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The benefits of flexibility: The value of wind energy with hydropower ☆

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HIGHLIGHTS

- We assess the market value of wind power in power systems with hydropower.
- When moving from 0% to 30% wind penetration, hydropower mitigates the value drop by a third.
- 1 MWh of electricity from wind is worth 18% more in Sweden than in Germany.
- Sensitivity analysis indicates high robustness.

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ABSTRACT

Several studies have shown that the revenue of wind power generators on spot markets ("market value") diminishes with increasing deployment. This "value drop" is mostly observed in power markets that are dominated by thermal power plants, such as in Germany. This paper assesses the wind market value in power systems where hydroelectric stations with large reservoirs prevail, such as in Sweden. Due to their dispatch flexibility, such hydropower compensates for wind power output variability and thereby mitigates the wind power value drop. The market value of electricity from wind declines with penetration in both types of power systems, but it tends to decline at a slower rate if hydropower is present. This paper presents empirical evidence on the relevance of this effect derived from market data and numerical model results. Our results indicate that when moving from 0% to 30% wind penetration, hydropower mitigates the value drop by a third. As a result, 1 MWh of wind energy is worth 18% more in Sweden than in Germany. Sensitivity analyses indicate high robustness despite large parameter uncertainty: in 80% of all sensitivities, wind energy is valuable 12–29% more in Sweden than in Germany. The benefits of hydropower seem to level off at around 20% wind penetration. This suggests that the hydro flexibility is "exhausted" at this level. Low wind speed wind turbines, carbon pricing, and upgrades of hydropower generation capacity can lever the added value of hydro flexibility further. Not only is wind energy more valuable in the presence of hydropower, hydroelectricity also becomes more valuable if paired with wind power.

1. Introduction

Renewable energy-based power generation is on the rise. By 2015, worldwide wind and solar power capacity exceeded 650 GW (Fig. 1), nearly twice as much as total nuclear power capacity. Almost half of newly added capacity was based on renewables – of which wind and solar power represented about 70% [1]. In several countries the combination of wind and solar supplied 15% or more of electricity consumed, with Denmark being the world leader at over 40% (Fig. 2). Wind and solar power also provide a large market share in jurisdictions such as Texas, California, and Eastern Mongolia. Large-scale deployment of wind and solar power, until recently thought to be a long-distant future scenario, is taking place right now.

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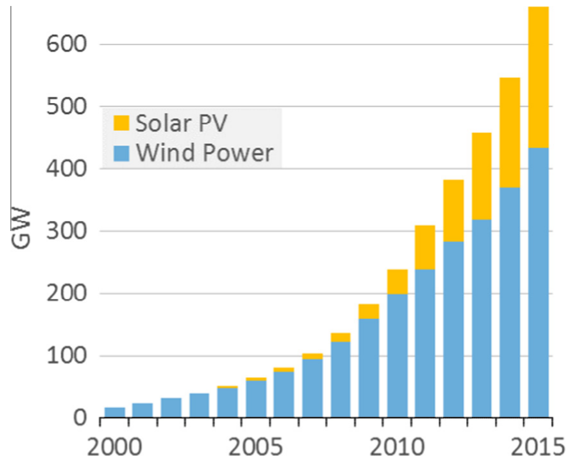

Fig. 1. Wind and solar power capacity installed globally. Own illustration based on data from REN21 [64].

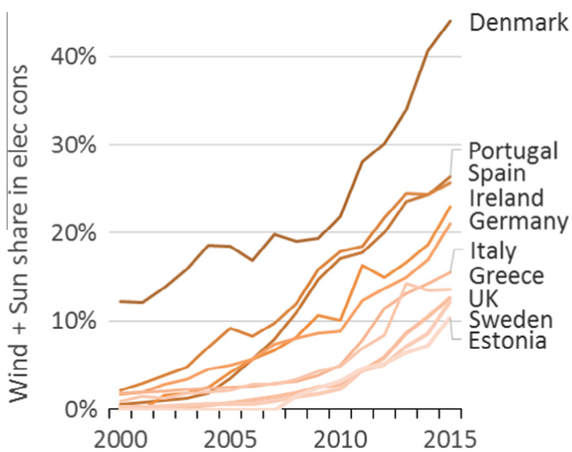

Fig. 2. In a number of countries, wind and sun supply more than 15% of power demand. Own illustration based on data from IEA Electricity Statistics.

The variable, or "intermittent", nature of renewable energy sources such as wind power, solar power, and ocean energy poses challenges when integrating these technologies into power systems. A number of properties specific to variable renewables are problematic for system integration [2,3], including the limited predictability of output, the fact that good wind sites are often distant from load centers, and the lack of rotating mass that can provide inertia. The most important property is the simple fact that the availability of the primary energy source fluctuates over time. Integration challenges materialize in different ways, for example through grid expansion or increased balancing needs.[1] This affects the economics of wind power generation either by increasing costs or reducing the value (revenue) of output. For example, the cost of balancing forecast errors materialize primarily as balancing costs.[2] The most significant economic impact of wind power variability, however, is likely to be the reduced spot market value of wind energy [10,11].

"Market value" is a useful concept to clarify this loss in economic value. Wholesale electricity markets clear at a high frequency, such as hour-by-hour, or more frequently. We define the market value of wind power as the wind-weighted average electricity price

$$\overline{P}_{wind} = \frac{\sum_{t=1}^{T} W_t \cdot P_t}{\sum_{t=1}^{T} W_t}, \tag{1}$$

where $t \epsilon T$ denotes all hours (or other time periods) of a year, W_t is the generation of wind power and P_t is the equilibrium electricity price. The wind market value is the wind-weighted average electricity price, or the average realized price for energy on wholesale spot markets (leaving aside support schemes and other income streams). The market value of solar, or any other power generating technology, is analogous to this.

The market value not only matters for investors, but has a fundamental socio-economic interpreta-tion. Under perfect and complete markets, the increase in market value corresponds to the premium that consumers are willing to pay for generation from wind power: if the market value of wind power is USD 80 per MWh, one megawatt-hour has an economic benefit to society of USD 80. Hence, the "market value" [12] is identical to the "system value" [13] or "marginal economic value" [14]. The intersection of market value and levelized electricity costs defines the cost-optimal deployment level [15].

Many authors have stressed that the market value of wind and solar power is not the same as that of other power generating technologies (Grubb [16], Lamont [13], Borenstein [17], Joskow [12], Mills and Wiser [14], Gowrisankaran et al. [18], Hirth et al. [19], to name a few). At high penetration rates, they tend to produce electricity at times of low prices, resulting in a low market value. This implies that comparing generation costs across technologies is quite meaningless.

For many applications, it is convenient to study the *relative*, rather than the absolute market value. Historical observations of electricity prices, for example, show they vary with business cycles. Assessing the market value of wind power *relative to the average electricity price* is a straightforward way to correct for such cycles. This relative price is called the "value factor". The value factor VF_{wind} is defined as the ratio of the wind-weighted to the time-weighted average electricity price (base price),[3]

$$VF_{wind} \equiv \frac{\overline{P}_{wind}}{\overline{P}}, \tag{2}$$

where the base price $\overline{P}$ is

$$\overline{P} \equiv \frac{1}{T}\sum_{t=1}^{T} P_t. \tag{3}$$

The value factor is a metric for the valence of electricity with a certain time profile relative to a flat profile [20]. The wind value factor compares the value of actual wind power with varying winds to its value if winds were invariant [21]. In economic terms, it is a relative price where the numeraire good is the base price. A decreasing value factor of wind implies that wind power becomes less valuable as a generation technology compared to a constant source of electricity.

In power systems that are dominated by thermal generation technologies ("thermal systems"), we can observe that the market value of wind and solar power declines as their contribution to annual electricity consumption increases. This is shown by German data (Fig. 3), and the model-based literature confirms this observation (Fig. 4).

The value drop of wind (and solar) power potentially jeopardizes their long-term economic competitiveness; decarbonizing

[1] On balancing requirements, see Ortega-Vazquez and Kirschen [4], Holttinen et al. [5], and Hirth and Ziegenhagen [6].

[2] For estimates of balancing costs, see Farahmand and Doorman [7], Louma et al. [8], and González-Aparicio and Zucker [9].

[3] Other denominators exist. Hirth et al. [19] use the load-weighted price. Here we follow the convention and use the time-weighted price (simple average).

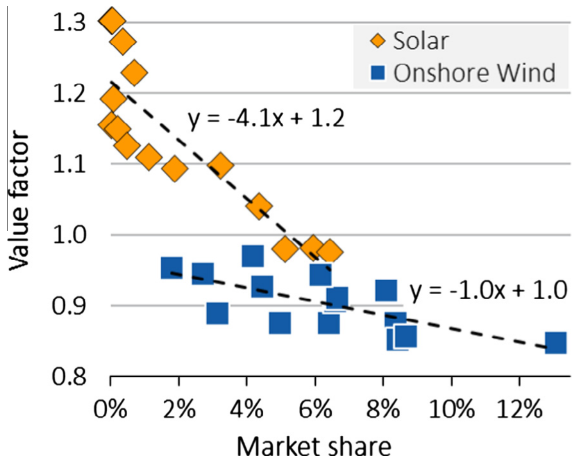

Fig. 3. The market value of wind power and solar power in Germany 2001–2015, expressed as market value over average power price. Own illustration based on data from Destatis, TSOs, and EPEX Spot.

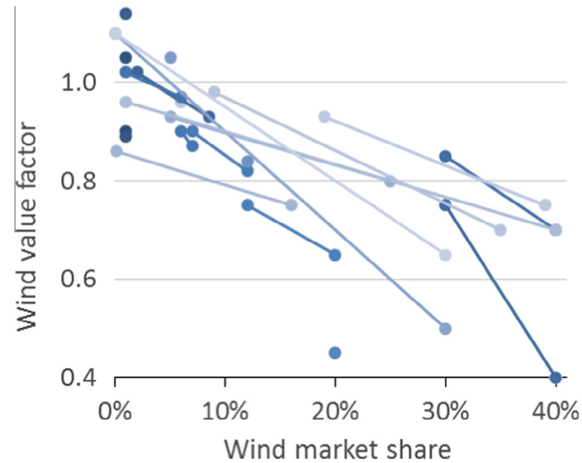

Fig. 4. Market value estimates from the literature. Each line represents one study, the dots indicating the minimum and maximum penetration rates. Own illustration.

the electricity sector, phasing out support schemes, and reaching renewable energy policy targets become considerably more challenging. A thorough understanding of the magnitude of the value drop is therefore of utmost relevance.

For thermal power systems, vast evidence exists on the value drop of wind (and solar) power. The literature can be grouped into three clusters:

- Theoretical (analytical) models, including Grubb [16], Lamont [13], and Hirth and Radebach [22]. Stylized analytical models help uncover the major mechanisms at play, but cannot be used to determine reliable quantitative estimates.
- Estimates from market data, including Sensfuß [23], Sensfuß and Ragwitz [24], Fripp and Wiser [21], and Hirth [25,26]. Market observations cannot be used to reliably estimate the market value at high penetration rates, since very few cases of such high rates exist today – and these may not be very representative.
- Estimates from numerical (computer) models, including Obersteiner and Saguan [27], Boccard [28], Green and Vasilakos [29], Energy Brainpool [30–32], r2b research to business consulting [33], Valenzuela and Wang [34], Swider and Weber [35], Lamont [13], Nicolosi [36], Kopp et al. [37], Mills and Wiser [14,38,39], Hirth [25,26], Hirth and Müller [40], Zipp and Lukits [41], Fraunhofer ISE [42], and Gowrisankaran et al. [18]. Numerical models are heavily used to study this topic. Their quality and appropriateness, however, is often hard to evaluate from outside, because model code and input data are seldom disclosed.

For power systems with large quantities of reservoir hydropower ("hydro systems"), comparable evidence is lacking. In fact, several such studies identify the role of hydroelectricity, as a source of flexibility, as being a crucial research gap. The landmark works by Mills and Wiser [14,38,39] are a notable exception. However, while accounting for hydroelectricity, these studies do not focus on the impact that it has on market value of wind power. Gebretsadik et al. [43] study the interaction of wind power and hydroelectricity in terms of capacity credit, but not market value. A comprehensive qualitative and quantitative discussion of the market value of wind power in power systems that are dominated by hydroelectricity is lacking. This paper aims to fill this gap.

We expect hydropower to have a significant impact on the market value of wind power, as water reservoirs are used to store energy for times when it is needed. Our hypothesis is that the embedded flexibility of hydropower significantly mitigates the wind value drop, as it can be used to compensate for the variable output of wind parks. This paper contributes to the literature by presenting new empirical data and new model results for the market value of wind power in a power system dominated by hydroelectricity. We use the case of Sweden, where hydropower supplies half the electricity demand, which we contrast with Germany where hydropower reservoirs are absent.

Both market data and model results indicate that hydropower indeed helps to secure the value of wind power. When moving from zero to 30% wind penetration (throughout the paper, penetration is reported in annual energy terms), the value drop reduced by one third in the hydro system (Sweden) compared to the thermal system (Germany). At 30% penetration, the market value of wind power is 18% higher in the hydro systems. Input parameter uncertainty is captured by running a large number of sensitivities. In 90% of all sensitivity runs, Swedish wind energy is 12% or more valuable than Germany wind energy. This indicates remarkable robustness of this core. The choice of the weather year has a strong impact on results; a more flexible power system tends to level the difference between thermal and hydro systems. Low wind speed turbines, tight climate policy, and hydro turbine upgrades tend to increase the gap between wind value in hydro and thermal power systems.

2. Price setting in thermal and hydro systems

Price setting in wholesale electricity markets works quite differently in thermal ("capacity constrained") and in hydro ("energy constrained") power systems. In thermal systems, the "supply stack" or "merit order" model can explain price setting quite well (Fig. 5). Thermal power generators bid into the market at their variable costs of production, which are the costs of fuel, emissions, and wear and tear of equipment. The market clearing price is determined by the intersection of net demand and thermal supply. Net (residual) demand is demand net of wind and solar power generation. The short-term thermal supply curve remains relatively constant throughout the year, while net demand fluctuates from hour to hour. Prices fluctuate significantly during the course of days, weeks, and seasons. Moreover, they spike in individual hours of peaking net load. Windy hours tend to have depressed prices,

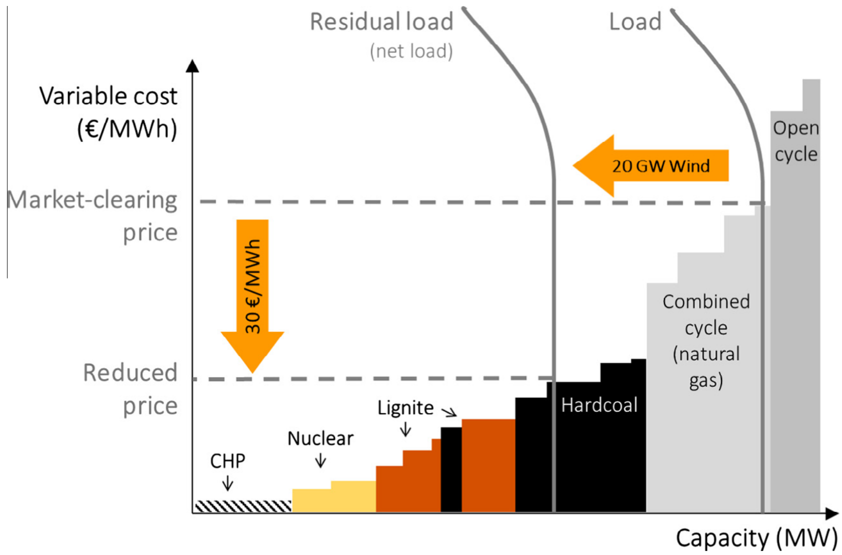

Fig. 5. The market clearing price in a thermal power system with and without wind power. Own illustration.

which reduces the market value of wind power. Some have called this the "self-cannibalization effect" [44].[4]

In contrast to thermal systems, price setting in hydro systems is inherently intertemporal. Hydro generators receive a given amount of water inflow during the year and have to choose *when* to generate electricity. They anticipate the periods of highest electricity prices and determine the expected income per MWh of output ("water value"). This is the opportunity cost at which they bid into the market. This leads, most of the time, to much more stable prices. In extreme situations, however, such as an unanticipated scarcity of energy just before the spring flood, prices spike often for a period of several days to weeks. In practice, hydro dispatch is subject to a large number of additional constraints, including turbine capacity, environmental restrictions (e.g., minimum flow constraints), hydro cascades, and river icing. Forsund [45] discusses hydropower economics at length and depth.

We expect the flexibility of hydro reservoirs to mitigate the value drop of wind power in hydro systems compared to thermal systems. The magnitude of this effect is an empirical question.

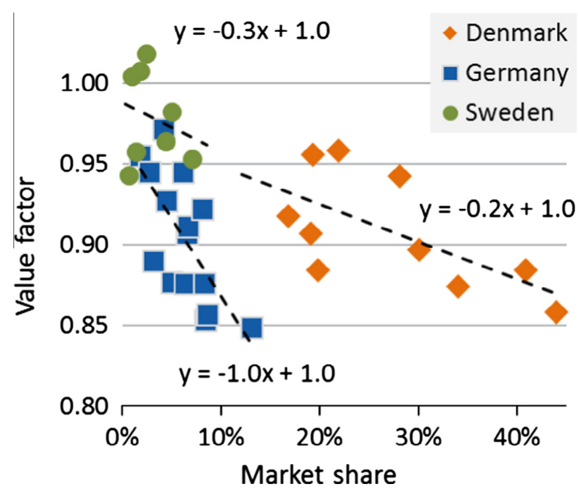

Fig. 6. The wind market value in Germany, Denmark and Sweden 2001–2015. Own illustration based on data from IEA electricity statistics, TSOs, EPEX Spot, and Nordpool Spot.

3. Observed market data

As a first piece of evidence, Figs. 6 and 7 present market data from 2001 to 2015 from Germany, Denmark and Sweden. Germany lacks hydro reservoir power (but has a limited level of pumped hydropower), while Sweden has a hydro share of 50%, all of which stems from reservoirs. Denmark has no hydropower but is highly interconnected to both Sweden and Norway, where hydropower supplies nearly 100% of demand.

In all three countries, the value of wind power drops with penetration, but the rate of decline is much higher in Germany than in the Nordic countries. If Denmark and Sweden are both treated as hydro systems, the estimated value drop is about a third in size of the German drop. In Germany, each percentage point increase in market value leads to a decline of the value factor by a full percentage point; in the Nordics the drop was 0.3.

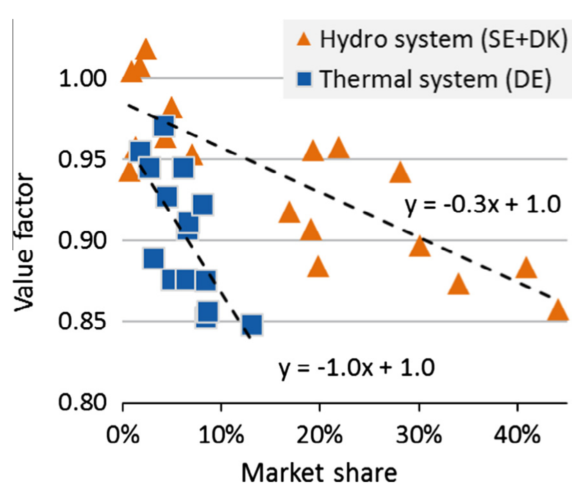

Fig. 7. Denmark and Sweden grouped. Own illustration based on data from IEA electricity statistics, TSOs, EPEX Spot, and Nordpool Spot. The impact of the features not modeled (right column) is based on personal assessment.

[4] This is not the "merit order effect" – the impact of wind power on the simple average electricity price (base price), see Sensfuß [23]. Here we discuss the impact of wind power on the wind-weighted average price (market value). The merit-order effect is transitory, where the market value remains depressed in the long term.

In the following, a numerical model is used to explore the empirical significance of this difference for higher penetration rates and under a wider set of parameters.

4. The modeling approach

The power market model EMMA was used for this study. This section briefly outlines the model and describes in more detail the modifications that were incorporated to model hydropower. An exhaustive model description is available as supplementary material to this article and on http://neon-energie.de/emma.

4.1. The power market model EMMA

The open-source Electricity Market Model EMMA is a techno-economic model of the integrated Northwestern European power system, covering Germany, France, Belgium, The Netherlands, Poland, Sweden, and Norway. It models both dispatch of and investment in power plants, minimizing total costs with respect to investment, production and trade decisions under a large set of technical constraints. In economic terms, it is a partial equilibrium model of the wholesale electricity market with a focus on the supply side. It calculates long-term optima (equilibria) and estimates the corresponding capacity mix as well as hourly prices, generation, and cross-border trade for each market area. Model formulations are parsimonious while representing wind and solar power variability, power system inflexibilities, and flexibility options with appropriate detail – such as an hourly granularity. Technically, EMMA is a linear program with about two million non-zero variables.

EMMA has been used by various publications to address a range of research questions.[5] It is open-source; the model code, as well as all input parameters and documentation, are freely available to the public under the Creative Commons BY-SA 3.0 license and can be downloaded from http://neon-energie.de/emma.

4.2. Hydro modeling in EMMA

For this project, hydropower was introduced into EMMA. Three types of hydropower are distinguished: run of the river hydropower with an exogenous generation profile; pumped hydro storage without inflow; and reservoir hydropower with inflow but without the option to pump.

Hydro modeling in EMMA is stylized and parsimonious, but captures the crucial aspects of hydropower. Our goal was not to replace existing detailed dispatch and planning tools, but to develop a model that is fast and flexible enough to co-optimize thermal and hydro dispatch and investment in a large number of sensitivity runs. Four core equations characterize hydropower in EMMA: a turbine capacity constraint; a reservoir constraint; an intertemporal reservoir level relationship; and a minimum generation constraint. Run of the river hydropower has a reservoir size of zero; pumped hydro storage has no water inflow.

While thermal investments are modeled, hydro capacity is assumed to be constant to reflect the lack of significant development sites in Europe. As with all other generation technologies, hydropower is modeled as one technology per country, rather than as individual power plants. Table 1 summarizes the hydropower assumptions by country.

Overall, these assumptions are rather optimistic with regards to hydro flexibility. Cascades, icing and internal transmission constraints tend to limit real-world hydro dispatch flexibility more than is modeled here. In other words, the model estimates are likely to present an upper boundary for the beneficial impact of hydropower on the wind market value.

Table 1
Hydropower capacity assumptions in EMMA.

	Run of the river		Pumped hydro storage	Reservoir hydropower	
	Capacity	Generation	Capacity	Capacity	Generation
Sweden	–	–	–	13.7 GW	67 TW h
Norway	–	–	–	25.0 GW	123 TW h
France	12 GW	34 TW h	4.2 GW	9.2 GW	11 TW h
Germany	4 GW	20 TW h	6.8 GW	–	–
NLD, BEL, POL	<1 GW	<1 TW h	–	–	–

Source: Eurelectric PowerStatistics, national statistics. German PHS includes Luxemburg. Swedish and Norwegian capacity is adjusted to reflect maximal historical generation, rather than the technical installed capacity.

4.3. Model runs: long-term optimum

EMMA was used to calculate the long-term economic equilibrium (or green-field optimum) of the power market for different levels of wind penetration between zero and 30% in annual energy terms. The same wind penetration rate in energy terms was applied in each country. For each hour of the year the electricity price was determined as the shadow price of consumption. In the electric engineering power system literature, this is often labeled "system lambda", because it is derived from shadow prices of one of the constraints of an optimization model. Following this, the wind value factor was determined for each country according to Eqs. (1)–(3).

4.4. Assessment of model quality and appropriateness

"All models are wrong but some are useful" George Box wrote in 1976. This also applies, of course, to EMMA. EMMA is a stylized model and there are many features of the real world that are not fully captured. Table 2 summarizes key features of power systems and markets that are likely to have a significant effect on the market value of wind power. The left hand side lists the features that are captured in EMMA. The right hand side lists those that are not, split between those that are likely to have a positive or negative impact on the market value. Overall, we are convinced that the setup of EMMA makes it well suited for an assessment of the long-term market value of wind power.

In the context of this study, two major limitations stand out: first, hydroelectricity is modeled relatively roughly; second, internal transmission constraints within countries are not modeled. This is particularly important for Norway and Sweden, where severe constraints are currently reflected in bidding zones. Both limitations are likely to overstate the market value of wind power in Sweden.

5. Model results: benchmark

The wind value factor in Germany and Sweden at penetration rates between 0% and 30% for central ("benchmark") parameter assumptions represent the core results of this study. They are displayed in Fig. 8.

At low penetration, the value of wind power in both countries is almost identical. With increasing penetration rate, the market value of wind power drops in both regions, although it drops faster in Germany. The Swedish drop is reduced by about a third, leading to a 12 percentage point (18%) higher market value at 30%

[5] Hirth [25,26,46], Hirth and Ueckerdt [47], Hirth and Müller [40], and Hirth and Steckel (submitted).

Table 2
Model features that are likely to significantly impact the wind market value.

Features modeled	Features not modeled
• High resolution (hourly granularity) • Long-term adjustment of capacity mix • Realistic (historical) wind power, hydro inflow pattern, and load profiles • System service provision • Combined heat and power plants • Hydro reservoirs • Pumped hydro storage • Interconnected power system (imports and exports) • Cost-optimal investment in interconnector capacity • Thermal plant start-up costs • Curtailment of wind power • Balancing power requirements	*Impact likely to be positive (including these features would change value factor upwards)* • Price-elastic electricity demand, e.g. from industry, electrical heating, or e-mobility • Inclusion of more countries *Impact likely to be negative (including these features would change value factor downwards)* • Internal transmission constraints (SWE, GER) / bidding areas • More detailed modeling of hydro constraints (cascades, icing, environmental restrictions) • Shorter dispatch intervals (15 min) • Market power of non-wind generators • Ramping constraints of thermal plants • Year-to-year variability of wind and hydro capacity factors, and correlation among these • Business cycles/over-investments • Imperfect foresight

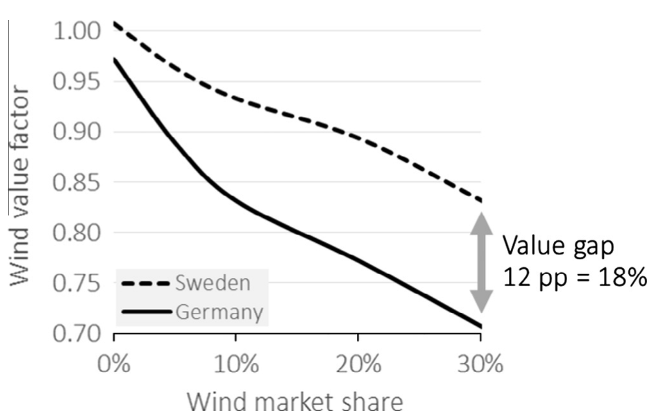

Fig. 8. The market clearing price in a thermal power system with and without wind power.

penetration. For each percentage point increase in market share, the value factor drops by 0.8 points in Germany, but only by 0.5 points in Sweden.

Fig. 9 shows the difference in value factor, or "value gap", between the two countries. Up to 20% penetration, the gap widens (wind loses value faster in Germany than in Sweden). Beyond that point, it levels off (wind value drops almost in parallel in both countries). This result seems to suggest that the hydro flexibility is "exhausted" at a wind market share of 20% and cannot further mitigate a loss in value.

Fig. 10 shows the absolute (€/MWh) wind market value in both countries. In the long-term economic equilibrium, base prices become very similar across countries and penetration rates. As a consequence, absolute and relative market value patterns become very similar. Due to space constraints, we will restrict the display of figures to value factors in the remainder of the article.

These results are subject to significant parameter uncertainty. We present robustness analyses and sensitivities in the following section.

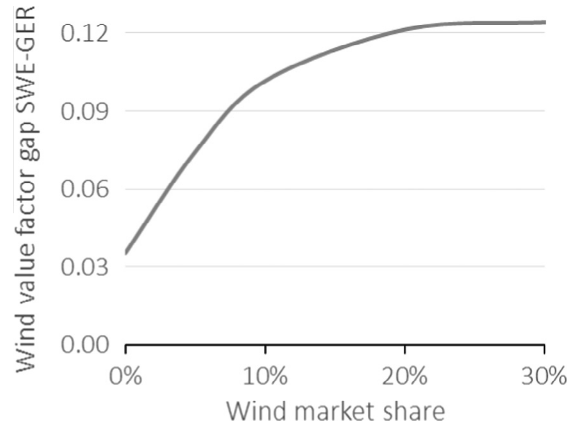

Fig. 9. The gap between Swedish and German wind value. Around 20%, the value gap levels off.

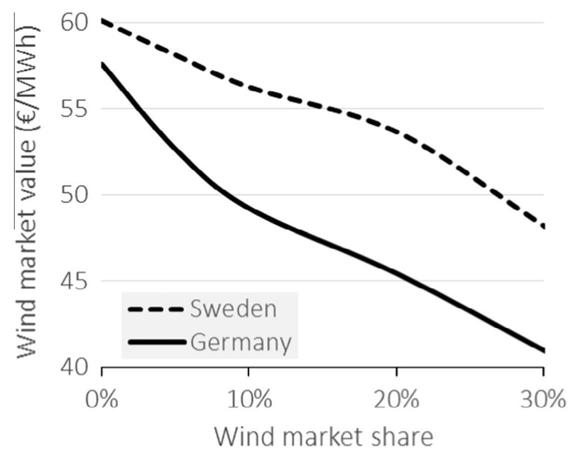

Fig. 10. Absolute wind market value (€/MWh).

6. Model results: sensitivities

To check for robustness with respect to parameter assumptions, a large number of sensitivity runs were performed. For each sensitivity, one parameter was changed. Sensitivities included variations of:

- thermal plant parameters such as fossil fuel price levels, plant efficiency, plant availability, natural gas price seasonality and investment costs;
- hydro parameters such as inflow and reservoir constraints, turbine capacity, and the capacity and cost of pumped hydro storage;
- thermal dispatch flexibility such as CHP must-run constraints, ancillary service constraints, and minimum load limits;
- the historical year for wind power generation and load time series;
- climate policy as reflected in the carbon price;
- interconnector capacity;
- nuclear policy, both uniform and differentiated among countries, including a phase-out and exogenously set levels of nuclear power;
- solar photovoltaics capacity;
- wind power technology in the form of low wind speed turbines of different specific ratings;
- investor risk as reflected in the discount rate; and

- power market design in the form of capacity mechanism and price caps.

These sensitivities amount to 335 model runs. The choice of weather emerged as having a large impact on results. As a consequence, all sensitivities were calculated using another meteorological year, doubling the number of model runs to 670. To make this computationally feasible, we reduced the number of countries in the sensitivities from seven to three, modeling only Sweden, Germany, and France. Figs. 11 and 12 compare the results for all countries (bold lines) to the reduced set (dotted lines). The differences are very small, hence reducing the number of countries seems justified.

A complete list of results can be found in Appendix.

We first discuss the results in aggregate to evaluate robustness and uncertainty and then elaborate on individual sensitivities.

6.1. Robustness and uncertainty range

The following figures summarize the mean and variation of results for all sensitivities. Fig. 13 reports the mean, 10%, and 90% quantiles for Germany. Fig. 14 displays results for Sweden and Fig. 15 for the value gap. As we lack information about the distribution of uncertain parameters (random variables), this is not a rigorous Monte Carlo simulation. The 10% percentile curve merely indicates that 10% of all sensitivity runs resulted in value factor estimates below the curve.

Despite significant parameter uncertainty, the core result is robust with respect to parameter uncertainty: at high penetration rates, wind power is more valuable in hydro-dominated Sweden than in thermal-dominated Germany. At 30% penetration, this is the case *in every single sensitivity*. In 90% of all sensitivities, the gap is larger than 9 percentage-points.

6.2. Meteorological years

The choice of the meteorological year has a major impact on results. We tested the years 2008–2012 and chose 2012 as a benchmark year for the results above. In each case, consistent time series for load and wind in-feed were used. Water inflow to hydro reservoirs, however, was not varied.

Fig. 16 displays the value factor in Sweden and Germany. Three observations stand out. First, in both countries, the initial (low penetration rate) market value is strongly affected by the choice of the weather year; in most years, the initial value factor is above unity, resembling earlier findings [25]. In both countries, wind power also benefits from seasonal correlation with electricity consumption; winters tend to feature both stronger winds and higher electricity demand (the one exception being Germany 2012). Second, the German market value at high penetration is quite insensitive to choice of the year. Finally, the Swedish market value remains sensitive at high penetration. The results presented here can only be a first step: the impact of year-to-year variation of level and distribution of wind speeds, and of water inflow, is a promising area for further research.

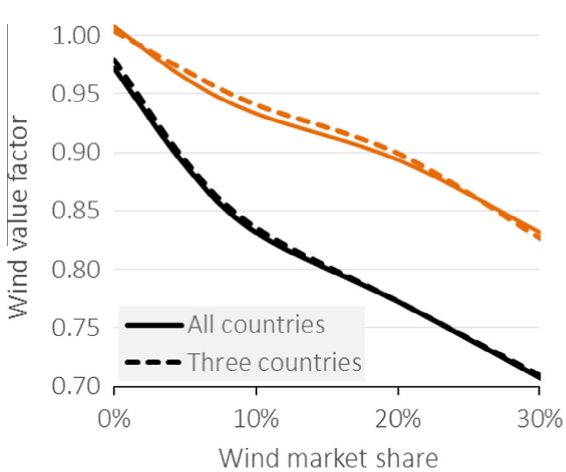

Fig. 11. The market value of wind power in Sweden (orange) and Germany (black) for all countries modeled (bold lines) and three countries modeled (dotted lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

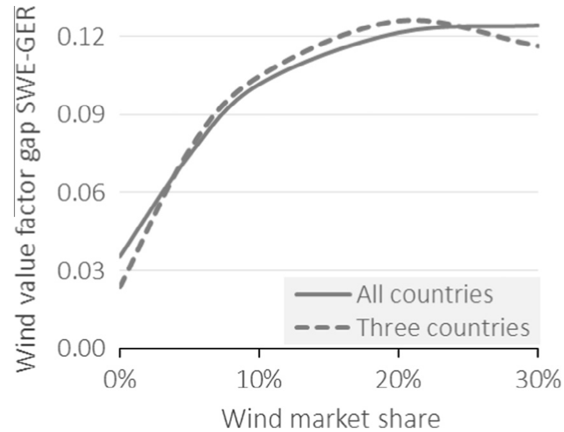

Fig. 12. The gap between Swedish and German wind value.

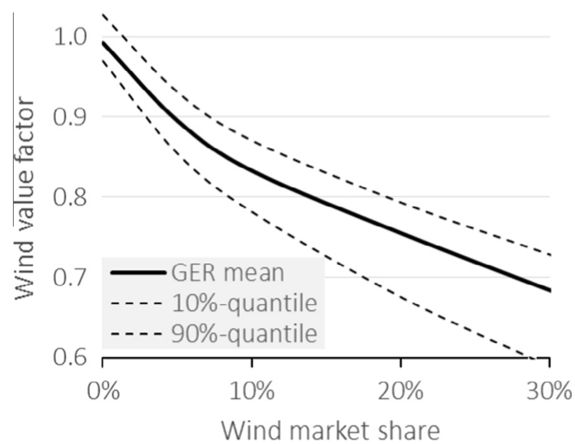

Fig. 13. The distribution of German market value in all sensitivity runs. A significant decline is observed across sensitivities.

At 30% penetration, the wind value gap between the two countries varies between 8 and 14 percentage points, depending on the weather year (Fig. 17). The benchmark year 2012 has a gap of 12 points, close to the mean value (this is the reason it had been chosen as a benchmark). Taking all weather years into consideration, the result seems to confirm that the gap flattens out at about 20% wind penetration.

6.3. Climate policy

Climate policy is modeled as a fixed price on CO_2 that is uniformly applied across all countries; in the benchmark, a price of 20 €/t was assumed. Changing the CO_2 price has a dramatic impact on results.

Unsurprisingly, lowering the CO_2 price reduces the market value of wind power, as it reduces the variable costs of competing

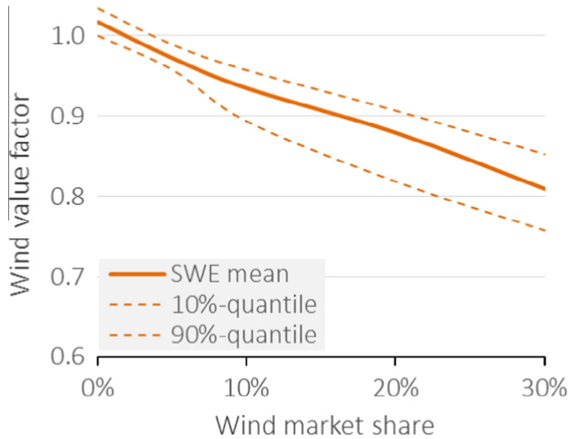

Fig. 14. The distribution of Swedish market value in all sensitivity runs. Overall, the value drop is much less pronounced.

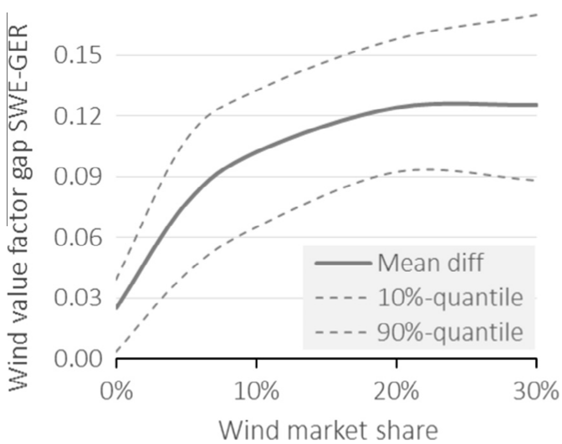

Fig. 15. Beyond 10% wind market share, in all sensitivities the wind market value is higher in Sweden than in Germany. At 30%, the value gap ranges from 9 to 17 points (10–90%-quantile) with a mean of 13 points.

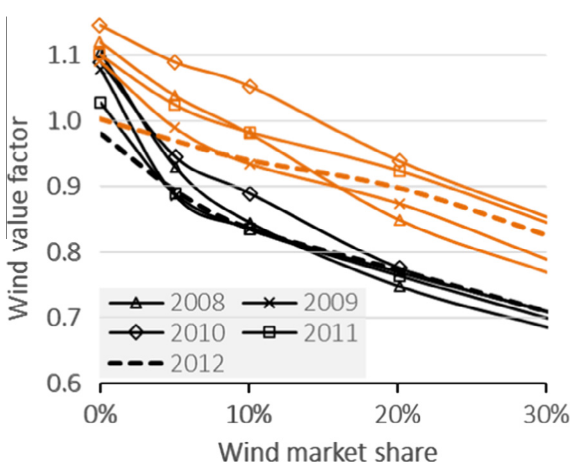

Fig. 16. Value factor for Germany (black) and Sweden (orange) for different weather years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fossil fueled generators. Maybe surprisingly, increasing the carbon price *also* reduces the value of wind power, both in the value factor and absolute market value (Fig. 18). The reason for the negative effect of higher CO_2 prices on wind value lies in the effect of

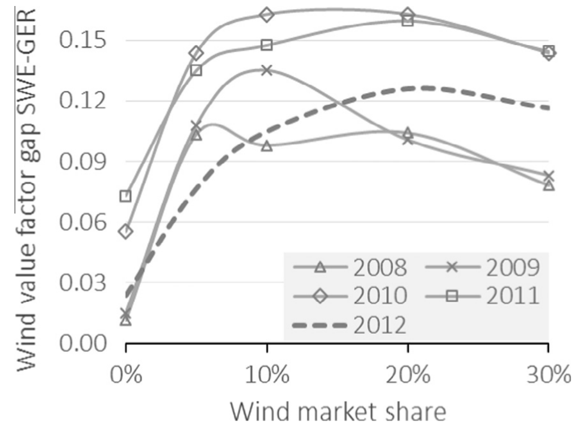

Fig. 17. The value gap between Sweden and Germany for different years.

investments in competing low-carbon technologies. Nuclear power and carbon capture plants (CCS) are the only non-variable low-carbon technologies in the model, as hydropower capacity is fixed. These are both base load technologies with high initial investment and relatively low variable costs, i.e. they are economically designed to run around the clock. Base load capacity increases the slope of the merit-order curve and reduces the market value of wind power (Fig. 19). However, carbon prices below a certain threshold (here roughly 40 €/t CO_2) do not trigger any nuclear or CCS investments. Up to this point, carbon pricing simply increases the costs of fossil plants, increasing the electricity price and the market value of wind energy. Beyond this threshold, the base load investment effect dominates the emission cost effect.

Of course this phenomenon disappears if nuclear power and CCS cannot be built due to political or other reasons, and the effect is reduced in size if investments are capped. To benefit from stricter climate policy, wind power needs low-carbon mid and peak load generators as counterparts, rather than base load plants. Flexible hydropower plays such a role. Both high and low carbon prices reduce the wind value much less in Sweden than in Germany (Fig. 20). At both higher and lower carbon prices, the wind value gap between hydro and thermal systems widens (Fig. 21). At 100 €/t CO_2 and a wind penetration rate of 30%, Swedish wind power is, remarkably, 35% more valuable than German wind power. In other words, tight climate policy increases the value added by hydro flexibility.

Another way to assess the impact of carbon pricing is to determine the cost-optimal level of wind power. For a carbon price of 100 €/t CO_2, we determine the cost-optimal quantity of wind power for different levels of reductions in wind generation costs (levelized electricity costs, LEC). Fig. 22 shows that the result is impressive; if costs decline by 30% from current levels, wind power supplies only 5% of electricity in Germany, but 30% in Sweden. This result is not driven by differences in the cost of wind energy; the same LEC has been assumed in all model regions. The different levels of optimal wind penetration are mostly a result of the presence of hydropower in Sweden. Recall, however, that this is a long-term optimum that does not assume any existing nuclear capacity. At 30% cost reduction the model builds only 2.5 GW of nuclear capacity in Sweden.

6.4. Interconnector capacity

Long-distance transmission can help smooth wind power fluctuations. To assess the impact of interconnector capacity, we first set it to zero and then double it relative to current levels. At low market shares, the market values in both countries move closer

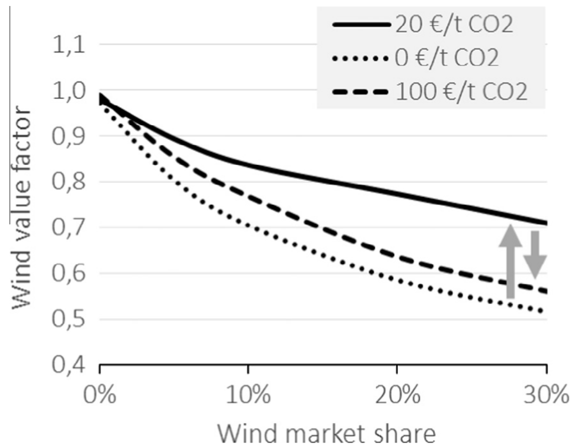

Fig. 18. The wind value factor in Germany for different carbon prices. The arrows indicate changes for increasing carbon prices from 0 €/t to 20 €/t and from 20 €/t to 100 €/t.

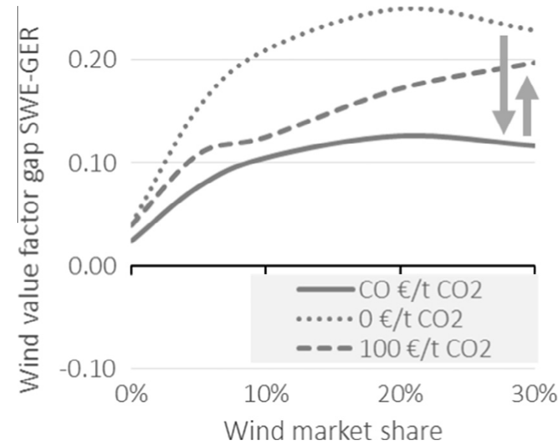

Fig. 21. The value gap between Sweden and Germany for different CO_2 prices. High *and* low carbon prices increase the gap.

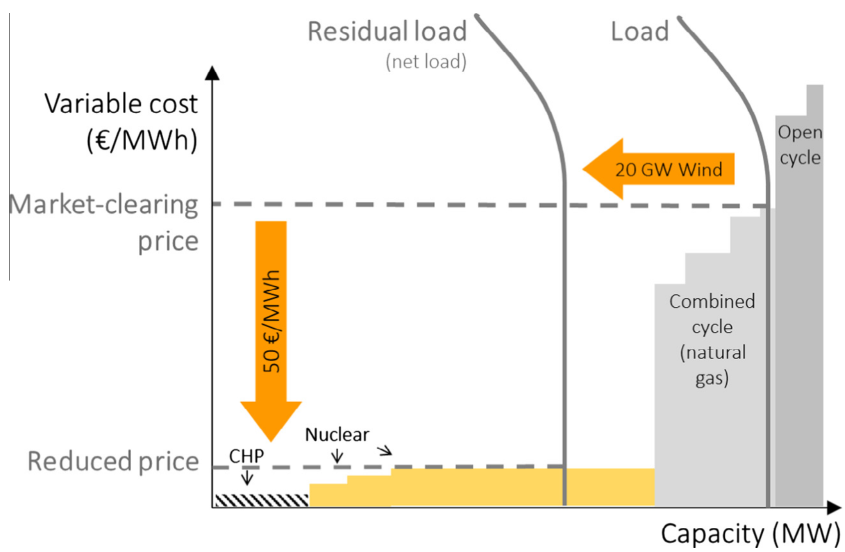

Fig. 19. The price drop is more pronounced if a lot of low variable cost capacity is present (contrast with Fig. 5).

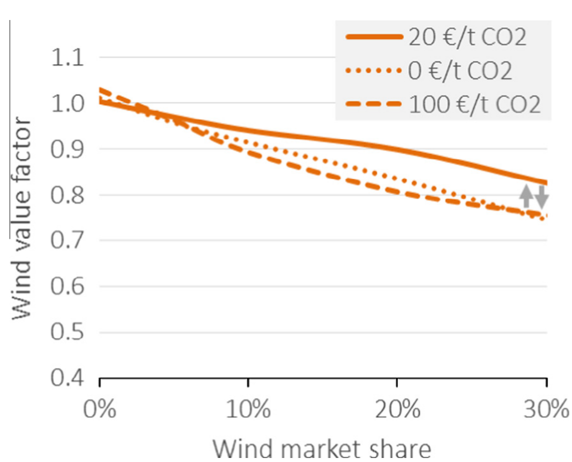

Fig. 20. The wind value factor in Sweden for different carbon prices.

to each other, implying a negative effect on Swedish market value. At high market share, wind power benefits from increased interconnectivity in *both* countries, although the benefit is greater in Germany (Fig. 23).

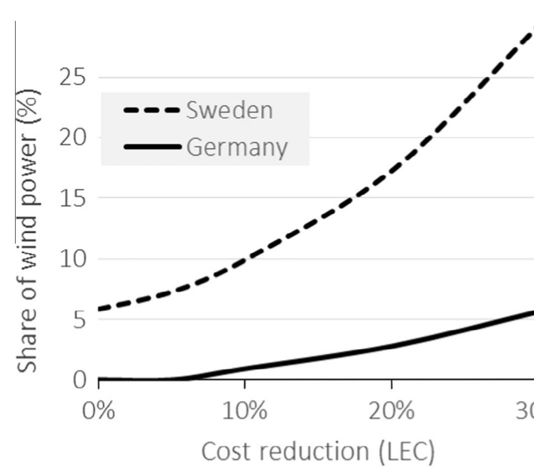

Fig. 22. The cost-optimal share of electricity supplied from wind power in Germany and Sweden (the same LEC is assumed in both countries).

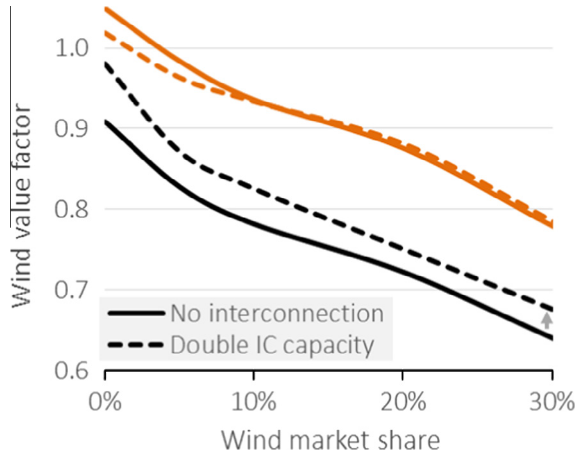

Fig. 23. Value factor for Germany (black) and Sweden (orange) without interconnection (bold) and with double current interconnector capacity (dotted). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

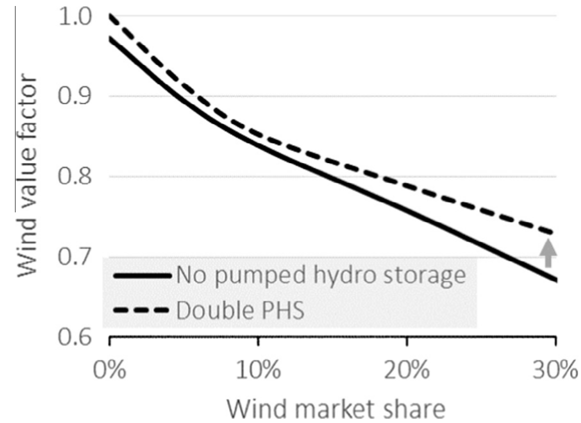

Fig. 24. Wind value in Germany without storage and with double the current storage capacity.

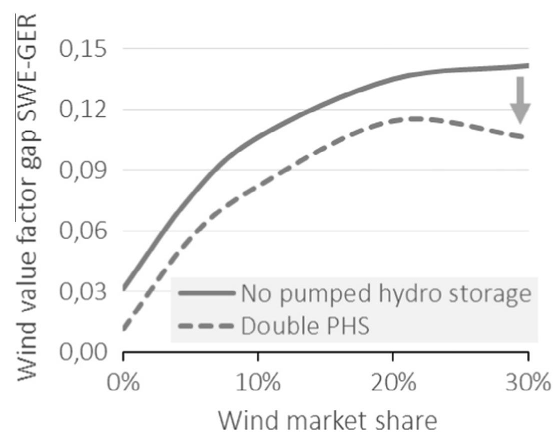

Fig. 25. More storage narrows the gap to Swedish wind value.

We interpret this finding as representing two effects. On the one hand, more transmission capacity is beneficial for wind power, as it helps smooth geographical generation. On the other hand, more interconnector capacity into Sweden allows German wind power to use Swedish hydro as a flexible resource. During windy periods, Sweden tends to import more electricity, which hurts Swedish wind generators. Both effects work in the same direction for German wind, but in opposing directions for Swedish wind, hence the larger benefit of transmission expansion for German wind.

6.5. Power system flexibility

Increasing the flexibility of the German (thermal) power system tends to improve the wind value in Germany and narrow the gap at high penetration rates. There are various forms of power system flexibility [3,48], most obviously electricity storage [49,50]. These have been called "integration options" [51] because they facilitate the integration of variable renewables into power systems, or "mitigation measures" [39] and tend to mitigate the value drop. Here we discuss two types of integration options: pumped hydro storage and a relaxation of must-run constraints on thermal power plants.

6.5.1. Pumped hydro storage

Figs. 24 and 25 display wind value for different quantities of pumped hydro storage. The wind value in Sweden is unaffected by increasing continental storage capacity; at high penetration rates German wind power benefits somewhat, and the gap with Sweden closes a little.

6.5.2. Must-run

Two important must-run constraints for thermal power plants stem from the combined production of power with heat (CHP) or with system services. For empirical evidence of their relevance in the German power market see Hirth [46]. Technological advances such as heat storage and batteries allow for constraints on power plant dispatch to be eased [52,53]. Both countries have high CHP capacity, so relaxing these must-run constraints improves the wind value in both countries (Fig. 26) without significantly affecting the value gap (Fig. 27).

6.6. System-friendly wind turbines

Wind turbine technology has evolved substantially during the past decade. The "low wind speed" turbines that have entered the market are taller and have a larger rotor-to-generator ratio (a lower specific rating per area swept by the rotor). These turbines capture more energy at low wind speeds. This advancement in wind turbine technology has been described as a "silent revolution" [54].[6] In the United States, the specific rating of newly installed turbines has dropped from 400 W/m^2 to 250 W/m^2 during the past 15 years [61]. With a lower specific rating, electricity is generated at a more constant rate, which can potentially increase the economic value of the electricity, or, in other words, have better system integration properties.

Hirth and Müller [40] estimate that low wind speed turbines lead to a market value that is 15% higher at a 30% penetration rate, in thermal power systems. Here we evaluate the interaction of low wind speed technology with hydropower. We contrast a standard turbine (Enercon E82 evaluated with ERA-Interim wind speed data at 90 m hub height) with a low wind speed turbine (E115 evaluated at 120 m hub height). It emerges that low wind speed turbines mitigate the market value drop dramatically in *both* power systems (Figs. 28 and 29). In fact, the value increase due to low wind speed design is even slightly higher in Sweden than in Germany.

This finding might come as a surprise. Hirth and Müller report that the additional value of low wind speed turbines is lower in highly flexible power systems (more storage, more interconnection,

[6] Molly [55–57], IEA [58], de Vries [59], Gipe [60], Wiser and Bolinger [61], and Fraunhofer IWES [62], and Fraunhofer IWES [63] provide more background on the technology and history of low wind speed turbines.

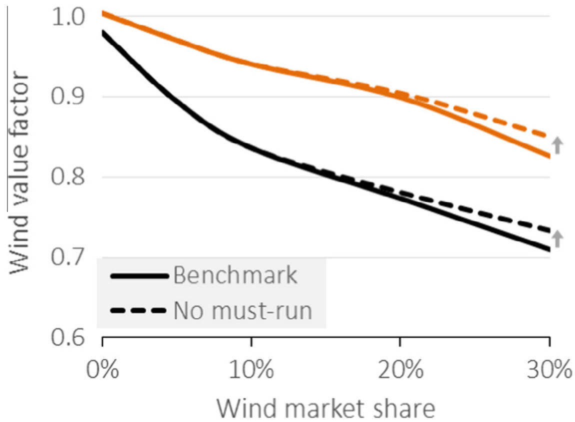

Fig. 26. Wind value in Germany (black) and Sweden (orange) with and without must-run constraints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

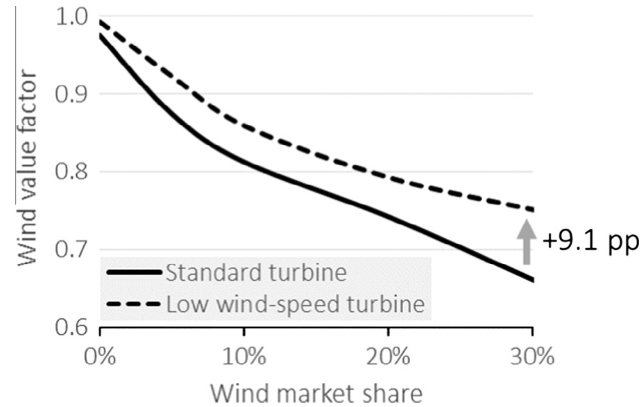

Fig. 28. Wind value factor in Germany. The market value of low wind speed turbines is significantly higher than that of a standard turbine. The reason is that they generate electricity more constantly.

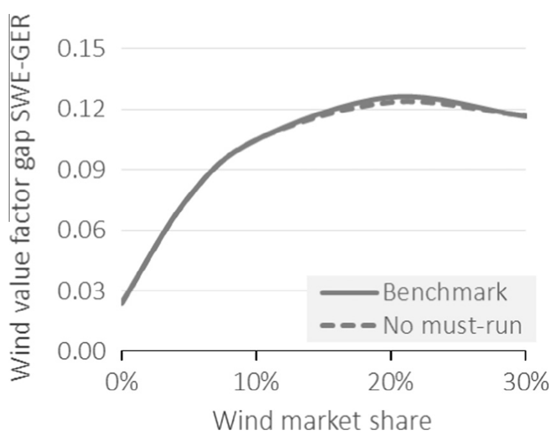

Fig. 27. The gap in wind value with and without must-run.

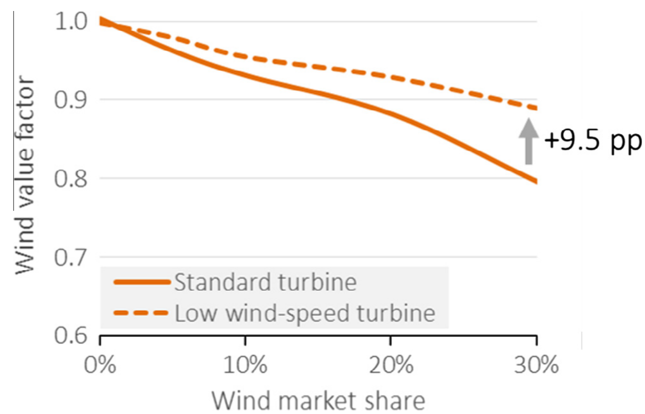

Fig. 29. The market value gain is even larger in Sweden. The value added by low wind speed turbines seems to be as high in hydro systems as in thermal systems.

more flexible thermal plant dispatch). In their words, "system-friendly wind turbines" are a substitute for "wind-friendly power systems"; the benefits of stable wind generation and flexible power systems are not cumulative. The findings of this study seem to contradict their interpretation; the benefit of hydropower flexibility is as large for low wind speed turbines as for high wind speed turbines; the benefit of low wind speed turbines is as great in hydro systems as in thermal systems.

6.7. Hydropower parameters

One reason why hydropower has only a limited benefit for wind power is the relatively high utilization of Nordic hydropower. Both Swedish and Norwegian hydropower has an effective capacity factor of about 70% (recall Table 1). This high capacity factor limits the possibility of shifting energy from one point in time to another, compensating for the variable output of wind parks. The high capacity factor implies that there is not too much room to maneuver.

This interpretation is supported by sensitivities on hydropower parameters. Four separate runs were conducted:

- increasing hydropower as a whole – generation capacity, reservoir size, and inflow (energy) – to capture the possibility of investments;
- increasing (tightening) the minimum flow constraint, a possible consequence of the implementation of the EU Water Framework Directive;
- increasing generation capacity individually, in order to capture the possibility of turbine upgrades that leave reservoir size and inflow unchanged;
- increasing the reservoir size individually, in order to capture the possibility of upgrading hydro dams while leaving annual energy (water inflow) and generation capacity unchanged.

Increasing minimum flow constraints has a slightly negative impact on the value of wind power, as expected. Increasing reservoir size has a slightly positive impact. Surprisingly, increasing hydropower as a whole by 50% has only a small positive effect. What does increase the value of wind power, however, is an upgrade of turbine capacity (Fig. 30); the value gap increases from 11 to 13 points. In fact, increasing capacity without annual energy output means that the capacity factor is reduced from 70% to 50%; in term of dispatch characteristics, hydropower technology moves from a "base load" towards a "peak load" plant.

7. The value of hydropower

Large-scale deployment of wind power not only affects the market value of wind power, but also that of other power plant types. It tends to increase the value of flexible sources, particularly if capacity cannot be expanded (cf. Mills and Wiser [39]). Clearly, hydropower is such a case.

Our model results indicate that hydropower benefits from wind deployment, albeit not much (Fig. 31). At 30% wind penetration,

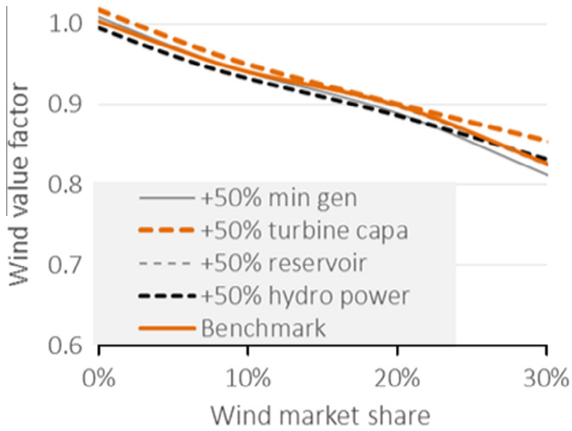

Fig. 30. The value factor of Swedish wind power for different hydropower assumptions.

the spot market value of each MWh generated by hydropower (the water value) is 5% greater than without wind power.

EMMA accounts for balancing reserves. It requires a certain amount of synchronous generation to be online at any one time. Balancing reserves become scarcer, such that the price of providing such reserves increases (Fig. 32). This is another potential benefit of hydropower.

8. Summary

The results of this paper are summarized as follows:

- **Theory suggests wind power should benefit from hydroelectricity.** The presence of reservoir hydropower mitigates the wind value drop, as hydro stations are used to compensate for the fluctuating output of wind parks. Hydro systems provide a less hostile environment for variable renewables than thermal power systems.
- **Empirical evidence supports this hypothesis.** Both market data and numerical model results show that the market value of wind energy declines with penetration, but it tends to decline more slowly in markets with a lot of hydroelectricity.
- **Benchmark estimate: 18% higher value.** When moving from zero to 30% wind penetration, hydropower mitigates the value drop by a third. As a result, one MWh of electricity from wind is worth 18% more in Sweden than in Germany.
- **High robustness despite high uncertainty.** These point estimates are subject to significant uncertainty. 80% of all sensitivity runs lead to a value increase of 12–29% around the point estimate of 18%. The sign is highly robust; there is a value increase in all sensitivities.
- **The benefits of hydropower level off at around 20%.** This seems to suggest that the hydro flexibility is "exhausted" at this level.
- **Low wind speed turbines are as beneficial in hydro systems as in thermal systems.** The combination of hydro reservoirs with low wind speed turbines lead to a very stable market value for wind power. Our point estimate indicates a value factor of 0.9 – nearly 50% more than classical wind turbines in a thermal system.
- **Climate policy levers the value added by hydro flexibility.** The value added by hydro flexibility is larger when carbon prices are high. Capital-intensive, low carbon base load generators interact unfavorably with wind power in thermal systems – this is much less of a problem in hydro systems. If hydroelectricity is present, a high carbon price triggers significant growth of wind power. Given the same cost parameters, a high carbon price primarily triggers nuclear investments if hydropower is absent.
- **Upgrading hydropower turbines**, thereby reducing hydro capacity factors, helps to boost the value of wind power further. It also helps to increase the value of hydroelectricity.

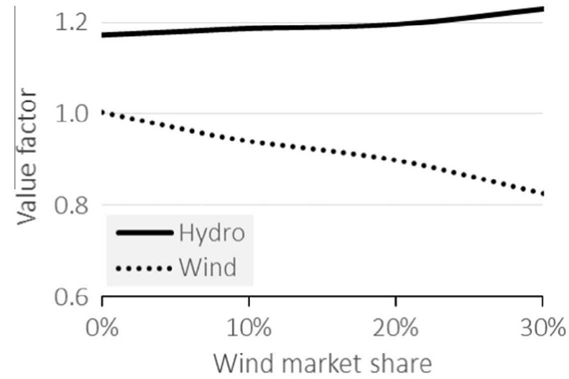

Fig. 31. The market value of hydropower and wind power in Sweden (benchmark).

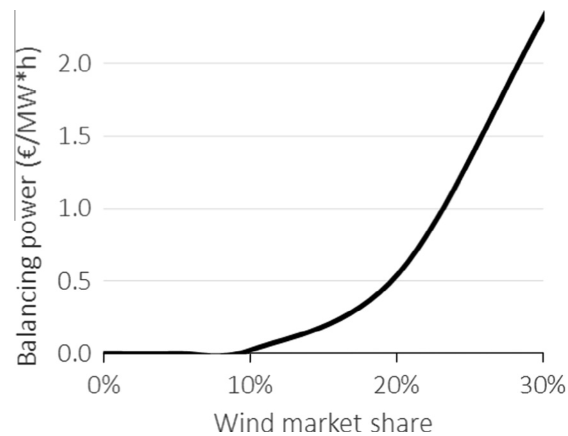

Fig. 32. The price of balancing power in Sweden (benchmark).

9. Conclusion

The decision where to locate wind power should not only be driven by cost minimization, but also by value consideration. This is as true for private investors as for policy-makers. Wind power should not be built where it is cheapest to produce electricity, but where its net benefits are greatest. Hydro reservoir power helps to maintain a high value of wind power despite its variable nature.

Hydropower is an embedded, pre-existing flexible resource that should be harnessed. A long-term policy implication is that it might be sensible to build most wind power in electricity systems in which hydroelectricity is present, or to co-develop hydropower and wind power.[7] In the context of variable renewables, hydropower should be regarded primarily as a flexible resource, rather than as an energy resource. It is likely that the optimal hydro station configuration moves towards higher installed capacity per annual energy output if variable renewables are considered.

[7] However, in hydro-dominated power systems the upscaling of wind power can be a more difficult process. See http://www.svenskenergi.se/Global/Nyheter%20-%20dokument/Rapport%20Hirth%20april%202016/Reasons%20for%20the%20price%20drop_ppt.pdf.

There are several promising directions for future research. Our results should be validated against a more detailed hydropower dispatch model that accounts for the internal constraints in the Nordic transmission network. Exploring the relationship of hydropower and low wind speed turbines is both promising and highly relevant in practice. Finally, a future assessment of wind power in hydro systems should incorporate year-to-year variation of water and wind availability (and the correlation of these two). Rather than modeling one year, the life-time market value of wind power could be determined. High quality weather data and hydrological models are required for this.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.07.039.

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