Marginal Emission Factors in Power Systems: The Case of the Netherlands

Parnian Alikhani[a], Nico Brinkel[b], Wouter Schram[c], Ioannis Lampropoulos[d]
and Wilfried van Sark[e]
Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands

Keywords: Electricity System, Cross-Border Exchange, Decarbonization, Marginal Emission Factors, Merit Order.

Abstract: The Marginal Emission Factor (MEF) is a consistent metric with increased accuracy, compared to the average emission factor, to evaluate the avoided emissions as a result of changes in electricity consumption caused by new technologies and policies. In this study, a method is developed to model MEFs by constructing merit order profiles in interconnected power systems. The proposed method is applied in a case study of the Netherlands for the years 2018 to 2022. This method, in contrast to previous studies that developed marginal emission profiles, does not neglect the share of the electricity demand which is met by countries in neighboring bidding zones. In this study, the results suggest that ignoring electricity trading significantly underestimates the marginal emission factors. It is found that the key factors resulting in clear temporal shifts in the marginal emission profiles are fuel and CO_2 prices. Even though the installed capacity of fossil-fueled electricity generation has declined over time, these are mainly the power plants that operate at the margin and often set electricity prices at the wholesale level. Overall, the MEF profiles obtained using the proposed method could be readily employed in detailed evaluations of the emission optimization of distributed power systems to support decarbonization.

1 INTRODUCTION

Given the adverse effects of anthropogenic climate change, impact studies exploring strategies to achieve maximum greenhouse gas (GHG) emission reduction and power systems decarbonization are of great importance. Developing techniques or metrics to accurately assess the reduction of CO_2 is an important step in properly assessing both supply strategies and demand-side management measures (Lampropoulos et al., 2013), (Brown and Chapman, 2021). Electricity sector CO_2 emissions vary per location and over time.

There are two approaches to assess the CO_2 emissions of power systems based on the average emission factor (AEF), and the marginal emission factor (MEF). Not only these emission factors make it possible to assess the CO_2 emissions associated with power systems operations, but can also serve as a driving force behind individuals' and businesses' electricity consumption behavior.

The AEF is calculated by dividing total CO_2 emissions from electricity generation by the total amount of generation over a certain period of time (typically one year) and represents a mixture of all generation sources. In contrast, the MEF reflects the emission intensity of the first power plant responding to an intervention at a given time interval and represents the emissions factor of the generator that is operating at the margin. When using AEFs to assess the emission impact of an intervention (e.g., a demand response action), it is assumed that a change in electricity generation is evenly distributed over all generation facilities. This is not in accordance with the operation of electricity markets (Schram et al., 2019). Comparing average and marginal emissions factors revealed that AEFs largely fail to correctly estimate the avoided emissions resulting from an intervention (Siler-Evans et al., 2012). Generators do not ramp up production equally, instead, the generator at margin responds to a change in demand and the emissions of this single generator should be attributed to this demand

---

[a] https://orcid.org/0000-0003-1678-1588
[b] https://orcid.org/0000-0001-9973-2890
[c] https://orcid.org/0000-0003-3407-7893
[d] https://orcid.org/0000-0001-8566-4970
[e] https://orcid.org/0000-0002-4738-1088

Alikhani, P., Brinkel, N., Schram, W., Lampropoulos, I. and van Sark, W.
Marginal Emission Factors in Power Systems: The Case of the Netherlands.
DOI: 10.5220/0011855700003491
In *Proceedings of the 12th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2023)*, pages 50-57
ISBN: 978-989-758-651-4; ISSN: 2184-4968

change (Woody et al., 2022).

Variation in MEFs by the hour of the day is important for the evaluation of technologies and policies designed to incentivize an increase or decrease in electricity consumption at specific times of the day. Another essential use of hourly MEFs is to accurately estimate the decrease in emissions associated with non-dispatchable renewable generation, which typically is equivalent to the effect of a reduction in load (Holland et al., 2022).

Several studies have been conducted in recent years to develop methods to calculate MEFs and outline the importance of the topic. Hawkes (Hawkes, 2010) developed a regression-based approach to construct MEF profiles for the UK by evaluation of power system historical data. This methodology has been applied in subsequent studies as well (Holland et al., 2015), (Thomson et al., 2017). This method might not be feasible if significant changes in the power system occur. The most accurate approach is based on electricity market models by taking into account power plant dispatch. In such models, changes in the power systems could be taken into account. Generators at the margin are not usually published. Schram (Schram et al., 2019) proposed a method to estimate the marginal power plant based on the Day-Ahead Market (DAM) price and the marginal costs of a power plant.

There are several studies using MEFs to estimate emissions-saving in demand-side management. In Ontario, passenger Electric Vehicle (EV) charging profiles optimization to minimize MEF led to 50% lower EV emissions (Tu et al., 2020). Similar results were obtained applying regional-specific MEFs where optimized charging of EVs reduced emissions by as much as 31% for standard use and 59% for vehicle-to-grid (V2G) use (Hoehne and Chester, 2016). In addition, the trade-off between electricity cost and MEFs using multi-objective optimization and optimal solutions using Pareto frontiers for EV-controlled charging was investigated in (Brinkel et al., 2020).

While several studies have investigated AEF and MEF, there is no prior study, to the best of our knowledge, that considers electricity produced by generators in neighboring countries/states and cross-border trade as a result of electricity market coupling. Employing an electricity-interconnected market is referred to as market coupling which aims to harmonize various systems of electricity exchanges and, in particular, to reduce price differences by linking control areas and market areas. Integration of the European electricity markets is an approach to contribute to the decarbonization of the European energy system and increasing the security of supply. In the early 2000s, some Central Western Europe (CWE) countries started to move towards market coupling in agreements with several regional initiatives (TenneT, 2021b). The convergence in market prices across CWE countries is one of the main targets of market integration. Therefore, transmission capacities allocated to cross-border trading and the level of price convergence have increased over time. Full price convergence within CWE reached 48% of the hours in 2021 (TenneT, 2021a). Higher price convergence contributes to better European market integration, and market coupling has created efficient trading at the day-ahead stage (Gissey et al., 2019).

A large and highly interconnected grid has many economic and operational constraints, which make challenging the identification of marginal generation units (Siler-Evans et al., 2012). Due to the increased market coupling, the generator at the margin that responds to a change in demand might be not located in the studied country, but in one of the surrounding bidding zones. This can considerably affect the marginal emission factor profiles for electricity, in particular when the variation in the electricity generation capacity mix between bidding zones is significant. The concept of market coupling has not been integrated into the methods proposed in previous studies to generate marginal emission profiles.

In this study, we develop a method to model MEFs for national power systems by constructing merit order profiles of all generation facilities while taking cross-border trade into account. Next, the approach is applied to the case of the Netherlands to derive MEFs from 2018 to 2022. This method takes into account the electricity imported by considering the power plants in CWE countries with a high amount of hours of DAM price convergence with the Netherlands. The proposed approach is also compared with the results of a scenario in which electricity trading is neglected.

In Section 2, the methodology is presented. The case study and datasets are discussed in Section 3. In section 4, the results of the proposed method for a given case study are presented. Section 5 contains the key conclusions.

2 METHOD

The construction of the MEF profiles is based on the countries' generation facilities and historical data and is developed using the approach proposed by (Schram et al., 2019). This method calculates the marginal costs of each power plant in one country, and marginal costs are linked with the DAM price to find which generator is at the margin. However, this method neglects that a high level of price convergence has been observed in recent years within the CWE region (ENTSO-E, 2021).

Full price convergence refers to exact same price between two neighboring bidding zones. The market coupling could cause the marginal generator to be located in another bidding zone. Price convergence between bidding zones indicates that the DAM clearing was not restricted by transmission constraints between bidding zones, causing the same merit order to be applied to both countries. Hence, a moment of price convergence between two or more bidding zones indicates that the same generator is at the margin in these bidding zones. In this study, it is assumed to have electricity exchange within CWE countries at times with full price convergence.

After collecting and pre-processing the data sets which are explained in section 3, the merit order construction is the first step in modeling the MEFs profile. This is the electricity generation mix ranked based on ascending order of marginal operation costs (MC). MC (in €/MWh) of facility i is the sum of three components, namely the fuel costs, the emission costs, and the variable operating costs (Biggar and Hesamzadeh, 2014), and thus could be obtained as follows (Schram et al., 2019):

$$MC_i = \frac{FP_i}{\eta_i} + \frac{EF_i}{\eta_i} \times CP + VOC_i \tag{1}$$

where FP is the price of fuel (in €/MWh$_t$), η is the conversion efficiency, EF is the emission factor of the fuel (in tCO$_2$/MWh$_t$), CP is the EU Emission Trading System (ETS) CO$_2$ price (in €/tCO$_2$), and VOC is the Variable Operational Costs (in €/MWh).

The marginal emissions (ME) (in tCO$_2$/MWh) of facility i which is determined to be at margin are obtained as follows (Schram et al., 2019):

$$ME_i = \frac{EF_i}{\eta_i} \tag{2}$$

For constructing the MEF profile, first, the facility at the margin is determined by the clearing prices of the DAM. Then, the MEF profile can be created using the marginal facility's emissions. To identify the marginal power plant, the following assumptions related to the marginal facilities are made:

- To determine the marginal operating facility, the power plant with marginal costs closest to the spot price is assumed to be the marginal operating facility.
- When the investigated country's DAM price is equal to the DAM price of other bidding zones, we take into account all power plants generating at the investigated country and other bidding zones with the exact same DAM price. It is assumed that there is electricity exchange within the CWE region at times when the price fully converges.
- When the investigated country's DAM price is not equal to any other bidding zones' DAM prices, we take only the investigated country's power plants into account.
- When the investigated country DAM price is negative, we assume that renewable resources are at the margin.
- When the investigated country's DAM price is lower than one-third of the lowest MC of considered power plants, we assume that renewable resources are at the margin as well. It is assumed that electricity with lower prices is generated from renewable sources.

In addition, several other assumptions have been made to construct the merit order and MEF profiles which are as follows:

- Hard coal, Natural Gas (NG), Lignite, Nuclear, and Renewable Energy Sources (RES) are identified as the marginal energy supply sources based on their generation capacity in the countries.
- All power plants are assumed to operate at their maximum efficiency; efficiency losses of operating at partial load are not considered.
- Coal and natural gas plants with a capacity under 100 MW are excluded from the list due to their low efficiencies.
- No assumptions about future scenarios are made.
- It is assumed that market participants bid based on the marginal costs of their power plants.
- Bid strategies of retailers were not considered.

3 CASE STUDY SPECIFICATIONS AND DATA COLLECTION

The methodology is applied to the Dutch power system for the years 2018 to 2022. The countries in CWE with a high number of hours with full price convergence with the Netherlands are Germany, Belgium, France, Austria, and Denmark. **Table. 1** indicates the price convergence time percentages that occurred every year with the above-mentioned countries. In recent years, prices have converged considerably. However, in 2022, the Russo-Ukrainian War significantly affected the energy markets, resulting in a decrease in electricity price convergence.

Table 1: Countries in CWE that have the highest amount of hours with full price convergence in 2018-2022.

Year	Germany	Belgium	France	Austria	Denmark
2018	36.09%	40.48%	37.07%	33.95%	19.05%
2019	49.28%	46.77%	42.65%	44.55%	37.36%
2020	48.95%	49.75%	44.67%	44.25%	38.64%
2021	53.73%	51.70%	48.64%	48.49%	51.10%
2022	38.89%	36.14%	33.49%	33.60%	38.12%

To construct the MEF profiles, several datasets are required as input. First, the characteristics of all generation facilities, namely each unit's installed capacity, efficiency, and generation types, which are obtained using the JRC open power plants database (JRC, 2019). CO_2 prices in addition to fuel prices for coal, NG, and uranium are collected from Investing (Investing, 2022). Lignite price is collected from Federal Statistical Office of Germany (German Federal Statistical Office, 2022). VOC is assumed to be 2.56 €/MWh for NG-fired facilities, 3 €/MWh for coal-fired power plants, and 6.4 €/MWh for nuclear power plants (De Vita et al., 2018). The emission factor of bituminous coal, natural gas, lignite, uranium, and RES are determined as 0.341, 0.202, 0.364, 0.031, and 0.015 tCO_2/MWh_t, respectively (Koffi et al., 2017).

4 RESULTS AND DISCUSSION

4.1 Marginal Emissions Factors of the Case Study

In **Fig. 1** the MEF profiles by the hour of the day and day of the year, from 2018 to 2022, are illustrated. The heatmap shows a clear change in the MEF profiles over the years. In 2018, during the peak hours (i.e., 8:00-10:00 and 17:00-19:00), MEFs are relatively low which coincides with high DAM prices, and MEFs increase outside the peak times. In 2019 and 2020, this trend is reversed, and higher MEFs are obtained during the morning and afternoon hours when demand is ramping up, and lower MEFs are acquired in the late evening when the demand decreases. There are several shifts in trends in 2021 and 2022, which make the trends seem inconsistent throughout the year.

The main reasons behind these shifts are the change in NG and CO_2 prices. As shown in **Fig. 2**, marginal costs of NG power plants are higher than other facilities in 2018 which makes NG frequently the marginal fuel source. NG prices decreased in 2019 and 2020, explaining the shift in the daily MEF pattern from 2018 to 2019, when peak hours with higher prices coincided with higher emission factors from coal or lignite generators. Later at the end of 2021, a significant rise in NG price as well as the increase in CO_2 price lead to NG power plants being at the margin during high-demand hours when DAM price is high. Moreover, the increase in CO_2 price results in the marginal cost of coal-fired power plants increasing more than NG plants due to their higher emission factor.

The MEF profiles of a randomly chosen day e.g. 16 September in both 2018 and 2020 are illustrated in **Fig. 3** to visualize how the MEF pattern changes over time. In 2018, the MEF profile mostly behaves the opposite of the DAM price trend, however, it almost follows the DAM price behavior in 2020. This demonstrates that scheduling demand to minimize cost is not always the best strategy from an environmental point of view since it could increase the amount of CO_2 produced by power plants. **Fig. 4** shows the daily average and 7-day rolling average MEFs. As a result of changes in marginal fuel, MEFs show a trend to decline from 2019 through 2021 and significant rises in the second half of 2021 and 2022.

Fig. 5 shows how marginal generation sources have shifted over the last four years. The fraction of time that different units are at the margin is identified for each year. The share of NG as the marginal generator has increased since 2018. This development has largely been due to NG's declining price worldwide in recent years until 2021 along with CO_2's sharp rise in price, resulting in NG replacing coal. It is shown that the coal power plants started responding more again to marginal changes in 2021. The price of coal was significantly low compared to that of NG after the pandemic in 2021. As a result, NG facilities, which emit less CO_2 per generated unit of electricity, have been at the margin less in 2021 and 2022 than years earlier. Nuclear, Lignite, and RES generators are rarely at the margin due to their low marginal costs and insufficient installed capacity to satisfy the entire demand.

In addition, a considerable increase in RES generation and a reduction in load demand in 2019 and later in 2020 due to the global pandemic lead to a decrease in DAM prices which are driven by supply and demand. DAM price changes as well as a decrease

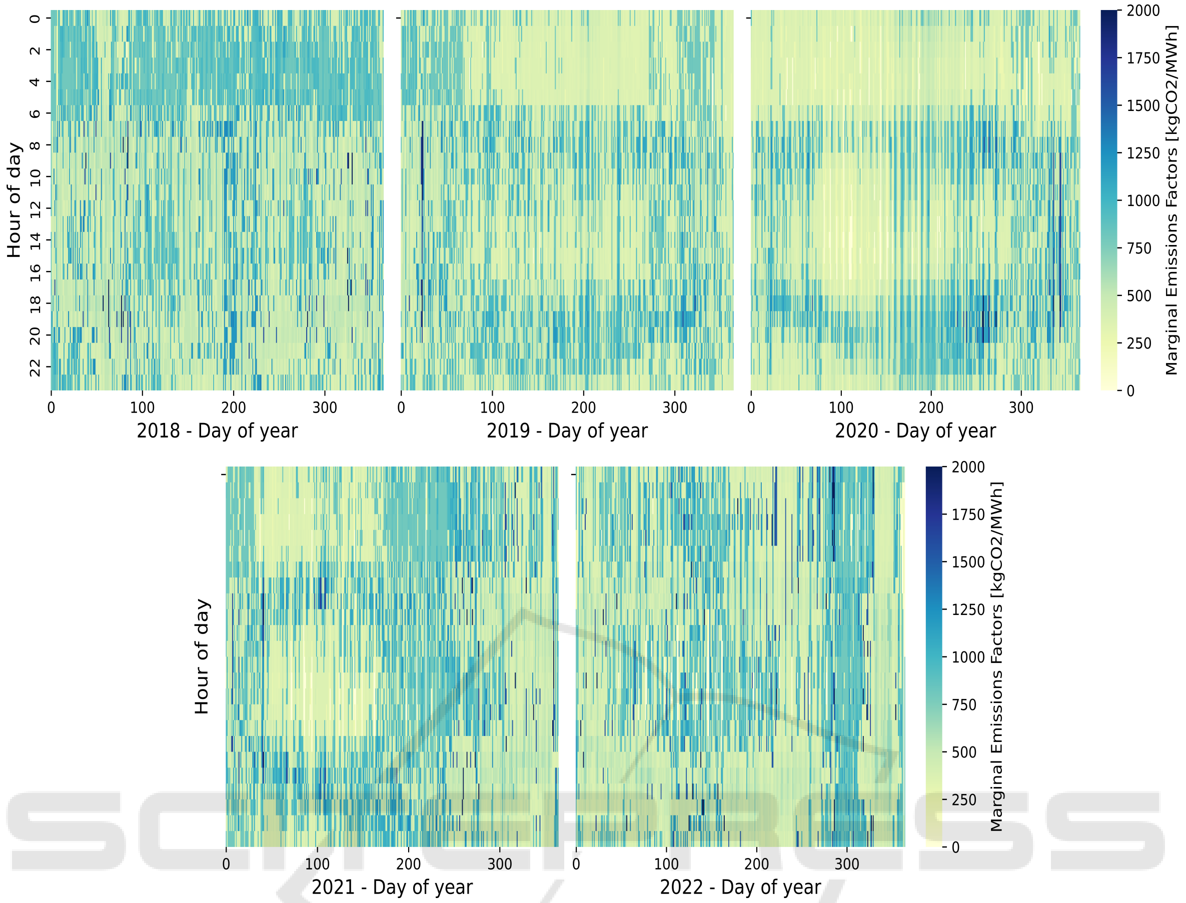

Figure 1: Hourly marginal emission profile for the Netherlands from 2018 to 2022.

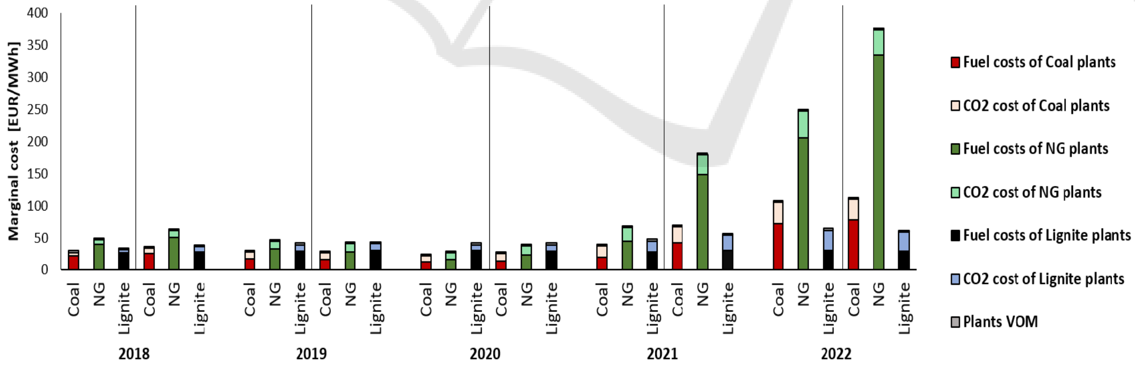

Figure 2: The marginal cost of each type of power plant per half a year. It includes fuel, CO_2, and variable operational costs taking into account the average efficiency of each type of power plant.

in NG prices made coal-burning power plants, as the biggest emitters, be at the margin less than before and result in less CO_2 emissions.

Even with a 20.85 percentage point (p.p.) increase in renewable energy generation from 2018 to 2021, fossil-fueled generation units remained the main power plants at the margin, whilst producing only 63% of the Netherlands' electricity in 2021 (CBS, 2022). There were 99.44% of times when fossil fuels were marginal in 2018. Despite renewable energy reducing this share to 96.24% in 2021, the marginal power plant still relies heavily on fossil fuels. Additionally, there is a 13.06 p.p. increase in the marginal generator's dependency on imports from neighboring bidding zones in 2021 versus 2018, demonstrating the improvement in European electricity market

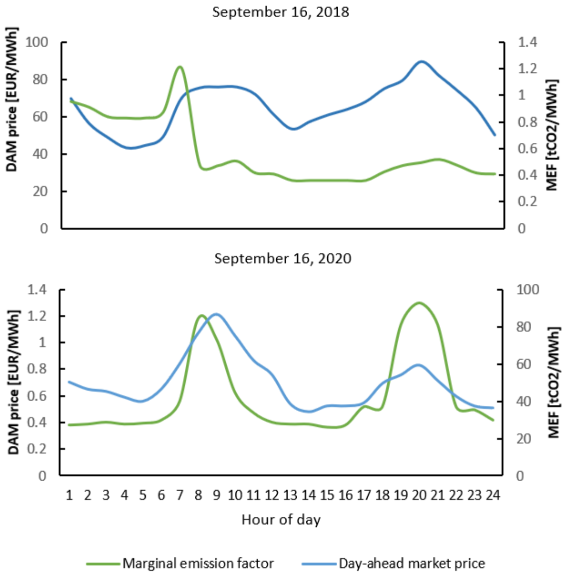

Figure 3: Day-ahead price versus marginal emission factor for 16 September 2018 and 2020.

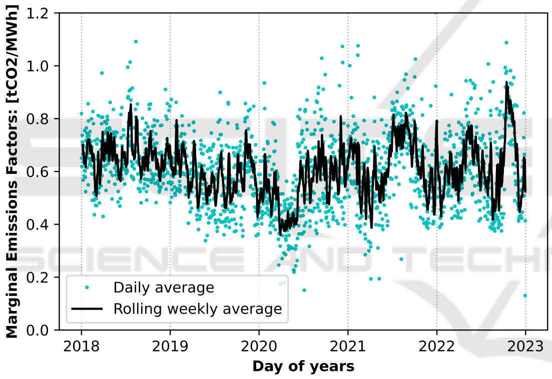

Figure 4: Daily average and 7-day rolling average marginal emission factors over the studied years.

coupling. The Dutch electricity grid appears to be largely balanced by interconnections with Germany. The Russo-Ukrainian War negatively affected the energy market in 2022, resulting in a decrease in the level of price convergence.

4.2 Performance Evaluation of the Proposed Method

Fig. 6 shows the range of emission factors for power plants in the Netherlands and other bidding zones that take efficiencies into account. Power generated from lignite and nuclear, along with numerous hard coal and natural gas power plants with different efficiencies located in neighboring countries, would be eliminated in case of neglecting power exchange impact.

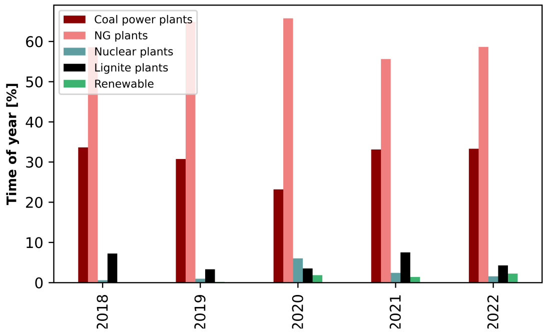

Figure 5: Percentage of hours for each type of fuel being at the margin per year.

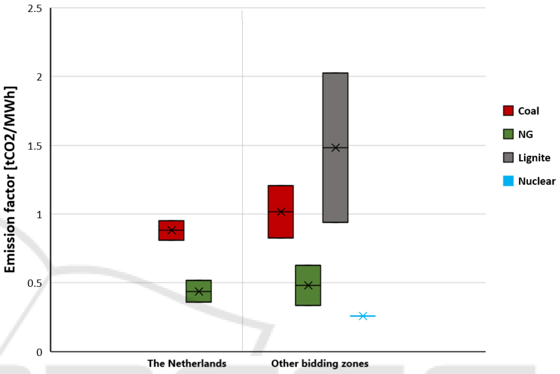

Figure 6: An overview of the emission factors of power plants in the Netherlands and other bidding zones.

As a result, marginal generator emissions in the other bidding zones are not taken into account when calculating MEFs.

MEF profiles without taking into account electricity exchange with other bidding zones are also constructed for comparison of the results of this study. **Fig. 7** illustrates the mismatch between MEFs that are constructed using the proposed approach and those that neglect trading in 2018. Observations indicate that MEFs are underestimated when power exchanges are neglected, and the proposed approach improves the accuracy of emission factors for the power sector. If the model neglects electricity trade among neighboring bidding zones, then only power plants in the Netherlands are taken into account. This ignores the emission factors of power plants that do not exist in the country, i.e., lignite and nuclear. Hence, ignoring the electricity exchange leads to underestimating the emission factors by not accounting for electricity generated from other units, especially units with higher emissions, such as coal and lignite installed in other bidding zones.

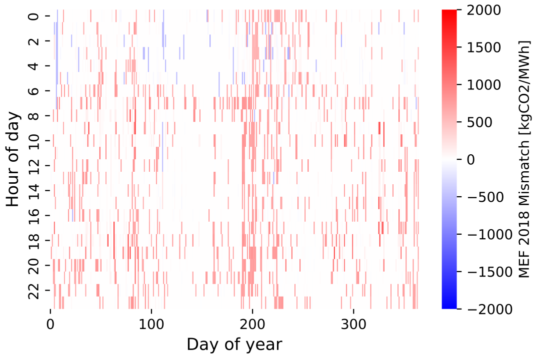

Figure 7: Marginal emission factors differences between scenarios considering versus ignoring electricity imports.

5 CONCLUSIONS

In this paper, we provide an approach for the determination of MEF profiles from the electricity sector and applied the method to the case of the Netherlands from 2018 to 2022 via generation facilities merit order construction. The impact of electricity trade with other bidding zones is taken into account, leading to higher accuracy compared to ignoring electricity trade, which results in underestimating emission factors. Although the share of electricity generated from renewable sources has increased substantially over the past few years, electricity prices are still largely determined by carbon-intensive power plants at the margin. Variations in MEF profiles and shifts in marginal power plants are primarily caused by fuel and CO_2 prices. It is expected that future developments will increase the share of renewables and increase the variability of marginal generation as a result. Although the current share of renewable energy in the electricity mix account for only a small share of the marginal mix, this is expected to change in the future. The consequences of these changes for a future scenario could be investigated in future work.

In conclusion, the proposed MEF construction approach is well suited to be used in the emissions optimization of distributed power systems to promote decarbonization e.g., scheduling of electricity demand and evaluating load shifting potentials.

ACKNOWLEDGEMENTS

This study is supported by the Dutch Ministry of Economic Affairs and Climate Policy and the Dutch Ministry of the Interior and Kingdom Relations through the ROBUST project under grant agreement MOOI32014. This study is also supported by the Horizon 2020 program and the ARV project under grant agreement 101036723.

REFERENCES

Biggar, D. R. and Hesamzadeh, M. R. (2014). *The economics of electricity markets*. Wiley Blackwell.

Brinkel, N., Schram, W., AlSkaif, T., Lampropoulos, I., and Van Sark, W. (2020). Should we reinforce the grid? cost and emission optimization of electric vehicle charging under different transformer limits. *Applied Energy*, 276:115285.

Brown, M. A. and Chapman, O. (2021). The size, causes, and equity implications of the demand-response gap. *Energy Policy*, 158:112533.

CBS (2022). More electricity from renewable sources, less from fossil sources. https://www.cbs.nl/en-gb/news/2022/10/more-electricity-from-renewable-sources_less-from-fossil-sources, Accessed: December 9, 2022.

De Vita, A., Kielichowska, I., Mandatowa, P., Capros, P., Dimopoulou, E., Evangelopoulou, S., Fotiou, T., Kannavou, M., Siskos, P., Zazias, G., et al. (2018). Technology pathways in decarbonisation scenarios. *Tractebel, Ecofys, E3-Modelling: Brussels, Belgium*.

ENTSO-E (2021). Transparency platform; day-ahead prices. https://transparency.entsoe.eu/transmission-domain/r2/dayAheadPrices/show, Accessed: January 13, 2023.

German Federal Statistical Office (2022). Preise - erdgas- und stromdurchschnittspreise. https://www.destatis.de/, Accessed: January 9, 2023.

Gissey, G. C., Guo, B., Newbery, D., Lipman, G., Montoya, L., Dodds, P., Grubb, M., and Ekins, P. (2019). The value of international electricity trading. *A project commissioned by Ofgem*.

Hawkes, A. (2010). Estimating marginal co2 emissions rates for national electricity systems. *Energy Policy*, 38(10):5977–5987.

Hoehne, C. G. and Chester, M. V. (2016). Optimizing plug-in electric vehicle and vehicle-to-grid charge scheduling to minimize carbon emissions. *Energy*, 115:646–657.

Holland, S. P., Kotchen, M. J., Mansur, E. T., and Yates, A. J. (2022). Why marginal co2 emissions are not decreasing for us electricity: Estimates and implications for climate policy. *Proceedings of the National Academy of Sciences*, 119(8):e2116632119.

Holland, S. P., Muller, N. Z., Mansur, E. T., and Yates, A. J. (2015). Environmental benefits from driving electric vehicles? *National Bureau of Economic Research: Cambridge MA*.

Investing (2022). Stock market quotes and financial news. https://www.investing.com/, Accessed: October 5, 2022.

JRC (2019). European commission open power plants database(jrc-ppdb-open). http://data.europa.eu/89h/

9810feeb-f062-49cd-8e76-8d8cfd488a, Accessed: October 5, 2022.

Koffi, B., Cerutti, A., Duerr, M., Iancu, A., Kona, A., and anssens Maenhout, G. (2017). Com default emission factors for the member states of the european union - version 2017. https://data.jrc.ec.europa.eu/dataset/jrc-com-ef-comw-ef-2017, Accessed: October 5, 2022.

Lampropoulos, I., Kling, W., Ribeiro, P., and van den Berg, J. (2013). History of demand side management and classification of demand response control schemes, ieee power & energy society general meeting. *Vancouver BC*.

Schram, W., Lampropoulos, I., AlSkaif, T., and Van Sark, W. (2019). On the use of average versus marginal emission factors. In *SMARTGREENS 2019-Proceedings of the 8th International Conference on Smart Cities and Green ICT Systems*, pages 187–193. SciTePress.

Siler-Evans, K., Azevedo, I. L., and Morgan, M. G. (2012). Marginal emissions factors for the us electricity system. *Environmental science & technology*, 46:4742–4748.

TenneT (2021a). Annual market update 2021, electricity market insights. https://www.tennet.eu/company/publications/technical-publications/, Accessed: August 16, 2022.

TenneT (2021b). Market news. https://www.tennet.eu/market-newsw, Accessed: October 2, 2022.

Thomson, R. C., Harrison, G. P., and Chick, J. P. (2017). Marginal greenhouse gas emissions displacement of wind power in great britain. *Energy Policy*, 101:201–210.

Tu, R., Gai, Y. J., Farooq, B., Posen, D., and Hatzopoulou, M. (2020). Electric vehicle charging optimization to minimize marginal greenhouse gas emissions from power generation. *Applied Energy*, 277:115517.

Woody, M., Craig, M. T., Vaishnav, P. T., Lewis, G. M., and Keoleian, G. A. (2022). Optimizing future cost and emissions of electric delivery vehicles. *Journal of Industrial Ecology*.