

Assessment of the Marginal Emission Factor associated with Electric Vehicle Charging

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Abstract—The scientific community is coming to recognize that marginal emission factors should be employed to assess the footprint of short-term interventions. There is still however disagreement on the methodologies and on the boundaries of the system to be assessed. This study argues that in an interconnected European context imports of power must be included in the calculations. Accordingly it proposes an extension of existing lean approaches taken from the literature in order to account for cross-border flows. The analysis shows that even countries with an almost carbon-free generation mix, like Switzerland, may sustain very high marginal emission factors. The application of the developed model to the case of e-mobility suggests that electric vehicles could have emissions levels comparable to modern conventional cars. The study also warns that the complexity of the system, even when simplified to a single agent, makes the effects of different charging profiles not intuitive.

I. INTRODUCTION

E-mobility is often presented as a major player in the battle to reduce emissions of carbon dioxide (CO₂). Replacing a conventional internal combustion engine vehicles (ICEV) with a plug-in hybrid (PHEV) or battery electric (BEV) solution certainly reduces or even eliminates CO₂ emissions at the tailpipe. However, electrification of the power-train ultimately shifts the emissions from the engines of cars to the sites where electricity is produced. This has raised the issue of finding methods to allocate the appropriate energy mix to the charging electricity of the car. The very nature of alternating current (AC) electricity makes the question “where does the electricity come from?” completely insignificant; the question rather becomes which electricity generators would ramp up to cover the additional load. Most of the approaches identify these generators with the entire generation or consumption mixes, i.e. they assume that all the domestic and sometimes also the foreign generators would proportionally and synchronously ramp up to cover the additional load [1]–[5]. This methodology overlooks the technological and economical differences between different assets, as well as the cost-minimisation principles that lie behind the behaviour of power plant operators

A second solution often presented in the literature employs a marginal approach that tries to identify which assets are involved in the supply of the additional demand. Hadley [6] and Elgowainy [7] obtain such figures by simulating the cost-optimal dispatch of electricity from the entire power sector, both before and after the introduction of PHEVs. The generation mix obtained as a difference between the

two scenarios is then considered as the marginal mix, which supplies electricity to the PHEVs. This approach requires a detailed knowledge of the system and does not allow for an easy inclusion of imports. McCarthy [8] and Axsen [9] also simulate a cost-driven dispatch of electricity, but they cluster the production mix into three categories: non dispatchable plants like renewables and baseload, load-driven assets as hydro or imports and fossil power plants which are defined as the only providers of marginal energy. This method nicely accounts for the technological differences between assets, but imports are not modelled as a marginal source of energy and their mix is thus ignored. Moreover, hydro production is not operated cost-optimally but so as to minimise fossil power production. Ma [10] and Garcia [11] apply a linear regression on the historical generation data of the UK and Portugal respectively to compute the countries’ marginal emission rates. The process requires copious and detailed historical data but its simplicity and intuitiveness make it a valuable tool to quickly estimate the marginal CO₂ of countries. Both however omit imports and their mixes, given the almost-closed nature of the British and Portuguese power systems.

Techniques to compute marginal electricity mixes have been pursued also independently from the evaluation of e-mobility footprint. Ryan [12] and Hawkes [13] present a rich overview of existing methods and the latter eventually opts for the linear regression technique later employed in [10] and [11]. Hawkes’ analysis of the UK shows very good fitting results and the potentiality of this simple approach to detect more complex patterns, such as influence of seasons and load on the marginal emissions. Siler-Evans [14] also successfully applies the linear regression to estimate the marginal emissions of the U.S. electricity system. Both studies however ignore the impact of cross-border flows and imports.

Linear regressions on historical data appear thus as a quick tool to estimate marginal CO₂ emissions at different temporal resolutions, while implicitly modelling operational constraints of the system. The price to pay is the need of sufficient data to perform robust regressions at the desired time scale. Following the regulation (EU) No 1227/2011 on wholesale energy market integrity and transparency (RE-MIT) and the commission regulation (EU) No 243/2013 on submission and publication of data in electricity markets, access to hourly generation data from all around Europe is

becoming viable.

Another reason why the linear regression approach has not usually been applied to European countries is the high level of integration between their electric systems. This implies that physical flows of power between countries cannot be ignored while evaluating any type of electricity mix. We propose an extension of the linear regression method in order to include electricity from cross-border flows.

This work will also show that not every country is suitable for a linear regression analysis. One of these examples is Switzerland, which was chosen as test country due to the authors' location and the availability of high quality mobility data (see subsection II-A). The reason lies in the specific structure of the Swiss power systems, with details provided in subsection II-B. This brought to the development of a hybrid approach, the Imports Shift Model, that resembles the cost-optimal dispatch model from [8]. A detailed description of the mechanism is provided in subsection II-C. The linear regression approach was instead successfully applied to the Swiss neighbouring countries, with a variation described in subsection II-D that allows to capture more patterns at different time scales. We present some preliminary results in section III and we conclude with some comments and outlook in section IV.

II. DATA AND METHODOLOGY

A. Charging Patterns

We here explain the construction of detailed load curves associated with e-mobility assuming that the only available option is home charging. In this demonstrative study we only provide preliminary results for a simple plug-and-charge strategy, but extensions to smarter schemes are straightforward. The main data source is the 2015 result of the *Mikrozensus Mobilität und Verkehr* (MZMV) [15], which is a survey about private mobility behaviour carried out in Switzerland every 5 years. The data allow us to infer the distribution of the times at which people brought the car back home and of the distances they drove. We then assume the followings:

- car owners would switch to BEVs without changing their driving routines;
- BEVs have battery capacities able to supply power for all required distances;¹
- batteries of vehicles are fully charged in the morning before they leave the house;
- specific electricity consumption of BEVs at the grid is in the range 0.276 – 0.325 kWh/km;²
- charging rate constant and equal to 6.6 kW.³

The MZMV dataset is sufficiently large to allow for further investigations: for the purpose of this study, a different

¹Since the focus of the analysis is on specific CO₂ emissions (gCO₂/km), the results are not affected by the maximum battery capacity and the correlated all-electric-range.

²The lower value is taken from [7], where calculations includes real-world energy demand, non-propulsive loads and charging losses. We additionally applied transmission and distribution losses, equal to 7.52% [16]. The latter value comes from in-house calculations supported by ongoing field measurements. It is found that non-propulsive loads, especially heating, affect BEVs at a much higher extent than in ICEV, thus firmly increasing the real-world energy demand.

³Nominal rate of the on-board charger installed on most of commercial BEVs.

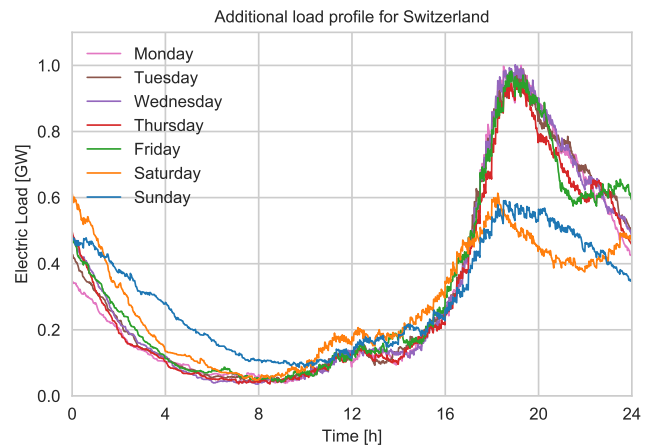


Fig. 1. Charging patterns for every day of an average week, supposing electrification of 20% of the national distance driven.

analysis for every day of an average week has been carried out. Figure 1 shows the resulting load curves for every day of a generic week, were 20% of the national vehicle-km performances to be electrified: as a reference, the average Swiss load in 2015 was 6.6 GW [16].

The plot shows the similarity between charging patterns during working days, although Friday presents a higher peak around midnight due to people going out for the evening. Interestingly, Saturday and Sunday display lower peaks than working days because fewer people come back home at the same time. However, the higher load of Sunday night suggests that trips on Saturdays are longer and demand more electricity. This is also confirmed by the official results summary from MZMV [17].

B. Swiss Power System

The Swiss power sector is dominated by nuclear and hydro generation, which provide base and variable load respectively. Few conventional thermal plants complete the portfolio, but they are also currently operated for base load. Hydro production is further split into run-of-river and (pumped-)storage generation, but only the latter is capable of actively adjusting its load and providing flexibility to the system. However the amount of water available for generation is fixed and hydro power plants cannot increase their net yearly production.⁴ The resulting setting resembles the framework proposed in [8] with hydro power plants free to adjust their dispatch but not able to ultimately provide marginal energy. This task belongs to flexible assets which can increase their total production, but in the Swiss case this can be achieved only by imports.

On the other hand, imports do not behave as a conventional marginal asset: they are triggered by a reduction in domestic generation, rather than by an increase in electricity demand. Imports do not increase when it would be the most profitable, but when for hydro storage it is the least. This is proved by the inverse relationship between the first differences of net imports and hydro storage production: historical data return a R^2 of 0.665 for such correlation.

⁴For simplicity, we neglect the role played by pumped-storage plants, which account for about 5% of total hydro production [16].

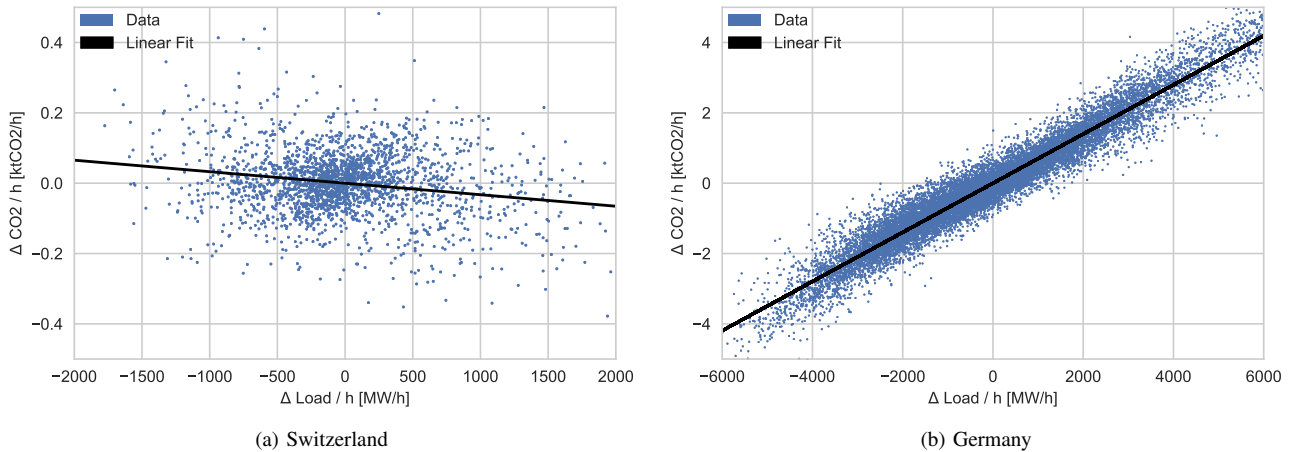


Fig. 2. Change in system CO₂ emissions against variation of total load. Non-dispatchable renewable sources such as solar and wind are omitted; cross-border flows are included.

This mechanism explains why Switzerland is not suitable for the linear regression approach, which relies on the implicit assumption that every asset operates marginally, increasing the production proportionally to the demand.

Figure 2a displays the result of the linear fitting applied to the Swiss case and Table I gives the associated R² score. The fitting result is particularly poor also due to the disparity in CO₂ intensity between the Swiss generation mix and foreign imports (especially from Germany).

C. The Imports Shift Model

The Swiss power system is modelled as follows. The electricity load and exports to be supplied are the same as in 2015, with the addition of e-mobility load computed above (subsection II-A). Installation or decommissioning of power plants is instead omitted.⁵ All hydro storage operators are lumped into a single, smart agent, who can decide whether to supply the additional e-mobility load. If it does, it will also look for the most convenient moment where the needed water can be spared. The hydro agent can thus shift in time the depletion of reservoirs and the associated generation of electricity. The procedure is cost-optimal and rests on the realised prices of the Swiss spot-market [19]. In this way we emulate the real strategy of hydro operators. The reference production profile for hydro storage plants is obtained from the ENTSO-E transparency platform [20].

Finally, electricity imports are increased in order to satisfy the residual demand, including e-mobility. The design of this mechanism reflects the existing reverse correlation between imports and hydro storage generation, as discussed in subsection II-B. Historical data from the Transmission System Operator of Switzerland, Swissgrid, are used to derive the base imports/exports profiles [21]. Since Italy delivers a negligible amount of imports to Switzerland, only cross-border flows from Austria, Germany and France are considered. Swissgrid data allow to model the likelihood of a kWh to be imported from each of the three exporting

⁵The implicit assumption is that e-mobility arises while the other sectors do not reduce their electricity consumption, i.e. every kWh demanded by BEVs is an additional kWh demanded by the entire system as a whole. The most conservative scenario of the Swiss energy perspectives (*weiter wie bisher* = business as usual) supports this assumption [18].

countries. The analysis showed that time and seasonality do not play a relevant role in this phase, but Germany turns out to be the country where most of the additional, *marginal*, imports come from.

The following technical and operational constraints have also been included:

- minimum and maximum power rates for the national hydro production in order to ensure its availability for positive and negative ancillary services [21];
- maximum transmission capacity for cross-border lines, from the modelling data for the Ten Year Network Development Plan by ENTSO-E [22].

Figure 3 graphically shows how the cost-optimal algorithm works. The principle of the model is thus embodied in its name, Imports Shift Model. The ultimate marginal "assets" able to supply e-mobility are imports, but hydro operators' strategy may shift physical imports with respect to the timing of BEVs charging. This implies that we cannot directly track the CO₂ intensity of a specific charging operation. We can only discuss the *total* emissions caused by *all* the charging electricity demanded during a period of time.

D. Foreign Electricity Mix

The structure of the model translates the assessment of the environmental footprint of e-mobility into an estimation of the CO₂ intensity of foreign electricity mixes. Austria, France and Germany were assumed to be the only countries exporting power to Switzerland. Contrary to the latter, the three exporting countries prove to be well fitted for the linear regression approach, as confirmed by the R² scores presented in Table I. The input data to the model were, as in [13], the hourly variation of load and the hourly change in

TABLE I
R² SCORES FOR DIFFERENT FITTING MODELS

Model	Austria	Germany	France	Switzerland
Linear Regression	0.628	0.949	0.646	0.041
Decision Tree	0.687	0.947	0.676	n.a.
Combined Model	0.699	0.952	0.687	n.a.

TABLE II
MARGINAL AND AVERAGE EMISSION FACTORS

Emission factor [gCO ₂ /kWh]	Austria	Germany	France
Marginal	252.3	759.7	133.5
Average	60.1	424.9	34.8

direct CO₂ emissions due to domestic generation. However, as suggested in [8], non-dispatchable generation, such as solar and wind, was excluded from the analysis. On the other hand, the CO₂ incurred through cross-border flows was included, with the CO₂ content aligned with the average emission intensity of the exporting country as of [23]. The source for domestic generation data and cross-border flows was the ENTSO-E transparency platform [20]. Figure 2b shows the linear fitting between the generation data from Germany and their emissions.

The marginal emission factors obtained with the linear regression and their comparison with official average intensities (2014) from [23] are shown in Table II. The figures mark the higher CO₂ content of marginal assets compared to the entire power plant fleet. This highlights the importance of choosing the appropriate emission factor when performing an environmental assessment.

An in-depth analysis of the three neighbouring countries showed that seasonality and hour of the day substantially affect the marginal emission factor. In order to capture these more complex patterns, the same input data have been clustered through a decision tree regressor [24]. However, given the predominant linear correlation between total load and emissions, a subsequent linear regression has been applied to every single leaf of the decision tree. The resulting fitting scores are shown in Table I, with the last modification labelled “Combined Model”. These scores refer to a test dataset, which was not overlapping with the training data. It

TABLE III
DIRECT CO₂ EMISSIONS [gCO₂/km]

Electricity Consumption [kWh/km]	0.276	0.325	
BEV, Imports	DOE = 5 %	86.4	101.8
Shift Model	DOE = 20 %	90.9	108.5
BEV, Swiss consumption mix		38.2	45.0
Fleet, 2021 European target		95.0	
HEV (real-world demand [7])		133.3	
ICEV (real-world demand [7])		190.0	

is important to highlight that, in order to avoid overfitting, the decision tree was pruned. The results indicate that capturing those more complex patterns allows to improve the prediction power of the model, especially in countries with a weaker linear correlation between load and CO₂ emissions.

III. RESULTS

A set of preliminary results obtained with the Imports shift model is presented in Table III. The first 2 rows show the model’s output for different Degrees of Electrification (DOE) of the fleet, distance-wise. The 2 columns assume instead different specific real-world electricity demands.

Many reference values are provided, including the emission levels of a BEV obtained with the consumption mix of Switzerland [25], 138.5 gCO₂/kWh.

The order of magnitude of the difference between our model and the consumption mix highlights the criticality of properly assessing the “origin” of the electricity. When consistently using real-world performances, BEVs always produce less direct CO₂ emissions than ICEVs and HEVs. The emission levels obtained with our model are however higher than the 2021 European target for the fleet of new cars. BEVs currently do not account for any direct emission towards the target, but these results suggest that a different approach may be necessary.

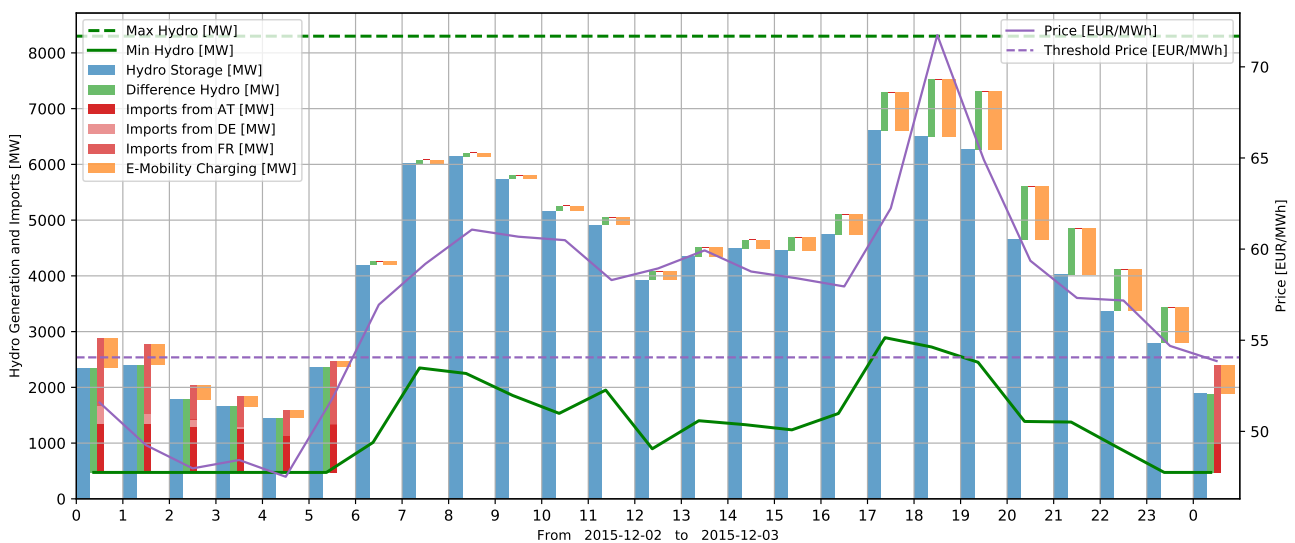


Fig. 3. Example of optimisation during a single day. Orange columns indicate the additional load demanded by plugged BEVs; blue bars represent hydro generation before introduction of BEVs; green columns indicate hydro response to the new input, with generation that can either increase or decrease; stacked red bars indicate additional imports required to supply the residual demand (one shade for each country of origin). In purple the hourly spot-market price and the threshold price which determines the hydro response to the additional load. The example shown assumes electrification of 20% of the performances and a specific electricity demand of 0.325 kWh/km.

IV. CONCLUSIONS

The study proposes an extension of existing techniques to compute marginal emission rates in order to account for electricity imports in highly interconnected regions. Such extensions demonstrate that even countries whose generation mix is basically carbon-free, such as Switzerland, may be characterized by severe marginal emission factors. This strongly affects the carbon content of the electricity supplied to BEVs. First calculations provide distance-specific emissions in the range 86 – 109 gCO₂/km, which are comparable to the 2021 European target for the fleet of all new cars.

In addition, the analysis illustrates that not every country's mix can be successfully characterized through a simple linear regression model. This highlights the importance of understanding the properties of a system before going into modelling, so that the most appropriate technique can be applied.

The paper finally signals that by including just one agent the system becomes complex enough that BEV charging decouples from the physical generation of electricity. Therefore, the evaluation of different charging strategies is not straightforward and the complexity of the system should be accounted for.

The model is still under development and the precise sensitivity of the results to the input parameters is yet to be assessed.

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