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Indirect CO_2 emissions of electric vehicles: Insights from real-world vehicle use

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Abstract

Greenhouse gas emissions, in particular CO_2 emissions, are a major environmental problem caused mainly by the transportation and the energy sectors. Electric vehicles have been proposed as a solution for mitigating greenhouse gas emissions in road transport. At the same time their potential emission reduction depends on the emissions from the generation of electricity used to charge the vehicles. This study analyzes indirect emissions of electric vehicles to examine optimization potential using real-world data. The results of the study suggest that charging during the daytime is associated with the usage of more electricity from renewable energy sources than charging in typical non-work hours. However, due to the highly violate character of renewable energy sources the differences are rather small. Also, CO_2 emissions per kilometer driven depend on driving patterns influencing the energy demand of the vehicles. Accordingly, optimization potential using renewable energy-oriented time course of charging is found to be rather small with an average greenhouse gas emission reduction of 4%. Thus to achieve the potential of electric vehicles to solve environmental issues requires the optimization of driving and charging patterns as well as measures for reducing the carbon intensity in the electricity grid.

Keywords: electric vehicles, charging patterns, driving patterns, vehicle data assessment, indirect emissions, greenhouse gas emissions

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1. Introduction and motivation

Reducing greenhouse gas emissions, in particular carbon dioxide (CO_2), is a major environmental challenge in Europe. Significant greenhouse gas emissions come from the energy and transportation sectors. In Germany, for instance, 37% of CO_2 emissions are from the energy supply and a further 18% from the transportation sector. Although total greenhouse gas emissions in the country decreased by 28% between 1990 and 2015, emissions in the energy sector and especially in the transport sector increased slightly during this time (UBA, 2016). Accordingly, government efforts for mitigating environmental problems in recent years have increasingly focused on developing measures to address the challenges in these sectors.

In the transportation sector, the main challenges are related to road vehicles since 90% of greenhouse emissions are caused by road transportation and these emissions have barely changed since 1990 (UBA, 2015). Accordingly, more environmental friendly vehicles (e.g., electric vehicles) are discussed as a potential solution for mitigating these problems. The government supports the uptake of electric vehicles by formulating goals and policies in this area (Bundesregierung, 2009, Haugneland et al., 2009). The German government has been subsidizing the purchase of electric vehicles since May 2016 aiming to speed up the transition to more environmental friendly mobility (Bundesregierung, 2016). Simultaneously, while electric vehicles do not produce any direct emissions during operation, there are still indirect emissions (i.e., from the generation of electricity used for charging the vehicles) (Hacker et al., 2011). Hence, an important prerequisite to achieve emission reductions using electric vehicles requires utilizing renewable energy sources for the electricity supply.

In the energy sector, the transition in Germany to a low greenhouse gas electricity supply is an ongoing process within a large scale national program. Ambitious goals have been set by the government including a 35% increase in the share of electricity generated using renewable sources by 2020 and increasing to 50% by 2030 (Bundesregierung, 2010). Although a significant improvement (i.e., 15%) has been achieved in 2016 compared to 2010, to date on average about 2/3 of the electricity generation is still from fossil and/or nuclear fuels (AGEE-Stat, 2017). In addition, these values represent an average share over the period of a year. Most renewable electricity sources are highly volatile and, compared to conventional sources, less controllable (Kasten et al., 2016).

Consequently, the environmental friendliness of electric vehicle is highly dependent on the electricity source. As electricity is still mainly generated using conventional sources and the transition to more environmental-friendly supply is an ongoing process, analyzing the relationship between both can provide valuable insights. Previous studies addressed indirect emissions of electric vehicles examining the relationship between electricity mix in the grid and vehicles´ charging patterns. Most of these studies used microscopic model simulation approaches by either simulating the power grid, vehicles' charging behavior, or both (Rotering & Ilic, 2011, Dallinger, 2012, Schuller et al., 2015, McLaren et al., 2016). Few studies have used real-world data for estimating this relationship under actual conditions (e.g. Kugler et al., 2016, Dittus et al., 2016). Estimated indirect emissions of electric vehicles vary depending on vehicles' energy consumption, charging behavior, and data on electricity mix. The average estimated values considering the German electricity mix which can be found in the literature are mostly in the range of 70 and 117 gram CO2-eq per kilometer (Öko-Insitut e.V. & ISOE, 2011, Ramachandran & Stimming, 2015, Dittus et al., 2016). A comparison of these values with the average direct emissions level of new passenger cars sold in Europe in 2016 (118.1 grams of CO_2/km (EEA, 2017)) suggest a rather small difference between the CO_2 emissions levels of electric vehicles and conventional vehicles. This raises not only the question which are the factors affecting the indirect CO_2 emissions, but also how to optimize the process in order to reduce these.

McLaren et al. (2016) found that the carbon intensity in the energy grid has a greater impact on electric vehicles' indirect emissions than charging patterns. However, they also found noticeable differences in the emissions depending on the charging patterns, with a positive effect of charging patterns in relation to carbon intensity in the grid. In addition, charging at work was found to result in lower emissions while restricting charging events to off-peak hours leads to an increase in emissions. The results of various other studies confirm these outcomes and examine more detailed potential of optimizing the charging process (van Vliet et al., 2011, Schuller et al., 2015, Dallinger et al., 2012). Different smart charging strategies have been proposed, including renewable-oriented charging, shifting charging events to hours with a high share of renewable electricity, and cost-oriented charging by shifting charging times to periods with low energy prices and/or low demand (Kasten et al., 2016). Focusing on reducing CO_2 emissions of electric vehicles, potential of renewable energy-oriented charging strategy are highly dependent on different factors, such as regional characteristics of power systems determining the demand and design of such charging approaches (Kasten et al., 2016). Dallinger et al. (2012) suggest an increase of about 6% in the share of electricity from renewable sources trough optimized demand-side management, but higher emissions caused by the utilization of coal when applying this strategy. The authors concluded based on further analysis improvement of emissions only with the installation of additional renewable energy sources. A case study analysis conducted by Dittus et al. (2017) suggests that even owning a photovoltaic power station does not necessary result in the use of 100% renewable energy. The authors estimated that only about 16-20% of the charged energy was from photovoltaic source. Overall, different approaches are proposed for analyzing the relationship between electricity mix and charging behavior. Strategies for optimizing charging with renewable electricity sources are highly dependent on factors including characteristics of the power system and charging behavior.

The aim of this paper is to analyze the indirect emissions of electric vehicles under real-world conditions. We use a test fleet of electric vehicles which were in regular use to gain insights on this topic. The analysis focuses on the indirect CO_2 emissions caused by the electricity generation depending on charging and driving patterns of the vehicles. Additional emissions from the manufacturing of the vehicles and batteries are outside the scope of this paper. Similarly other indirect and direct emissions related to the electric vehicles use (e.g., air pollutants and noise) are omitted. The analysis is done for Germany as it is a suitable case-study for integrating renewable electricity into a mass-market for electric vehicles. All vehicle and electricity data is therefore specific to Germany.

2. Methodology and data

2.1. Study set up and methodology overview

In order to address potential greenhouse gas reductions using electric vehicles, a test fleet was set up in Berlin. The vehicles were used by companies and private persons. Additional costs for the purchase of an electric vehicle compared to a conventional one were partly covered as an incentive to participate in the study. During the field test, vehicle data were collected over a period of one year using onboard devices or direct vehicle data provision due to the OEM. In order to analyze indirect CO_2 emissions, detailed data on electricity generation and consumption for the same time period, as well as data on CO_2-equivalent emission factors for different electricity sources were purchased. Using a final data set including vehicle data and electricity mix data, indirect CO_2 emissions of the vehicles are estimated. The factors influencing emissions and optimization potential are then analyzed and discussed.

2.2. Database

The vehicle data set includes aggregated information about the trips and charging events (e.g., start and end time of each activity, mileage, state of charge, outside temperature, GPS positions, distance travelled, and consumed energy). The data set structure and data pre-processing steps are outlined in Kolarova et al. (2017). In order to isolate the effect of vehicle model characteristics (e.g., model-specific energy consumption), all analyses presented in this paper are performed for only one vehicle type. Thus, a reduced sample consisting of 80 electric vehicles is used in this paper. The vehicles are used commercially with a few exceptions (i.e., private trips for commuting to work). After data cleaning, for the observation period of one year we obtained 95,954 records of sufficient quality (i.e., 41,903 trips, 13,914 charging activities, and 40,137 stops/parking events).

Detailed data on the electricity generation and consumption in Germany for 2016 are from Agora Energiewende (2017). Agora Energiewende, a joint initiative of the Mercator Foundation and the European Climate Foundation, use several data sources and methods to provide comprehensive electricity data for Germany (Agora Energiewende 2016b). The data set gives the hourly share of various energy sources (e.g., coal, natural gas, solar, wind), total demand and supply, energy imports and exports for Germany for each day of the year, and price per kWh.

To calculate emissions of electric vehicles, emission factors for the various energy sources are taken from GEMIS, an open source energy and environmental model (IINAS, Öko-Institut e.V., 2016). Table 1 summarizes the emission factors used for in our calculations. Note that the emission factors provided by GEMIS include additionally emissions related to the whole life-cycle of the energy generation including transport, supply, and materials, but exclude disposal.

Table 1. Emission factors per electricity source (GEMIS 4.95, IINAS, Öko-Institut e.V., 2016)

Electricity source	CO_2-equivalent [g CO_2/kWh]
Hard coal	894
Lignite	1008
Natural gas	410
Nuclear	55
Hydro	3
Wind onshore/ offshore	9
Solar (PV)	109
Biomass	194
Others	587

2.3. Analysis

In order to analyze the indirect CO_2 emissions of the electric vehicles, we match the collected vehicle data with hourly data electricity grid data. Before merging the vehicle data with the electricity data, pre-processing steps are performed with both data sets separately.

The electricity data set are expanded to include the additional variable of gram CO_2/kWh. This is done by assigning each of the energy sources with its CO_2-equivalent emission factor and computing the average value per hour. The hourly share of renewable electricity is also estimated. The pre-processing steps performed with the vehicle data set included computing the electricity consumption for each trip and analyzing characteristic charging patterns of the vehicles. To estimate the electricity consumption per trip, we use the difference between the state-of-charge at the end and at the beginning of each trip. To analyze characteristic charging behavior, a cluster analysis is applied to group vehicles with similar charging patterns. We use a similar approach as proposed by Axsen et al. (2011) and Robinson et al. (2013). The main difference in our approach is that these authors use the relative share of charging events which took place each hour of the day, whereas we use the relative share of electricity charged per hour of the day. Using the amount of electricity charged allows us to consider additionally fast and standard charging. In the first step of the analysis, we create individual daily charging patterns for each of the vehicles in the sample. Next, we perform a hierarchical cluster analysis using a ward linkage method and a squared Euclidian distance including the individual daily charging patterns. In the cluster analysis, each vehicle is characterized by 24 variables representing the relative share of the electricity charged in each of the 24 hours. The identified clusters display typical temporal charging behavior condensed to characteristic groups.

Finally, the expanded vehicle and electricity set are merged together. Matching the emissions associated with the charging activities and considering the individual electricity demand of the vehicles, indirect CO_2 emissions related to the regular use of the vehicles are estimated. In a further step the potential for optimization of the charging process applying renewable energy-oriented charging are examine using a rule-based simulation.

3. Results

3.1. Electricity generation and demand

Initial analysis of the electricity mix shows that electricity demand and generation in Germany follow a daily cycle; more electricity is generated in the daytime and less is generated (and consumed) in the night until early morning (Figure 1). The share of renewable sourced electricity varies strongly depending on weather conditions. For instance, solar power is only available during daytime, while availability of wind power is less predictable and varies significantly. Accordingly, the hourly share of renewable energy for 2016 was between 11% and 66%, with an average of 30% (standard deviation of 11). Seventy five percent of the values were lower than or equal to 37% share of renewable energy. The estimated average value for electrictiy consumption in 2016 using the Agora Energiewende and the GEMIS data was 498 g CO_2/kWh. The average value for the same year published by the Germany Federal Environmental Agency was 580 g CO_2/kWh, which is due to the use of different emissions factors (Icha & Kuhs, 2017). Nevertheless, all analysis presented in this paper are based on the emission factors provided by GEMIS (IINAS, Öko-Institut e.V., 2016). Thus, some differences to other recently published estimations may occur.

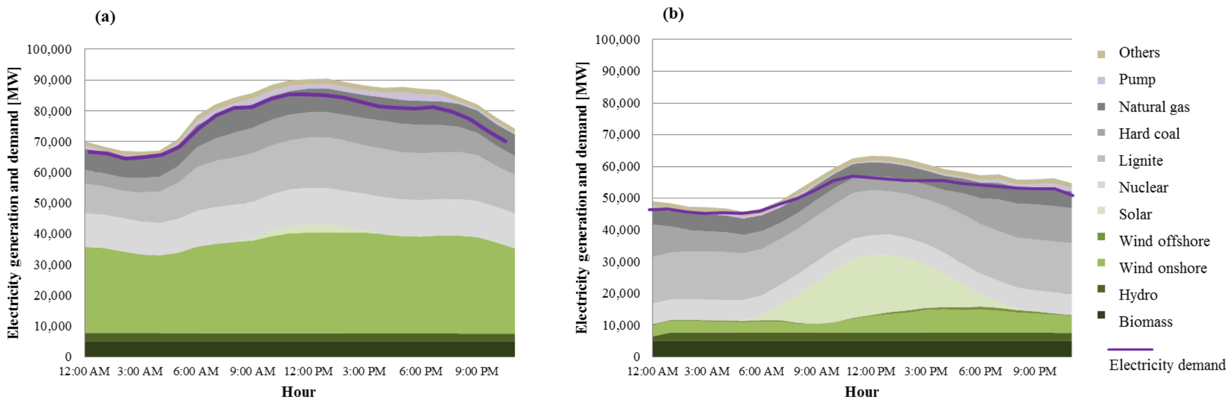

Fig. 1 (a) Electricity mix on one random day in January 2016; (b) Electricity mix on one random day in July 2016

3.2. Energy demand and charging patterns

Analysis of the energy demand of the selected vehicle model shows an average energy consumption of 0.16 kWh/km (standard deviation of 0.05), with a median of 0.15 kWh/km. The values range between 0.08 and 0.3 kWh/km; seventy five percent of the values are lower than or equal to 0.19 kWh/km. Factors influencing energy demand of the electric vehicles include outside temperature, topography of the routes, and speed (i.e., accelerating and breaking behavior). Respectively, differences between the single vehicles could be observed depending on their driving behavior and routes. These are not further analysed in this paper since they were not a focus of the estimations.

The analysis of the identified characteristic charging patterns show that most of the electric vehicles in the sample charge during the daytime (i.e., cluster 2, cluster 5, and cluster 6). Only one of the clusters represents a charging pattern which is characterized with charging activities during the late afternoon/evening (i.e., cluster 3). Two of the clusters (i.e., cluster 1 and cluster 4) include vehicles which charge during the early morning.

The driving patterns of the vehicles differ between the identified clusters. Since the test fleet consists mainly of commercially used vehicles, most of the driving activities took place during the day (i.e., during working hours). The two peaks representing the highest share of driving activities, in the morning and in the afternoon, by cluster 1 suggest that vehicles belonging to this cluster were also used for private trips (e.g., commuting to and from work). The high share of electricity charged during the daytime, combined with the simultaneous high share of driving activities by most of the clusters suggest short recharging activities between trips.

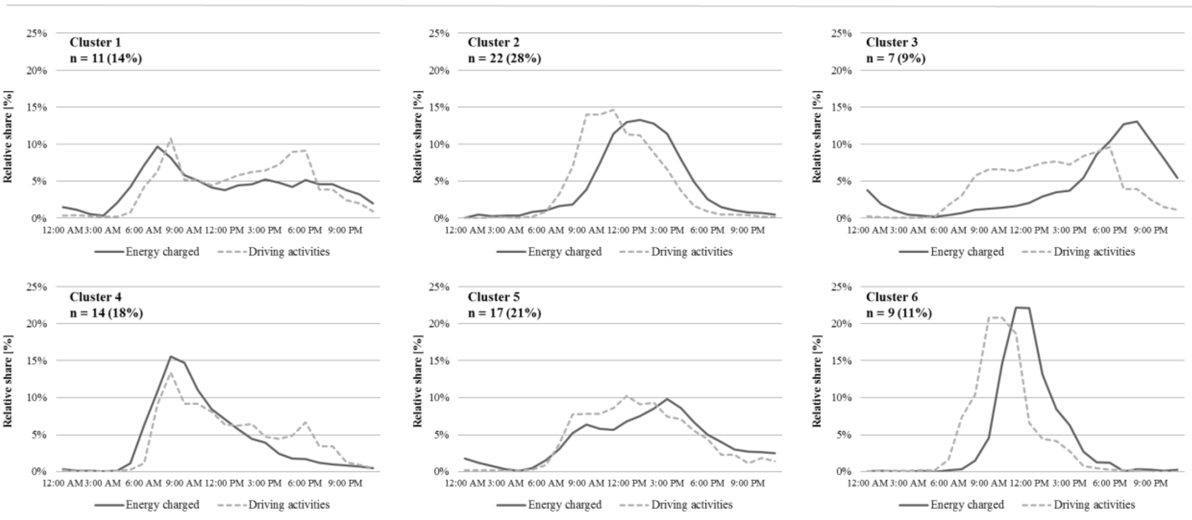

Fig. 2. Identified characteristic charging patterns

Further analysis of the characteristic driving behavior of the vehicles belonging to the different clusters shows some notable differences. Vehicles belonging to cluster 3 or cluster 6 have slightly higher energy demand than vehicles belonging to any of the other clusters. Also, vehicles belonging to the clusters 1, 4 and 5 drive on average between 44 and 49 kilometers per day which is about 10 kilometers more than the daily distance driven by the vehicles belonging to the other clusters. At the same time, the average speed per trip is for all clusters between 21 and 33 kilometers per hour indicating that all vehicles were used rather in urban environment.

3.3. Indirect CO_2 emissions

The indirect CO_2 emissions of the vehicles are calculated using the electricity mix during the time of charging events and vehicles' electricity consumption during the associated trips. Additionally, by computing the indirect emissions, we also consider energy loses during the charging process. Previous studies find up to 20% power loses during charging events (FfE, 2011, Apostolaki-Iosifidou, 2017). We use this value for the emissions estimation adding 20% energy demand to the electricity charged during charging activities in order to estimate the maximum emissions. Table 2 summarizes the descriptive statistics of the estimated gram CO_2/kWh associated with the electricity composition during the charging activities as well as the CO_2 emissions estimated per kilometer for the whole sample. The results show that the average indirect CO_2-equvalent emissions for the selected vehicle model were 92 gram CO_2 per kilometer. Seventy five percent of the values are less than 114 grams CO_2/km.

Table 2. Descriptive statistics of the estimated indirect CO_2 emissions

Statistics	g CO_2/kWh	g CO_2/km
Mean (standard deviation)	490 (72)	92.4 (30)
1st quartile	440	67.2
Median	498	85.2
3rd quartile	547	114
Minimum	229	24
Maximum	645	173

Comparing the indirect emissions related to the characteristic charging patterns show that the differences in the average CO_2/kWh between the single clusters are very small (up to 10 grams CO_2/kWh). However, there are noticeable differences between the vehicles which are charged during the daytime (i.e., cluster 2, cluster 4, and cluster 6) and vehicles with charging activities which usually start in the afternoon or evening (i.e., cluster 3, and cluster 5) or in the early morning (i.e., cluster 2). Vehicles charging during daytime use on average a higher share of renewable electricity than vehicles charging during typical non-work hours (Figure 3).

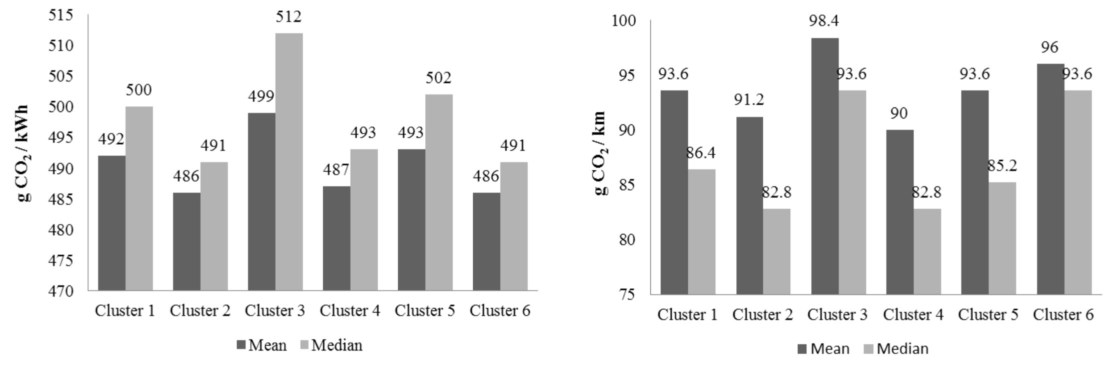

Fig. 3. Indirect CO_2 emissions related to different charging patterns

When comparing the indirect emissions in terms of CO_2 per kilometer for the different clusters, some new tendencies can be observed (see Figure 3). Vehicles which belong to clusters using electricity associated with lower average CO_2 emissions than other clusters were found not having necessary lower CO_2 emissions per kilometer driven. This difference results among other factors because the energy demand of the vehicles depends strongly on their driving behavior and trip related conditions (e.g., accelerating and breaking behavior, outside temperature, and topography of the routes). Thus, considering how vehicle-specific use influences their indirect CO_2 emissions both charging patterns as well as driving characteristics and conditions have to be considered.

3.4. Optimization potential using renewable energy-oriented charging

Next we simulate a renewable electricity-oriented charging behavior of the electric vehicles in order to analyze the potential for additional CO_2 emission reductions. We do this using a rule-based simulation to shift charging activities to a time of the day with a higher share of renewably generated electricity. Driving time was considered as a time in which the vehicle cannot be charged. Also, only locations where vehicles usually charge are considered. Other locations where vehicles are parked during the day (e.g., the destination) are not considered as possible charging locations due to the uncertainty regarding availability of charging infrastructure. Most of the charging activities of the vehicles in the fleet (75%) are rather short, i.e. were lasting not longer than 2 hours and 35 minutes. This indicates also the average state of charge of 59% of the battery at the beginning of a charging event. By 75% of the charging activities, the vehicles were plugged in longer than the time required for the charging process. This results in an average plug-in time without electricity flow of about 1 hour and 43 minutes (median = 1 hour; standard deviation = 2 hours). Accordingly, all charging activities are rescheduled either within the plug-in time or within the parking time of the vehicles after the charging activity. Figure 4 shows the simulated changes for the entire sample. Charging activities in the morning hours (between 7:30 and 10:00 am) are shifted to noon hours which are characterized with a higher share of renewable electricity (i.e., mostly solar energy). Charging activities which began in the afternoon and the associated vehicles park overnight, are rescheduled to night hours (between 12 and 5 pm).

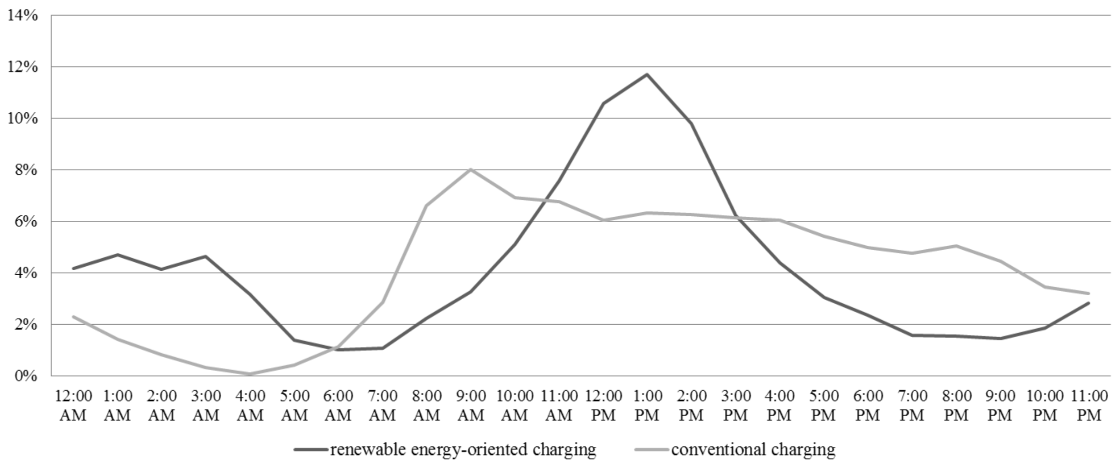

Fig. 4. Changes in the charging patterns of electric vehicle

The results of the simulations show a very small improvement in terms of CO_2 per kWh charged. Figure 5 provides an overview on the range of improvement. The boxplots show the median, the 1^{st}, and the 3^{rd} quartile as well as the outlier values. Overall, about one third (32%) of the charging events could not be improved since the charging activity already took place during favorable hours in terms of emissions, or there was no additional parking time after finishing the charging activity which made rescheduling the activity impossible. Consequently, the average improvement is a reduction of CO_2 emissions by 4.25% (standard deviation of 5.9) with a median of 1.73%. Most of the values (75%) have less than a 6% improvement. The outlier values indicate that an improvement of single charging activities can reduce emissions by 15-40%.

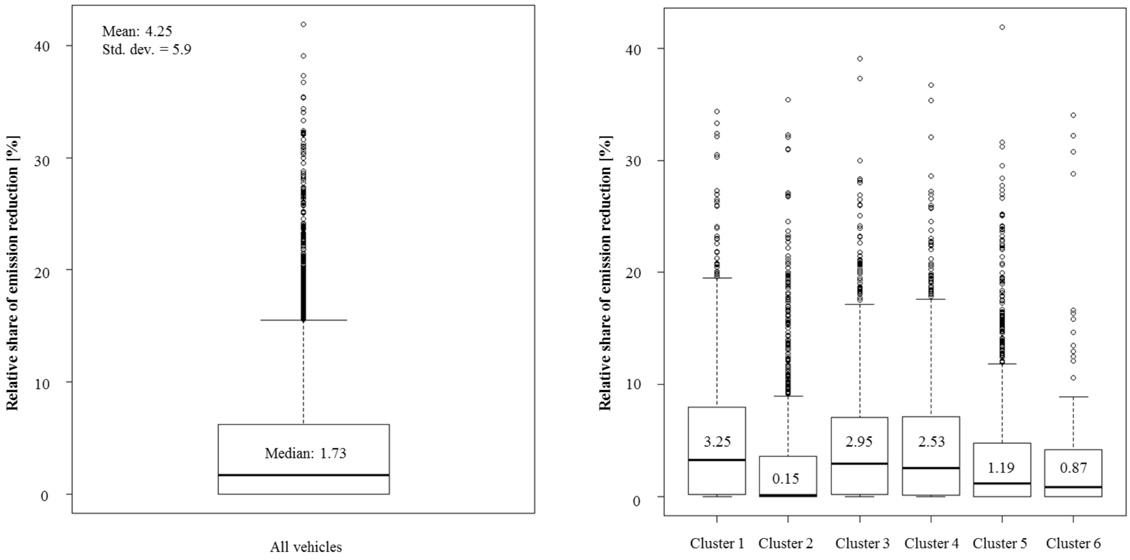

Fig. 5. Potential for CO_2 emissions savings using renewable energy-oriented charging

Comparing the different charging patterns shows that the main improvements can be observed within the charging patterns starting in the evening (i.e., cluster 4) or in the early morning (i.e., cluster 1 and cluster 4). Since vehicles belonging to cluster 2 or cluster 6 already charged during favorable hours (i.e., with high share of renewable electricity) there is almost no improvement in the emissions from these vehicles. Similarly cluster 5 shows only marginal improvements. Another reason for the small improvements within the last three mentioned clusters is that charging activities during daytime are usually shorter than charging activities starting in the evening or early morning.

4. Discussion and conclusion

The aim of this study is to estimate CO_2 emissions from electric vehicles under real-world driving and charging conditions. Thus driving and charging data from 80 electric vehicles, the electricity mix, and the associated CO_2-equivalent emission factors were merged and analyzed. In comparison to many previous approaches, added value of the present study is using detailed real world on both, vehicle usage and energy production.

The results show a relationship between driving and charging patterns of electric vehicles and the indirect CO_2 emissions. There are noticeable differences between the vehicles which charge during the daytime and vehicles with charging activities starting in typical non-work hours (i.e., in the early morning, in the afternoon, or in the evening). Charging during the daytime is associated with a higher share of electricity from renewable energy sources. Accordingly, vehicles charged during daytime show lower indirect emissions. However, due to the highly violate character of electricity from renewable energy sources, especially from wind power, the differences in CO_2 emissions in gram per kilometer are rather small between clusters of different charging behavior (about 10%). Also, results of the optimization potential analysis indicate that applying renewable energy-oriented charging does not necessary lead to significant improvements with the current share of renewable electricity in the grid. Moreover, the final estimated indirect CO_2 emissions per kilometer driven also depend on the individual energy demand of the vehicles. This in turn is influenced by various factors (i.e, different trip, route characteristics). Accordingly, the optimization potential of renewable energy-oriented charging on CO_2 emissions shows an average improvement of only 4.25%.

Indirect emissions of electric vehicles are lower than direct CO_2 emissions of a conventional new vehicle (see EEA, 2017). However, when comparing only indirect emissions of electric vehicles and direct emissions of conventional vehicles, this difference appears rather small. When also considering the indirect emissions of conventional vehicles caused by production and supply of fuel, which are about an additionally 15% of the direct emissions (Öko-Insitut e.V. & ISOE, 2011), the environmental balance of electric vehicles is better than conventional cars. When comparing the average emissions of electric vehicles and the determined potential of further reduction by optimized charging behavior to emissions of conventional vehicles relativizes the environmental benefit of EVs in terms of CO_2 emissions under current conditions of energy production. This suggests a need for more radical steps to reduce the carbon intensity of the electricity grid or other strategies for coping with the violate character of renewable energy sources (e.g., electricity storage solutions).

The limitations of this study also have to be discussed. One limitation is the small sample size, which is not a representative sample. Overall, comparing the results to previous studies, we found many similarities. Indirect CO_2 emissions of electric vehicles are proven to be highly dependent on carbon intensity in the electricity grid. When considering the current share of electricity from renewable energy sources in Germany, the results show that the contribution of electric vehicles to reducing greenhouse gas emissions highly depends on the transition to a low greenhouse gas electricity supply. At the same time, the results do not confirm that renewable energy-oriented charging is a sufficient solution for improving CO_2 emissions from electric vehicles as presented in previous studies.

Consequently, electrifying vehicles can only be environmentally successful when these challenges are undertaken together with measures for increasing the share of electricity from renewable energy sources. Future research should focus on the analysis of an entire fleet of electric vehicles and on the link between the transportation and energy sectors. Also, concurrent to the expansion of public charging infrastructure a scenario assuming ubiquitous charging might be interesting as a higher potential of reducing emissions can be assumed. Various research questions remained to be answered in this field. For example, the relationship between increasing electricity demand due to a mass-market of electric vehicles will likely have significant impacts on the electricity grid, which should be examined. Further, the optimal utilization of electricity from renewable energy sources must be optimized for such a mass-market of vehicles. Potential conflicts between other sectors (e.g., household, industry) need to be examined to avoid simply shifting the burden.

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