Can Carbon Pricing Counteract Renewable Energies' Self-Cannibalization Problem?

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Abstract: Support payments for renewable energies (RE) are a key climate-change policy in many jurisdictions globally. However, RE feed-in lowers the wholesale electricity price, thus cannibalizing their own market values. Despite steep cost degression, self-cannibalization endangers the hopes that RE may eventually survive in the market independently from subsidies. We apply a flexible econometric model to quantify the self-cannibalization effect together with influential factors that may counteract the problem. Our data are for the German electricity market, which is characterized by a high and increasing share of intermittent RE. We show that wind and solar infeed significantly cannibalize their own market values and that a meaningful carbon price can substantially counteract this problem. Thus, market-based climate policy may significantly boost RE's integration. This is also relevant for other countries' climate agendas. However, once power generation is fully decarbonized, support from carbon pricing will lapse and the design of the energy market will need to be reconsidered.

Keywords: Carbon price; Cannibalization effect; Merit-order effect; Renewable energy; Market values

JEL Classification: D4, H2, Q4, Q5

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1 Introduction

Renewable energies (RE) are essential to decarbonize energy systems around the globe. The Intergovernmental Panel on Climate Change estimates that a global RE share of more than 70% is needed to limit global warming to 1.5°C (IPCC, 2018). Yet, an increasing market penetration of RE reduces the wholesale price of electricity (i.e. the so called merit-order effect), thereby "cannibalizing" their own market values.[1] Regionally and temporarily correlated infeed from wind and solar power plants even aggravates this problem. This is worrisome against the hopes that RE may eventually survive in the market independently from any financial aid. If RE's market values deteriorate faster than their costs, RE's competitiveness with conventional fossil-fuelled technologies would be in danger (c.f. Lòpez Prol et al., 2021; Zipp, 2017). However, a 'meaningful' price on CO_2 emissions may counteract the cannibalization effect of RE, as we argue in this study. Hence, a climate policy that sets on market-based incentives to abate greenhouse-gas emissions may at the same time help integrating a vast share of RE by counteracting the cannibalization effect.

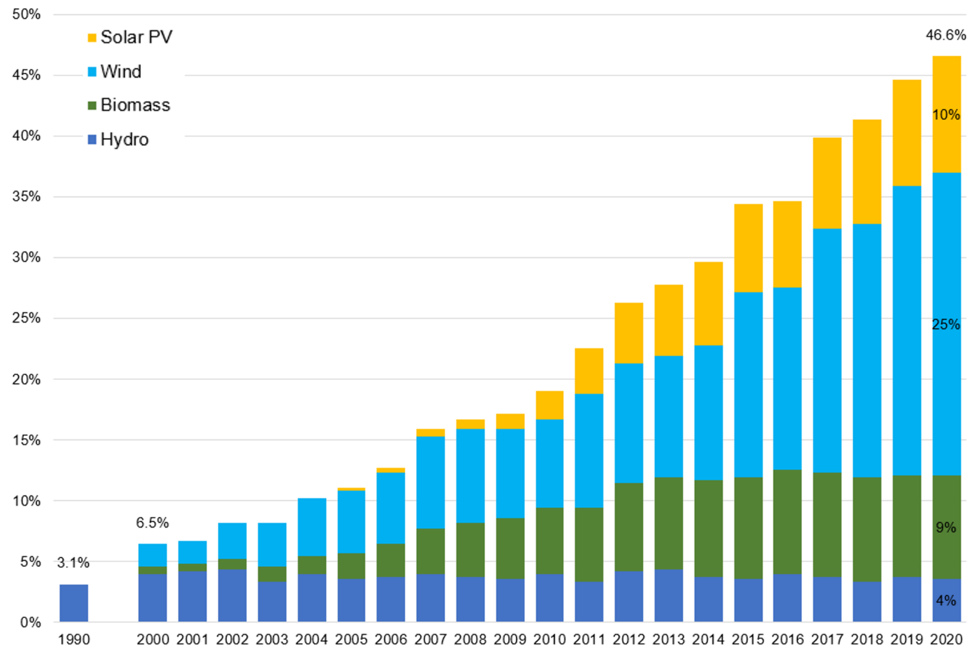
In the last two decades, Germany has experienced a severe and continuous increase in the share of RE in electricity consumption from 6.5% in 2000 to 46.6% in 2020 (see Figure 1). The main source of growth was wind, followed by solar electricity, while biomass has stagnated since 2012 and hydropower remained constant over time. Moreover, the share of RE is expected to grow much further, given the ambitious RE goals set by the German government of 80% by 2030[2] and nearly 100% by 2050[3]. This leads to the natural question of how to design and operate an electricity system dominated by intermittent renewable energy sources. One important aspect of which is whether the state has to keep on financing RE via support payments. The answer to this question depends foremost on the development of RE's levelized costs of energy (LCOE) and market values. On the one hand, RE's LCOE tend to deteriorate faster than anticipated and are expected to decrease further (López Prol and Schill, 2021; Schmidt et al., 2017), raising hopes that RE may eventually reach economic maturity and become competitive with conventional, polluting electricity generating technologies. On

[1]The market value of an electricity production unit is determined by the revenue it can generate. The market value (or unit revenue) of a renewable power station thus depends on the correlation between resource availability (wind speed or sunshine) and electricity prices or demand in a given hour (Fell and Linn, 2013). In this study, we use the terms "market value" and "unit revenue" synonymously.

[2]www.euractiv.com/section/energy/news/new-german-coalition-aims-for-80-renewable-power-by-2030-more-gas-as-back-up/, 29 January 2022.

[3]www.bmwi-energiewende.de/EWD/Redaktion/Newsletter/2020/10/Meldung/topthema.html, 29 January 2022.

Figure 1: RE in total gross electricity consumption, DE (%)



Source: own calculations based on data from BMWi (2021a).

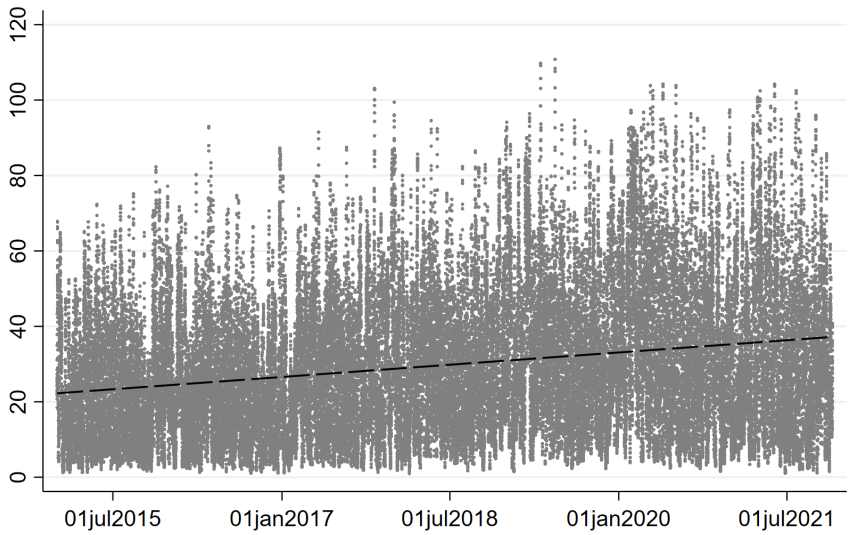
the other hand, RE's decline in market values thwarts their potential success, underlining the necessity for research on potential countermeasures against the self-cannibalization effect of RE.

Since about 2017, we can increasingly observe hours of RE infeed coming close to, or even overshooting, electricity demand (see Figure 2), resulting in low to even negative electricity spot prices (see Figure 3).[4] Moreover, while the price of emission certificates in the EU Emission Trading System (EU ETS) remained low until mid of 2017 (i.e. mean of €6.29/tCO_2 during 01jan2015–30jun2017), it increased to well above €60/tCO_2 by mid of 2021 and reached a peak at almost €100/tCO_2 for the first time in February 2022. These peculiarities make it a relevant case for empirically investigating the self-cannibalization of RE's market values in Germany, as well as how carbon pricing may help alleviate the problem.

This study uses an ex-post econometric analysis of high-frequency data from Germany on electricity spot prices and day-ahead forecasts of RE infeed volumes, together with a set of control variables (e.g. infeed from conventional electricity technologies, load, input prices, net imports, and seasonality fixed effects) to assess the self-cannibalization effect of wind and solar power. Following Lòpez Prol et al. (2021), we calculate daily market values from hourly data.

[4]Negative prices are a consequence of some types of conventional power plants, which are willing to accept negative bids to meet their production restrictions (e.g., must-run, ramping, and cycling constraints) during high RE infeed.

Figure 2: Share of wind and solar in total electricity consumption, hourly (%)

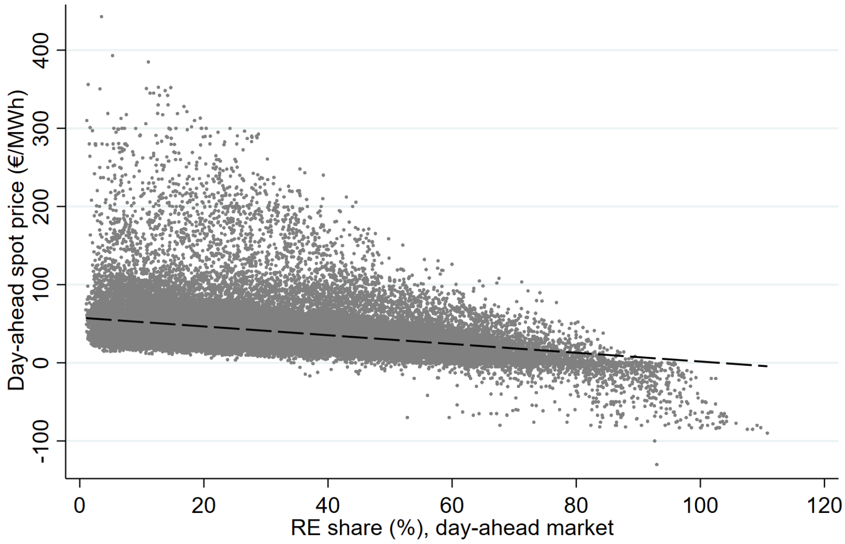


The graph visualizes the hourly shares of electricity infeed from wind and solar power in electricity consumption in Germany's day-ahead market. Shares greater than 100% are possible during hours of high solar radiation and high wind speed and imply exports to other countries.

Importantly, we also collected data on the EU ETS emissions allowance price, as to test its impact on the market values of RE. We employ a highly flexible model to estimate non-linear impacts. Econometric identification comes from the exogeneity of wind and solar electricity production, which is determined by weather. This way, our estimates can be interpreted as causal effects. We find economically pronounced results. An increase in wind and solar electricity decreases their respective market values, although the effect is concave (diminishing) for solar, but convex (intensifying) for wind. Noteworthy in this regard, the average daily infeed from wind (284 GWh per day) is almost three times larger than from solar power (107 GWh). In contrast to the negative impact of RE, we find a pronounced positive effect of the carbon price on the market values of RE. This is evidence that carbon pricing can counteract RE's self-cannibalization effect.

Our paper complements the existing literature in several ways. (i) We provide a rich discussion about the functioning and challenges of future energy markets, which have to deal with a significant share of intermittent RE. We thus consider that RE's generation occasionally overshoots load during windy and sunny hours, followed by hours of RE supply shortages, which are to be balanced by complementing technologies. (ii) We analyze RE's self-cannibalization empirically and provide an estimate of a promising countermeasure in the form of carbon pricing, which turns out to significantly elevate the market values of RE. This is novel and has not yet been analyzed econometrically, as far as we know. In this respect, we also address claims that more research is needed on RE pathways after support is phased out (Melliger

Figure 3: Electricity spot price & RE share



The graph visualizes the hourly day-ahead spot price of electricity against the hourly share of electricity infeed from wind and solar power in electricity consumption. RE shares greater than 100% are possible during hours of high solar radiation and high wind speed and imply exports to other countries.

and Chappin, 2022) and on mitigation measures to the cannibalization effect of RE (Lòpez Prol et al., 2021). (iii) To the best of our knowledge, this is the first study on RE's market values or wholesale price effects utilizing data on high carbon prices (up to around €50/tCO_2 during our sample period; see Figure 5). This may be because the EU emissions allowance price only started to increase in 2018 and reached a level of well above €40/tCO_2 not before 2021. Moreover, with few exemptions (e.g. Britain's carbon tax for the power sector, c.f. Gugler et al., 2021, or Sweden's carbon tax, mostly for the mobility sector, c.f. Andersson, 2019) such high carbon prices could not be observed outside Europe. (iv) We extend existing econometric studies on the market value of RE by applying a highly flexible econometric model, allowing to estimate non-linear impacts through higher-order terms and variable interactions. To the best of our knowledge, no other study has used such a flexible model to assess the self-cannibalization of RE, although it seems natural that non-linearities and interaction effects may play an important role. (v) This study uses recent data from Germany, which advanced to one of the world's leading countries in terms of wind and solar electricity[5], with an increasing number of hours where RE infeed overshoots load (see Figure 2). This makes it a relevant case for investigation, with policy implications for other countries, with ambitious RE targets. In

[5] According to Ember – a climate charity (formerly known as Sandbag) – Germany ranks fourth (behind Denmark, Uruguay, and Ireland) among the countries with the highest percentages of wind and solar in electricity production in 2020: https://ember-climate.org/commentary/2021/07/08/top-15-wind-and-solar-power-countries-in-2020/, 20 January 2022.

contrast, other related econometric studies employ older data and from regions characterized by significantly lower shares of wind and solar electricity (e.g. Lòpez Prol et al., 2021, for California during 01/2013–06/2017; Clo et al., 2015, for Italy during 01/2008–10/2013; Zipp, 2017, for Germany/Austria during 01/2011–12/2013). (vi) Finally, we add on the debate on market-based climate policy versus other measures (e.g. command-and-control instruments or subsidies) (see, e.g., Hepburn et al., 2020; Rosenbloom et al., 2020; Patt and Lilliestam, 2018) and derive several policy conclusions, which are also informative for other countries, as to guide the global decarbonization transition of the power sector based on empirical evidence.

2 Background

2.1 Self-cannibalization

The two most promising forms of RE, wind and solar power, create challenges via their weather-dependent output intermittency. This bears two consequences, which are often discussed as drawbacks of RE. Firstly, the 'merit-order effect' states that, for a given installed RE capacity, whenever the sun shines or the wind blows, RE infeed depresses the wholesale price of electricity. As a result, RE infeed pushes some marginal technologies (e.g. gas-fired plants) out of merit (i.e. the extensive-margin effect) and decreases the variable profits for all other technologies in the market (i.e. the intensive-margin effect) due to a lower wholesale electricity price. Secondly, wind and solar electricity follow generation profiles dependent on the weather. These generation profiles determine their revenues according to the capture prices (i.e. the value that owners of renewable power sell their electricity at). A solar plant, for example, generates predominantly during peak hours,[6] implying that its capture prices are above the daily average wholesale spot price. Intuitively, how wholesale electricity prices develop during daytime matters for the owner of a solar power station, whereas price developments during nighttime are irrelevant. In contrast to solar, wind's generation profile is rather flat across the hours of the day in Germany. As more wind and solar capacity is added over time, the wholesale prices will deteriorate according to the generation profiles of RE. Hence, the fact that sunshine and wind are geographically clustered, implies that sunshine or wind decrease the market value of *all* solar or wind production units at the same time. This is coined as the 'cannibalization effect'.

[6]In Germany and Central Europe, the hours from 8am until 8pm are typically considered peak hours. Solar power's infeed profile overlaps well with this period, reaching a peak at around noon.

In light of the ongoing debate about whether a high average RE share in the electricity production mix (e.g. 80% per year or more) can sustain in an energy system without having to rely on any subsidy payments, the self-cannibalization effect may be viewed as a focal problem that deserves the attention of policy makers and academic scholars.

2.2 Support measures for RE

Despite near-zero marginal costs, wind and solar power have initially relatively high fixed costs (per unit of capacity), hampering their competitiveness with other conventional electricity generation technologies, such as nuclear, gas, or coal power stations. Thus, the preponderance of states in Europe, the U.S., and elsewhere have been granting financial support payments (e.g. guaranteed feed-in tariffs, feed-in premia, support for RE capacity investments) or tax credits (often in combination with renewable portfolio standards) in order to push the market penetration of RE. The economic justification for RE subsidies goes back to the infant-industry argument (e.g., Sunderasan, 2011), stating that early-stage technology adoption needs supportive measures to allow for the realization of cost reductions through learning by doing (Lòpez Prol et al., 2021; Reichenbach and Requate, 2012), optimization of production processes (Jankowska et al., 2021), R&D, and technological advancement (Newell et al., 1999; Fischer and Newell, 2008). Although steep learning curves have already drastically reduced the LCOE of various renewable technologies (Melliger and Chappin, 2022; IRENA, 2020), conventional technologies still dominate the global power provision. Once an RE technology matures and achieves competitiveness, subsidies should be cut back (Reichenbach and Requate, 2012; Melliger and Chappin, 2022). However, it is worth mentioning that many fossil fuels also still enjoy generous subsidy payments (IRENA, 2020), for which economic theory does not offer any justification and which represent another obstacle against the competitiveness of RE (Timperley, 2021). It is thus necessary to eliminate market distortions that support fossil fuels.

Nevertheless, there is a high-level debate among economists and policy-makers whether RE can, in principle, achieve technological maturity and become profitable without having to rely on any financial aid (e.g., Held et al., 2019). In this regard, it is often claimed that over time and with further cost savings of RE, market-based measures should become more prevalent (e.g., IRENA, 2021). Market-based measures are, according to theory, more cost efficient than other measures, such as subsidies or command-and-control regulations (see, e.g. Linn and Shih, 2019; Helm and Mier, 2021; Borenstein, 2012; Fell and Linn, 2013). For example, auctioning off financial support needs (e.g. feed-in premiums) for RE plants has already superseded high and non-differentiated feed-in tariffs granted during the early stages of RE deployment in the EU (EC, 2014). Moreover, the state could ensure an investor-friendly market environment, which may support private sector investment into RE, for example, via power purchase agreements (Jones and Rothenberg, 2019). However, the threat of self-cannibalization of RE may eventually thwart RE's competitiveness.

2.3 Carbon pricing

In the wake of climate change and its negative consequences, emissions trading schemes and carbon taxes, which represent the main types of carbon pricing, are being increasingly adopted around the world. On the road to decarbonizing the economy, carbon pricing represents an important policy option (Hepburn et al., 2020). The idea goes back to Pigou's seminal work in 1920 (Pigou, 1920). Carbon pricing aims to price the negative externality of emissions, such as CO_2 and other greenhouse gases (often measured in CO_2 equivalents), to reduce their release. However, according to the highly influential "Report of the High-Level Commission on Carbon Pricing" (Stiglitz et al., 2017), it may require a mix of different climate policy measures, including carbon prices of at least \$40-80/tCO_2 by 2020 and \$50-100/tCO_2 by 2030 to achieve international climate targets.[7]

While the coverage of global emissions by a carbon-pricing scheme was only 15.1% in 2020, it widened to 21.5% in 2021, and the number of carbon pricing instruments expanded from 58 to 64 during this period (World Bank, 2021). In our study, emissions of German electricity producers are covered by the EU ETS – the second-largest emissions trading scheme after China's national ETS. An ETS requires electricity producers (and other firms covered) to hold an emission certificate for each ton of CO_2 equivalent released into the atmosphere. Hence, the price of emissions allowances increases the production costs of power plants according to their emissions intensity. This way, carbon pricing sets *market-based incentives* to all energy producers to reduce emissions. By contrast, *non-market-based approaches* may result in efficiency losses (going back to the "general theory of second best" by Lipsey and Lancaster, 1956; see also Borenstein, 2012).

Due to different CO_2 intensities, lignite-fired power plants are more affected by carbon pricing than hard coal plants and significantly more affected than natural gas plants. The

[7]Converted into Euros, this corresponds to €36-72/tCO_2 by 2020 and €45-90/tCO_2 by 2030.

emissions factors of lignite, hard coal and natural gas are about 0.375, 0.363, and 0.240 tCO_2 equivalent per MWh of electricity output (EC, 2017). Carbon pricing mainly elevates the steeper part of the merit order curve, because this is where most of the thermal plants are located. Accordingly, carbon pricing leads to a higher electricity price whenever a fossil fuelled power plant is the marginal production unit. This is why a (meaningful) carbon price increases the wholesale price of electricity and thus elevates the market value of RE.

In this regard, an increasing carbon price would not only reduce the competitiveness of fossil-fuelled power plants (gas, coal, and lignite plants) relative to RE, by elevating their marginal costs according to their emission intensities, but also counteract the cannibalization effect through increasing RE's market values. Brown and Reichenberg (2021) lay a theoretical foundation for this argument and provide simulation results. Yet, this theory has so far not been put to an empirical test using real-world data. In any case, a stronger orientation of climate policy toward market-based measures, with a particular commitment to a sufficiently high carbon price, would potentially help minimizing the fiscal burden on the grounds of efficiency, thereby strengthening public support for a green energy transition (Gugler et al., 2021).

The wholesale price of EU ETS allowances has largely remained below expectations (Böhringer, 2020) since the system was introduced in 2005, because of a surplus of allowances, including a generous policy of crediting low-carbon investments in third countries for allowances (Ellerman and Buchner, 2007). Koch et al. (2014) also find that the economic activity and the expansion of RE partly explain the low price in the early phases of the system. To reduce the surplus of allowances and counteract undesirable effects, the system saw reforms, including banking and borrowing of allowances, back-loading of auctions, and the introduction of a Market Stability Reserve (MSR). As the EU ETS matured, the allowance price has risen sharply since 2018, almost doubling during the last months of the sample (see Figure 5).

The impact of a specific carbon price level on a particular RE technology is, nevertheless, uncertain and depends on many peculiarities, such as the generation profile of the RE technology, load, the emissions factor of the marginal technology that determines the electricity spot price, and other exogenous market circumstances. It is thus an empirical task to estimate the impact of different carbon price levels on RE's market values. Nonetheless, the carbon price will lose its supportive power for RE's market values during times of no infeed from fossil-fuelled power plants (e.g. whenever RE and other low-emission technologies, such as nuclear, generate enough electricity to displace fossil fuels).

3 Data

3.1 Market values

We calculate the market values of wind and solar power, following the established literature (Lòpez Prol et al., 2021; Clo et al., 2015; Hirth, 2016; Winkler et al., 2016), which will serve as the dependent variables in our econometric model.[8] We start with the aggregation of hourly revenues to obtain the daily revenue of each technology

$$R_{n,t} = \sum_{h=1}^{24} p_h \cdot q_{n,h}, \tag{1}$$

where p_h is the day-ahead wholesale electricity price and $q_{n,h}$ is technology n's forecasted electricity production. We then use the daily revenue (eq. (1)) to calculate the market value (eq. (2)), which represents the realized average revenue, weighted by actual infeed:

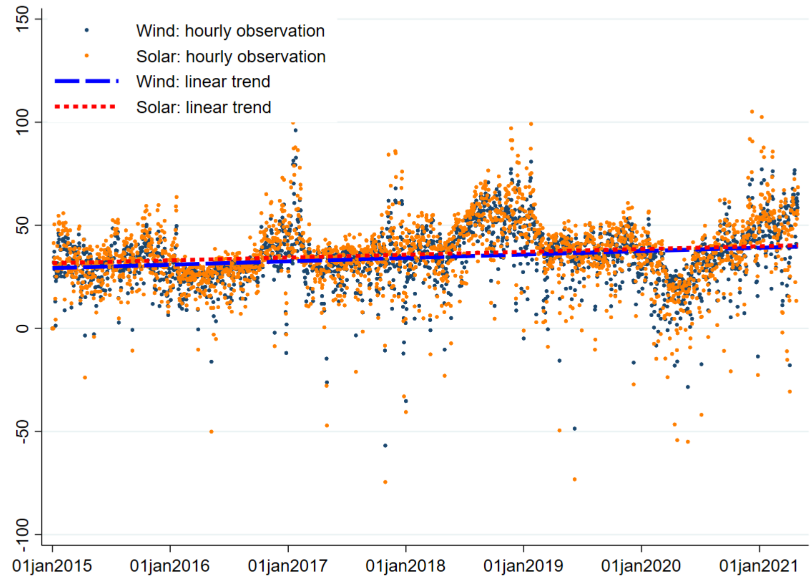
$$MV_{n,t} = \frac{R_{n,t}}{\sum_{h=1}^{24} q_{n,h}}, \tag{2}$$

Figure 4 displays technology-specific market values over the sample period 01/2015-04/2021. Although the market values appear to be fairly constant (even modestly increasing) over time, the graph hides significant ceteris-paribus infuences by confounding influential factors (e.g. of changes in the carbon price, load, RE infeed, etc.), which might partly offset each other (and as our econometric analysis will uncover).

We should mention that the relevant literature applies not only market values (as an "absolute" measure), but also value factors (VF), as a "relative" measure (see, e.g. Lòpez Prol et al., 2021; Clo et al., 2015; Hirth et al., 2015; Hirth, 2016). It is calculated as the absolute market value relative to the average electricity price: $VF_{n,t} = MV_{n,t}/\bar{P}_t$), where $\bar{P}_t$ is the average electricity price ($\bar{P}_t = \sum_{h=1}^{24} p_h/24$). The idea is that the average electricity price represents the market value of a hypothetical power plant that continuously produces electricity and thus faces the electricity price at every hour. While Lòpez Prol et al. (2021), Hirth (2016) and Clo et al. (2015) include VF in their studies, we focus on market values, because such a hypothetical power plant does not exist in the energy system, and thus the comparison and interpretation of a ratio

[8] In the literature, the terms "unit revenues" and "market values" are used synonymously.

Figure 4: Market values (€/MWh)



This figure depicts hourly market values of wind and solar power in Germany and their linear trends during the sample period. This graph, however, masks potentially offsetting influential effects from other market trends (e.g. increasing carbon prices and increasing RE infeed), which our econometric analysis tries to uncover.

between market value and average wholesale electricity price are not meaningful for our study. Furthermore, we believe that using market values of wind and solar will allow us to make better statements about the resulting investment incentives into these technologies. According to Hirth (2016), the VF approach corrects for price fluctuations that follow business cycles. In our regression specifications, we control for these factors, using fixed effects. Therefore, we believe that absolute market value is a better measure to analyze the cannibalization effect of RE and figure out whether or not renewables can live without subsidies or other policy instruments.

3.2 Data sources

We use high-frequency data (i.e. hourly and daily) for the German wholesale electricity market for the period 01/2015–04/2021.[9] Hourly electricity generation and renewable production day-ahead forecasts differentiated by generation type, cross border physical flows (which we use to quantify net imports), load, and day-ahead prices are obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E, 2021). Since the day-ahead electricity price is the reference price for calculating market values, we use data on day-ahead forecasts

[9]Our sample includes the period of the Coronavirus disease in Germany, starting mid of March 2020. This time is characterized by a collapse in economic activity and energy demand due to containment measures (Haxhimusa and Liebensteiner, 2021). We therefore present alternative estimates on the restricted sample, 2015/01/01–2020/01/31, prior to COVID-19 in Figure A2 of the Appendix. The results stay fully robust.

Table 1: Sample statistics

Variable	Mean	Std. Dev.	Pctl 10	Pctl 25	Pctl 50	Pctl 75	Pctl 90
Dependent variable							
Market value RE (€/MWh)	34.50	14.55	18.14	26.86	34.18	42.76	51.83
Market value wind (€/MWh)	34.46	13.81	19.15	27.34	34.06	42.14	51.44
Market value solar (€/MWh)	36.01	17.27	17.12	27.63	35.75	45.34	55.34
Variables of Interest							
RE infeed forecast (GWh)	391.14	191.28	182.96	249.16	350.93	496.70	664.18
Wind infeed forecast (GWh)	284.01	205.99	73.48	126.53	225.33	389.07	598.58
Solar infeed forecast (GWh)	107.02	69.57	20.06	41.08	103.13	164.15	203.50
Control variables							
Price of CO_2 (€/tCO_2)	15.79	10.42	5.13	6.41	10.55	25.02	28.09
Load (GWh)	1,318.79	143.28	1,095.09	1,227.99	1,336.42	1,421.43	1,497.80
Natural gas infeed (GWh)	105.58	64.99	32.64	51.66	89.83	150.37	201.14
Nuclear infeed (GWh)	199.99	35.66	154.29	176.96	195.68	224.96	249.73
Price of gas (€/MWh)	16.39	4.86	10.24	13.28	16.49	19.85	21.98
Net electricity imports (GWh)	-113.12	88.88	-219.66	-174.76	-122.37	-57.29	8.96
Underlying variables							
Electricity spot price (€/MWh)	35.43	13.85	20.17	27.89	34.81	42.91	52.18

Sample period: 2015/01/01–2021/04/30. 2,309 daily observations.

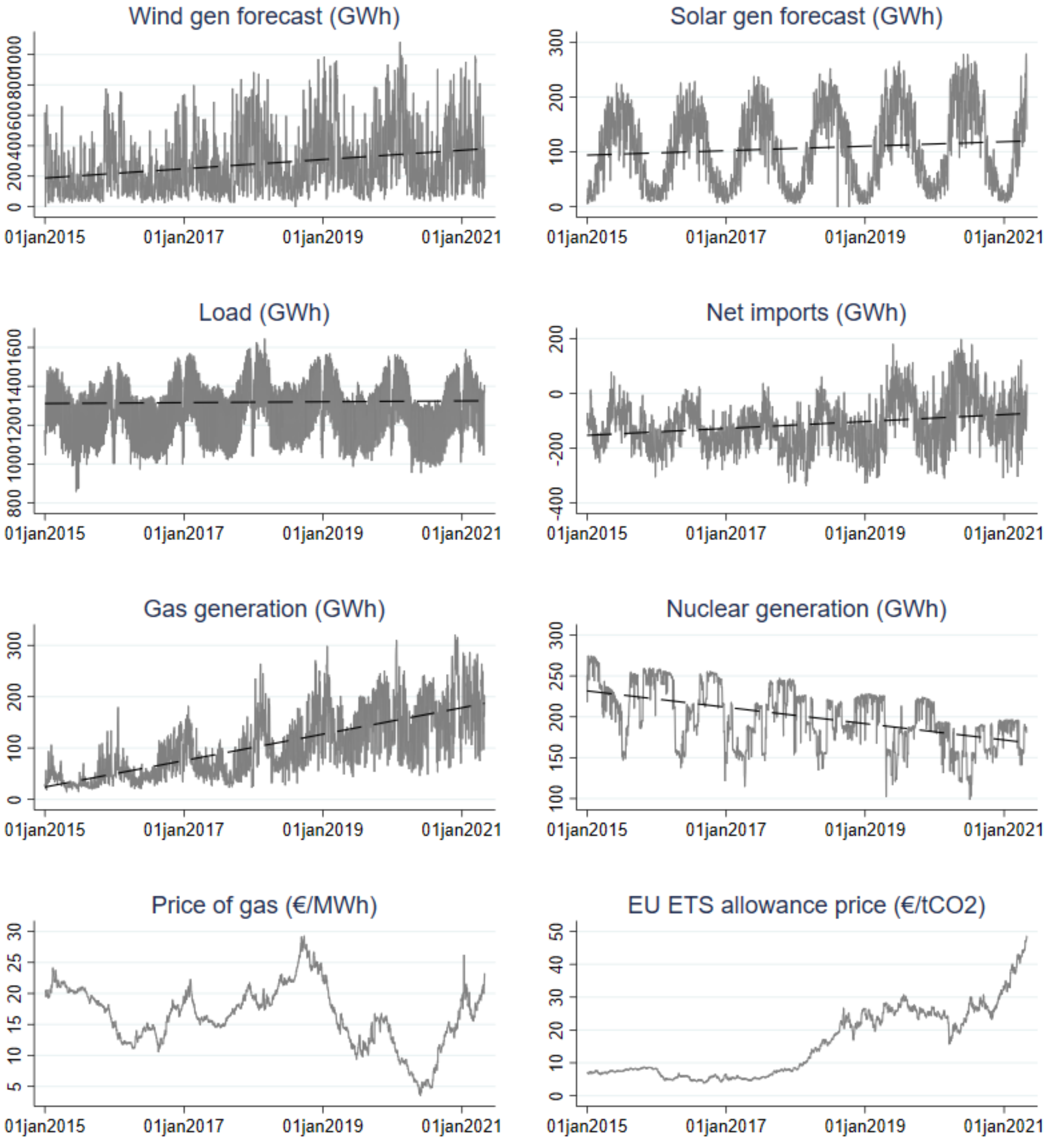
for RE generation. Please note, however, that there is an almost perfect correlation between day-ahead forecasted and actual generation of RE (wind onshore: 0.985, wind offshore: 0.952, solar: 0.994).

To control for changes in input prices, we use the Dutch TTF future price of natural gas[10] in a daily resolution, provided by the financial markets platform "investing.com". We converted the price in USD to EUR using the daily exchange rate from the European Central Bank. The daily EU ETS emissions allowance spot price in €/tCO_2 is obtained from the European Energy Exchange AG EEX (2021).

A summary of descriptive statistics of our sample is presented in Table 1. Moreover, market developments of our right-hand-side variables are depicted in Figure 5. We can see that wind infeed, and to a lesser degree solar infeed, increase, on average, over time. However, their production profiles are highly intermittent. Load varies strongly by season, but its long-term trend remains fairly constant. Net imports are highly volatile and increasing, on average. Gas generation is increasing, while nuclear generation is decreasing (due to the planned nuclear phaseout by the German government) over time. The price of gas does not follow a clear trend but varies between around 5 and 30 €/MWh. Moreover, the EU ETS allowance price in €/tCO_2 increased over time from well below 10 €/tCO_2 to almost 50 €/tCO_2 by the end of April 2021.

[10]Dutch TTF natural gas base-load future from the ICE in EUR/MWh, stated at the Intercontinental Exchange (ICE).

Figure 5: Market developments of right-hand-side variables



This figure depicts the developments (and linear trends) of right-hand-side variables during our sample period 2015/01/01–2021/04/30.

4 Research design

4.1 Identification

In this section, we discuss our econometric approach to identify the effects of wind and solar infeed and carbon pricing on the market values of wind and solar. An unbiased estimation of the effects of interest requires wind and solar infeed as well as the carbon price to be exogenous to the market values of wind and solar power, conditional on all other included control variables.

For variable RE, the exogeneity assumption is likely to hold, because weather conditions (wind speed and solar radiation) determine the feed-in levels of wind and solar power installations. Moreover, wind and solar electricity have zero marginal costs and can thus feed into the system before other technologies with positive marginal costs. In addition, German wind and solar installations enjoy prioritized feed-in at guaranteed tariffs, thus feeding into the system whenever possible. Thus, it is most likely that wind and solar infeed is exogenous (at least in the short run). The carbon price, on the other hand, is determined by supply and demand for emission certificates, whereas in the short run, the market values of wind and solar should not have material impact on the price level of emission allowances.

4.2 Simple linear model

We start our analysis with a simple linear model of market values as a function of our main variables of interest, namely the day-ahead forecasts of wind (W) and solar (S) infeed,[11] as well as the allowance price of CO_2-equivalent emissions (P_{CO2}). We also include a set of other variables to control for the influence of potentially confounding effects. These variables are the load (L), infeed of must-run nuclear power (Nuc), infeed of peaking natural gas (Gas), the price of natural gas (P_{gas}), net electricity imports (IM), as well as fixed effects for days-of-week (D_{dow}), months (D_m), and years (D_y) to control for seasonality and other temporal effects.

$$\begin{aligned} MV_{n,t} = \; & \beta_W W_t + \beta_S S_t + \beta_{PCO2} P_{CO2,t} + \beta_L L_t + \beta_{Nuc} Nuc_t + \beta_{Gas} Gas_t + \\ & \beta_{Pgas} P_{gas,t} + \beta_{IM} IM_t + D_{dow} + D_m + D_y + \epsilon_t . \end{aligned} \tag{3}$$

[11] We use forecasts of wind and solar infeed in units (MWh) in our model. In contrast, López Prol and Schill (2021) use relative measures, namely wind and solar infeed in percent of load. When we apply relative measures instead of units, our results stay qualitatively robust.

The subscript n denotes the technology ($n = wind, solar$). This means, we run two regressions for the two dependent variables MV_W and MV_S. The subscript t stands for each sample hour. ϵ is a heteroscedasticity and first-order autocorrelation consistent error term.

This simple model delivers first evidence, which is easily interpretable, because the coefficient estimates directly represent marginal effects. For instance, the estimate of $\hat{\beta}_W$ tells us by how much (in €/MWh) the market values of wind ($MV_{W,t}$) and solar ($MV_{S,t}$) would change for a marginal increase in the day-ahead forecast of wind infeed (W) by one MGWh per day. The drawback is that this simple model only estimates constant linear relationships, thus neglecting potential non-linearities or interdependencies among some of the predictor variables. Hence, we proceed by estimating a richer, more flexible model.

4.3 Flexible model

In a more flexible specification, we allow for interaction effects and squared terms, to allow for interdependencies and non-linear effects:

$$\begin{aligned} MV_{n,t} = \; & \beta_W W_t + \beta_{W^2} W_t^2 + \beta_S S_t + \beta_{S^2} S_t^2 + \beta_{PCO2} P_{CO2,t} + \beta_{PCO2^2} P_{CO2,t}^2 + \beta_L L_t + \\ & \beta_{L^2} L_t^2 + \beta_{Nuc} Nuc_t + \beta_{Nuc^2} Nuc_t^2 + \beta_{Gas} Gas_t + \beta_{Gas^2} Gas_t^2 + \beta_{Pgas} P_{gas,t} + \\ & \beta_{Pgas^2} P_{gas,t}^2 + \beta_{IM} IM_t + \beta_{IM^2} IM_t^2 + \beta_{WS} W_t \cdot S_t + \beta_{W \cdot PCO2} W_t \cdot P_{CO2,t} + \\ & \beta_{WL} W_t \cdot L_t + \beta_{S \cdot PCO2} S_t \cdot P_{CO2,t} + \beta_{SL} S_t \cdot L_t + \beta_{PCO2 \cdot L} P_{CO2,t} \cdot L_t + \\ & D_{dow} + D_m + D_y + \epsilon_t. \end{aligned} \tag{4}$$

This flexible model is an extension of related studies (e.g. Lòpez Prol et al., 2021; Clo et al., 2015; Welisch et al., 2016) estimating the effect of RE on market values in more simplistic models (similar our simple linear model presented in Section 4.2).[12]

From this model's estimates, we can calculate non-linear predictions of RE's market values for ceteris-paribus changes in variables of interest, x (e.g. forecasted wind and solar infeed or carbon price): $\partial \widehat{MV}_n / \partial x$. For example, the predicted market values of wind with respect to a change in wind feed-in would be $\partial \widehat{MV}_W / \partial W = \hat{\beta}_W + 2 \cdot \hat{\beta}_{W^2} \cdot W + \hat{\beta}_{WS} \cdot \bar{S} + \hat{\beta}_{W \cdot PCO2} \cdot \bar{P}_{CO2} + \hat{\beta}_{WL} \cdot \bar{L}$, where bars over variables indicate their sample means. The predicted values can then be

[12] We also run a model, which estimates the compound effect of of how RE infeed (RE, i.e. wind plus solar infeed) impacts the market value of compound RE: $MV_{RE,t} = \beta_{RE} RE_t + \beta_{RE^2} RE_t^2 + \beta_{PCO2} P_{CO2,t} + \beta_{PCO2^2} P_{CO2,t}^2 + \beta_L L_t + \beta_{L^2} L_t^2 + \beta_{Nuc} Nuc_t + \beta_{Nuc^2} Nuc_t^2 + \beta_{Gas} Gas_t + \beta_{Gas^2} Gas_t^2 + \beta_{Pgas} P_{gas,t} + \beta_{Pgas^2} P_{gas,t}^2 + \beta_{IM} IM_t + \beta_{IM^2} IM_t^2 + \beta_{RE \cdot PCO2} RE_t \cdot P_{CO2,t} + \beta_{RE \cdot L} RE_t \cdot L_t + \beta_{PCO2 \cdot L} P_{CO2,t} \cdot L_t + D_{dow} + D_m + D_y + \epsilon_t$. (5)

assessed for any wind infeed level W (see Figure 6).

5 Results

Simple linear models

Table 2 shows the regression estimates concerning the market values of wind and solar electricity (MV_W, MV_S). Columns (1) and (2) provide estimates from our simple linear model, for which the coefficient estimates can be interpreted as constant marginal effects. In both models, the coefficient estimates on wind and solar are negative and statistically significant, implying that a marginal increase in wind or solar, ceteris paribus, decreases the market values of wind and solar, whereas their magnitudes differ quite substantially.

Looking at specification (1), the cannibalization effect on wind is more pronounced with wind infeed than with solar infeed (the coefficients are statistically significantly different at the 1% level). A marginal change in wind or solar electricity by one GWh decreases the unit revenue of wind by 0.045 €/MWh or 0.033 €/MWh, respectively. We can also calculate an elasticity: Evaluated at sample means (see 1), an increase in wind or solar infeed by 10% (i.e. 28.4 GWh or 10.7 GWh, respectively), decreases the market values of wind or solar by 3.7% ($= -0.045 \cdot 28.4/34.46$) or 0.98% ($= -0.033 \cdot 10.7/36.01$), respectively. Specification (2) shows that the market value of solar electricity gets also significantly cannibalized with increasing wind and solar penetration. A marginal change in wind or solar infeed by one MWh decreases the market value of solar power by 0.049 €/MWh or 0.092 €/MWh, respectively. The elasticities for sample means are -4.0% ($= -0.049 \cdot 28.4/34.46$) or -2.7% ($= -0.092 \cdot 10.7/36.01$), respectively. In conclusion, this is evidence that wind and solar power cannibalize their own market values.

Importantly, in both specifications (1) and (2), we find that a marginal change in the carbon price increases the market values of wind and solar electricity. An increase in the carbon price by one €/tCO_2 increases the market values of wind by 0.90 €/MWh and that of solar by 0.83 €/MWh – an economically pronounced effect. Hence, the estimates from the simple linear models corroborate our suspicion that an intensification of carbon pricing counteracts the self-cannibalization of renewables.

Looking at other control variables, our results in specifications (1) and (2) indicate that a higher electricity demand and a higher price of gas significantly elevate the market values of wind and solar power. The fist effect aligns well with Ruhnau (2022), who shows that an

Table 2: **Main regression results: market values of wind and solar**

	(1)	(2)	(3)	(4)
	Simple linear models		Flexible models	
	MV_W	MV_S	MV_W	MV_S
W	-0.04515***	-0.04924***	-0.12566***	-0.11330***
	(0.00186)	(0.00232)	(0.01258)	(0.01810)
S	-0.03299***	-0.09219***	-0.13850***	-0.31357***
	(0.00387)	(0.00545)	(0.02864)	(0.04806)
P_{CO2}	0.90241***	0.82864***	1.48600***	1.72050***
	(0.06600)	(0.09030)	(0.27012)	(0.37689)
L	0.04323***	0.05279***	0.02486	0.03734
	(0.00349)	(0.00459)	(0.02041)	(0.03204)
Gas	0.02539***	0.03719***	0.09671***	0.12532***
	(0.00614)	(0.00833)	(0.01503)	(0.02288)
Nuc	-0.02297***	-0.02374**	0.11496**	0.21964***
	(0.00723)	(0.00955)	(0.05504)	(0.07735)
P_{gas}	0.96081***	1.14313***	0.95827***	1.07024***
	(0.07058)	(0.08766)	(0.20651)	(0.29320)
IM	-0.01515***	-0.00429	-0.02647***	-0.02575***
	(0.00331)	(0.00450)	(0.00353)	(0.00514)
$W \cdot W$			-0.00002***	-0.00002***
			(0.00000)	(0.00001)
$S \cdot S$			0.00006*	0.00031***
			(0.00004)	(0.00006)
$P_{CO2} \cdot P_{CO2}$			-0.01412***	-0.02097***
			(0.00343)	(0.00454)
$W \cdot S$			-0.00000	-0.00008**
			(0.00002)	(0.00003)
$W \cdot P_{CO2}$			0.00007	0.00021
			(0.00015)	(0.00021)
$S \cdot P_{CO2}$			0.00089***	0.00061
			(0.00029)	(0.00040)
$L \cdot L$			-0.00000	-0.00001
			(0.00001)	(0.00001)
$W \cdot L$			0.00007***	0.00006***
			(0.00001)	(0.00001)
$S \cdot L$			0.00005***	0.00011***
			(0.00002)	(0.00003)
$P_{CO2} \cdot L$			-0.00005	-0.00003
			(0.00016)	(0.00023)
$Gas \cdot Gas$			-0.00021***	-0.00025***
			(0.00005)	(0.00008)
$Nuc \cdot Nuc$			-0.00037***	-0.00065***
			(0.00014)	(0.00020)
$P_{gas} \cdot P_{gas}$			0.00062	-0.00067
			(0.00586)	(0.00827)
$IM \cdot IM$			-0.00002*	-0.00007***
			(0.00001)	(0.00002)
FE dow, months, years	yes	yes	yes	yes
Observations	2,309	2,309	2,309	2,309
R^2	0.842	0.811	0.868	0.838
p-value: $\beta_W = \beta_S$	0.00	0.00		

Notes: Heteroscedasticity and autocorrelation consistent (Newey-West) standard errors in parentheses. *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01–2021/04/30.

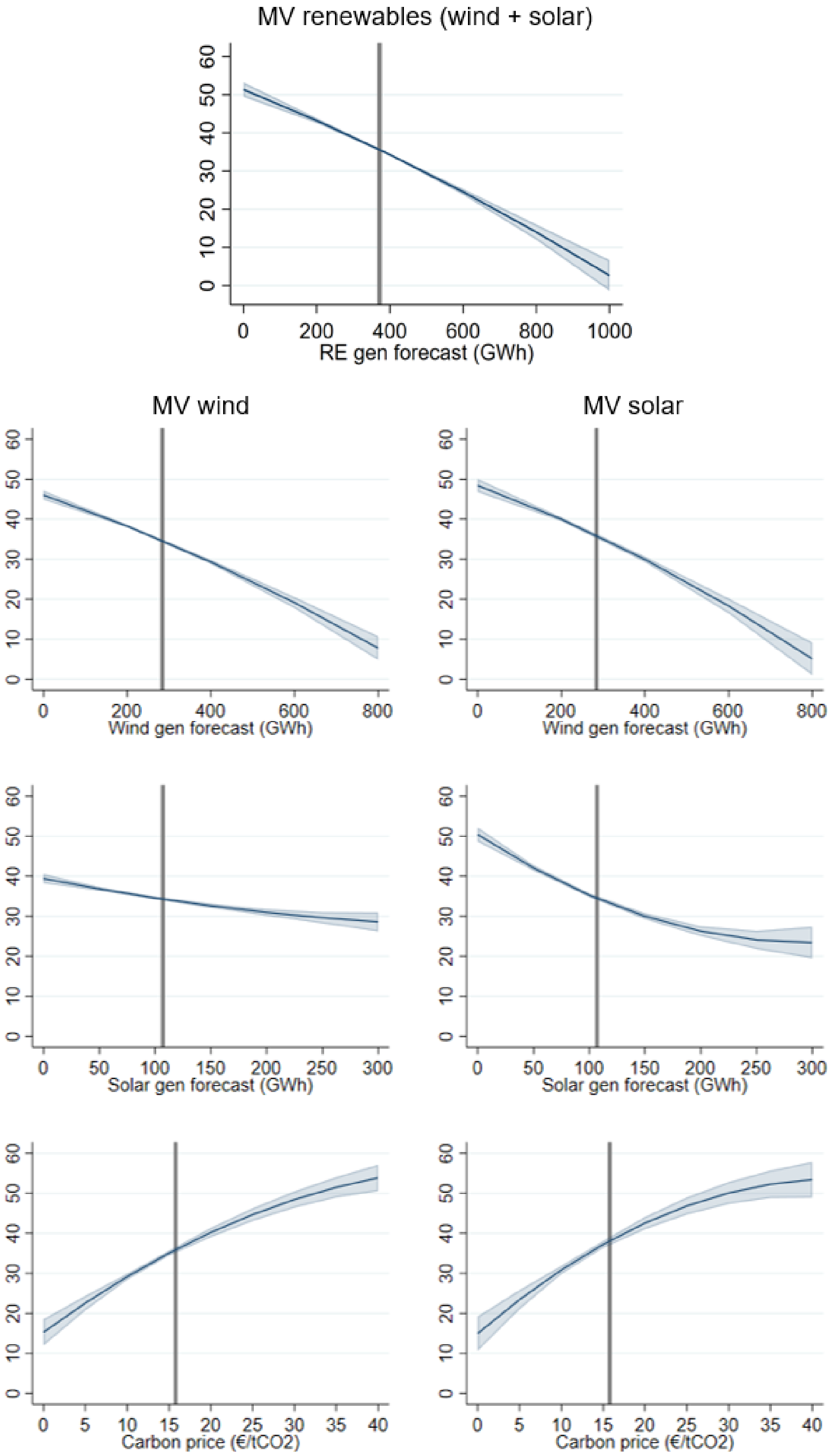
increase in flexible load (from hydrogen electrolyzers) may significantly counteract RE's self-cannibalization problem. Moreover, we expect electricity demand to increase during the next decade, because of an intensification of sector coupling (e.g. increasing e-mobility, hydrogen electrolysis, electrification of residential heating). For example, BMWi (2021b) forecasts an increase in load by 13% during 2020–2030, which may help elevate RE's market values. On the other hand, it is more difficult to predict the development of the gas price in Europe. The current "energy crisis" and the Russian invasion of Ukraine led to an explosion of gas prices for an uncertain duration. The estimates also indicate that imports decrease the market values of wind and solar power, which is not surprising, given that imports reduce the wholesale electricity price (Gugler et al., 2018).

More flexible models

Let us now move to the more complex models (3) and (4), as presented in Table 2. These models estimate the variation in the market values of wind and solar, using a more flexible functional form, including squared and interaction terms. In this case, the coefficient estimates (see Table 2) are not readily interpretable. For this reason, Figure 6 visualizes *model predictions* of RE market values for sample values of (day-ahead forecasts of) wind and solar infeed, and the carbon price, while all other variables are held constant at their sample means. The grey vertical line indicates the sample mean of each independent variable. Appendix Figure A3 extends the analysis by showing analogously the impact of other right-hand-side variables (i.e. load, gas generation, nuclear generation, and price of gas).

For an initial overview, the top panel of Figure 6 shows the compound effect of how RE infeed (wind plus solar infeed) impacts the market value of compound RE. The effect is negative, concave, and pronounced. Holding other confounding factors constant, the market value of RE falls almost to zero for high RE infeed (1,000 GWh or more). The lower panels of Figure 6 disentangle the effects for wind and solar power. We can see that the market values of wind and solar fall with increasing infeed of wind and solar electricity. It is worth noting that solar power's penetration (with up to about 300 GWh) per day is much less pronounced than wind's (with up to more than 600 GWh per day). Especially for high levels of wind penetration in the range of 800 GWh, the market values of wind and solar electricity fall below 10 €/MWh, ceteris paribus. This means, holding all other variables at their sample averages, wind and solar power installations turn economically unprofitable with high wind penetration. The negative effect

Figure 6: Predicted market values of renewable energies dependent on key variables of interest (€/MWh)



The Figure shows predicted values of market values (MV) of RE in €/MWh for ceteris-paribus changes in key variables of interest. Other variables are held constant at their sample means. Predicted values are based on regression models 3 (for wind), 4 (for solar), and 5 (for RE). Vertical lines in gray indicate the sample mean of each independent variable. The 95% confidence intervals are based on heteroscedasticity and autocorrelation consistent standard errors.

on the market values of wind and solar electricity even tend to intensify with higher levels of wind infeed (indicated by the concave function), meaning that an increasing share of wind infeed tends to amplify the self-cannibalization problem.

Solar infeed is less pronounced than wind's, yet for high solar infeed levels the negative effect on the market values of wind and solar is comparable to (or even a bit more pronounced than) that of wind infeed. This is evidence that wind and solar cannibalize themselves, and that the effect is economically significant. While other empirical investigations (e.g. Lòpez Prol et al., 2021) already provided evidence supporting the theory of a self-cannibalization effect of renewables, our results are estimated from data on a significantly higher market penetration of wind and solar electricity (in Germany) and suggest that the self-cannibalization effects are indeed pronounced and non-linear. Without any political interference, variable renewable energy technologies may not survive on their own in the market.

Nonetheless, the good news for wind and solar installations is that an increasing carbon price counteracts the self-cannibalization effect. Figure 6 shows a perceptible increase in the market values of wind and solar power for an increase in the carbon price. A carbon price of 40 €/tCo_2 can – ceteris paribus – more than offset the negative influence of high wind infeed. However, the function is estimated to be concave, so that the positive effect of the carbon price on the market values of wind and solar tends to flatten out with carbon prices well beyond 40 €/tCO_2. One explanation may be that with high carbon prices, the marginal costs of fossil fuel technologies increase and thus, in the short run, get partly replaced by electricity imports from abroad. In such a scenario, the augmenting effect of higher marginal costs of fossil fuel technologies on the wholesale price of electricity would get compensated by a price-dampening effect of electricity imports (e.g. from France having a high share of cheap nuclear power).

Let us briefly discuss the influence of other right-hand-side variables on the predicted market values values, as presented in Appendix Figure A3. An increase in load significantly elevates the market values of wind and solar power. The effect turns out to be almost linear. More electricity generation from gas-fired power plants modestly increases wind and solar market values. Nuclear power generation has a modestly concave influence, thus decreasing RE market values for higher nuclear generation levels. An increase in the price of natural gas has a pronounced positive and almost linear impact on RE market values. An increase in net imports (which implies a decreasing electricity price) moderately lowers RE market values.

6 Discussion of countermeasures against the self-cannibalization problem

Mills and Wiser (2015) found that bulk power storage and geographic diversification of RE facilities can mitigate the self-cannibalization effect of RE. Lòpez Prol et al. (2021) argue that any measures to increase power system flexibility, such as energy storages, demand management, or geographically diverse interconnection lines, may also help mitigate the problem. Ruhnau (2022) finds that flexible load additions (e.g. from hydrogen electrolyzers) during times of low electricity prices is another countermeasure. Analogously, our models also yield that increasing electricity demand lifts the market values of renewables. Moreover, increasing input prices (e.g. the price of natural gas) result in higher market values of RE. Another important argument is that phasing out subsidy payments for fossil fuels, which are still prevalent in many countries around the globe, would create a level paying field between RE and fossil fuels (IRENA, 2021). Our finding that a carbon pricing can significantly offset the cannibalization effect, seems yet to be another promising policy measure to counteract RE's cannibalization and boost their competitiveness. This has several reasons.

First, many economists and policy makers may agree that subsidies for RE may be justified to overcome their infant-industry state. Once the RE's LCOE have fallen significantly (as may be the case already or in the near future; see, e.g. the discussion in López Prol and Schill, 2021) or once RE have reached a significant market share in a given country, it may be worthwhile to follow other market-based measures to tackle the emissions externality while at the same time meeting other second-order conditions, such as incentivizing investment in low-carbon electricity generation technologies. Hence, the introduction and intensification of carbon pricing may be a promising strategy that lives up to these goals. This is, for example, what the German Council of Economic Experts (CGEE, 2021) has recently declared as a promising avenue for Germany's near-future transition path.

Second, an increasing number of countries and regions have been adopting carbon pricing measures, either via carbon taxes or via cap-and-trade emissions certificate programs, or are planning on intensifying carbon pricing. Appendix Figure A1 visualizes carbon prices of several emission trading schemes around the globe, showing generally increasing price trends. In this respect, the EU ETS saw a drastic increase of its emissions allowances price since mid 2017, from a price as low as €5/tCO_2 (Haxhimusa and Liebensteiner, 2021) to currently €90/tCO_2[13] After Brexit and the consequent exit from the EU ETS, Great Britain has implemented an ambitious national emissions trading scheme, which currently yields higher carbon prices than the EU ETS. China's ETS has passed its three-years pilot phase by the end of 2020, and will likely see increasing allowance prices given that the emissions cap will be decreased every year. Another example is Canada's carbon tax, which is set to increase every year. As of 1 April 2021, the federal minimum tax is set at C$40 and set to be increased gradually to C$170 in 2030. It is thus reassuring that a high carbon price can significantly counteract the reduction of RE's market values for an increasing market penetration.

However the cure of carbon pricing to the self-cannibalization effect of RE has a limitation. Carbon pricing can only elevate RE's market values as long as there are CO_2-intensive production units in the electricity supply mix, for which the carbon price can lifts their marginal costs and consequently the spot price of electricity. Once the market is fully decarbonized (which will unlikely be the case in the near future, but at least serves as a benchmark scenario), a carbon price will ultimately have no impact on the electricity spot market any longer.

7 Conclusion

Many jurisdictions around the globe grant financial support payments for renewable energies in order to foster their market integration and to decarbonize the energy sector. Decreasing costs of RE have spurred the hopes that RE may eventually become economical and thus persist in the market independently of any support payments. However, RE feed into the system at zero marginal costs, and their infeed is geographically and temporarily clustered (due to weather conditions). Hence, during times of high wind and solar electricity production, wholesale electricity prices plummet, eroding RE's market values. This is coined as the "self-cannibalization effect" of renewables. It endangers the competitiveness of RE with conventional fossil power plants, undermines a potential market maturity of RE, reduces investment incentives into green technologies, and altogether may impede the energy transition.

In this study, we have investigated to what extent the market value of RE in the German energy market is affected by the cannibalization effect. As Germany is a pioneer in the field of the energy transition towards RE, this makes it a relevant case and can provide valuable lessons

[13] EUA price, as of 02 February 2022, obtained from the European Energy Exchange (EEX; https://www.eex.com/en/market-data/environmental-markets/spot-market).

for other countries that seek to increase the share of renewable energy. Using a rich data set and a highly flexible econometric model, we find that the self-cannibalization effect of RE is pronounced, empirically confirming the theory of self-cannibalization. This is a concern, as it works against the intended self-sustaining survivability of RE in the market. Importantly, we provide compelling empirical evidence that carbon pricing – a first-best policy to the emissions externality according to the neoclassical economic theory – presents a promising countermeasure. We show that a carbon price of about 40 €/tCO_2 can, ceteris paribus, offset the self-cannibalization effect of a high RE infeed level. To the best of our knowledge, this is the first study to empirically investigate the effect of a high carbon allowance price (arising from the EU ETS) on RE's market values.

One important policy advice from this study is thus that a "sufficiently high" carbon price elevates the competitiveness of RE and may make them independent of subsidy payments. A downside of this advice is that if a state is reached in which power generation is completely decarbonized, the effect of carbon pricing will be extinguished. In such a case, the energy system will face new challenges and the market design will have to be rethought. One possible option could then be to switch from an energy-only to a capacity market.

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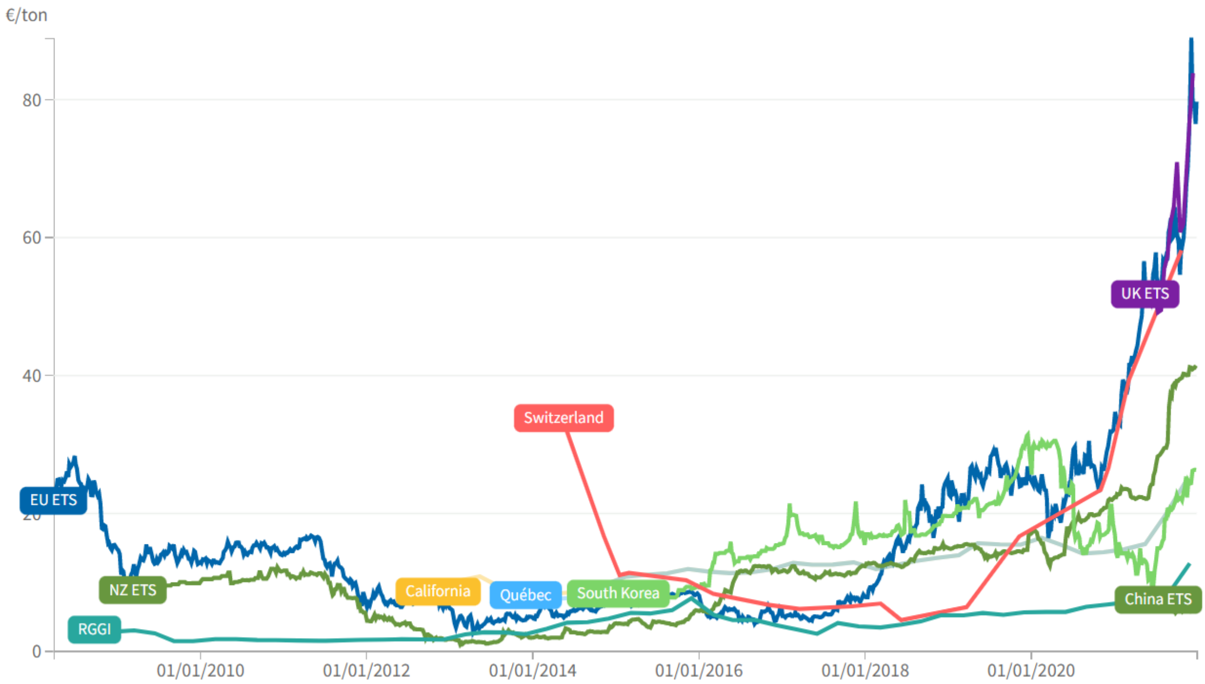
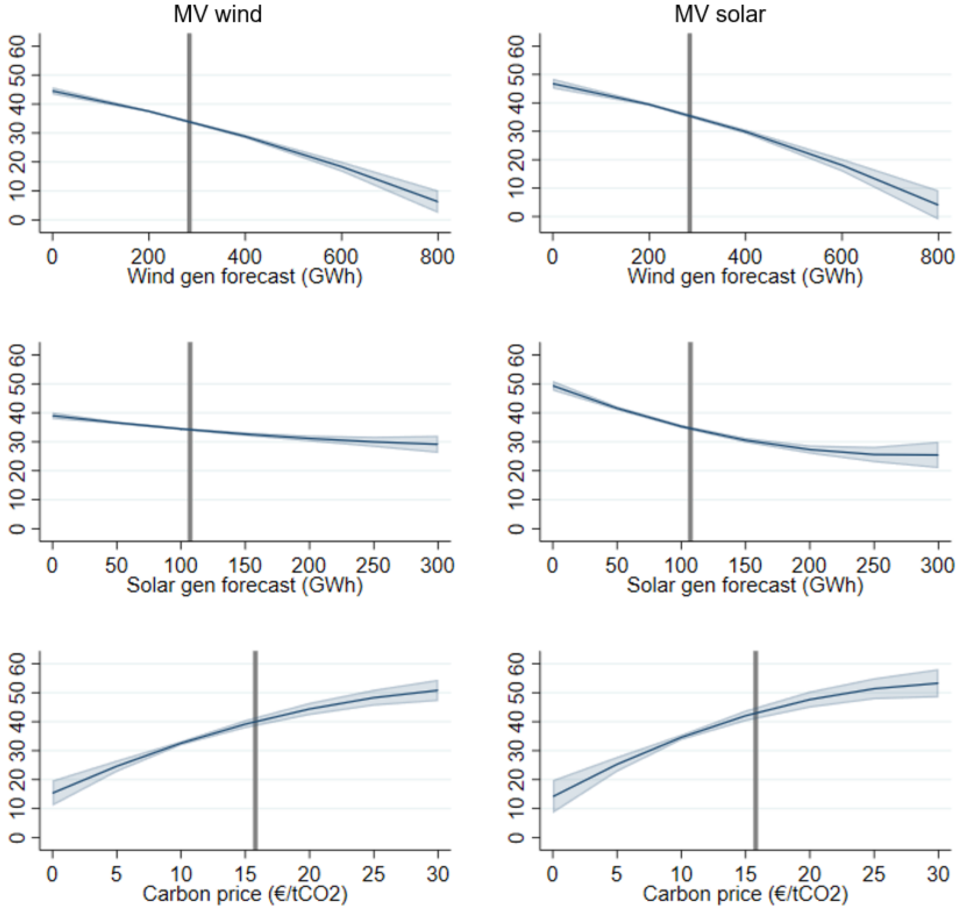
Appendix

Figure A1: Carbon prices from several ETSs



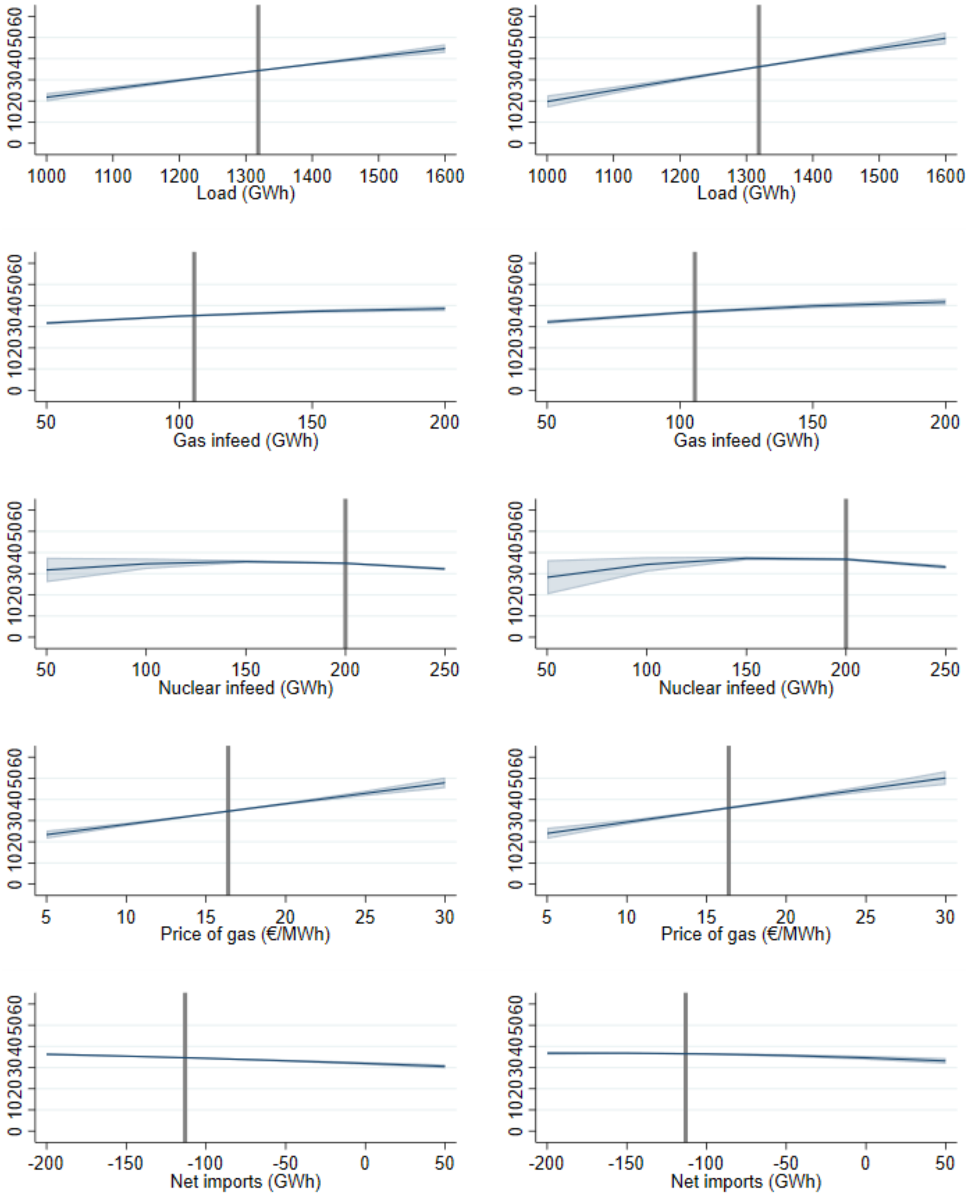
Source: screenshot of the International Carbon Action Partnership's Allowance Price Explorer; https://icapcarbonaction.com/en/ets-prices, 2 February 2022.

Figure A2: Predicted values of market values of wind and solar (€/MWh). Restricted sample prior to COVID-19: 2015/01/01–2020/01/31



The Figure shows predicted values of market values (MV) of wind and solar in €/MWh. Other variables are held constant at their sample means. Sample period restricted to 2015/01/01–2020/01/31. The maximum carbon price was €30/tCO_2, which is why we restricted the predictions accordingly. Vertical lines in gray indicate the sample mean of each independent variable. The 95% confidence intervals are based on heteroscedasticity and autocorrelation consistent standard errors.

Figure A3: Predicted market values of renewable energies, additional right-hand-side variables (€/MWh)



This figure extends Figure 6 by additional right-hand-side variables. The Figure shows predicted values of market values (MV) of RE in €/MWh. Other variables are held constant at their sample means. Predicted values are based on regression models 3 (for wind) and 4 (for solar). Vertical lines in gray indicate the sample mean of each independent variable. The 95% confidence intervals are based on heteroscedasticity and autocorrelation consistent standard errors.