System Impacts of Electric Vehicle Charging in an Evolving Market Environment

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Abstract

Reductions in greenhouse gas emissions are a strong incentive for the large scale introduction of electric vehicles. Studies that quantify these environmental benefits have to incorporate emissions caused by generating the electricity used to power the vehicles. We show that an approach that uses the average CO$_2$ intensity of power generation is inaccurate and one needs to consider the generation capacity that is deployed for the extra load of electric vehicles. Moreover, we show the strong sensitivity of the results on different market environment aspects like charging patterns, generation portfolios, the share of wind energy and CO$_2$ prices. This strong sensitivity implies that it is very hard to accurately predict future emission reductions of electric vehicles.

Introduction

Owing largely to environmental reasons, a great interest has been shown in the development and the large scale introduction of electric vehicles (EVs \(^1\)). For example, the Dutch government has expressed the ambition to be a guiding nation in electric transportation and aims to have 1 million electric cars on the road between the year 2020 and 2025 [1]. Apart from the fact that the use of EVs eliminates local pollution problems near roads, the possible reduction in CO$_2$ emissions is a strong incentive for electrical transportation. When assessing the reductions in CO$_2$ emissions of electric vehicles, one needs to compare emissions caused by gasoline

\(^1\)In our analysis there is no difference between full electric vehicles or plug-in hybrid electric vehicles (PHEVs), so we use the term EV for both.
combustion with emissions caused by power generation used for charging the EV batteries. In [2] an overview of PHEV impact studies is given and one section is dedicated to the net change in greenhouse gas emissions. It is shown that results from different impact studies vary significantly due to differences in generation portfolios of the power systems under consideration. From [2] it can also be concluded that most of the reviewed studies base their results on average generating mixes, whereas a few do specifically take the merit order and the actual dispatch of plants needed to meet the extra load of EVs into account. In particular in [3], the authors have considered PHEV impacts (emissions and costs) in different regional power systems in the US. They find that these impacts might vary substantially due to the fact that different marginal generation is used for EV charging in different portfolios. Moreover, they even show how the added generation employed for EV charging will change towards the year 2030. They do not quantify, however, how this will translate in specific greenhouse gas emissions caused by EV charging.

Our study therefore aims to analyze in more detail how EV emissions are related to different times of charging and different generation portfolios. Furthermore, we will focus on how these numbers might change if portfolios and/or merit orders will change due to the penetration of wind energy and CO2 pricing. Although our primary focus is on European electricity markets, with a special emphasis on the Dutch electricity system, the research method and conclusions apply to liberalized electricity markets in general.

Research method

The purpose of this research is to understand relations between EV charging impacts and different aspects that form the electricity market environment in which the EV charging takes place. We consider four aspects: 1) The time of charging 2) the portfolio of power plants 3) the amount of installed wind power generation 4) CO2 price.

The basis for our analysis is an indicative list of power plants that together form the Dutch generation capacity [4, 5, 6]. This list of plants is based upon the Dutch TSO data [6], to which all electricity producers have to report their installed capacity. In the Netherlands, the generation capacity is roughly divided into 25% coal plants, 60% gas plants and 15% other types of generation, mostly nuclear, waste incineration and wind plants [5]. The capacity, efficiency and variable operation and maintenance costs of all individual plants are known or estimated and together with the fuel costs this allows us to compute the marginal costs of each plant. Ignoring start-up and ramping costs (and rates), the marginal costs essentially determine the merit order of plants according to which the power
plants are dispatched to meet the system load. We then compare this merit order or supply function with the 2006 time series of system load for the Netherlands [6]. In this way we find for each time unit (15 minutes in this case: the time resolution of the demand time series) the marginal plant, which enables us to compute the instantaneous electricity price: the marginal costs of the marginal plant. For ease of calculation, we assume, by matching the demand with the available power plants in the Dutch system, that interconnection capacity with neighboring power systems can be ignored. Caloric values of the different fuel types (e.g. as given in [7]), together with plant efficiencies allow us also to compute the instantaneous \( \text{CO}_2 \) emissions of electricity generation. Fig. 1(a) shows the supply function of the Dutch power plant portfolio, together with the \( \text{CO}_2 \) emissions of the plants ranked according to marginal costs, Fig. 1(b). The latter curve is from now on referred to as \textit{marginal emission function}.

We do not consider upstream emissions. Emissions of nuclear, hydro, waste incineration, biomass and wind have all been set to zero. We will now proceed to discuss the four aspects of the market environment we consider in some more detail.

Time of charging

The effect of the time of day of charging is evaluated by considering two cases: charging at night (at minimum system load) and charging in the evening.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Merit order and marginal emission function of power plants for the Dutch generation portfolio.}
\end{figure}
Figure 2: Extra system load caused by EV charging.

(a) Two different types of daily charging profiles for a total number of EVs of one million.

(b) System load on a summer day.

(c) System load on a winter day.

(at maximum system load; hereafter referred to as peak charging). The extra load of the electric vehicles is modelled based on the following assumptions:

- There are one million EVs [1].
- The average daily commuting distance traveled by car is 30 km [8].
- The electric vehicle efficiency is 5km/kWh [9].
- Maximum charging rate is 1 kW. Although some studies mention charging rates up to 10 kW or even 15kW (e.g. [10]), we assume a much slower charging rate because there is time till the next morning to charge 6 kWh in the car battery. This assumption is also inspired by possible distribution network constraints that might arise if EV numbers increase substantially. In this light, the slowest charge rate possible is desirable.
- Night charging takes place between 0.00h and 8.00h, where the total system load increase linearly from 0 to 1 GW between 0.00 and 2.00 and decreases to 0 between 6.00h and 8.00h.
- Peak charging takes place between 16.00h and 8.00am, where the total system load increase linearly from 0 to 1 GW between 0.00 and 2.00 and decreases to 0 between 6.00am and 8.00am.

The extra demand from EV charging has been added to the known system load time series to obtain new time series. The charging profiles have been plotted in Fig. 2(a), together with two typical demand profiles on a summer and winter day, Figs. 2(b) and 2(c).

**Generation portfolio**

To consider the effect of the generation portfolio on the EV charging impacts, we consider two distinct generation portfolios. The first one has already been described and is based on the Dutch portfolio. The second one is inspired by German
fuel mix statistics [5], which are characterized by a large share of coal and lignite (50%), nuclear (20%), gas(20%). Hydroelectricity and wind make up the rest of the portfolio. Based upon Dutch and the German powerplant statistics, we create a portfolio that is representative for the German portfolio, although we will refer to it as alternative portfolio. The total installed capacity still has the value of the Dutch total installed capacity used for the original Dutch portfolio, for reasons of a fair comparison between the two cases.

By the same method of using fuel prices [5] and heating values [7], we construct the merit order (Fig. 3(a)) of our alternative portfolio and its CO\(_2\) emissions, i.e. the marginal emission curve (Fig. 3(b)). It should be noted here that because nuclear plants have a must-run character, we have artificially put their marginal costs at zero, so they are first in the merit order.

**Installed wind energy capacity**

We consider the effect of wind power by adding a certain amount of installed wind capacity in the portfolio. We use a measured time series of wind power output of the western Danish system as described in [11], see Fig. 4. This time series is the aggregated output of all wind power production in the western Danish system, which is geographically comparable in size to the Dutch system, so there is no reason to expect a greater smoothing effect...
due to a larger geographic dispersion. We consider an installed wind power capacity ranging between 0 and 20 GW. For the instantaneous wind power output we multiply the total installed capacity with the time series of Fig. 4.

CO₂ price

In Europe, electricity generators fall under the Emissions Trading System [12]. This puts a value on the emission of CO₂ and is hence incorporated in the calculation of marginal costs. The effect of CO₂ prices is that it will shift the more polluting generation types towards the end of the merit order. Since its introduction in 2005 prices have fluctuated mainly between 10 €/ton and 30 €/ton, but as new phases of the ETS program near, one could expect higher prices. We therefore look at CO₂ prices ranging from 0 €/ton to 100 €/ton.

Results

Reference case

As a reference case, the situation where no electric vehicles are present is considered. In this case, we find a yearly average electricity price of 53 €/MWh which lies close to the 2006 average APX price of 58 €/MWh [13]. The fact that the APX price is somewhat higher than our modeled price, is not surprising considering that we, in effect, assume that generators bid according to marginal costs. In reality some generators might at times exert market power by bidding higher than marginal costs or withholding capacity. For the average CO₂ emission of electricity production, we find a value of 0.60 ton/MWh, which is again in close agreement with literature values of 0.55-0.60 ton/MWh [8]. The close agreement with literature values we find for the average electricity price and CO₂ emissions can be considered a contribution to the validation process of our model.

Results for the Dutch Portfolio

The most important findings for the case of the typical Dutch energy portfolio are listed in Tab. 1. First of all we notice the difference in CO₂ emissions between night charging and peak charging due to the system load (including EV charging) at night being mostly around 9 GW, whereas peak loads range between 12 GW and 17 GW (summer and winter). Comparing this with the marginal emission curve from Fig. 1(b), we conclude that for night charging the most efficient gas plants are the marginal plants and for peak charging the less efficient gas plants are dispatched. Worth noting is the fact that both at night and at system peak, EV charging emissions are still lower than the average CO₂ intensity of all electricity generation. This is due to the fact that the most polluting coal plants are included in the average CO₂ intensity, but do not contribute to the extra emissions caused by EV
charging. A final observation here is the fact that the extra system load caused by charging the electric vehicle is too modest to significantly alter the yearly averaged electricity prices or emissions.

**Results for an alternative portfolio**

The results for the alternative portfolio are listed in Tab. 2. In the situation with no EVs, we have an average electricity price of 24 €/MWh. Recalling that the alternative portfolio was inspired by the German portfolio, this is significantly lower than the German wholesale price of approximately 50 €/MWh [14]. We have however effectively assumed that generators bid according to marginal costs and do not withhold capacity. In the German market there have been strong indications of generators exerting market power [15], with wholesale electricity prices doubling between 2002 and 2006. This result underlines the fact that we do not take into account any market dynamics or strategic behavior whatsoever and we have to treat resulting electricity prices with care.

We observe remarkable differences in comparison with the Dutch portfolio results. Most notable are the much higher emissions for both peak and night charging. This can not be readily understood if one takes into account that the average CO₂ emission of electricity production is about equal to the Dutch case. Invoking the marginal emission curve plotted in Fig. 3(b) explains this result: the most polluting generation is found towards the end of the merit order. So, the extra emissions caused by EV charging are always higher than the average emission. The marginal emission curve also explains the fact that peak charging is in this case less polluting than night charging; a result that is opposite to the Dutch situation. Night charging is mostly done at a system load where either lignite or coal plants are the marginal plants, whereas peak charging takes place in the regime where gas plants are marginal.

The fact that we find equal average CO₂ intensities of electricity generation for the Dutch and the alternative portfolio and completely different emissions caused by EV charging, unmistakenly points out that using average CO₂ intensities for calculating the environmental impacts of EVs is inaccurate.

**The effect adding wind energy to the portfolio**

When wind energy is added to the portfolio, prices and emissions of EV charging will change due to the fact that wind has zero marginal cost and hence shifts all other generation to the right in the merit order. Figs. 5(a) and 5(b) show the effect of installing extra wind generation on the EV charging emissions on the Dutch and the alternative portfolio respectively. The results are again markedly different between the two different portfolios. In the Dutch case, initially wind power replaces the least efficient gas plants at the end of the merit or-
Table 1: Simulation results for the Dutch electricity sector for different scenarios.

<table>
<thead>
<tr>
<th>Case</th>
<th>CO$_2$-emission for EV charging (kg/kWh)</th>
<th>CO$_2$-emission for all electricity (kg/kWh)</th>
<th>Price for EV charging (€/kWh)</th>
<th>Price for Electricity (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No EVs</td>
<td>-</td>
<td>0.60</td>
<td>-</td>
<td>0.053</td>
</tr>
<tr>
<td>EV Night</td>
<td>0.45</td>
<td>0.59</td>
<td>0.050</td>
<td>0.053</td>
</tr>
<tr>
<td>EV Peak</td>
<td>0.53</td>
<td>0.59</td>
<td>0.058</td>
<td>0.054</td>
</tr>
</tbody>
</table>

Table 2: Simulation results for the alternative portfolio.

<table>
<thead>
<tr>
<th>Case</th>
<th>CO$_2$-emission for EV charging (kg/kWh)</th>
<th>CO$_2$-emission for all electricity (kg/kWh)</th>
<th>Price for EV charging (€/kWh)</th>
<th>Price for Electricity (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No EVs</td>
<td>-</td>
<td>0.60</td>
<td>-</td>
<td>0.024</td>
</tr>
<tr>
<td>EV Night</td>
<td>1.25</td>
<td>0.61</td>
<td>0.015</td>
<td>0.025</td>
</tr>
<tr>
<td>EV Peak</td>
<td>1.05</td>
<td>0.61</td>
<td>0.030</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Figure 5: CO$_2$-emissions of EV charging as a function of installed wind power generation.

(a) Dutch portfolio.

(b) Alternative portfolio.

At some point there is so much wind power that occasionally coal plants will be the marginal plants and the average EV charging emissions will start to rise again.

In the alternative portfolio, initially the most polluting plants are pushed out of the merit order by wind power and we observe rising emissions. At some point nuclear plants will become the marginal plants and the EV charging emissions will decline again.

Another noteworthy feature is that in both cases the differences in emissions between night charging and peak charging vanishes when more than 10GW of wind is installed. This can be understood by realizing that the probability distribution of system load of these two cases will approach each other with increasing stochastic generation. Fig. 6 illustrates this point: the two distinct peaks caused by the diurnal cycle are smeared out over a larger...
range. Figures like Fig. 6 are usually represented as load duration curves, but in this case it is more instructive to use the probability density of system load.

Regarding the influence of wind power on the average costs of EV charging, it was found that they decrease more or less linearly with increasing wind power capacity and the results are not shown here. This more linear behavior can be understood realizing that, by definition, the merit order is a monotonically increasing function, see Figs. 1(a) and 3(a). The large fluctuations we observe in the EV emissions as a function of wind are mostly due to the non-trivial shape of the marginal emission curve (Figs. 1(b) and 3(b)).

**Effect of CO₂ price**

Fig. 7 shows the relation between CO₂ price and EV charging emissions for the different charging patterns, portfolios and installed wind capacity.

![Figure 6: Probability distribution of the system load minus wind power generation.](image)

![Figure 7: CO₂ emissions of EV charging as a function of CO₂ price.](image)
For the Dutch portfolio, we observe that there is only a noticeable effect for CO\textsubscript{2} prices higher than 20-25 €/ton. An explanation for this can be found in the difference between coal and gas prices. In Figs. 1(a) and 1(b) we observe that coal is about 20 €/MWh cheaper than gas, and emits about 1 ton/MWh. So, only a CO\textsubscript{2} price higher than 20 €/ton will start shifting the coal plants in the merit order. For higher CO\textsubscript{2} prices the effect is modest.

For the alternative portfolio, there is immediately a large effect noticeable. The reason for this is that already with low CO\textsubscript{2} prices, nuclear and lignite plants will shift in the merit order and these are exactly the two types of plants that have the largest difference in CO\textsubscript{2} emission.

The effects of CO\textsubscript{2} price on the costs of EV charging can be described in a rather straightforward manner: increasing CO\textsubscript{2} prices lead to linearly increasing prices for EV charging. These results are not shown here.

**Combined effects**

In the previous sections we have seen how different aspects influence CO\textsubscript{2} emissions of EV charging. It is instructive to also see the combined effect of all these aspects. Fig. 8 essentially contains all information we have presented so far. Without going through all the specific dependencies again, we can conclude a few things from this figure. An important conclusion based on this figure would be the strong sensitivity of the emissions for every single aspect we have considered. This would make any prediction one does about the future emissions of EV charging very difficult. Basically, one needs to exactly where and in which of those four graphs we are at the time that is predicted.

A second observation here is the range in which the CO\textsubscript{2} emissions of EV charging can be found: approximately from 0.4 to 1.4 kg/kWh, or a factor of 3.5.

**Analysis**

From the previous it has become clear how many factors can influence the emissions caused by charging EVs. Essentially however, these emissions are determined by two things: 1) the merit order of plants and 2) the change EVs cause in the load duration curve. We will now show this in a more detail. The total yearly CO\textsubscript{2} emissions caused by charging EVs can be expressed as the difference in the total emissions in the situation with EVs and the total emissions without EVs (the reference case):

$$M_{Charging} = M_{tot,EV} - M_{tot,NoEV}$$  \hspace{1cm} (1)

where $M$ denotes the total mass of CO\textsubscript{2} in tons. The marginal emission (ton/MWh) at a some point in time given a certain demand $Q$ is denoted as $e_m(Q)$ and is simply the emission of the marginal
Figure 8: CO₂ emissions as a function of CO₂ price and installed wind capacity for both peak and night charging, and both portfolios.
plant. The CO$_2$ emissions of power plants ranked according to the merit order, that was shown in Figs. 1(b) and 3(b), display this function. The total emission per unit time at a certain time $t$ is then given by

$$m(Q(t)) = \int_0^{Q(t)} e_m(Q')dQ'$$  \hspace{1cm} (2)$$

Eq. 2 says that the total emission at a certain time point equals the cumulative emissions from all power plants that are used for generation at that time. For the the total yearly emissions, one could integrate Eq. 2 over time, or alternatively, use the distribution function of $Q$ defined as:

$$F(Q) = P(Q' \leq Q) \text{ for } -\infty < Q < \infty$$  \hspace{1cm} (3)$$

where $P(Q' \leq Q)$ should be understood to be the probability of a load smaller than $Q$.

This function is normally referred to as the load duration curve: the amount of hours of the year that the load was smaller than a certain value. Usually, these curves are represented with the amount of hours on the horizontal axis and the load on the vertical. In this case it is more instructive to consider the amount of hours the load was larger than a certain value and represent it as a function of the load $Q$. Fig. depicts this function, which is understood to be $1 - F(Q)$, for the three cases we considered.

As expected, we observe that in the case of night charging the probability of a system load being slightly more than the minimum value of 8GW has increased markedly. Likewise, for peak charging the chances of a high system load have increased.

The total yearly CO$_2$ emissions can now be calculated with the help of the system load distribution and Eq. 2:

$$M_{\text{tot}} = T \int_0^\infty (1 - F(Q)) e_m(Q)dQ$$  \hspace{1cm} (4)$$

where $T$ denotes one year. By inserting Eq. 4 into Eq. 1, we find for the total CO2 emissions caused by charging the EVs the following expression:

$$M_{\text{charging}} = T \int_0^\infty \Delta F_i(Q)e_m(Q)dQ$$  \hspace{1cm} (5)$$

where $\Delta F_i(Q) = F_{\text{NoEV}}(Q) - F_{\text{EV},i}(Q)$ denotes the difference in load distribution function between the case with no EVs and case $i$, so in our case can be either $\Delta F_{\text{Peak}}$ or $\Delta F_{\text{Night}}$. The function $\Delta F_i(Q)$ can be interpreted as the extra (compared to the no EV-case) amount of hours that the system has a system load higher than $Q$. So if this function lies more in the right side of the graph, i.e. towards higher loads, especially the number of hours with high system loads will increase due to the EVs. Fig. 10 shows both $\Delta F_{\text{Peak}}, \Delta F_{\text{Night}}$ and the merit order of the alternative portfolio in one plot. The emission caused by EV charging is represented by the area overlapped by the $\Delta F$ functions and the CO$_2$ emission curve of the merit order. Accord-
ing to this figure, changing the generation portfolio or including a CO$_2$ price alters the marginal emission curve. It might shift the polluting plants right into the region with specific system loads occurring more frequently due the EVs. On the other hand, changing the time of day of charging or adding wind power (which is seen as negative load) shifts and/or spreads out the $\Delta F$ functions.

**Conclusions**

The most important conclusions that follow readily from this study can be summarized as follows:

- Using the average CO$_2$ intensity of electricity generation to estimate the emissions caused by charging electric vehicles leads to inaccurate outcomes.

- Both emissions and costs of charging electric vehicles depend strongly on the time of day of charging, the generation portfolio, the amount of installed wind power and the price of CO$_2$.

- CO$_2$ emissions of EV charging may range between 0.4 and 1.4 kg/kWh.

- The combination of the marginal emission curve and the change in load duration curve explains the observed results. Especially the non-trivial shape of the marginal emission curve results in widely varying EV charging emissions.

It should be stressed that, if governments want to achieve certain emission reductions in the transport sector, they should be cautious in their projections. We have showed that the emissions, and hence possible reductions, depend strongly on factors on which governments have no direct control in a liberalized market environment. A possible way to avoid this uncertainty could be to enforce special contracts between EV owners and energy suppliers, preferably in cooperation with distribution network operators. For example, the contracts could state
that only renewable energy is to be used for EV charging.

Taking this a step further leads to the situation where the flexibility of EVs can actually be used to increase the share of renewable energy sources as described by [16]. This notion also points out a rather strong assumption we have made in this paper: the EV charging takes place regardless of wind power output, system load and electricity price. In reality, one could think of far more sophisticated charging schemes, that indeed actively use the flexibility of EVs. This clearly is a good pathway for future research. Another suggestion for future research is to include charging characteristics that follow actual commuting data. Moreover, interconnected power systems should be taken into account, too.

References


