

On the Use of Average versus Marginal Emission Factors

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Keywords: Marginal Emission Factors, Merit Order, CO₂ 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 CO₂ emissions by renewables, or for scheduling shiftable loads in order to have the lowest CO₂ 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 CO₂ 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 CO₂ (an increase of 14.3% and 24.2%, respectively). Furthermore, we show the impact of CO₂ price on the merit order and show that even high CO₂ prices of 50 to 75 €/tCO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions and the abatement scenario by implicitly assuming constant CO₂ intensity (Harmsen and Graus, 2013).

Several studies have shown that the use of MEFs leads to increased accuracy of estimations of CO₂ savings. In England and Wales the use of the AEF led to an underestimation of CO₂ 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 CO₂ 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

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report the data of Dutch generation facilities. We also show the actual CO₂ 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 CO₂ price on the merit order, hereby offering guidance for policy makers in determining options to meet CO₂ 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:

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

where FP denotes the price of fuel (in €/MWh_t), η is the conversion efficiency, EF is emission factor of the fuel (in tCO₂/MWh_t), CP denotes the EU Emission Trading System (ETS) CO₂ price (in €/tCO₂), and VOC is the Variable Operational Costs (in €/MWh).

We follow IPCC (2006) and focus on CO₂ for GHG emissions in power generation. The marginal emissions ME (in tCO₂/MWh) of facility j are determined as follows:

$$ME_j = EF_j/\eta_j \quad (2)$$

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 CO₂ emissions in the case of combined heat and power production (Graus and Worrell, 2011). Here we chose to allocate CO₂ 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 €/tCO₂ (Investing, 2019). The EF of bituminous coal and natural gas were determined to be 0.341 tCO₂/MWh_t and 0.204 tCO₂/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 steel 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

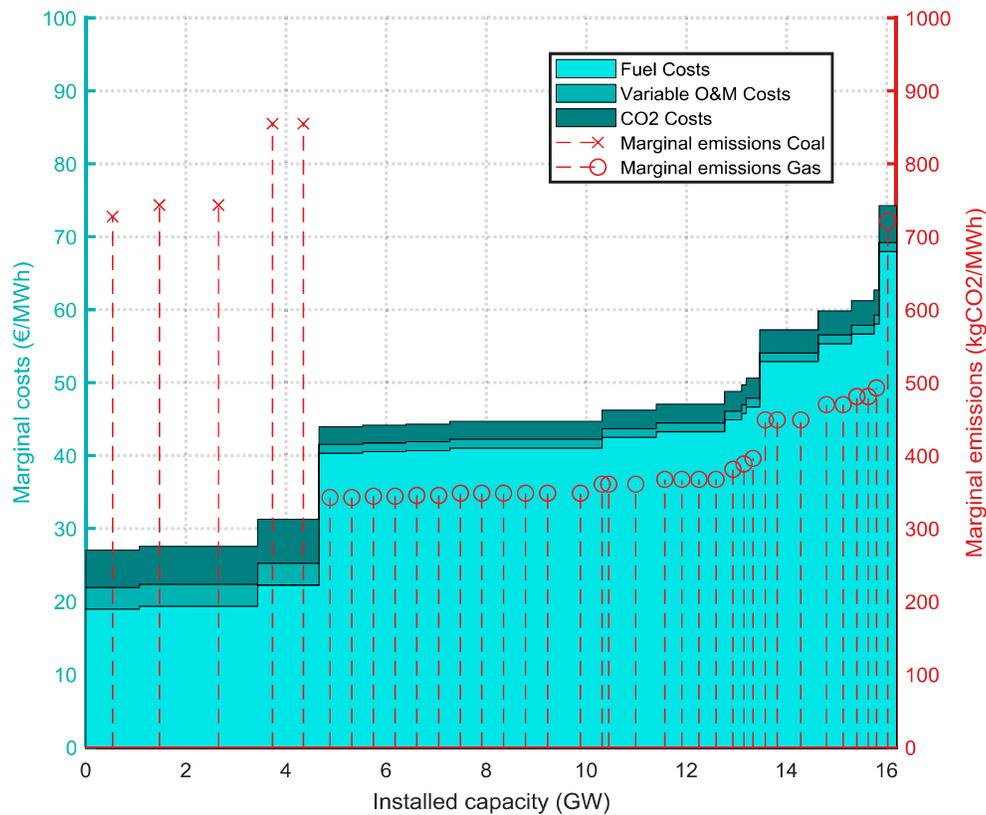


Figure 1: Merit order based on marginal costs (left y-axis, green) and marginal emissions (right y-axis, red) of the facilities operating in 2014 (see Table 1). Each marker represents a power plant; the distance on the x-axis between two markers reflects the size of the facility.

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 tCO₂/MWh, compared to around 350 tCO₂/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 CO₂ price was 9.28 €/t CO₂ (Investing, 2019). During most

of the day, gas-fired power plants operate at the margin, while during the night coal-fired power plants

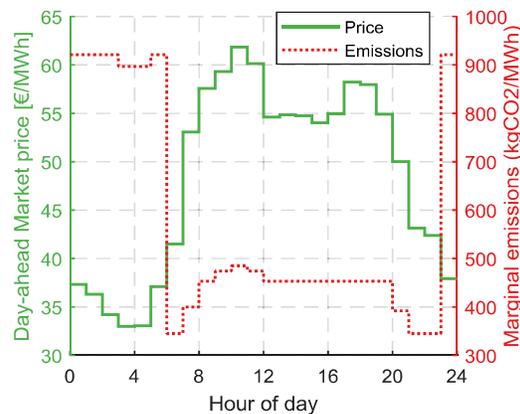


Figure 2: Marginal costs and emissions on 11-01-2018.

^f Must-run facilities are excluded

Table 1: Overview and characteristics of all thermal power plants in the Netherlands, using a CO₂ price of 7 €/t CO₂.

Facility Name	Main Fuel	Installed capacity (MW)	In Operation	Decommissioned	Efficiency	Marginal costs (€/MWh)	Marginal emissions (kg CO ₂ /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 plantsⁱ 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 increased electricity 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 CO₂ 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 CO₂ impact of wind from 2.9 Mt CO₂ when using the AEF to 3.6 Mt CO₂ when using MEFs (+24.2%) and from 0.36 Mt CO₂

to 0.42 Mt CO₂ (+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 CO₂ Price

Figure 3 shows the merit order of all Dutch thermal power plants for various CO₂ prices. A CO₂ price of 25 €/tCO₂ 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 €/tCO₂, 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

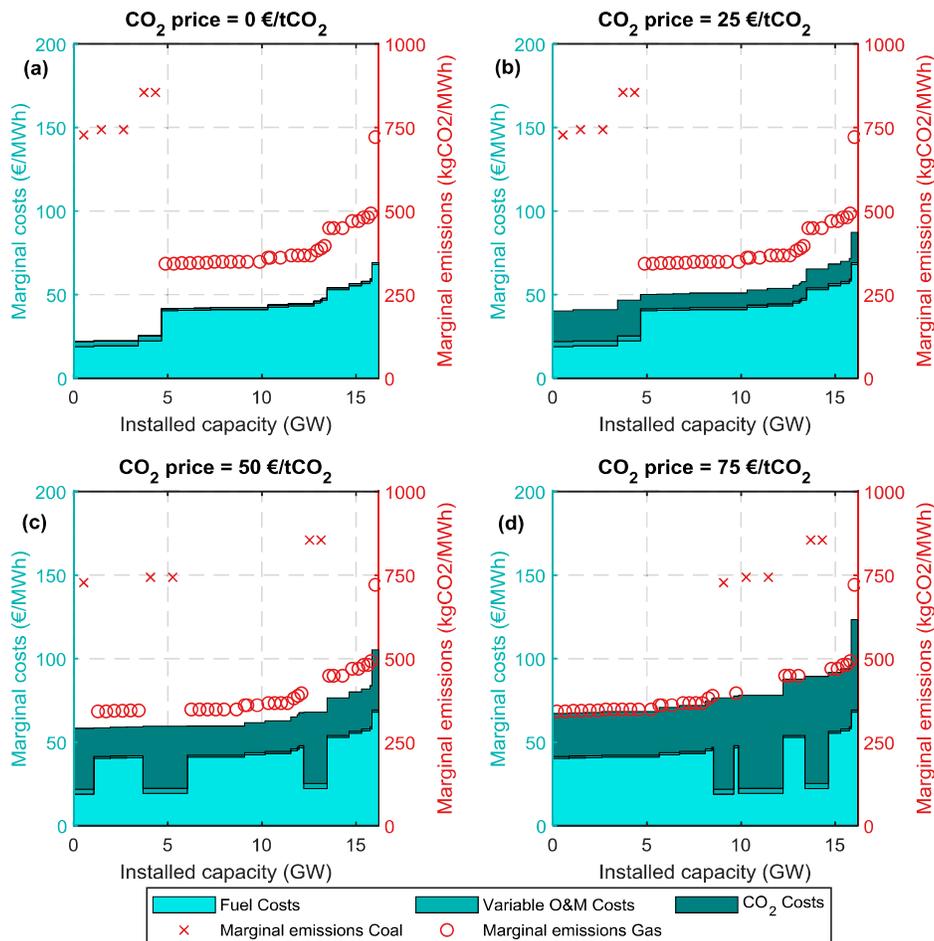


Figure 3: Impact CO₂ price on merit order of all Dutch thermal power plants. See Table 1 for overview power plants.

plants, which went in operation in 2015 and 2016, remain base load. This only changes when prices are increased to 75 €/tCO₂ (figure 3d). Hence, stating one CO₂ 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 CO₂ taxes on top of the European level policies. Furthermore, this shows that even high CO₂ prices are not able to push all coal-fired power plants out of the merit order, despite their higher emissions. Either very high CO₂ 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 CO₂ 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 CO₂ 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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