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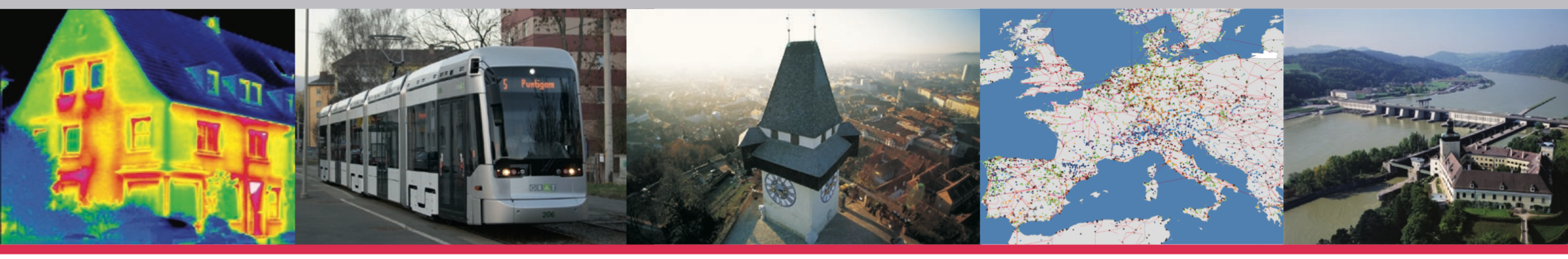

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WORLD ENERGY COUNCIL AUSTRIA

REGIONALE ENERGIEASPEKTE (SESSION A6: FR, 10:30-12:30, I11)

Mag. Elvira LUTTER (Programm- und Research-Managerin beim Österreichischer Klima- und Energiefonds)		
Resch, Schöniger, Totsching, Suna, Geipel, Liebmann	TU Wien / Energy Economics Group	UNTERSUCHUNG VON ERFORDERNISSEN UND AUSWIRKUNGEN EINER ERNEUERBAREN STROMVERSORGUNG IN ÖSTERREICH BIS 2030
Panzer	Vorzeigeregion Green Energy Lab	SCALE UP-MEHRWERT FÜR ENDKUNDEN DURCH UMSETZUNG VON NACHHALTIGEN ENERGIESERVICES
Holzleitner	WIVA P&G – Wasserstoff-initiative Vorzeigeregion Austria Power & Gas	WIE DIE TRANSFORMATION EINER VOLKSWIRTSCHAFT AUF EINE WEITESTGEHEND CO2-NEUTRALE STRUKTUR GELINGEN KANN: EINE ENERGIEMODELLREGION STELLT SICH VOR
Hribernik	Vorzeigeregion NEFI – New Energie for Industry	DEKARBONISIERUNG DER INDUSTRIE – CHANCEN DURCH TECHNOLOGISCHEN WANDEL
Graf	Energie Steiermark AG	DIE ENERGIE STEIERMARK HEUTE UND MORGEN. WIE SICH DIE TRANSFORMATION DER ENERGIEWIRTSCHAFT IN DER PRAXIS AUSWIRKT

ENERGIE- UND ELEKTRIZITÄTSMARKT (Stream C)

ELEKTRIZITÄTSMÄRKTE (SESSION C1: MI, 17:00-19:00, I1)

Dipl.-Ing. Mathias SCHAFFER (Leiter der Abteilung Energieforschung & Innovationsmanagement der Energie Steiermark AG)		
Trattnig, Haubenhofer	FH JOANNEUM Gesellschaft mbH / Energie-, Mobilitäts- und Umweltmanagement & Energy and Transport Management	20 JAHRE STROMMARKTLIBERALISIERUNG IN ÖSTERREICH - EINE SUBJEKTIVE BESTANDSAUFNAHME MIT AUSBLICK
Pugl-Pichler, Tyma, Süßenbacher, Todem	Austrian Power Grid AG	KAPAZITÄTSMECHANISMEN IN EUROPA – RECHTLICHER RAHMEN UND STAND DER UMSETZUNG
Knaus, Harrucksteiner, Holzmann, Zwieb	Austrian Energy Agency	PREISKONVERGENZ IM CWE FBMC
Weber, Herr	IZES gGmbH	MODELLIERUNG VON MARKT-KOPPLUNG MITHILFE EINER STANDARDISIERTEN MERIT-ORDER
Blume-Werry(*), Huber, Resch, Haas	Axpo Holding AG	POLITICS VS MARKETS – WAS TREIBT DIE WERTIGKEITEN VON WIND UND PV?

ENERGIESYSTEM- UND MARKTMODELLE I (SESSION C2: DO, 8:20-10:00, I1)

Dipl.-Ing. Reinhard WOLLONER (Abteilungsleiter VERBUND Trading GmbH)		
Wiedner, Todem, Wornig	Austrian Power Grid AG	FLEXIBLE SOFTWARE-UMGEBUNG FÜR STROMMARKT- UND NETZMODELLE (VAMOS – VARIED MARKET MODEL OPERATING SYSTEM)
Schmitz(*), Böttger	Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik (IEE)	ANALYSE DER AUSWIRKUNGEN UNTERSCHIEDLICHER DETAILGRADE IN EINEM KRAFTWERKSEINSATZMODELL
Reinert(*), Söhler, Baumgärtner, Bardow	RWTH Aachen University / Institute of Technical Thermodynamics	OPTIMIZATION OF REGIONALLY RESOLVED ENERGY SYSTEMS BY SPATIAL AGGREGATION AND DISAGGREGATION
Müller(*), Stüber	Technische Universität München, Lehrstuhl für Erneuerbare und Nachhaltige Energiesysteme	EIN ANALYTISCHER ANSATZ ZUR IDENTIFIKATION MODELLRELEVANTER ZEITREIHENCHARAKTERISTIKA
Weber, Herr	IZES gGmbH	MODELLIERUNG VON BLOCKGEBOTE IN N LOG N LAUFZEIT

Politics vs Markets: what drives value factors and capture prices of renewables?

Eike Blume-Werry*[12], Claus Huber[2], Gustav Resch[1], Reinhard Haas[1]

Kurzfassung:

Mit zunehmender Marktreife von Wind und PV Anlagen, sowie steigendem Zubau außerhalb von Förderregimen, gewinnen auch Markterlöse und Kannibalisierungsrisiken der Erneuerbaren an Bedeutung. Die meisten Studien analysieren die Wertigkeiten und Kannibalisierungsraten von Erneuerbaren bei unterschiedlichen Marktanteilen. Dieser Beitrag führt dies weiter und untersucht inwiefern andere Faktoren indirekt relative Wertigkeiten und Markterlöse von Wind und PV zusätzlich beeinflussen. Dazu modellieren und analysieren wir eine Reihe von Szenarien mit veränderten Gas-, Kohle- und CO_2-Preisen, sowie abgeänderten Verfügbarkeiten von Wind und PV über die nächsten 30 Jahre. Die Ergebnisse zeigen, dass höhere Gas- und CO_2-Preise zu geringeren relativen Wertigkeiten von Wind und PV führen, während niedrigere Preise das Gegenteil bewirken. Höhere oder niedrigere Kohlepreise hingegen haben nahezu keine Auswirkungen auf die relativen Wertigkeiten von Wind und PV. Veränderte Verfügbarkeiten von Wind und PV bewirken ein substanziellen Merit Order Effekt bei den Marterlösen, aber keine Quer-Kannibalisierung zwischen Wind und PV.

Keywords: Kannibalisierung, Wertigkeiten, Markterlöse, Erneuerbare

1 Introduction

Capture prices of a given power generation unit describe the average market prices the unit earns (Byrne et al., 2016). If a generation unit was constantly producing electricity its capture prices would equal base prices. Non-dispatchable generation units such as photovoltaics (PV) and wind turbines produce electricity whenever there is sufficient solar radiation or wind. Their capture prices are therefore set by the market prices they achieve during the hours they operate[3]. Wholesale market prices in turn, are determined by the intersection of supply and demand at any given hour[4].

A growing deployment of wind or PV increases the supply during hours they generate electricity, which in turn leads to lower market prices. The higher the penetration of wind or PV, the lower are capture prices they earn. One refers to this as cannibalisation as each additional unit of wind or PV cannibalises the market revenues of the existing units by shifting the residual load curve to the left during sunny or windy hours[5].

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3 Capture prices of renewables are sometimes also referred to as 'market value of variable renewable energy sources (VREs)'.

4 For a more detailed discussion on price-setting on short-run electricity markets see Blume-Werry et al., 2019.

5 The residual load is commonly defined as the difference between actual power demand and the non-dispatchable stochastic power generation of photovoltaics and wind turbines (Schill, 2014, p. 65). A shift of the residual load to the left as a result of increased supply from variable renewable sources has been labelled 'merit-order effect' (Sensfuß et al., 2008). This merit-order effect describes the impact of the low marginal cost renewables on base prices whereas the cannibalization refers to capture prices of wind or PV.

In economics, the term cannibalisation has been used predominately in marketing to describe how the sales of a new product *cannibalises* i.e. reduces the sale of an existing product by same company. Energy economists only started using the term in the last decade to describe the aforementioned phenomenon of lower capture prices at higher penetration rates for variable generation sources i.e. wind and PV (Troy and Twohig, 2010, p. 6).

Historically, market shares of wind and PV have been rather low compared to conventional generation technologies. Furthermore, they used to and still are in many cases supported through some form of support mechanism, some of them (still) offering operators a fixed strike price per unit of electricity generated, independent or largely independent of market prices. In this kind of circumstances, cannibalisation of wind and/or PV is not a pressing issue for renewable plant operators.

However, with growing penetration of renewables electricity sources in a given system the question arises to what extent wind and PV cannibalise their own market revenues. This is becoming an increasingly critical issue as many renewable support schemes are nowadays more market based, requiring operators to sell their produced electricity themselves (direct marketing) and projects of subsidy-free renewables in Europe are on the horizon. In this context, it is increasingly suggested that Power Purchase Agreements (PPAs) are in the process of taking over government support schemes for renewables as the central instrument to mitigate market risk for investors and operators of renewables (Evans, 2017; Heiligtag et al., 2018, pp. 2–3; Huneke et al., 2018, p. 2; Klinger and Driemeyer, 2019). Anyhow, it is a subsequent question what factors influence the cannibalisation of renewable energy sources. It is the core objective of this article to analyse market and policy-based drivers of cannibalisation in order to get a clearer picture of how different factors influence the cannibalisation of wind and PV in Europe.

Even though capture prices are often given in absolute terms, using relative prices can be more sensible as it enables better comparison across different studies and markets over time (Hirth, 2016, p. 211, 2013, p. 220). We therefore use relative prices expressed as percentage relative to the base price and refer to them as value factors[6]. In other words: a wind turbine with a value factor of 0.85 achieves market prices of 85 per cent of the base price. If the base price that a constantly producing generator would earn was for example 100 €/MWh over the duration of a given time period (e.g. one year) the capture price of the wind turbine would equal 85 €/MWh. In mathematical terms the value factor describes the wind or PV weighted average electricity price over a given time period (usually one year), i.e. achieved hourly market prices of wind or PV generation divided by the base price, that is the average market price[7].

$$\text{value factor}_{wind/PV} = \frac{\text{avg. capture price}_{wind/PV}}{\text{base price}}$$

Next to the decreasing value factors of wind and PV that come with higher market shares, the variable or intermittent nature of wind and PV bears system integration challenges. Systems with a high share of wind and PV typically experience higher balancing needs and costs (Batalla-Bejerano and Trujillo-Baute, 2016; Farahmand and Doorman, 2012). Further, any power system with significantly increasing shares of variable renewables requires notable network expansions to accommodate the new intermittent technologies. The fact that suitable wind sites are often located far from demand centre increases the need for (often

[6] In the literature the terms ‘value factors’ and ‘market value factors’ are used interchangeably.

[7] Sometimes referred to as time-weighted price or simple average price in contrast to the load-weighted price.

costly) grid expansions. These system integration costs are, however, not the focus of this paper. It is nevertheless important to keep those in mind when discussing power systems with high penetration rates of wind and/or PV.

2 Literature review

A number of scholars have researched capture prices and value factors of wind and PV at different penetration levels. Hirth (2016) groups the existing literature into three clusters based on methodology used. The three clusters *«market data», «theoretical (analytical) models»* and *«numerical (computer) models»* help to categorise the literature.

Market data literature determines historic value factors or capture prices of renewables based on existing market data. Sensfuß (2007) researches the value of renewable production in Germany at comparable low penetration rates in the 2000s and finds value factors just below 1 for wind and value factors above 1 for PV (Sensfuß, 2007; Sensfuß and Ragwitz, 2011). Hirth (2015, 2013) complements this work and finds lower value factors at higher penetration rates. Other analyses of market data such as those by Clò and D'Adamo (2015) or Ederer (2015) support this (Riva et al., 2017; Welisch et al., 2016; Zipp, 2017). Whilst market data analyses provide real world evidence of lower value factors of wind and PV at higher penetration rates, it is not suitable for predicting value factors in systems with large shares of variable renewable production. This is due to the fact that currently only few markets with high penetration rates exist and experience from those may not be transferable. The Danish power system for instance is characterised by large shares of wind energy yet it is heavily influenced by the much larger German market as well as the large flexibility of the Norwegian market and is thus not representative for other markets.

Literature based on theoretical or analytical models supports understanding different dynamics and mechanisms. The research shows inter alia that value factors of wind and PV are driven by the corresponding production patterns and are higher if they coincide with demand peaks (Grubb, 1991; Hirth and Radebach, 2015; Lamont, 2008).At higher market shares value factors of generation technologies are higher if the generation is less intermittent which explains why PV value factors decline more significantly with higher penetration rates than value factors of wind (Hirth and Radebach, 2015). In order to obtain quantitative results and estimate value factors at different penetration level under different circumstances, most scholars employ numerical computer models rather than theoretical analytical models.

The largest strand of literature on the matter is based on numerical computer models quantifying value factors and capture prices. The authors agree on the general dynamic of shrinking value factors of wind and PV with a growing market share of the respective generation technology (Green and Vasilakos, 2010; Hirth, 2016, 2015, 2013; Hirth and Müller, 2016; Höfling, 2013; Kopp et al., 2012; Mills and Wiser, 2014a, 2014b, 2012; Obersteiner and Saguan, 2009; Odeh and Watts, 2019; Riva et al., 2017; Sioshansi, 2011; Valenzuela and Wang, 2011; Winkler et al., 2016). The models the researchers use differ *inter alia* in their scope, input data, accuracy, time and geographical resolution. As a result computed value factors also differ yet the principle of lower value factors at higher penetration rates is a core commonality.

Fewer authors have researched what factors other than the penetration rate or market share drive the value factor of wind or PV. Winkler et al. (2016) model a wide range of scenarios and find inter alia that CO_2- and fuel prices influence not only base prices but also value factors of PV and wind significantly. In their greenfield setting, without a given power plant portfolio, the scenario dependent different conventional capacity mixes also represent an influential factor.

Hirth, 2013 analyses a range of PV and wind value factors influencing parameters in North-western Europe. He observes that fuel price variations have different effects on value factors dependent on scenarios and scenario-dependent conventional capacity mixes, which means that higher fuel prices may result in lower value factors of renewables (Hirth, 2013, p. 230). Similarly, higher carbon prices can result in lower wind value factors in his analysis, even though lower carbon prices strictly lead to reduced value factors of wind and PV (Hirth, 2013). A number of these findings of both Winkler et al. (2016) and Hirth (2013) stem inter alia from model built conventional capacity parks that in some cases are far from real-world settings in Europe.

This is a central aspect in which our analysis differs from those of Winkler et al. (2016) and Hirth (2013) as the capacity mix in our model computations is not greenfield but based on the current (2019) European power plant portfolio and further (less radical) developments thereof. We therefore try to stay closer to a real-world setting and expected developments. To this end, the sensitivities researched such as fuel and CO_2 price changes are less extreme as in the two analyses described, which is also what Winkler et al. call for (Winkler et al., 2016, p. 478). The models used differ in their geographical scope. Whereas we model 20 interconnected European countries, Hirth models six and Winkler et al. no specific countries as such (Hirth, 2013; Winkler et al., 2016)[8]. A wider geographical approach is useful as other research has found that value factors of renewables can profit from flexible generation (such as flexible hydropower in the Alps or Nordics) and higher interconnector capacities (Hirth, 2016; Mills and Wiser, 2014a; Riva et al., 2017).

Given rapid deployment of wind and PV in Europe and changes in deployment projections over the last years it is sensible to analyse value factors of wind and PV using newer and up-to-date data. Especially offshore wind has matured as a generation technology over the last years and experienced significant cost reductions, becoming most evident recently in several tenders in Germany, Denmark, United Kingdom and the Netherlands. We will therefore evaluate offshore wind value factors in the same way as onshore wind and PV which not all previous studies were able to do.

3 Methodology

It is the objective of this work to acquire insights on driving factors of value factors/capture prices of variable renewable generation, i.e. PV and onshore and offshore wind. In order to do so, the authors use the techno-economic model Green-X[9] to model the European power market. The modelling process incorporates the dispatch and investment in power plants, minimisation of total investment costs as well as production and trade decisions, all with a range of technical constraints. In economic terms, the model is a partial equilibrium model of wholesale electricity markets, focussing on the supply side. It includes an up-to-date power plant database[10] of all twenty countries including plants that are planned or set to be

[8] For further model specific descriptions see Winkler et al. (2016) and Hirth (2013).

[9] Green-X is a fundamental power model covering twenty interconnected European countries. It allows for the investigation of future deployments in the power and renewable sector including accompanying costs and benefits. It enables the derivation of a detailed quantitative assessment of renewable electricity sources deployed in a real-world policy context on a national and European level for the power, heat and transport sectors. It has been successfully applied for the European Commission within several tenders and research projects to assess the feasibility of '20% renewable electricity sources by 2020' and for assessments of its developments beyond that time horizon. In addition, Green-X can be used for a detailed quantitative assessment of the hourly market prices of the European power markets (Everts et al., 2016; Huber, 2004).

[10] Small-scale plants and non-hydro renewables are grouped into clusters.

decommissioned, as well as an up-to-date database of all interconnectors among those countries.

Aside from the Green-X model power plant database, the model also adds further capacities endogenously. The endogenous capacity additions are based on economic criteria with support schemes and political frameworks taken into account, which is especially important for renewable technologies, first and foremost wind and photovoltaics.

The actual modelling can be described as a three-level process. In a first step, the endogenous and exogenous capacity additions/deductions (the latter from the aforementioned power plant database) are determined. The second step consists of computing the hourly power plant dispatch based on the determined power plant portfolio (taking into consideration interconnector capacities, power plant availability and power demand). A marginal cost-based merit order curve determines the marginal power plants for every hour in addition to country-specific power prices. The third step examines the economic viability of new power plants and calculates final market prices. For the latter, the model also estimates incomes from ancillary services based on information provided by TSOs regarding historic ancillary services.

The model was calibrated in a way to most accurately represent the current European power market and replicate hourly day ahead prices on the power exchanges. As far as market data are available, market data are used for most primary energy sources that were taken from the Intercontinental Exchange (ICE) at the time of the modelling (Autumn 2019).

For transfer capacities between countries, the model uses current data and planned additions from the European network of transmission system operators for electricity (ENTSO-E). Within countries the model assumes that no congestions exist. To model yearly power demand, historic GDP and power consumption data of different providers are used for an accurate calibration. The influence of energy policies on power consumption such as increases and reductions in demand through the deployment of electric vehicles or energy saving measures is taken into account. For the modelling of the hourly demand, the model uses historic load profiles, whereby changes in consumption behaviour are considered.

For this research, a series of model runs covering a time horizon from 2019 to 2050 were completed. A base scenario functions as a reference and a series of runs simulate different developments. Higher and lower natural gas and coal prices represent market developments, whilst we regard increased wind and/or PV productions as political factors, resting upon the assumption that renewable capacity deployments are predominantly politically steered. Carbon prices or more specifically European Union Emission Trading Scheme (EU ETS) European Union Allowances (EUAs) prices can arguably be regarded either as a market or a political factor. Ceteris paribus these inputs factors (natural gas, coal and CO_2 prices) were varied by 2, 5 and 10 EUR_{2018}/MWh_{th} (natural gas), by 2 and 4 EUR_{2018}/MWh[11] (hard coal) and by 5, 10, 15 and 20 EUR_{2018}/tCO_2 (CO_2) respectively to observe subsequent changes of value factors.

As for the renewable production, we modelled 10 per cent variations of yearly production of wind (both onshore and offshore), PV, wind onshore only and finally wind (onshore and offshore) together with PV. It is important to keep in mind that the capture prices of all the scenarios are not comparable, since base prices are not constant across the scenarios. PInstead we use annual value factors to determine the influence of the different parameters as they reflect a relative rather than an absolute value. By subtracting the reference scenario

[11] Prices for hard coal with a calorific value of 6000 kcal/kg in USD/t were converted to EUR/MWh with a calorific value of 7000 kcal/kg using an FX rate of 1.15 EUR-USD and a conversation factor of 6.98. A change of 4 EUR/MWh represents a relative variation of approximately 40 per cent at current prices.

value factor for every generation technology off the corresponding scenario specific value factor, we get a figure indicating the changed parameter's influence on the value factor.

Last but not least, one crucial element driving capture prices of variable renewables is the weather. In order to ensure comparability all above described scenarios were modelled using the same typical year with respect to solar radiation, wind speeds, and hydrological conditions. Nevertheless, we analysed thirty years of weather data to assess ranges of full load hours for wind and PV. The results of this analysis are then compared and set in relation to researched drivers of wind and PV cannibalisation.

4 Results

This section presents how wind and PV value factors and capture prices are influences by the different drivers. First, the impact of the market-based drivers natural gas and coal prices are analysed before the influence of carbon prices as a market and policy driver is evaluated. The last drivers that are analysed are different availabilities of first PV, then wind and finally wind and PV combined.

4.1 Natural gas prices

In order to assess the influence of natural gas prices on value factors of wind and PV, six scenarios with a natural gas price variation of 2, 5 and 10EUR_{2018}/MWh_{th} were modelled. The expectations are that natural gas price changes have a significant impact on wind and PV capture prices given that natural gas-fired power plants are usually regarded as the most influential price-setting technology on many European power markets (Blume-Werry et al., 2019; Genoese et al., 2015, p. 177; Roques et al., 2008, p. 1841). A subsequent question is how this impact on capture prices and power prices generally translates into value factors.

We find that natural gas prices have indeed a very significant impact on value factors of PV as well as onshore and offshore wind turbines. Across different modelled countries, higher natural gas prices lead to lower value factors of all three generation technologies. Whilst in absolute terms, capture prices rise, due to higher natural gas- and in turn higher power prices, PV and wind producers profit less from this higher price level than baseload producers. The discrepancy between value factors of the base case and the scenarios with higher and lower natural gas prices grows over time.

The reason for this is that during times when there is less renewable production the merit order curve shifts to the left, as we observe a reverse merit-order effect. Consequently, prices tend to be higher during times of low renewable infeed. With growing penetration of renewables, this effect gets more pronounced over time i.e. value factors shrink the more renewables are deployed in decarbonising power systems. It should be pointed out that this market phenomenon is not exclusive to the scenarios with altered natural gas prices but rather a general note.

With respect to higher and lower natural gas prices, we can differentiate between two effects on value factors. The first relates to hourly price setting. Hours during which natural gas-fired power plants set the price become more expensive in case of higher natural gas prices. During these hours there tends to be a lower renewable infeed notwithstanding significant differences between power systems. This means that a wind or PV operator may profit less from higher prices than a peak-load or even a base-load generator and we observe lower value factors than in the reference scenario. Vice-versa cheaper natural gas prices consequently trigger higher PV and wind value factors.

The second effect relates to developments of power generation portfolios over time and the growing decarbonisation of power systems. In the scenario with lower natural gas prices more natural gas-fired capacities remain in the system compared to the reference scenario. These resulting different generation portfolios are a profound driver of renewable value factors. This means that higher value factors for renewables in this period are inter alia down to fewer renewable deployment and thus less cannibalisation than in the reference scenario, which is an indirect result of the lower natural gas prices. Vice versa, in case of higher natural gas prices, the natural gas-fired generation is lower than in the reference scenario and slightly more wind and PV capacities are deployed. This causes a higher cannibalisation of value factors than in the reference scenario.

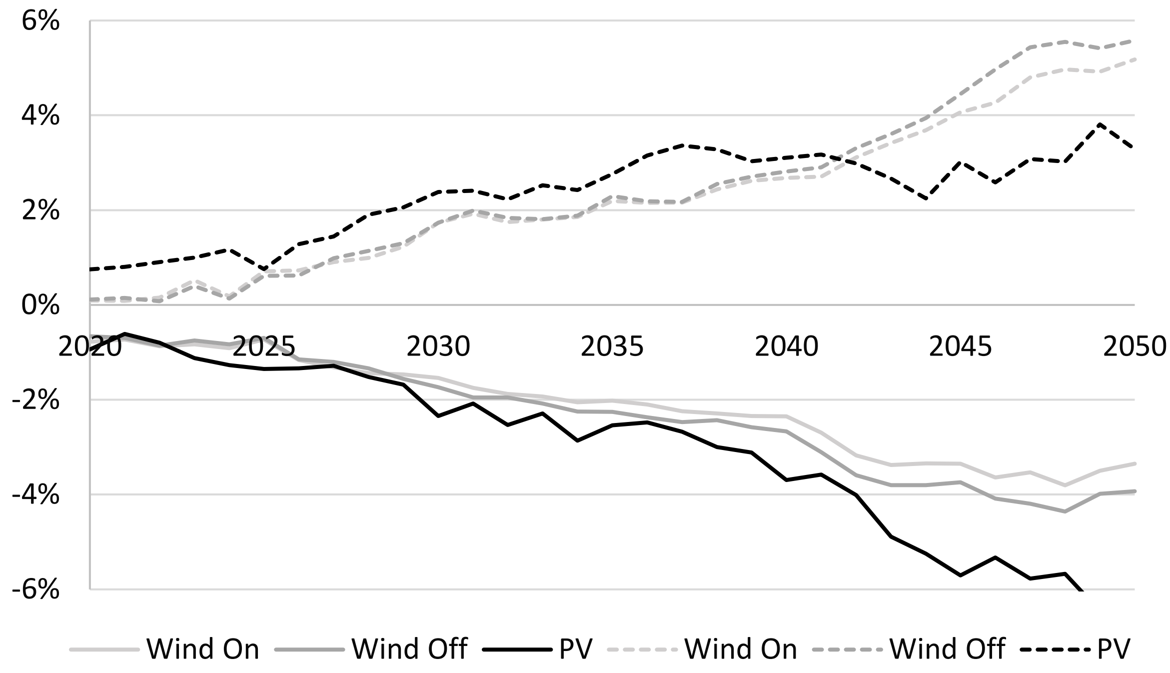

Figure 1: Variations of natural gas prices (± 5 EUR_{2018}/MWh_{th}) have significant effects on wind and PV value factors in Germany. Value factors rise compared to the reference scenario in case of lower natural gas prices (dotted lines) and decline in the scenario of higher natural gas prices (solid lines)

Altogether natural gas price changes have notable effects on the value factors of wind and PV. This mainly stems from the fact that natural gas is an important price-setting technology on many power markets thereby influencing general power price levels. In all cases, higher natural gas prices lead to lower value factors and vice versa. This shows that even though capture prices rise following higher natural gas prices, renewable producers profit less than baseload producers. In most cases, PV value factors tend to be slightly more affected by natural gas price changes than wind value factors. However, this does not hold true for all researched countries. Figure 1 shows the changes in relative wind and PV value factors compared to the reference scenario for Germany. It illustrates that the difference in value factors grows over time driven as aforementioned inter alia by different developing power plant portfolios.

In absolute terms, reverse effects take place. As a result of a general higher price level in the scenarios with higher natural gas prices, capture prices of wind and PV are significantly higher than capture prices in the reference scenario. Vice versa, in scenarios with lower natural gas prices, capture prices of wind and PV are also lower. At the beginning of the researched time horizon a variation of 5 EUR_{2018}/MWh_{th} of natural gas prices results in capture prices approximately 4-8 EUR_{2018}/MWh lower/higher than in the references scenario. The greater the role of natural gas in a given power system the larger the change in capture prices. The difference in capture prices compared to the reference scenario declines over time reaching virtually the level of capture prices in the reference scenario in most researched countries by 2050.

4.2 Coal prices

Four scenarios with coal price variations of 2 and 4 EUR_{2018}/MWh show how coal price changes affect value factors of PV panels and wind turbines. Previous studies have shown causal relationships between coal and power prices (Ferkingstad et al., 2011; Mohammadi, 2009; Moutinho et al., 2011). This influence of coal prices on power prices stems inter alia from the fact that coal-fired power plants - similar to natural gas-fired power plants - represent an important price-setting technology on several markets. Many European countries have presented coal phase-outs plans or are discussing ways to replace carbon intensive coal-fired power generation. In this light one can expect coal price variations to have at most negligible effects on wind and PV value factors towards the end of the researched time horizon (up to 2050).

Our results indicate that this is also the case for the near time horizon and that the modelled coal price changes have only marginal effects on PV and wind value factors. This is a notable result given the large relative variation of coal prices modelled.[9] In countries where coal-fired generation only takes a small share of the generation portfolio, the modelled coal price changes have virtually no effect on value factors of renewables. Yet even in places with significant coal-fired generation such as Poland or Germany, the coal price variations affect PV and wind value factors only marginally (see Figure 2).

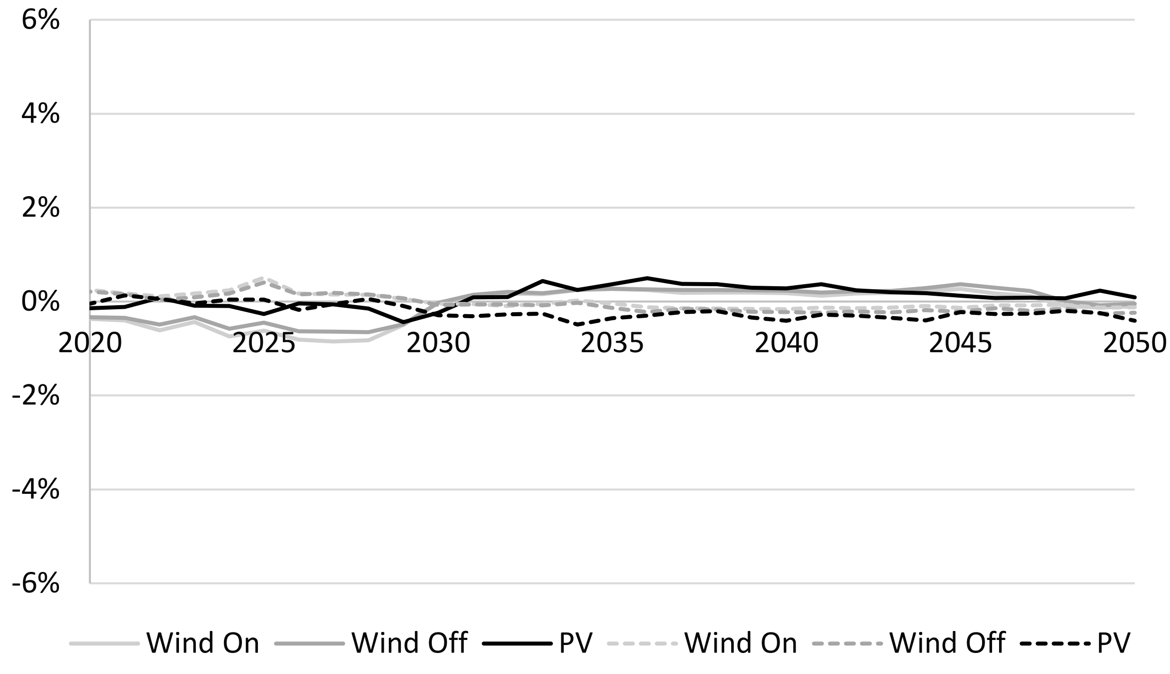

Figure 2: Wind onshore, wind offshore and PV value factors in Germany are only affected marginally in scenarios with higher (solid lines) and lower (dotted lines) coal prices (± 4 EUR_{2018}/MWh) compared to the reference case.

Capture prices, picturing the value of PV and wind in absolute terms reveal that in the near time horizon (until the mid 2020s) incomes for PV and wind operators are higher in case of higher coal prices and lower in case of lower coal prices. However, the higher coal prices also trigger an accelerated fuel switch (from coal to natural gas-fired generation) compared to the reference scenario, causing the effect to turn into reverse for the second half of the 2020s.

Altogether, the marginal changes of wind and PV value factors show that the renewable capture prices change in a very similar magnitude as the base price. The coal price variations have therefore different effects on wind and PV value factors to natural gas price variations. Whereas we see significant changes in value factors as a result of gas price variations, changes resulting from coal price variations are only marginal and, in many cases, negligible.

4.3 Carbon prices

Carbon prices represent a notable share of the marginal costs of fossil fuel-based power plants. An increase or decrease of carbon prices therefore changes the marginal cost of lignite, coal and natural gas-fired power plants and in turn the marginal cost based bidding prices on energy only markets. Carbon prices are expected to rise over the next decades to incentivise a further decarbonisation of the power sector and it is a subsequent question how carbon price changes affect value factors of variable renewables. Carbon prices were varied by 5, 10, 15 and 20 EUR_{2018}/tCO_2 in eight scenarios.

The results show somewhat similar effects on value factors and capture prices as changed natural prices. This is due to the fact that marginal costs of natural gas-fired power plants are set by a combination of natural gas prices and prices for carbon allowances.

The results indicate slightly different effects depending on power systems. In carbon intensive power systems such as Germany or Poland with considerable coal- and lignite-fired generation capacities higher carbon prices trigger an accelerated fuel switch from coal- and lignite-fired generation towards natural-gas fired generation. Lower carbon prices delay this fuel switch compared to the reference scenario. In less carbon intensive power systems, the effects on value factors and capture prices are indeed resembling those of varied natural gas prices closely.

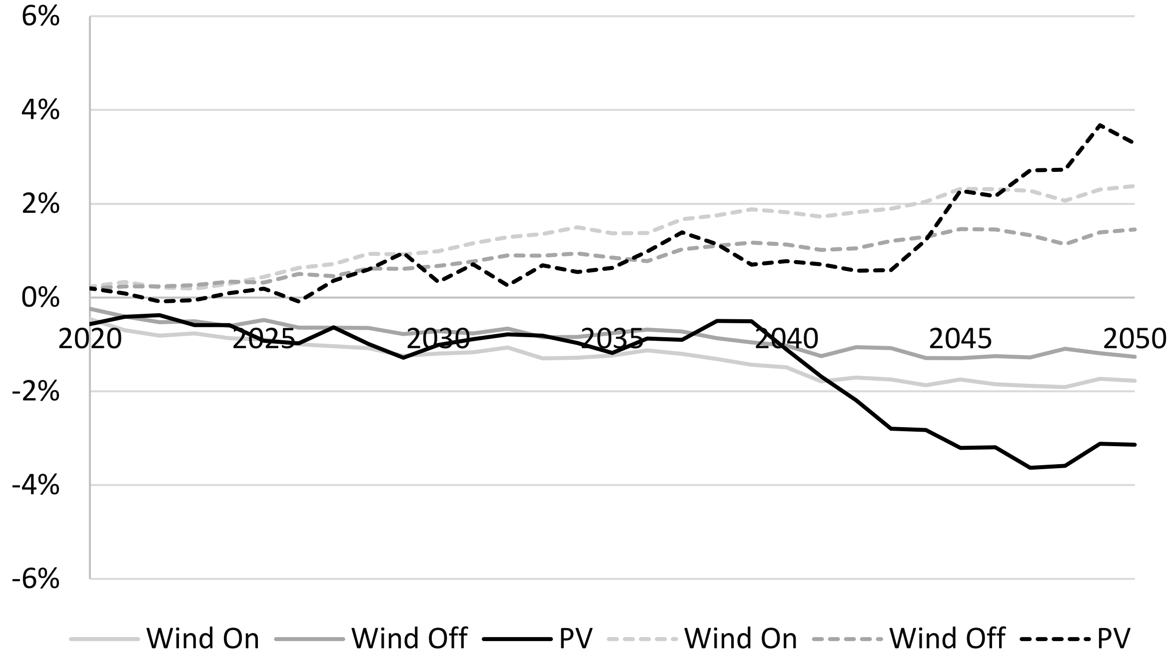

Figure 3: Higher carbon prices (+15EUR_{2018}/tCO_2) than in the reference scenario trigger lower wind and PV value factors (solid lines) whilst lower carbon prices (-15EUR_{2018}/tCO_2) result in higher value factors (dotted lines) in France.

Across the different power systems, higher prices for carbon allowances, trigger lower factors of wind and PV and vice versa. PV and wind value factors are affected in a similar fashion with no specific pattern recognisable across the researched countries. The higher and lower value factors compared to the reference scenario are down to the same reasons as in the scenarios with varied natural gas prices (see above).

Additionally, higher and lower prices for carbon allowances also impact the marginal costs of other fossil fuel-based power generation technologies, first and foremost coal- and lignite-fired generation. As discussed, varied marginal costs of coal-fired power plants have little effects on value factors of renewables. The results for countries with a considerable share of lignite-fired generation such as Czech Republic indicate that this also applies to lignite-fired generation, which is consistent given the baseload production profile of lignite-fired power plants.

Absolute capture prices show that the varied carbon prices change capture prices the most in carbon-intensive power systems. Generally, wind and PV capture prices are significantly higher/lower towards the beginning of the researched time horizon compared the reference scenario. Analogous to the scenarios with varied natural gas prices, that difference in value factors declines over time until there is virtually no more difference by 2050.

4.4 PV production

In two further scenarios, PV production profiles were increased and decreased by 10 per cent. The results indicate how PV and wind value factors change if PV production was 10 per cent higher or lower compared to the reference scenario. Higher PV production should result in a stronger cannibalisation and thus lower value factors for PV, whilst lower production should increase relative PV value factors compared to the reference scenario.

Indeed, increasing PV production profiles by 10 per cent lowers PV value factors considerably compared to the reference scenario. The opposite can be said for decreased PV production profiles. These effects can be described as significant with PV value factors being about 4 per cent lower/higher in most researched countries. In the near time horizon, it is less since PV capacities are substantially lower compared to later stages of the researched time horizon resulting in lower overall cannibalisation of value factors. The 10 per cent increase (and decrease) of PV production has of course most profound impact on value factors in countries with high shares of PV. In Spain for example (Figure 4) the impact on PV value factors is stronger than in Poland due to a higher share of PV in the generation mix.

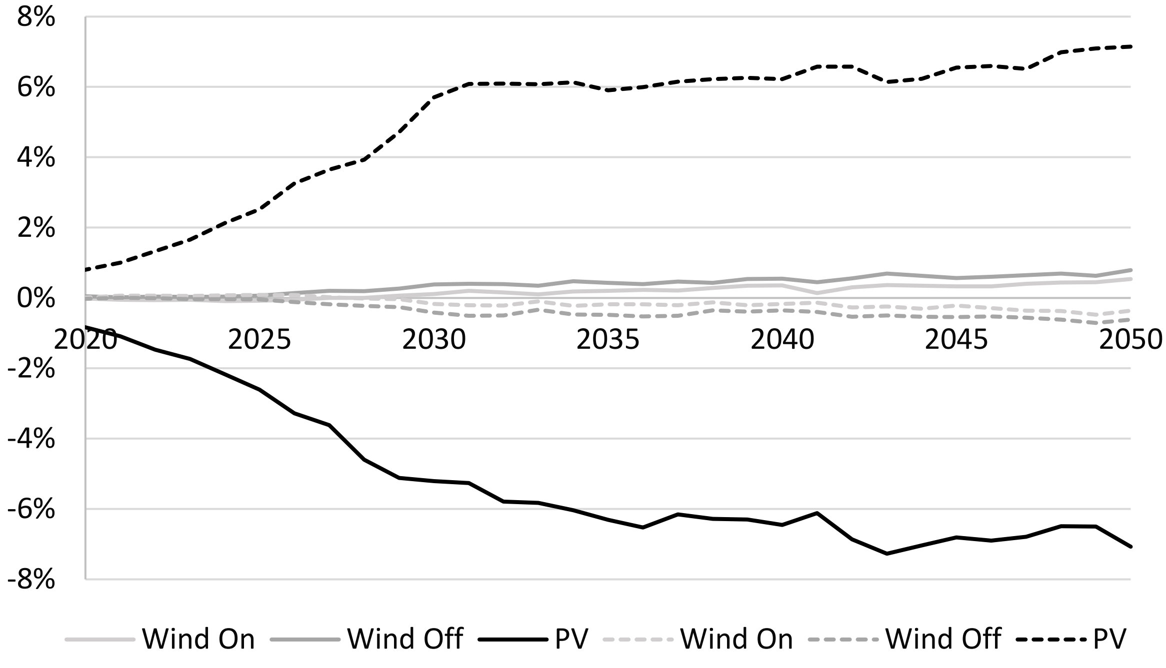

Figure 4: A 10 per cent increase (solid lines) and decrease (dotted lines) of PV production profiles has profound impacts on PV value factors in Spain compared to the reference scenario. The curves show a steep slope until 2030 and a gentler slope thereafter.

It is noteworthy that the results show a steep slope of decreasing/increasing value factors for the near time horizon (2020-2030). Post 2030 one can observe a plateauing of the curve (see Figure 4). The steep slope until 2030 relates to a considerable decline in PV value factors until 2030 in the reference scenario. Whilst current PV value factors are in most researched countries around 0.9 to 1, they decline until 2030 to approximately 0.7 to 0.8 due to a substantial increase of PV's share in countries' generation mix. Indeed, our modelled runs indicate a strong growth of PV until about 2030 and a more moderate growth thereafter. Simulating a 10 per cent increase and decrease of PV production profiles hereby shows profound effects on value factors. The plateauing is a result of the modest growth post 2030 which is mirrored in an only marginal increase of PV's share in the generation mix.

In terms of onshore and offshore wind value factors, the modelled changes of PV production profiles have only negligible effects. Wind value factors are thus largely independent of PV production. The results demonstrate that PV cannibalises its own value factors yet not those of either onshore or offshore wind.

With respect to capture prices rather than value factors, one can note that an increased or decreased PV production has some effect on wind capture prices. The changes are however, within those of base prices which is why the effect does not translate into changes of value factors. A 10 per cent higher PV production slightly lowers base prices (merit-order effect) and with it wind capture prices. A decreased production has reverse effects. In most countries wind capture prices rise or fall no more than 1EUR$_{2018}$/MWh as a result of the altered PV production. There is virtually no difference between onshore and offshore wind in this respect.

4.5 Wind onshore production

Modelled 10 per cent changes of onshore wind production profiles delivered very similar results as the same changes in onshore *and* offshore wind production profiles due to a strong correlation between onshore and offshore wind. Subsequently, only the results of the runs with combined altered onshore and offshore wind production profiles are presented and discussed in the following.

4.6 Wind production (onshore and offshore)

Production profiles or onshore and offshore wind were changed by 10 per cent to observe how value factors react to altered wind productions. These changes are expected to notably influence wind value factors and subsequent questions are how significant this will be and whether PV factors are also affected.

Altogether, we find that the changes trigger reduced and increased wind value factors. As expected, reduced wind profiles result in higher and increased wind profiles in lower onshore and offshore value factors. The effect is significant yet less profound than the PV profile change for PV value factors. Indeed, wind onshore and offshore value factors change by 1 to 4 per cent depending on the time and country as a consequence of the altered profiles. Generally, the effect is more substantial in systems with a large share of wind in the generation mix and differences between countries are more profound than in the case of altered PV profiles.

In countries where considerable offshore capacities are installed, offshore and onshore value factors are affected similarly. Elsewhere, the altered profiles have a slightly larger impact on onshore wind value factors. All in all, there is a strong correlation between the two.

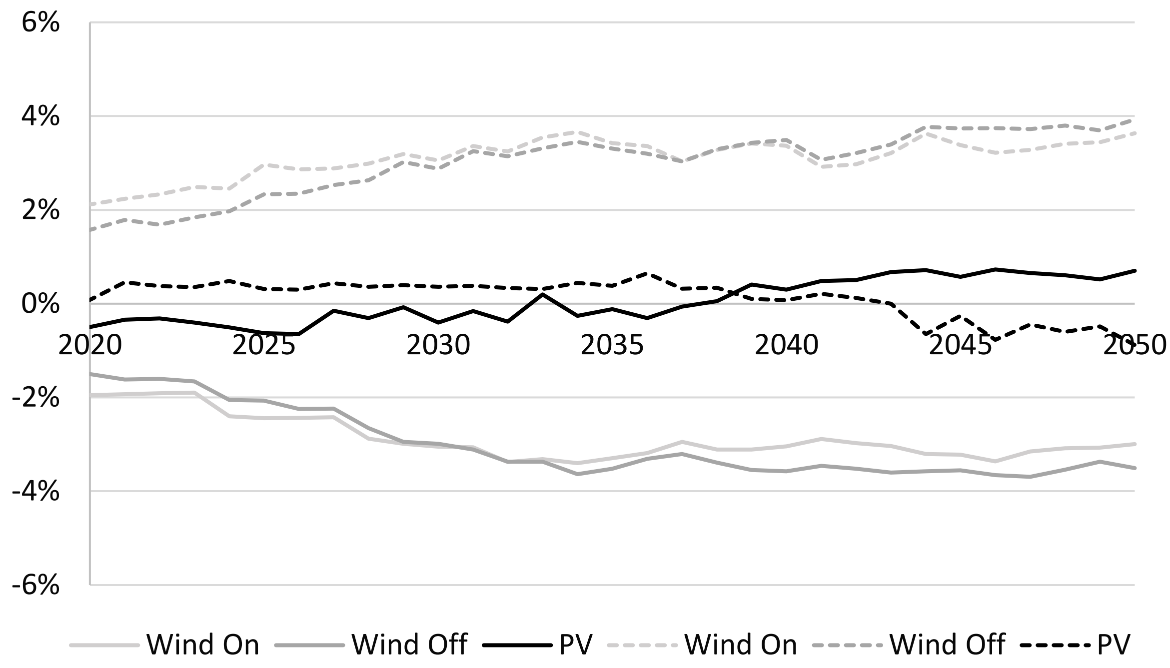

Figure 5: Increasing wind profiles by 10 per cent (solid lines) in Germany triggers lower wind value factors compared to the reference scenario whilst reduced wind profiles (dotted lines) result in higher wind value factors.

As for PV value factors, one can observe a marginal effect. Even though PV value factors are more affected that wind value factors in the scenarios of altered PV production profiles there is no distinctive pattern recognisable across researched power systems. The authors therefore attribute the minor effect simply to the larger production volumes of wind compared to PV.

Given that across the different power systems onshore and offshore wind take a larger share in the generation mix than PV, we observe a greater merit order effect and with it larger effects on capture prices. In some central European countries such as Germany and France PV capture prices change as much as in the scenarios of altered PV profiles.

4.7 Renewable production (PV and wind onshore as well as wind offshore)

The final scenarios researched are combinations of increased and decreased wind *and* PV profiles. For these, wind and PV profiles were increased by 10 per cent in one scenario and decreased by 10 per cent in the other, which represents a combination of the above described scenarios. In market or policy terms, it represents a stronger and weaker renewable deployment than anticipated in the reference scenario.

We find that the changes in relative value factors are almost identical to those of the earlier described scenarios in which only one technology profile (PV *or* wind) was altered. In other words, wind value factors are virtually identical to those of the scenarios with altered wind profiles and PV value factors to those of the scenarios with altered PV profiles.

Increasing or decreasing wind and PV profiles by 10 per cent has a more profound impact on PV value factors than it has on wind value factors. This is due to the fact that PV generation is concentrated on less hours a year compared to wind generation. Whilst there is a plateauing effect for PV value factors post 2030 (see above) the change in wind value factors compared to the reference scenario grows over time with increasing shares of wind in generation mixes yet stays below that of PV. The higher the share of wind or PV in a power system the greater the change in value factors following a ten per cent alteration of generation profiles.

The fact that the changes in value factors are almost identical to those of the earlier described scenarios with only one (PV or wind) altered generation profile indicates that there is no significant cross cannibalisation of wind and PV. However, this only holds true in relative terms. With respect to absolute capture prices, there is a merit order effect affecting both PV and wind as already observed in the previous scenarios.

The magnitude of this merit order effect is almost exactly the sum of the merit order effects noted in the scenarios of altered wind and PV production profiles. The merit order effects (and reversed merit order effects) ergo cumulate.

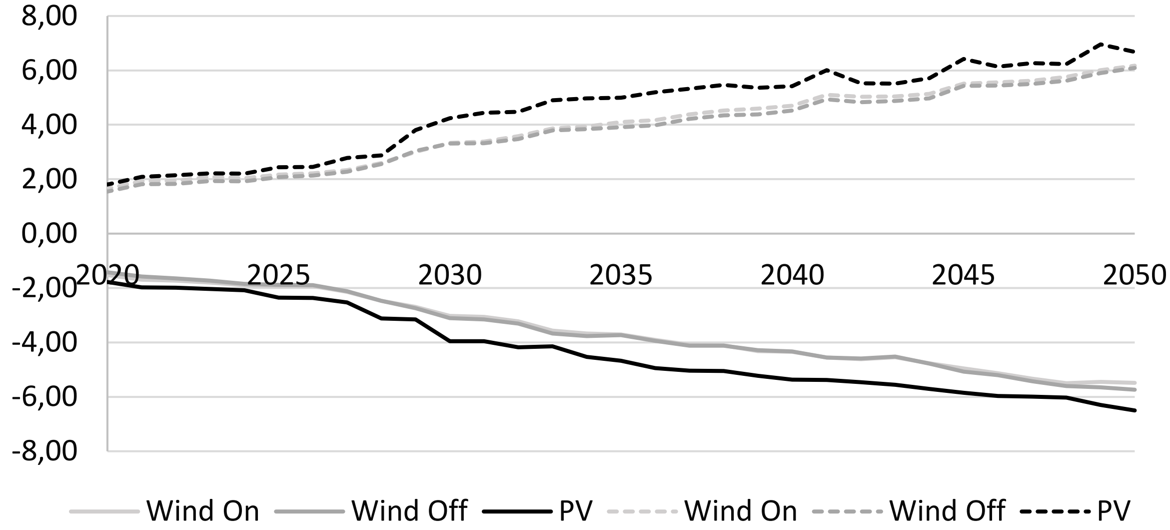

Figure 6: Changes in French wind and PV capture prices compared to the reference scenario in EUR_{2018}/MWh.

Just as for relative value factors, PV capture prices react more sensitive than wind capture prices to the researched changes in generation profiles. The difference between the curves is, however, on a smaller scale. Figure 6 shows that changing wind and PV production profiles by 10 per cent has profound impacts on wind and PV capture prices due to cannibalisation and merit order effects.

5 Discussion

The results of the model runs reveal a series of key findings to understand drivers of wind and PV value factors and capture prices. Value factors decline with a growing penetration of the respective technology confirming the results of aforementioned previous studies. However, factors other than wind and PV penetration rates also drive and influence wind and PV cannibalisation. Natural gas and carbon prices are significant drivers of wind and PV value factors and capture prices, whilst the influence of coal prices is limited.

In this sense, wind and PV value factors are driven by both markets and politics. Market drivers such as natural gas prices have noticeable effects on value factors and capture prices. Carbon prices which are arguably both a market and a political driver at the same time have similar effects. Regarding renewable deployments as political drivers, we observe significant changes to value factors and capture prices as a result of increasing or decreasing wind and/or PV profiles by 10 per cent. This means that regulatory changes that spur higher or lower wind or PV deployments (and with it total production volumes of wind or PV) than anticipated have substantial effects on revenues of wind or PV operators. For them the cannibalisation risk is ergo substantial yet market risks such as uncertainties regarding natural gas prices are also considerable.

We find a high level of correlation between onshore and offshore wind value factors as they react very similar to natural gas, coal and carbon price changes as well as changes in wind and PV production profiles. Depending on the power system and researched parameter (natural gas, coal and carbon prices), PV value factors may diverge from wind value factors, yet altogether they share the general trend and react similar to natural gas, coal and carbon price variations.

One can attribute the changes of value factors in the scenarios with varied natural gas and carbon prices to two market effects. The first relates to the production profile of natural gas-fired power plants. The variations of natural gas and carbon prices change the marginal costs of gas-fired power plants, which are commonly regarded as the most important price-setting technology on European power markets. Notwithstanding considerable differences between power systems, renewable infeed tends to be lower than average during hours when natural gas-fired power plants set the price. Hence, factors that change the marginal costs of natural gas-fired power plants upwards such as higher natural gas and carbon prices drive renewable value factors down and vice versa.

The second market effect and the more profound driver relates to developing power plant portfolio in the researched scenarios. Higher natural gas and carbon prices indirectly trigger inter alia more model endogenous renewable deployment than in the reference scenario. As a result, there is a higher cannibalisation and lower value factors, whilst the reserve effect is taking place in the scenarios with lower natural gas and carbon prices. It was not within the scope of this study to differentiate quantifiable between these direct and indirect market effects. Further research could contribute to a deeper understanding of this matter.

A key finding with respect to absolute capture prices is that in power systems with a large share of wind in the generation mix such as those of Germany, the United Kingdom and Denmark, a ten per cent increase/decrease of wind production profiles affects PV capture prices as much as a ten per cent increase/decrease of PV production profiles. This means that PV project risk analyses should pay attention to potential divergences of wind deployment to the anticipated deployment path since it has a significant impact on the profitability of PV projects. In other words, the merit order effect of additional wind deployment may affect the revenues of PV operators as much as the cannibalisation effect *and* merit order effect of additional PV deployment put together.

The merit order effect that comes with increased PV production is less substantial due to the smaller share of PV in the generation mix of most European power systems and ergo has a less profound effect on the profitability of wind projects.

It is a subsequent question how the discussed market and policy drivers of value factors compare to the most natural driver, the weather. An analysis of 30 years of weather data for the researched countries reveals bandwidths of wind and PV availabilities. We find a bandwidth of approximately 10 per cent for PV and approximately 15 per cent for onshore as well as offshore wind. In other words, over 30 years yearly PV full load hours diverge about five per cent from the average value whilst yearly onshore and offshore wind full load hours diverge slightly more. There are, by all means, differences between the researched power systems (e.g. in Spain, Portugal and Italy there is a lower bandwidth for PV) yet across the twenty researched European countries the above-named bandwidths can serve as a general orientation. The natural occurring yearly production fluctuation is therefore in the realm of the researched and discussed 10 per cent production profile variations. In the short run, the weather can thus be a very influential driver of PV and wind value factors and capture prices.

6 Conclusion

The objective of this study was to analyse market and policy-based drivers of cannibalisation to get a clearer picture of how different factors influence the cannibalisation of wind and PV in Europe.

The results demonstrate that wind and PV value factors and capture prices are driven by both politics and markets. Changes of natural gas prices substantially influence value factors and capture prices. Generally, wind and PV operators profit less from higher natural gas or carbon prices than pure baseload producers, as capture prices rise less than the base price. Vice versa, in case of lower natural gas or carbon prices, value factors of wind and PV rise, i.e. wind and PV capture prices fall less than the base price. In contrast to natural gas, coal price alterations representing another market-based driver researched, have only very limited influence on wind and PV value factors.

In terms of political drivers, changes of production profiles by 10 per cent reflecting (slightly) higher or lower PV and wind deployments have significant impacts on wind and PV value factors and capture prices and thus on incomes of wind and PV operators. We find no significant cross cannibalisation of wind and PV. Changes of PV production profiles have no effects on wind value factors, whilst changes of wind production profiles have marginal effects on PV value factors. We attribute this marginal effect to the larger share of wind in the generation mix, yet deem it insignificant.

In absolute terms i.e. capture prices the merit order effect of both PV and wind profile changes is substantial. Increasing or decreasing PV and/or wind production profiles by 10 per cent has a measureable merit order or reverse merit order effect. Even though altered PV production profiles have no effect on wind value factors, the subsequent merit order effect or reverse merit order effect influences wind capture prices. Given that wind value factors are not affected, the capture price changes are of the same magnitude as base price changes due to the merit order effect. For PV producers in countries with a sizeable wind portfolio, the merit order effect of additional wind production can be greater (in terms of absolute capture prices) than the merit order effect and cannibalisation effect of additional PV production combined. Hence, PV operators in those markets should follow wind deployment paths even though we find no significant cross-cannibalisation of wind and PV.

Future research in this area might be dedicated to shed light on the impact of increased sector coupling and the accompanying increases in system flexibility on value factors of wind and PV. Indeed, increased flexibility provision might prove an important driver of wind and PV value factors.

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