# On the Use of Average versus Marginal Emission Factors

Wouter Schram[a], Ioannis Lampropoulos[b], Tarek AlSkaif[c] and Wilfried van Sark[d]
*Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8A, Utrecht, The Netherlands*

Keywords: Marginal Emission Factors, Merit Order, $Co_2$ Price.

Abstract: In this paper, we propose using marginal emission factors instead of average emission factors for determining the impact of adding variable renewable electricity to the generation mix. Average emission factors assume constant emissions over time, which does not reflect reality. Therefore, they cannot be used for e.g. accurately determining the mitigated $CO_2$ emissions by renewables, or for scheduling shiftable loads in order to have the lowest $CO_2$ emissions. To solve this, we provide a method to construct the marginal emission profiles via the merit order and demonstrate the method by composing these for the case of the Netherlands. Using this method, we re-evaluate the $CO_2$ impact in 2014 of photovoltaic-generated electricity to be 0.42 Mt – compared to 0.36 Mt using the average emission factor - and for wind-generated electricity to be 3.6 Mt instead of 2.9 Mt $CO_2$ (an increase of 14.3% and 24.2%, respectively). Furthermore, we show the impact of $CO_2$ price on the merit order and show that even high $CO_2$ prices of 50 to 75 €/t$CO_2$ are not sufficient to phase-out new coal-fired power plants.

## 1 INTRODUCTION

Two options to mitigate greenhouse gas (GHG) emissions are to add variable renewable electricity to the electricity mix, or to decrease electricity demand through energy conservation measures. There are two main methods to determine the impact of such measures on the $CO_2$ emissions of a country. Mostly, an average emission factor (AEF) is used to estimate the emissions of the replaced electricity generation. This makes the implicit assumption that a decrease in conventional electricity generation, such as from coal- and gas-fired power plants, is evenly distributed over all generation facilities. However, this is not in line with the functioning of electricity markets, since in practice a decrease in requested supply results in decreased electricity generation of facilities operating at the margins.

The AEF is defined as the total direct $CO_2$ emissions of the electricity generation sector, divided by the total electricity generation over a certain period – usually one year (Mancarella and Chicco, 2009). The concept of marginal emission factors (MEF) focuses on the notion that renewably-generated electricity replaces the electricity generated by the price-setting power plants of a specific settlement period used in the market, e.g. 1-hour or 15-minutes trading interval (Siler-Evans et al., 2012). This is generally seen as a superior method over the use of AEFs, because the latter disconnects the actual contribution to $CO_2$ emissions and the abatement scenario by implicitly assuming constant $CO_2$ intensity (Harmsen and Graus, 2013).

Several studies have shown that the use of MEFs leads to increased accuracy of estimations of $CO_2$ savings. In England and Wales the use of the AEF led to an underestimation of $CO_2$ savings when determining the impact of energy efficiency measures (Bettle et al., 2006). Similar results were obtained for the case of California (Marnay et al., 2002). In addition, the environmental impact of increased wind power generation in Great Britain could be estimated more accurately by using MEFs (Thomson et al., 2017). In general, AEFs are lower than MEFs and therefore result in underestimation of $CO_2$ savings (Hawkes, 2010).

The contribution of this paper is threefold. First, we provide a straightforward method of designing marginal emission profiles. Second, we survey and

[a] https://orcid.org/0000-0003-3407-7893
[b] https://orcid.org/0000-0001-8566-4970
[c] https://orcid.org/0000-0002-1780-4553
[d] https://orcid.org/0000-0002-4738-1088



Schram, W., Lampropoulos, I., AlSkaif, T. and van Sark, W.
On the Use of Average versus Marginal Emission Factors.
DOI: 10.5220/0007765701870193
In *Proceedings of the 8th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2019)*, pages 187-193
ISBN: 978-989-758-373-5

report the data of Dutch generation facilities. We also show the actual $CO_2$ mitigation based on the marginal emission factors, and compare it with the average emission factor, which has not been done before for the Netherlands. Third, we show the impact of $CO_2$ price on the merit order, hereby offering guidance for policy makers in determining options to meet $CO_2$ emission targets.

# 2 METHODS

To compose marginal emission profiles, first the merit order needs to be constructed. This is the electricity generation mix sorted from lowest to highest marginal operating costs (i.e. the costs of increasing generation by one unit of energy, in this case MWh[e]).

Marginal costs *MC* (in €/MWh) of facility *j* is the sum of the fuel costs, the emission costs and the variable operating costs (Biggar and Hesamzadeh, 2014), and thus can be determined as follows:

$$MC_j = FP_j/\eta_j + EF_j/\eta_j * \mathrm{CP} + VOC_j \quad (1)$$

where $FP$ denotes the price of fuel (in €/$MWh_t$), η is the conversion efficiency, $EF$ is emission factor of the fuel (in $tCO_2/MWh_t$), CP denotes the EU Emission Trading System (ETS) $CO_2$ price (in €/$tCO_2$), and $VOC$ is the Variable Operational Costs (in €/MWh).

We follow IPCC (2006) and focus on $CO_2$ for GHG emissions in power generation. The marginal emissions $ME$ (in $tCO_2$/MWh) of facility *j* are determined as follows:

$$ME_j = \mathrm{EF}_j/\eta_j \quad (2)$$

Subsequently, there are two options for constructing a marginal emission profile. First, one can compose a generation mix based on the electricity demand in a specified time period, and take the marginal emissions of the price-setting facility. Second, one can take the day-ahead market (DAM) clearing prices, determine from this which facility was operating at the margin. Then, the emissions of this facility can be taken for the marginal emission profile. The latter is more accurate, as it reflects what historically happened. The former is more suitable when looking at future scenarios.

For constructing the merit order and marginal emission profiles, the following assumptions had to be made:

- To determine the marginal operating facility, we assumed that the facility with marginal costs closest to the spot price was the marginal operating facility.
- All facilities were assumed to operate at their maximum efficiency; efficiency losses of operating at partial load are not considered.
- There are several methods to allocate $CO_2$ emissions in the case of combined heat and power production (Graus and Worrell, 2011). Here we chose to allocate $CO_2$ emissions to power generation.
- Co-firing of biomass in coal-fired power plants was not included.
- The marginal operating facility was assumed to be located in the investigated country.
- No assumptions about future scenarios are made.
- Bid strategies of retailers were not considered.

In the following section, the proposed method is elucidated by applying it on a case study for the Netherlands.

# 3 RESULTS

## 3.1 Merit Order and Marginal Emissions Netherlands

To construct the marginal emission profile, various data were required as input. First, the generation portfolio of the Netherlands was established, using the databases of ENTSO-E (ENTSO-E, 2019b). For every facility, the installed capacity and the efficiency were determined. Table 1 shows all these values and the accompanying sources. Because of data availability, we chose 2014 as base year for obtaining data. Fuel price for coal was based on data from Statistics Netherlands; on average the price of coal was 9.1 €/$MWh_t$ for 2014 (CBS, 2017) and of natural gas prices 24.3 €/$MWh_t$ (Schoots et al., 2017). *VOC* was assumed to be 1.2 €/MWh for gas-fired power plants, and 3.0 €/MWh for coal-fired power plants (Brouwer et al., 2015). For 2014, *CP* was assumed constant at the average of 6.9 €/ $tCO_2$ (Investing, 2019). The *EF* of bituminous coal and natural gas were determined to be 0.341 $tCO_2/MWh_t$ and 0.204 $tCO_2/MWh_t$, respectively (IPCC, 2006). Velsen-24 was a special case; a peak-load facility that uses a mixture of blast furnace gas from nearby steal production and natural gas. Following the position of the Dutch government, we attribute an *EF* of 1.25 times the *EF* of natural gas for

[e] Unless otherwise specified, MWh electric is meant

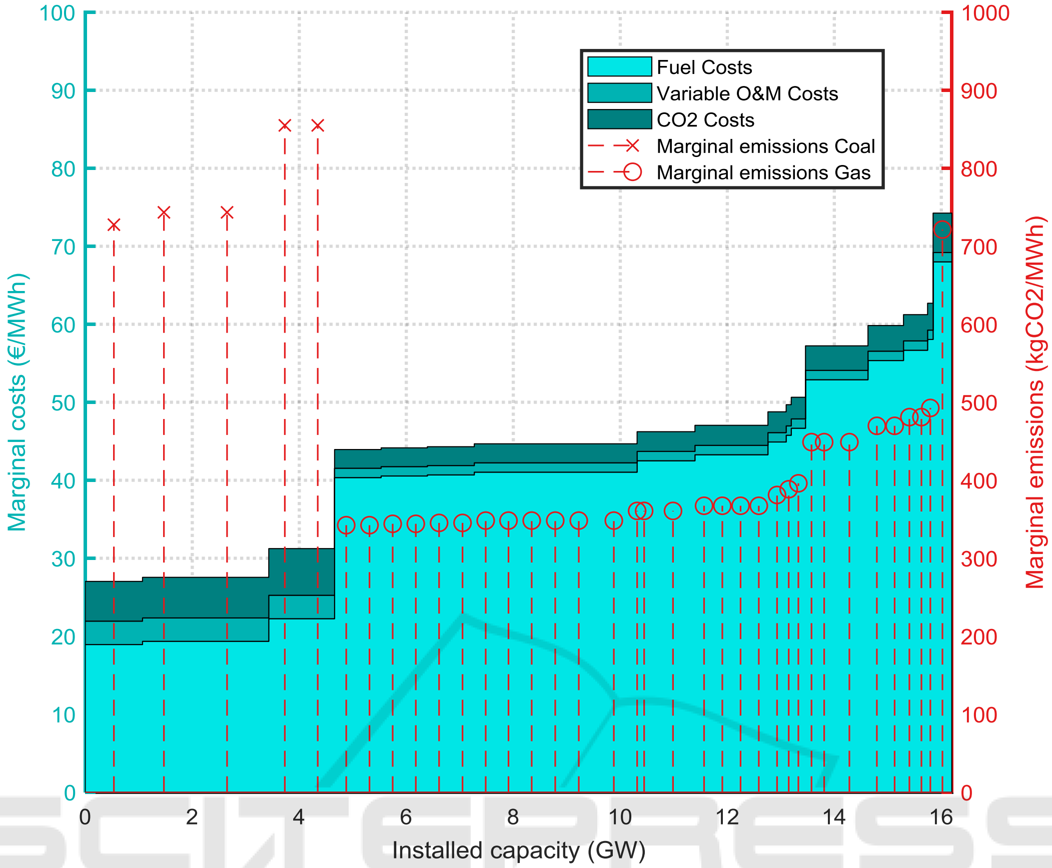


Figure 1: Merit order based on marginal costs (left y-axis, green) and marginal emissions (right y-axis, red) of the facilities opearting in 2014 (see Table 1). Each marker represents a power plant; the distance on the x-axis between two markers reflects the size of the facility.

this (Afman and Wielders, 2014). Figure 1 shows the resulting merit order and accompanying marginal emissions.

Table 1 lists the main characteristics for all Dutch centralized thermal power plants[f], their installed capacity, efficiency and the resulting *MC* and *ME*. Figure 1 shows the merit order, with for every individual facility the accompanying marginal emissions. At around 4.5 GW of installed capacity, we see the substantial gap of around 13 €/MWh between the most expensive coal-fired power plant, and the cheapest gas-fired power plant. These coal-fired power plants have much higher marginal emissions: around 850 $tCO_2$/MWh, compared to around 350 $tCO_2$/MWh for gas-fired power plants.

Figure 2 illustrates the marginal emission profile of a randomly chosen day, i.e. 11 January 2018. DAM-prices are taken from (ENTSO-E, 2019a) and $CO_2$ price was 9.28 €/t $CO_2$ (Investing, 2019). During most of the day, gas-fired power plants operate at the margin, while during the night coal-fired power plants

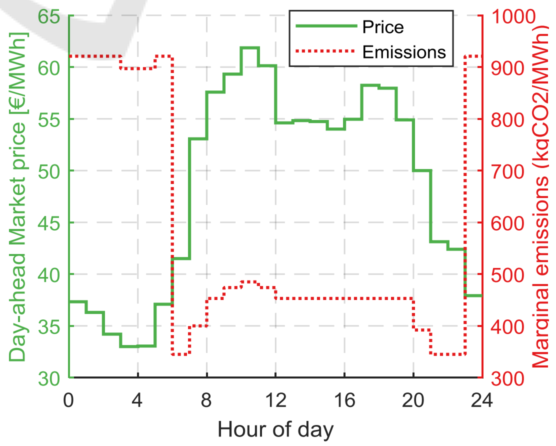


Figure 2: Marginal costs and emissions on 11-01-2018.

[f] Must-run facilities are excluded

Table 1: Overview and characteristics of all thermal power plants in the Netherlands, using a $CO_2$ price of 7 €/t $CO_2$.

| Facility Name | Main Fuel | Installed capacity (MW) | In Operation | Decommissioned | Efficiency | Marginal costs (€/MWh) | Marginal emissions (kg CO2 /MWh) | Source |
|---|---|---|---|---|---|---|---|---|
| Centrale Maasvlakte | Coal | 1.070 | 2016 | | 46.0% | 27.0 | 728 | (D66, 2015) |
| Eemshavencentrale | Coal | 1.560 | 2015 | | 46.0% | 27.5 | 743 | (D66, 2015) |
| Engie Centrale Rotterdam 11 | Coal | 730 | 2015 | | 46.0% | 27.5 | 743 | (D66, 2015) |
| Amer Bio WKC | Coal | 600 | 1994 | | 40.0% | 31.2 | 852 | (D66, 2015) |
| Centrale Hemweg | Coal | 630 | 1994 | 2020 | 40.0% | 31.2 | 852 | (D66, 2015) |
| Maasvlakte-2 | Coal | 520 | 1974 | 2017 | 39.0% | 31.9 | 874 | (D66, 2015) |
| Maasvlakte-1 | Coal | 520 | 1973 | 2017 | 38.0% | 32.7 | 897 | (D66, 2015) |
| Gelderland-13 | Coal | 602 | 1982 | 2015 | 38.0% | 32.7 | 897 | (D66, 2015) |
| Amer-8 | Coal | 645 | 1981 | 2016 | 37.0% | 33.5 | 921 | (D66, 2015) |
| Diemen-34 | Gas | 435 | 2012 | | 59.0% | 43.9 | 345 | (Nuon, 2018) |
| Centrale Hemweg (gas) | Gas | 435 | 2012 | | 59.0% | 43.9 | 345 | (Nuon, 2018) |
| Sloecentrale-10 | Gas | 432 | 2010 | | 58.7% | 44.1 | 347 | (Sloecentrale, 2018) |
| Sloecentrale-20 | Gas | 432 | 2010 | | 58.7% | 44.1 | 347 | (Sloecentrale, 2018) |
| Maximacentrale FL5 | Gas | 439 | 2010 | | 58.5% | 44.3 | 348 | (Seebregts et al., 2009) |
| Maximacentrale FL4 | Gas | 438 | 2010 | | 58.5% | 44.3 | 348 | (Seebregts et al., 2009) |
| Magnum Eemshaven 10 | Gas | 440 | 2013 | | 58.0% | 44.6 | 351 | (Nuon, 2018) |
| Magnum Eemshaven 20 | Gas | 440 | 2013 | | 58.0% | 44.6 | 351 | (Nuon, 2018) |
| Magnum Eemshaven 30 | Gas | 440 | 2013 | | 58.0% | 44.6 | 351 | (Nuon, 2018) |
| Moerdijk-2 | Gas | 426 | 2014 | | 58.0% | 44.6 | 351 | (RWE, 2018b) |
| Enecogen | Gas | 870 | 2011 | | 58.0% | 44.6 | 351 | (Seebregts et al., 2009) |
| Maasstroom Energie | Gas | 427 | 2010 | | 58.0% | 44.6 | 351 | (Seebregts and Daniëls, 2008) |
| Maasbracht-C (Claus) | Gas | 1.275 | 2012 | 2014[g] | 56.0% | 46.2 | 364 | (RWE, 2018a) |
| Rijnmond Energie | Gas | 820 | 2004 | | 56.0% | 46.2 | 364 | (Seebregts and Volkers, 2005) |
| Pergen-1 | Gas | 260 | 2007 | | 56.0% | 46.2 | 364 | (Seebregts, 2007) |
| Eemscentrale EC4 | Gas | 341 | 1996 | | 55.0% | 47.0 | 370 | (Siebelink, 2006) |
| Eemscentrale EC5 | Gas | 341 | 1996 | | 55.0% | 47.0 | 370 | (Siebelink, 2006) |
| Eemscentrale EC6 | Gas | 341 | 1997 | | 55.0% | 47.0 | 370 | (Siebelink, 2006) |
| Eemscentrale EC7 | Gas | 341 | 1997 | | 55.0% | 47.0 | 370 | (Siebelink, 2006) |
| Eemscentrale EC3 | Gas | 341 | 1996 | | 53.0% | 48.7 | 384 | (Siebelink, 2006) |
| Energiecentrale Den Haag | Gas | 95 | 1906 | | 52.0% | 49.6 | 392 | (Enipedia, 2018) |
| Diemen-33 | Gas | 266 | 1995 | | 51.0% | 50.6 | 400 | (Arcadis, 2009) |
| Lage Weide | Gas | 248 | 1996 | | 45.0% | 57.2 | 453 | (Croezen, 2016) |
| Eemscentrale EC20 | Gas | 695 | 1978 | | 45.0% | 57.2 | 453 | (Siebelink, 2006) |
| Merwede-12 | Gas | 225 | 1990 | | 45.0% | 57.2 | 453 | (Croezen, 2016) |
| Centrale Bergum CB10[h] | Gas | 332 | 1975 | | 43.0% | 59.8 | 474 | (Seebregts and Volkers, 2005) |
| Centrale Bergum CB20[h] | Gas | 332 | 1976 | | 43.0% | 59.8 | 474 | (Seebregts and Volkers, 2005) |
| Centrale RoCa[h] | Gas | 220 | 1997 | | 42.0% | 61.2 | 485 | (Seebregts and Volkers, 2005) |
| Centrale Swentibold[h] | Gas | 230 | 2000 | | 42.0% | 61.2 | 485 | (Seebregts and Volkers, 2005) |
| Merwede-11[h] | Gas | 103 | 1985 | | 41.0% | 62.6 | 497 | (Seebregts and Volkers, 2005) |
| Velsen-24 | BF-Gas[i] | 459 | 1975 | | 35.0% | 74.2 | 728 | (Seebregts and Volkers, 2005) |

[g] Planned to reopen in 2020

[h] Estimation based on average similar plants

[i] Blast furnace gas mixed with natural gas. Based on emission factor natural gas times 1.25 (Afman and Wielders, 2014)

operate at the margin. This shows that scheduling demand to optimize on costs mainly leads to increasedelectricity generation by coal-fired power plants, and thus to increased emissions.

When applied to the Netherlands in 2014, we end up with an average MEF of 629 kg/MWh (standard deviation of 278 kg/MWh), compared with an AEF of 503 kg/MWh. Our results are in line with the official Dutch statistics, where only the total yearly MEF is provided; an MEF of 636 kg/MWh (CBS, 2018b). We applied the marginal emission profile to determine the mitigated $CO_2$ emissions in the Netherlands in 2014 by wind- and PV-generated electricity, assuming these are linearly dependent on wind speed and solar irradiation, respectively (CBS, 2018a; KNMI, 2019).

This results in an updated $CO_2$ impact of wind from 2.9 Mt $CO_2$ when using the AEF to 3.6 Mt $CO_2$ when using MEFs (+24.2%) and from 0.36 Mt $CO_2$ to 0.42 Mt $CO_2$ (+14.3%). From this, one can also conclude that compared to PV, wind is producing more during hours when coal-fired power plants are operating at the margin, e.g. at night.

## 3.2 Impact of $CO_2$ Price

Figure 3 shows the merit order of all Dutch thermal power plants for various $CO_2$ prices. A $CO_2$ price of 25 €/t$CO_2$ does not lead to changes in the merit order, apart for the higher prices (figure 3b). The break-even price between the most efficient coal-fired power plants (46-47%) and the most efficient gas-fired power plants lies around 50 €/t$CO_2$, as can be seen in Figure 3c. With this price, the old coal-fired power plants become more expensive than many gas-fired power plants, whereas the new coal-fired power

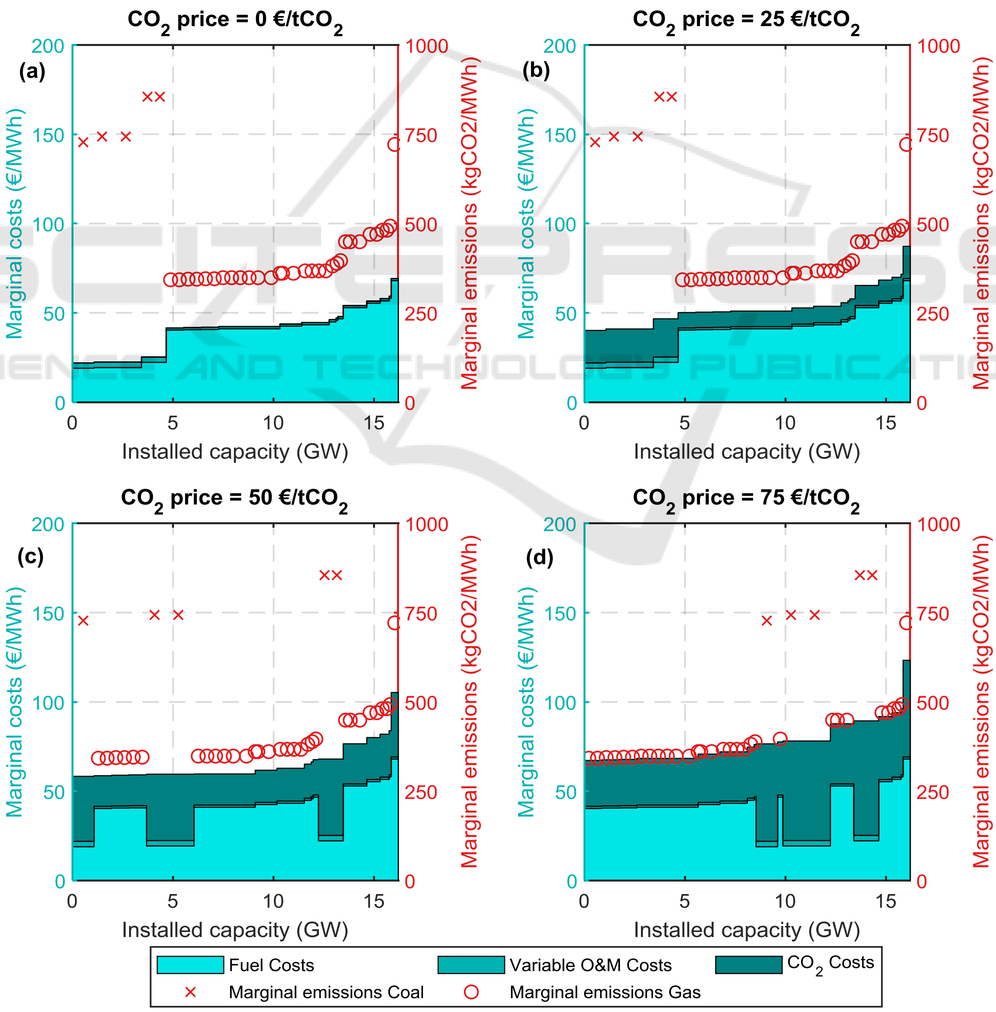


Figure 3: Impact $CO_2$ price on merit order of all Dutch thermal power plants. See Table 1 for overview power plants.

plants, which went in operation in 2015 and 2016, remain base load. This only changes when prices are increased to 75 €/t$CO_2$ (figure 3d).Hence, stating one $CO_2$ price that is needed for a shift from coal to gas is too simplistic; it is depending on the entire generating mix, and the relative age of the different facilities. This varies from country, providing a strong argument for national policies for $CO_2$ taxes on top of the European level policies. Furthermore, this shows that even high $CO_2$ prices are not able to push all coal-fired power plants out of the merit order, despite their higher emissions. Either very high $CO_2$ prices (from 100 euro per tonne), or additional measures are needed if policy makers decide these emissions should be decreased.

## 4 CONCLUDING REMARKS

In this paper, we presented a method for designing marginal emission profiles for a specific country based on its generation merit order and applied this for the case study of the Netherlands. The value of this approach can be understood from two perspectives. From a bottom-up perspective, consumers may reconsider the scheduling of their electricity demand. The operation of shiftable loads, such as electric vehicles, wet appliances and stationary storage devices can be scheduled considering the minimization of $CO_2$ emissions, in addition to cost, if the demand can be shifted to periods with cleaner periods. This can be from coal to gas in the nearby future, but also in a more distant future from periods with fossil-fuel based power plants operating at the margin to periods where renewables are operating at the margin. From a top-down perspective, the approach might help to better determine the impact of implementing renewables in the generation mix, and for determining adequate $CO_2$ prices to enforce a shift from coal to gas.

## ACKNOWLEDGEMENTS

This project is part of the PVProsumers4Grid Project, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 764786. Furthermore, this work has received funding in the framework of the joint programming initiative ERA-Net Smart Grids Plus as part of the CESEPS project, as well as from TKI Urban Energy (Project: B-DER, contract number 1621404).

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