based CO_2 emissions of the actual 2015 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 g CO_2/km in 2015 including the emission benefits from PV system usage for battery charging.

[2] Original battery mass 290 kg, multiplied by 1.5 to account for replacement after 8 years

6 IMPACT OF PV SYSTEM POWER USE ON BEV ENERGY COSTS

The energy costs for BEV charging are based on the energy costs survey of BDEW (2016). For 2015 this source indicates energy costs of 24.10 Ct/kWh excl. VAT (28.68 incl. VAT). If the BEV would have been charged exclusively with electricity from the grid this would be the costs for each kWh of charging energy.

In the 2015 use case with the calculated 20% PV share and the earnings of 12.22 Ct/kWh, which could have been realized if the PV power had been fed to the grid instead of using it for battery charging, the BEV energy costs drop by 9.86% to 21.72 Ct/kWh excl. VAT.

As already mentioned the earnings for PV electricity fed to grid depend on the date of first operation. Thus the impact of PV power used for charging on the energy cost reduction is highly sensitive to this date. Table 4 compares the achieved reduction of the real case with virtual other cases. Within the table only the dates and the resulting earnings are adapted to the guaranteed earnings indicated by Bundesnetzagentur (2016).

Table 4: Energy costs depending on date of first operation of PV system[3]

First operation of PV system:		**2012-07**	**2013-07**	**2014-07**	**2016-07**
Earnings for PV energy fed to grid excl. VAT	Ct/kWh	17.95	14.30	12.22	11.97
Cost for EV charging without PV system	Ct/kWh	24.10			
Cost for EV charging with PV-system	Ct/kWh	22.87	22.14	21.72	21.67
Energy cost reduction	%	5.10	8.13	9.86	10.06

The conclusion of this comparison is that economic benefits of PV power usage for BEV charging are higher, if the PV system is younger in terms of date of first operation. Hence installation of a PV system might be an appropriate action to reduce energy costs of vehicle operation for BEV users with a suitable charging behaviour.

7 SUMMARY AND CONCLUSIONS

In the German research project *InitiativE-BW – Elektrische Flottenfahrzeuge für Baden-Württemberg* the real life operation of electrified vehicles in the German federal state of Baden-Wuerttemberg is investigated. Within the project DLR follows a systemic approach also considering aspects of energy deployment. Thus a specific use case of the year 2015 has been analysed, where a locally installed PV system was utilized to provide power to charge the battery of a BEV.

For this study an algorithm for the identification of charging events in the building power consumption was developed. This algorithm was applied to the

[3] Assuming the 2015 case in terms of grid energy price, BEV energy demand and PV share

power flows recorded by the data logger of the PV system. As a result it could be determined, that in the year 2015 a share of 20% of the overall BEV charging energy was provided by the PV system.

From the user point of view the effect of using the PV system to charge the BEV resulted in an energy cost reduction of 9.8% compared to a reference case without a PV system. Detailed analysis revealed a strong dependency of the achievable cost reductions from the date of first operation of the PV system. This is a consequence of German Renewable Energy Act, which guarantees graduated earnings for PV power fed to electricity grid depending on the date of first operation. The main conclusions are, that recently built PV systems have a higher cost reduction potential than earlier installed systems and that the cost effectiveness of PV power used for BEV charging increases with rising costs for grid electricity.

The ecologic analysis of the combination of BEV and PV system revealed a reduction of CO_2 emissions related to BEV usage of more than 18% compared to a reference case without PV system. However, charging patterns need to be suitable to realise a notable impact on cost as well as on CO_2 emissions.

The investigation of the PV system in this specific use case will be continued for the year 2016. Furthermore the described methodology to derive temporally resolved CO_2 emissions will be applied to the whole fleet of vehicles equipped with data logging devices within the InitiativE-BW project.

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