THE MARKET VALUE OF WIND ENERGY

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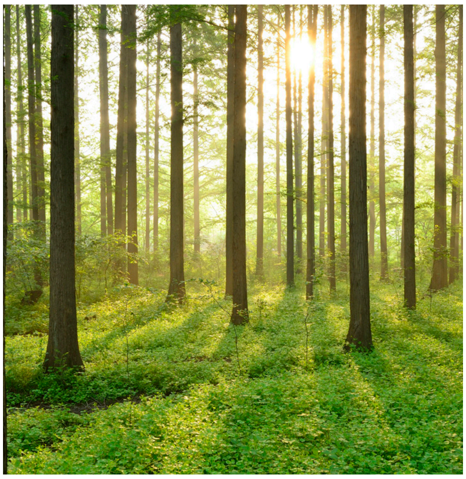

EFORIS

ELMARKNADENS FUNKTION
OCH ROLL I SAMHÄLLET

Energiforsk

THE MARKET VALUE OF WIND ENERGY

– thermal versus hydro power systems

LION HIRTH

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Foreword

EFORIS is a research program on electricity market design. The program was initiated by Energiforsk and involves dozens of highly reputable Swedish and international researchers.

This study was conducted by Dr. Lion Hirth, Neon Neue Energieökonomik GmbH, on behalf of EFORIS.

Sammanfattning

Ett flertal studier har visat att vindkraftens intäkter från spotmarknaden, det vill säga marknadsvärdet av producerad el, minskar i takt med att vindkraften byggs ut. Detta värdetapp har särskilt observerats på elmarknader som domineras av termiska kraftverk, till exempel på den tyska elmarknaden.

I denna studie analyseras vindkraftens marknadsvärde för ett kraftsystem med stor andel vattenkraft, till exempel det svenska elsystemet. Teoretiska modeller, marknadsdata och numeriska modellresultat visar genomgående att vattenkraften hjälper till att minska värdetappet för vindkraften. Marknadsvärdet av el från vindkraft avtar i takt med penetration av vindkraft, men värdeförlusten tenderar att minska i en långsammare takt om vattenkraft ingår som en del i elproduktionen.

Resultaten från den här studien tyder på att när andelen vindkraft växer från noll till trettio procent så bromsar vattenkraften värdetappet med en tredjedel. Det vill säga, 1 MWh el från vindkraft är värd 18 procent mer i Sverige än i Tyskland. Vattenkraftens utjämnade effekt planar dock ut vid omkring 20 procents vindkraftpenetration. Detta antyder att vattenkraften därefter inte längre kan bidra till att hålla emot de värdeminskande krafterna. Vindkraft som optimeras för låga vindhastigheter och utsläppsrätter för koldioxid kan öka intjäningsförmågan för vindkraft.

Summary

Several studies have shown that the revenues of wind power generators on spot markets ("market value") decline with increasing deployment. This "value drop" is mostly observed on power markets that are dominated by thermal power plants, such as Germany. This paper assesses the market value of wind power for power systems with large amounts of hydroelectric dams with large reservoirs, such as Sweden. Theory, market data, and numerical model results consistently indicate that hydropower helps mitigate the value drop of wind power. In other words, the market value of electricity from wind declines with penetration, but it tends to decline at a slower rate if hydropower is present. It is an empirical question by how much the drop is reduced. Our model results indicate that when moving from 0 percent to 30 percent wind penetration, hydropower mitigates the value drop by a third. As a result, 1 MWh of electricity from wind is worth 18% more in Sweden than in Germany. These point estimates are subject to significant uncertainty, but sensitivity analysis indicates high robustness. The benefits of hydropower level off at around 20 percent wind penetration. This seems to suggest that the hydro flexibility is "exhausted" at this level. Low wind speed turbines and carbon pricing can increase the added value of hydro flexibility.

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1 Introduction

Renewable energy-based power generation is on the rise. In 2014, worldwide wind and solar power capacity exceeded 500 GW (Figure 1). Almost half of global added capacity was based on renewables – of which wind and solar power represented about 70% (IEA 2015). 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% (Figure 2). Wind and solar power also provide a large market share of power systems 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.

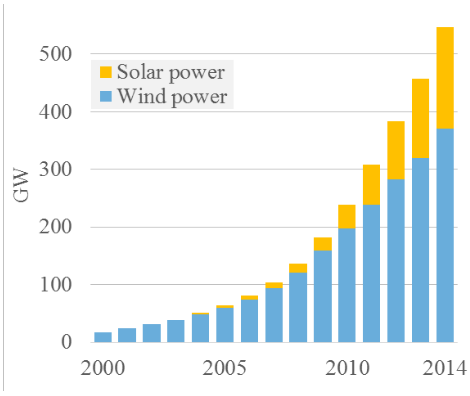

Figure 1. Wind and solar power capacity installed globally. Own illustration based on data from REN 21 (2015).

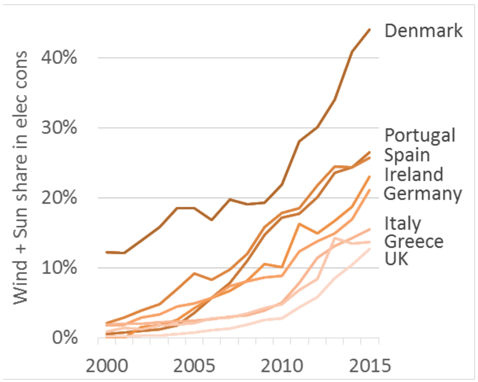

Figure 2. In a number of countries, wind and sun supply more than 15% of power demand. Own illustration based on data from IEA Electricity Statistics.

The variable, or intermittent, nature of certain renewable energy sources such as wind power, solar power, and ocean energy, poses challenges when integrating these technologies into power systems. Several properties specific to variable renewables are problematic for system integration (Grubb 1991a, IEA 2014). Most important of these is the simple fact that the availability of the primary energy source fluctuates over time. Integration challenges affect the economics in different ways, for example through grid expansion or increased balancing needs. The most significant economic impact of variable renewables is likely to be on the spot market value of sun- and wind-powered electricity (Ueckerdt et al. 2013, Hirth et al. 2015).

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

$$\bar{P}_{wind} = \frac{\sum_{t=1}^{T} W_t \cdot P_t}{\sum_{t=1}^{T} W_t}, \qquad (1)$$

where tϵT 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 $/MWh revenue that wind investors earn (leaving aside support schemes and other income streams). The market value of solar, or any other power generating technology, is analogous to this. Many authors have stressed that the market value of wind and solar power is not the same as that of other power generating technology (Grubb 1991b, Lamont 2008, Borenstein 2008, , Joskow 2011, Mills & Wiser 2012, Gowrisankaran et al. 2015, Hirth et al. 2016, to name a few).

For many applications, it is convenient to study the relative, rather than the absolute market value. Historical observations of electricity prices, for example, vary with business cycles. Assessing the market value of wind power relative to the average electricity price is a straightforward way to correct for factors. This relative price is called value factor. The value factor is calculated as the ratio of the hourly wind-weighted average wholesale electricity price and its time-weighted average (base price). Hence the value factor is a metric for the valence of electricity with a certain time profile relative to a flat profile (Stephenson 1973). The wind value factor compares the value of actual wind power with varying winds with its value if winds were invariant (Fripp & Wiser 2008). 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.

The base price is defined as

$$\bar{P} \equiv \frac{1}{T}\sum_{t=1}^{T} P_t, \qquad (2)$$

and the wind value factor as

$$VF_{wind} \equiv \frac{\bar{P}_{wind}}{\bar{P}}. \qquad (3)$$

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 (Figure 3). The model-based literature confirms this observation (Figure 4).

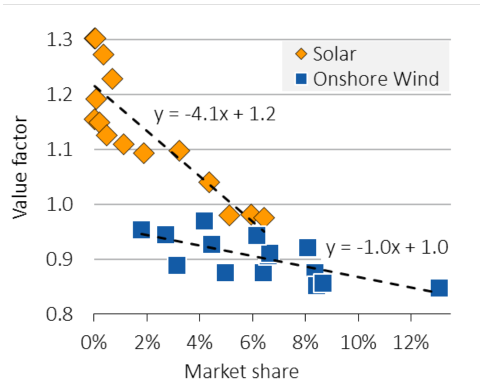

Figure 3. The market value of wind power and solar power in Germany 2001-15, expressed as market value over average power price. Own illustration based on data from Destatis, TSOs, and EPEX Spot.

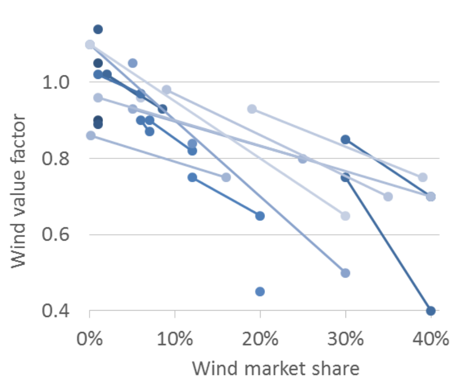

Figure 4. Market value estimates from the literature. Own illustration.

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

- Theoretical (analytical) models, including Grubb (1991b), Lamont (2008) and Hirth & Radebach (2016).
- Estimates from market data, including Sensfuß (2007), Sensfuß & Ragwitz (2011), Fripp & Wiser (2008), Hirth (2013, 2015a).
- Estimates from numerical (computer) models, including Obersteiner & Saguan (2010), Boccard (2010), Green & Vasilakos (2012), Energy Brainpool (2011, 2012, 2014), r2b (2013), Valenzuela & Wang (2011), Swider & Weber (2006), Lamont (2008), Nicolosi (2012), Kopp et al. (2012), Mills & Wiser (2012, 2013, 2014), Hirth (2013, 2015a), Hirth & Müller (forthcoming), Zipp & Lukits (2014), Fraunhofer ISE (2014), Gowrisankaran et al. (2015).

For power systems with large quantities of reservoir hydropower ("hydro systems"), comparable evidence is lacking. The landmark works by Andrew Mills and Ryan Wiser (2012, 2013, 2014) are a notable exception: their model does account for hydropower. However, these studies do not focus on the impact that hydropower has on market value of wind power. 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 hydropower significantly mitigates the wind value drop. We present empirical data and new model results for the Nordic region, where hydropower supplies half the electricity demand, in contrast to Germany where hydropower reservoirs are absent. Both observation and model results indicate that hydropower indeed helps in preserving the value of wind power. When moving from zero to 30% wind penetration in yearly 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 11% higher with the hydro systems. These are point estimates that are subject to significant uncertainty. 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 do the same.

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 (Figure 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 supply. Net (residual) demand is demand net of wind and solar power generation. The short-term supply curve remains relatively constant throughout the year, while net demand fluctuates from hour to hour. Prices fluctuate significantly during the course of days and the week, and spike in individual hours of net load peaks. Windy hours tend to have depressed prices, which reduces the market value of wind power. Some have called this the "self-cannibalization effect".[1]

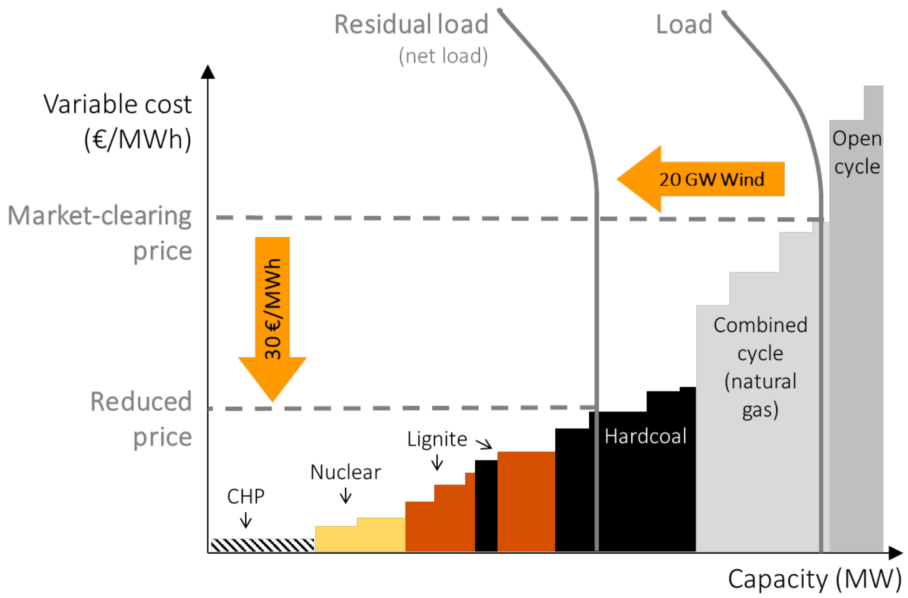

Figure 5. The market clearing price in a thermal power system with and without wind power. Own illustration.

In contrast to thermal systems, price setting in hydro systems is inherently intertemporal. Hydro generators receive a given amount of inflow during the year and have to determine *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 un-

[1] This is not the "merit order effect" – the impact of wind power on the simple average electricity price (base price). 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.

anticipated scarcity of energy just before the spring flood, prices spike often for a period of several days to weeks.[2]

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

[2] 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. Førsund (2007) discusses hydropower economics at length and depth.

3 Observed market data

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

In all jurisdictions, the value of wind power drops with penetration. If Denmark and Sweden are grouped as hydro systems, empirical observations suggest that the 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.

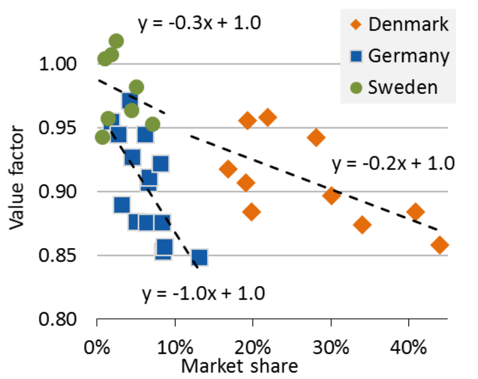

Figure 6. The wind market value in Germany, Denmark and Sweden 2001 to 2015. Own illustration based on data from IEA electricity statistics, TSOs, EPEX Spot, and Nordpool Spot.

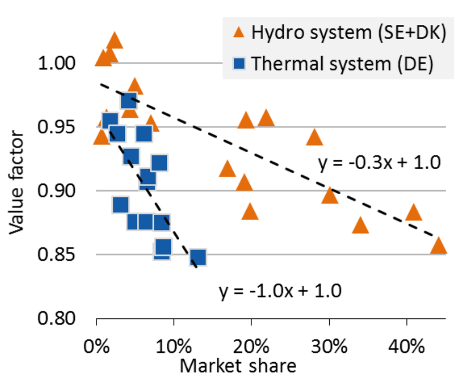

Figure 7. Denmark and Sweden grouped. Own illustration based on data from IEA electricity statistics, TSOs, EPEX Spot, and Nordpool Spot.

4 The modeling approach

This section outlines the power market model EMMA that was used for this study, and how it was modified to model hydropower.

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 for various publications to address a range of research questions.[3] EMMA is open-source: The model code as well as all input parameters and this 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 possibility 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 as well as investment in a large number of model 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. While thermal investments are modeled, hydro capacity are assumed to be constant, to reflect the lack of significant development sites in Europe. Hydro generation is modeled as one technology per country, rather than 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 hydro dispatch flexibility in reality more than is modeled here. In other words, the model estimates are

[3] Hirth (2013, 2015a, 2015b, 2015c), Hirth & Ueckerdt (2013), Hirth & Müller (forthcoming), Hirth & Radebach (2016).

likely to present an upper boundary for the beneficial impact of hydropower on the wind market values.

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.

4.4 ASSESSMENT OF MODEL QUALITY AND APPROPRIATENESS

"All models are wrong but some are useful" George Box famously wrote in 1976. This is, of course, true as well for the model employed here. EMMA is a stylized model and there are many features of the real world that are not fully captured by the model. 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 by those that are likely to have a positive impact on the market value and those that are likely to have a negative impact. 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 limitation stick 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 the severe constraints are reflected today in bidding zones. Both limitations are likely to overstate the market value of wind power in Sweden.

Table 1: Model features that are likely to significantly impact the wind market value

Features modeled	**Features not modeled**
• High resolution (hourly granularity)	*Impact likely to be <u>positive</u> (including these features would change value factor upwards)*
• Long-term adjustment of capacity mix	• Price-elastic electricity demand, e.g. from industry, electrical heating, or e-mobility
• Realistic (historical) wind power, hydro inflow pattern, and load profiles	• Include more countries
• System service provision	*Impact likely to be <u>negative</u> (including these features would change value factor downwards)*
• Combined heat and power plants	• Internal transmission constraints (SWE, GER) / bidding areas
• 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	• 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 / overinvestments

The impact of the features not modeled (right column) is based on personal assessment.

5 Model results: benchmark

Figure 8 displays the wind value factor for penetration rates between zero and 30% in Germany and Sweden for best-guess (benchmark) parameter assumptions. These estimates are the core result of this study.

At low penetration, the value of wind power in both countries is virtually identical. In both jurisdictions, wind benefits from the seasonal correlation with electricity consumption: winters tend to be windier and have higher electricity demand. With increasing shares, the market value of wind power drops in both regions. However, it drops faster in Germany. The Swedish drop is reduced by about a third, leading to a 13 percentage point (18%) higher market value at 30% 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.

Figure 9 shows the value gap between the two countries. Up to 20%, the gap widens with penetration (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.

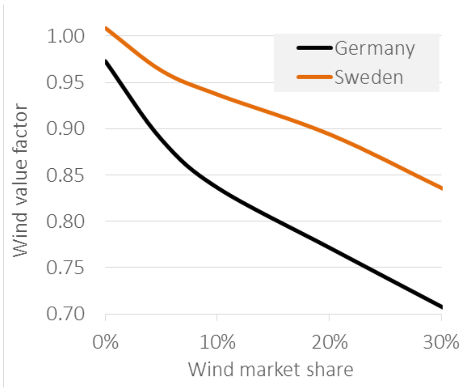

Figure 8. The market clearing price in a thermal power system with and without wind power.

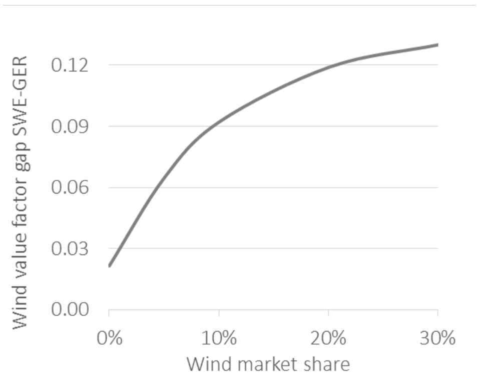

Figure 9. The gap between Swedish and German wind value.

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

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 amounts of nuclear power;
- solar photovoltaics capacity;
- wind power technology in 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.

Overall, 335 model runs were conducted.[4] To make this computational feasible, we reduced the number of countries in the sensitivities, modeling only Sweden, Germany, and France. Figure 10 and Figure 11 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.

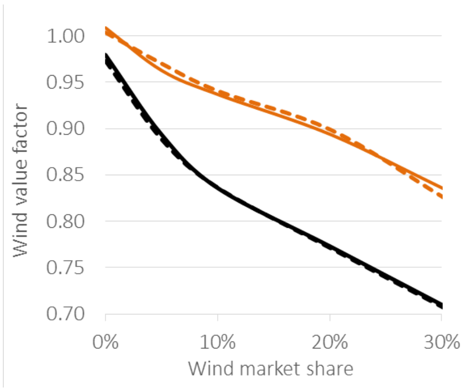

Figure 10. The market value of wind power in Sweden (orange) and Germany (black) for all countries modeled (bold lines) and three countries modeled (dotted lines)

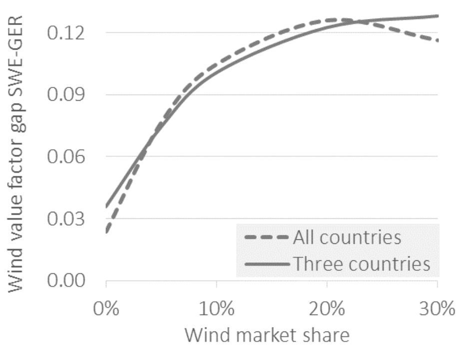

Figure 11. The gap between Swedish and German wind value.

A complete list can be found in the Appendix. We first discuss the results in aggregate to evaluate robustness and uncertainty and then elaborate on individual sensitivities.

[4] The choice of the weather turned out to have a large impact on results. As a consequence, all sensitivities were calculated with another meteorological year, doubling the number of model runs to 670. All results remained qualitatively unchanged.

6.1 ROBUSTNESS AND UNCERTAINTY RANGE

The core model result is robust with respect to parameter uncertainty: at high penetration rates, wind power remains more valuable in hydro-dominated Sweden than in thermal-dominated Germany. At 30% penetration, this is the case in every single sensitivity.

Figure 12, Figure 13 and Figure 14 report the mean value factor in Germany, Sweden, and the mean gap as well as the corresponding 10% and 90% percentiles. The results support the finding that the value gap between Germany and Sweden flattens out around 20%.

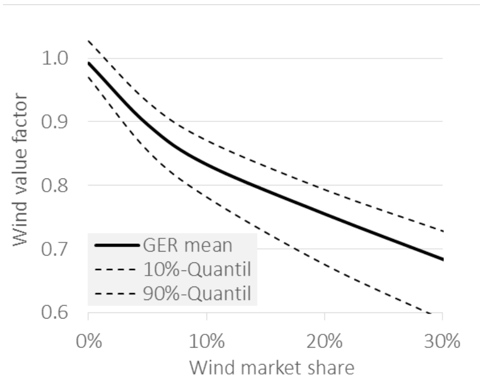

Figure 12. All sensitivities indicate a strong loss of wind power's market value in Germany.

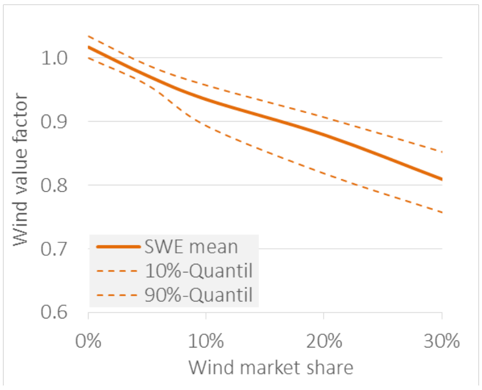

Figure 13. All sensitivities indicate a moderate loss of wind power's market value in Sweden.

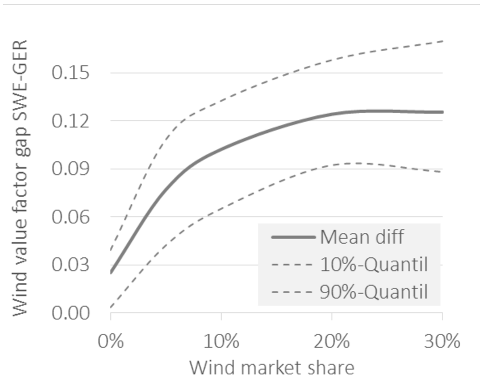

Figure 14. Beyond 10% wind market share, in all sensitivities the wind market value is higher in Sweden than in Germany. At 30%, the value gap ranges from 9 to 17 points (10% to 90%-quantil) with a mean of 13 points.

6.2 METEOROLOGICAL YEARS

The choice of the meteorological years has a major impact on results. We tested the years 2008-12 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. Figure 15 displays the value factor in Sweden and Germany. Three observations stick out: in both countries, the initial (low penetration rate) market value is strongly affected by the choice of the weather year; in Sweden, this remains true for high penetration rates; in Germany, the high penetration rate market values converge.

At 30%, the gap varies between 8 and 14 percentage points (Figure 16). 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). With all weather years, the result seems to be confirmed that the gap flattens out at about 20% wind penetration.

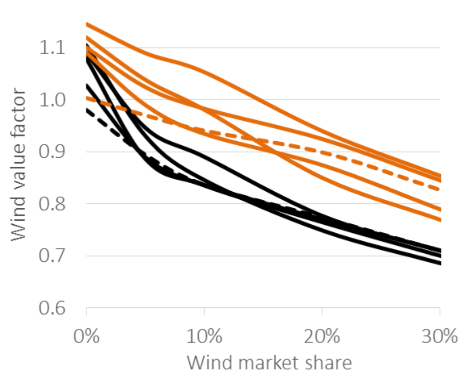

Figure 15. Value factor for Germany (black) and Sweden (orange) for different weather years.

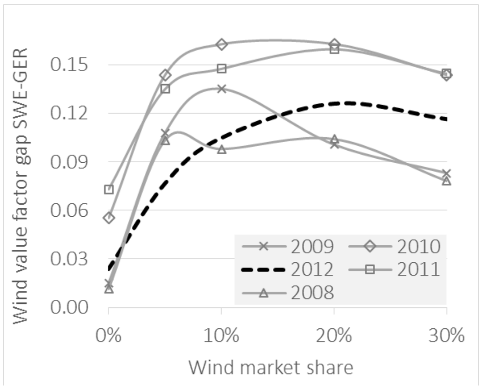

Figure 16. The value gap between Sweden and Germany for different years.

6.3 CLIMATE POLICY

Climate policy is modeled as a fixed price on CO2 that is uniformly applied across all countries; in the benchmark, a price of 20 €/t was assumed. Changing the CO2 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 fossil fueled generators. Maybe surprisingly, increasing the carbon price *also* reduces the value of wind power, both the value factor and absolute market value (Figure 17). The reason for the negative effect of higher CO_2 prices on wind value lies in investments in competing low-carbon technologies. Nuclear power and carbon capture plants (CCS) are the only non-variable low-carbon technologies in the model (the share of hydropower is fixed), and these two are base load technologies with high 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 (Figure 18). 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 VRE. Beyond this threshold, the base load investment effect dominates the emission cost effect.

Of course this effect disappears if nuclear power and CCS are impossible to build due to political or other reasons, and the effect is reduced in size if nuclear capacity is 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. The wind value is reduced much less in Sweden (Figure 19). At both higher and lower carbon prices, the wind value gap between hydro and thermal systems widens (Figure 20). At 100 €/t CO_2 and a wind penetration rate of 30%, Swedish wind power is a remarkable 35% more valuable than German wind power.

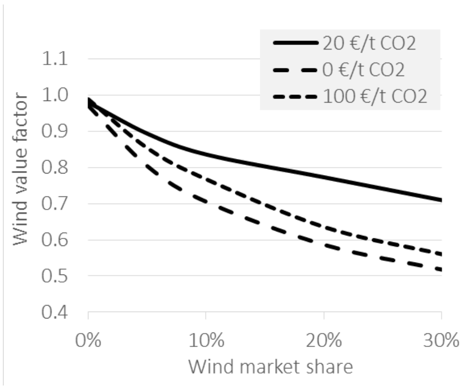

Figure 17. The wind value factor in Germany for different carbon prices.

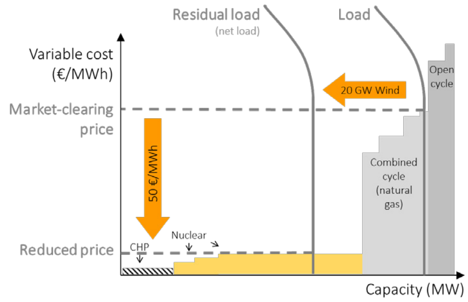

Figure 18. The price drop is more pronounced if a lot of low variable cost capacity is present. (Compare to Figure 5).

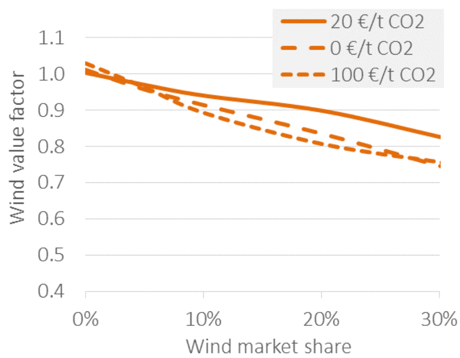

Figure 19. The wind value factor in Sweden for different carbon prices.

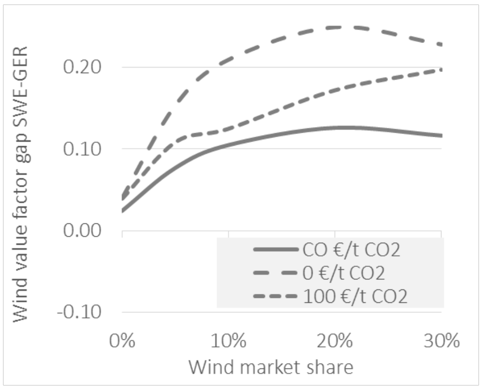

Figure 20. The value gap between Sweden and Germany for different CO_2 prices. High *and* low carbon prices increase the gap.

Another way to assess the impact of carbon pricing is to determine the cost-optimal amount 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 of wind generation costs (levelized electricity costs, LEC). Figure 17 shows the impressive result: if costs decline by 30% from current levels, wind power supply 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. Recall, however, that this is a long-term optimum that does not assume any nuclear capacity to be existing. At 30% cost reduction, there is only 2.5 GW of nuclear capacity in Sweden.

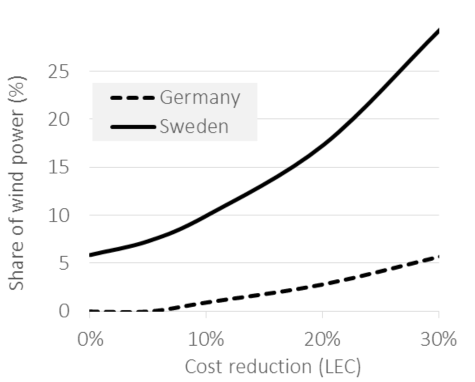

Figure 21. The cost-optimal share of electricity supplied from wind power in Germany and Sweden (the same LEC is assumed in both countries).

6.4 INTERCONNECTOR CAPACITY

To assess the impact of interconnector capacity, we first set it to zero and then double it relative to the current levels. At low market shares, the market value in both countries moves closer to each other, implying a negative effect on Swedish market value. At high market share, wind power benefits in *both* countries from increased interconnectivity. The benefit is larger in Germany (Figure 27).

We interpret this result as follows: there are two effects. On the one hand, more transmission capacity is beneficial for wind power, as it helps smoothing generation geographically. On the other hand, more interconnector capacity to Sweden allows German wind power to use Swedish hydro flexibility. In windy times, 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.

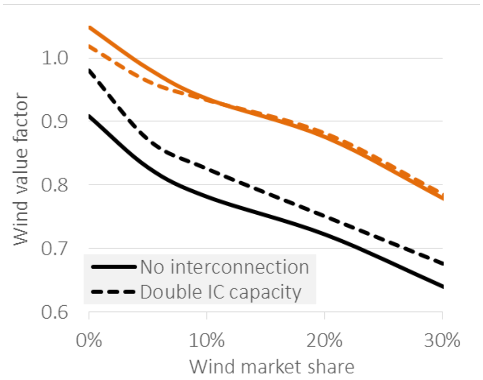

Figure 22. Value factor for Germany (black) and Sweden (orange) without interconnection (bold) and with double current interconnector capacity (dotted)

6.5 POWER SYSTEM FLEXIBILITY

Increasing the flexibility of the German (thermal) power system tends to improve the wind value in Germany and closes the gap at high penetration rates. There are various forms of power system flexibility. Here we discuss two, pumped hydro storage and a relaxation of mist-run constraints on thermal power plants.

Pumped hydro storage. Figure 23 and Figure 24 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 to Sweden closes – a little.

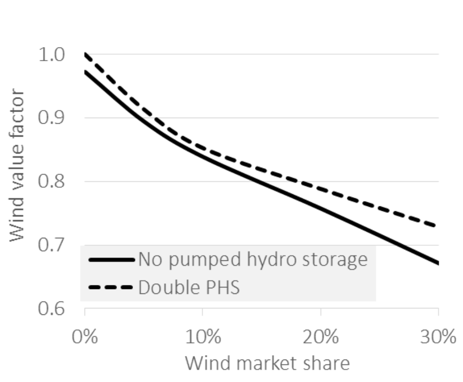

Figure 23. Wind value in Germany without storage and with double the current storage capacity.

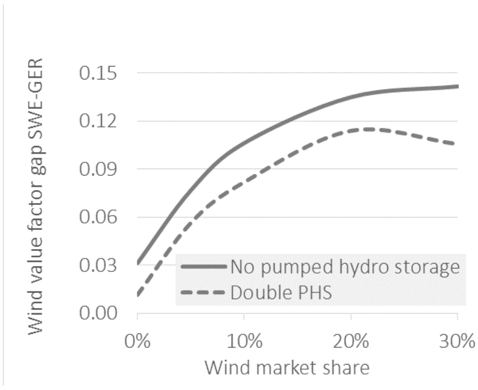

Figure 24. More storage closes the gap to Swedish wind value – but only at high penetration rates.

Must-run. EMMA models two important must-run constraints for power plants: combined provision of power with heat (CHP), and with ancillary services such as balancing power. Technological advances such as heat storage and batteries allow an easing of the constraints on power plant dispatch. Both countries have high CHP capacity. Relaxing these must-run constraints improves the wind value in both countries (Figure 25), but does not affect the difference much (Figure 26).

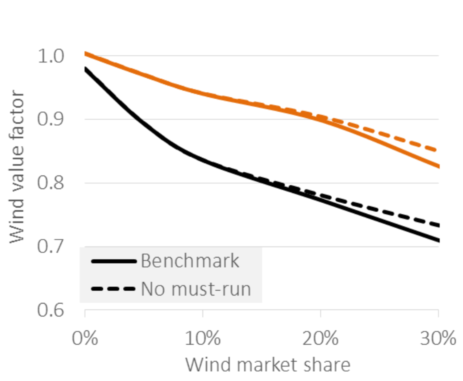

Figure 25. Wind value in Germany (black) and Sweden (orange) with and without must-run constraints.

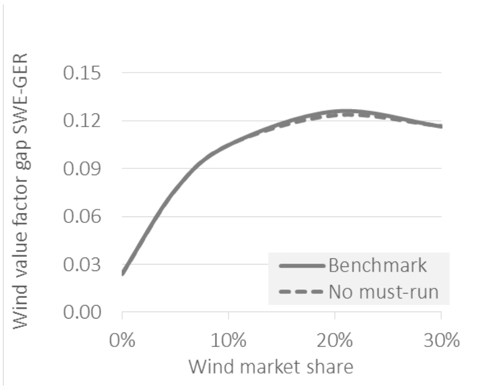

Figure 26. The gap in wind value with and without must-run.

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" (Chabot 2013).[5] In the United States, the specific rating of newly installed turbines has dropped from 400 W/m² to 250 w/m² during the past 15 years (Wiser & Bolinger 2015). With a lower specific rating, electricity is generated at a more constant rate, which can potentially increase the economic value of the electricity, or, equivalently, have better system integration properties.

Hirth & Müller (forthcoming) 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 90m hub height) with a low wind speed turbine (E115 evaluated at 120m hub height). It turns out that low wind speed turbines mitigate the market value drop dramatically in *both* power systems.

This finding might come as a surprise. Hirth & Müller had reported that the additional value of low wind speed turbines is lower in highly flexible power systems (more storage, more interconnection, 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 do not add up. Here, this does not seem to be true: 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 (Figure 27, Figure 28). At 30% wind penetration, the value factor of both standard and low wind speed turbines is 13 percentage points higher in Sweden than in Germany (Figure 29).

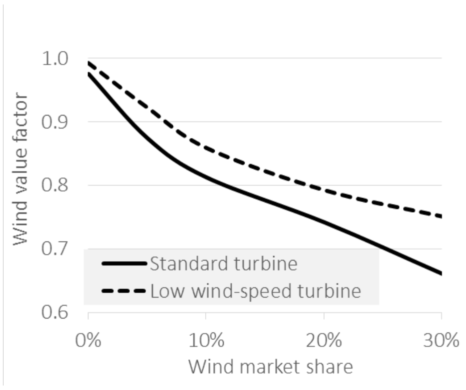

Figure 27. Wind value factor in Germany.

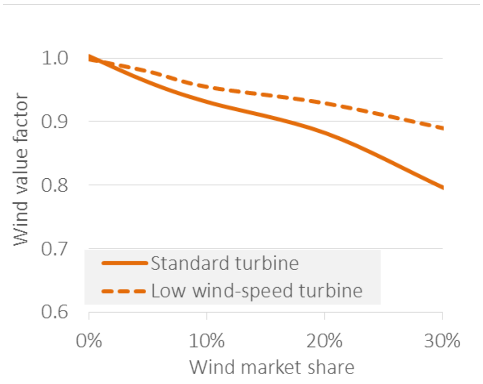

Figure 28. Wind value factor in Sweden.

[5] Molly (2011, 2012, 2014), IEA (2012), de Vries (2013), Gipe (2013), Wiser & Bolinger (2015), and Fraunhofer IWES (2013) provide more background on the technology and history of low wind speed turbines.

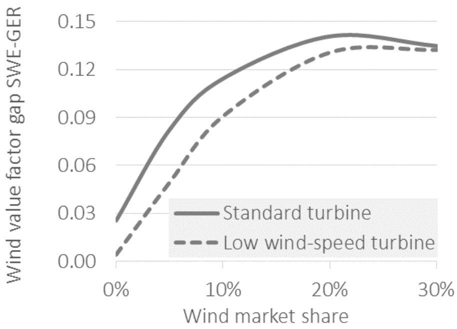

Figure 29. Value gap for standard vs. low wind speed turbines.

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 a capacity factor of about 70%. The high capacity factor limits the possibility to shift energy from one point in time to another, compensating the variable output of wind parks. In other words, the high capacity factor means that there is not too much room to maneuver.

This interpretation is supported by sensitivities on hydropower parameters. Increasing minimum flow constraints has a slightly negative impact on the value of wind power, as expected. Surprising, increasing hydropower as a whole by 50% does not have any significant impact. What does increase the value of wind power, however, is an upgrade of turbine capacity (Figure 30): the value gap increases from 11 to 13 points. In fact, the hydropower capacity factors is reduced to 50% – in term of dispatch characteristics, hydropower technology moves from a "base load" towards a "peak load" plant.

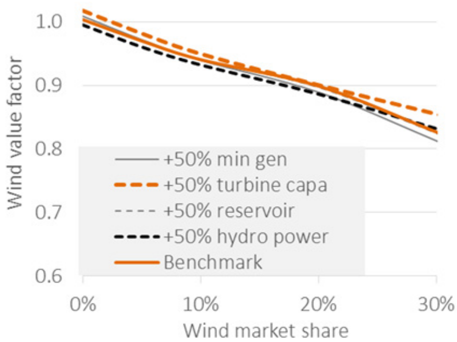

Figure 30. The value factor of Swedish wind power for different hydropower assumptions.

7 The value of hydropower

Large-scale deployment of wind power does not only affect the market value of wind power, but also that of other power plant types. It tends to increase the value of flexibility sources, particularly if they cannot expand. Clearly, hydropower is such a case.

Our model results indicate that hydropower does indeed provide benefits, albeit not many (Figure 32). At 30% wind penetration, the spot market value of each MWh generated by hydropower (the water value) is 5% greater than without wind power. On top of that, balancing reserves become scarcer such that the price of providing such reserves increases (Figure 33). This is another potential benefit for hydropower.

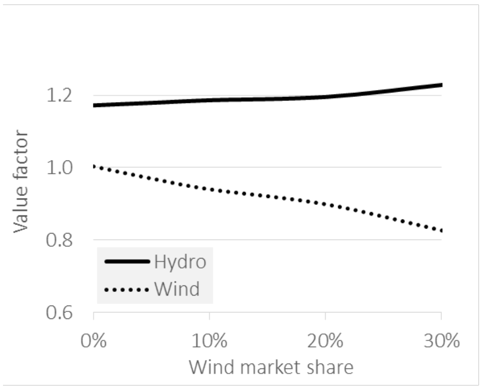

Figure 31. The market value of hydropower and wind power in Sweden (benchmark).

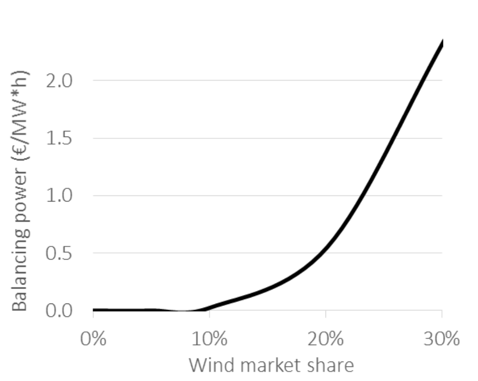

Figure 32. The price of balancing power in Sweden (benchmark).

8 Summary and conclusion

The results of this paper are summarized as follows:

- Theory, market data, and model results consistently indicate that flexible hydropower helps mitigate the value drop of wind power. In other words, the market value of electricity from wind declines with penetration, but it tends to decline more slowly if flexible hydropower is present.
- 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.
- These point estimates are subject to significant uncertainty. 80% of all sensitivity runs lead to a value increase of 12% to 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 around 20%. This seems to suggest that the hydro flexibility is "exhausted" at this level.
- 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.
- The value added of hydro flexibility is larger at high carbon prices. 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.
- Upgrading hydropower turbines, thereby reducing hydro capacity factors, helps boosting the value of wind power further.

This leads to the conclusions that the investor and public policy decision where to locate wind power should not only be driven by cost minimization, but also by value consideration. Wind should not be built where it is cheapest to produce electricity, but where the value of its output is higher than its costs. Hydro reservoir power helps to maintain a high value of wind power despite its variable nature.

Thera are several promising directions for future research. These results should be validated with 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 the base price. Rather than the market value of one year, the life-time market value of wind power could be determined, accounting for year-to-year variability of both wind and water inflow (and the correlation of these two). Good weather data and hydrological models are required for this.

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Appendix

		Germany					Sweden					absolute delta					relative delta					Drop			per pt		
		0%	5%	10%	20%	30%	0%	5%	10%	20%	30%	0%	5%	10%	20%	30%	0%	5%	10%	20%	30%	GER	SWE	Red	GER	SWE	Drop red
	Mean	0.99	0.90	0.83	0.75	0.68	1.02	0.97	0.93	0.88	0.81	0.03	0.08	0.10	0.12	0.13	0.03	0.09	0.12	0.17	0.19	0.31	0.21	0.10	1.0	0.7	33%
	10%-Quantil	0.97	0.85	0.78	0.68	0.59	1	0.96	0.89	0.82	0.76	0	0.04	0.07	0.09	0.09	0	0.05	0.08	0.12	0.12	0.25	0.16	0.07	0.8	0.5	24%
	90%-Quantil	1.03	0.93	0.87	0.79	0.73	1.03	0.99	0.96	0.91	0.85	0.04	0.11	0.13	0.16	0.17	0.04	0.13	0.17	0.23	0.29	0.42	0.27	0.14	1.4	0.9	40%
	90%-10%-Qtl	0.06	0.08	0.09	0.12	0.14	0.03	0.03	0.06	0.09	0.10	0.04	0.07	0.07	0.07	0.08	0.04	0.08	0.09	0.12	0.17	0.16	0.11	0.07	0.5	0.4	16%
	Min	0.90	0.80	0.70	0.56	0.44	0.97	0.93	0.88	0.70	0.59	-0.03	0.02	0.03	0.04	0.07	-0.03	0.02	0.03	0.04	0.09	0.19	0.10	0.00	0.6	0.3	-1%
	Max	1.10	0.97	0.95	0.91	0.82	1.15	1.09	1.05	0.95	0.90	0.14	0.16	0.21	0.25	0.23	0.15	0.19	0.30	0.43	0.44	0.55	0.42	0.19	1.8	1.4	56%
	Range	0.20	0.16	0.25	0.35	0.38	0.17	0.16	0.18	0.25	0.31	0.17	0.13	0.18	0.21	0.16	0.18	0.17	0.27	0.38	0.36	0.37	0.32	0.19	1.2	1.1	57%
Bench	**Bench**	**0.98**	**0.89**	**0.84**	**0.77**	**0.71**	**1.00**	**0.97**	**0.94**	**0.90**	**0.82**	**0.02**	**0.08**	**0.10**	**0.13**	**0.12**	**2%**	**9%**	**13%**	**16%**	**16%**	**0.27**	**0.18**	**0.09**	**0.9**	**0.6**	**34%**
	Bench aR	0.97	0.89	0.84	0.77	0.71	1.01	0.96	0.94	0.89	0.83	0.04	0.07	0.10	0.12	0.13	4%	8%	12%	16%	18%	0.27	0.17	0.09	0.9	0.6	35%
	Bench nR	0.97	0.91	0.84	0.78	0.73	0.99	0.97	0.94	0.90	0.86	0.02	0.06	0.09	0.12	0.13	2%	7%	11%	15%	18%	0.25	0.14	0.11	0.8	0.5	44%
Availability	FRA nuc seas	1.04	0.94	0.87	0.79	0.72	1.02	0.96	0.91	0.87	0.81	-0.03	0.02	0.04	0.08	0.08	-3%	2%	5%	10%	11%	0.32	0.21	0.11	1.1	0.7	35%
	moderate seas	1.02	0.92	0.85	0.78	0.72	1.01	0.97	0.92	0.88	0.81	-0.01	0.04	0.07	0.10	0.10	-1%	5%	8%	13%	13%	0.30	0.20	0.11	1.0	0.7	36%
	flat	1.04	0.94	0.87	0.79	0.72	1.03	0.98	0.92	0.87	0.81	-0.01	0.04	0.06	0.08	0.08	-1%	4%	6%	10%	12%	0.31	0.22	0.10	1.0	0.7	30%
CapPay	CapPayment	0.98	0.93	0.89	0.83	0.77	1.01	0.99	0.97	0.93	0.85	0.03	0.07	0.08	0.10	0.09	3%	7%	10%	12%	11%	0.21	0.16	0.05	0.7	0.5	25%
CO2	0 €/t	0.97	0.80	0.70	0.58	0.52	1.01	0.96	0.91	0.83	0.74	0.04	0.15	0.21	0.25	0.23	4%	19%	30%	43%	44%	0.45	0.27	0.19	1.5	0.9	41%
	50 €/t	1.00	0.88	0.78	0.68	0.63	1.03	0.98	0.92	0.84	0.80	0.04	0.10	0.14	0.17	0.17	4%	12%	18%	24%	27%	0.36	0.23	0.13	1.2	0.8	36%
	100 €/t	0.99	0.85	0.77	0.63	0.56	1.03	0.96	0.89	0.81	0.76	0.04	0.11	0.12	0.17	0.20	4%	13%	16%	27%	35%	0.43	0.27	0.16	1.4	0.9	37%
DiscountRate	0%	0.99	0.86	0.76	0.64	0.58	1.00	0.93	0.88	0.80	0.75	0.01	0.07	0.12	0.16	0.17	1%	9%	15%	24%	30%	0.41	0.25	0.16	1.4	0.8	39%
	3%	0.99	0.87	0.78	0.68	0.62	1.02	0.95	0.89	0.82	0.78	0.02	0.08	0.11	0.14	0.15	2%	9%	14%	21%	24%	0.37	0.24	0.13	1.2	0.8	35%
	15%	0.99	0.91	0.88	0.82	0.72	1.01	0.96	0.94	0.90	0.82	0.02	0.06	0.06	0.08	0.10	2%	6%	7%	10%	14%	0.27	0.19	0.09	0.9	0.6	31%
Efficiency	low efficiency	0.97	0.88	0.81	0.73	0.67	0.99	0.96	0.92	0.87	0.81	0.03	0.08	0.11	0.14	0.14	3%	10%	14%	19%	21%	0.30	0.18	0.12	1.0	0.6	39%
FuelPrice	doubleCoal	0.99	0.90	0.83	0.76	0.70	1.00	0.98	0.95	0.90	0.83	0.01	0.08	0.11	0.14	0.13	1%	9%	14%	19%	19%	0.29	0.17	0.12	1.0	0.6	41%
	doubleGas	0.96	0.85	0.79	0.72	0.65	0.97	0.93	0.89	0.84	0.78	0.01	0.08	0.10	0.12	0.13	1%	10%	13%	17%	20%	0.31	0.19	0.12	1.0	0.6	38%
	shaleGas	1.01	0.91	0.88	0.82	0.73	1.02	0.95	0.93	0.89	0.82	0.01	0.04	0.05	0.07	0.09	1%	5%	6%	8%	13%	0.28	0.20	0.08	0.9	0.7	28%
Hydro Para	+50% min gen	0.98	0.89	0.84	0.77	0.71	1.01	0.97	0.94	0.89	0.81	0.02	0.08	0.10	0.12	0.11	3%	9%	12%	15%	15%	0.28	0.20	0.08	0.9	0.7	29%
	+50% turbine ca	0.97	0.89	0.84	0.78	0.71	1.02	0.98	0.95	0.90	0.85	0.05	0.09	0.11	0.12	0.14	5%	10%	13%	16%	20%	0.26	0.16	0.09	0.9	0.5	37%
	+50% reservoir	0.98	0.89	0.84	0.77	0.71	1.00	0.97	0.94	0.90	0.82	0.02	0.08	0.10	0.12	0.11	2%	8%	13%	16%	16%	0.27	0.18	0.09	0.9	0.6	33%
	+50% everythin	0.98	0.90	0.84	0.78	0.71	1.00	0.96	0.93	0.89	0.83	0.02	0.07	0.10	0.11	0.12	2%	7%	11%	14%	17%	0.27	0.16	0.10	0.9	0.5	38%
InvestCost	expensive	0.99	0.91	0.85	0.79	0.71	1.00	0.97	0.93	0.89	0.83	0.01	0.06	0.08	0.10	0.12	1%	6%	10%	13%	17%	0.28	0.17	0.12	0.9	0.6	41%
MinGen	mtg0	0.98	0.89	0.84	0.78	0.72	1.00	0.97	0.94	0.90	0.83	0.02	0.08	0.10	0.12	0.11	2%	9%	13%	16%	16%	0.26	0.17	0.09	0.9	0.6	34%
	mtg29	0.98	0.89	0.84	0.77	0.69	1.00	0.97	0.94	0.89	0.80	0.03	0.08	0.10	0.12	0.11	3%	9%	12%	15%	16%	0.29	0.20	0.09	1.0	0.7	30%
	mtg34	0.98	0.89	0.84	0.76	0.67	1.01	0.97	0.94	0.88	0.78	0.02	0.07	0.10	0.12	0.11	2%	8%	12%	15%	17%	0.31	0.22	0.09	1.0	0.7	28%
	mtg39	0.99	0.90	0.84	0.75	0.64	1.01	0.97	0.94	0.86	0.76	0.02	0.08	0.10	0.11	0.11	2%	8%	12%	15%	17%	0.34	0.25	0.09	1.1	0.8	26%
NoNuc	allTech100	0.99	0.85	0.77	0.63	0.56	1.03	0.96	0.89	0.81	0.76	0.04	0.11	0.12	0.17	0.20	4%	13%	16%	27%	35%	0.43	0.27	0.16	1.4	0.9	37%
	NoNuc100	0.99	0.90	0.82	0.74	0.69	1.03	0.98	0.94	0.87	0.83	0.03	0.09	0.12	0.14	0.14	3%	10%	14%	18%	21%	0.31	0.19	0.11	1.0	0.6	37%
	NoNucCCS100	1.01	0.97	0.95	0.91	0.82	1.01	0.99	0.98	0.95	0.89	0.00	0.03	0.03	0.04	0.07	0%	3%	3%	4%	9%	0.19	0.12	0.07	0.6	0.4	38%
NTC	cheapIC	0.99	0.90	0.85	0.78	0.72	1.00	0.97	0.94	0.90	0.85	0.02	0.07	0.09	0.11	0.12	2%	8%	11%	14%	17%	0.26	0.16	0.11	0.9	0.5	40%
	today	0.90	0.83	0.79	0.73	0.65	1.03	0.97	0.94	0.87	0.78	0.13	0.14	0.15	0.15	0.13	14%	17%	19%	20%	20%	0.25	0.25	0.00	0.8	0.8	0%
	zeroNTC	0.91	0.83	0.78	0.72	0.64	1.05	0.98	0.94	0.87	0.78	0.14	0.16	0.15	0.15	0.14	15%	19%	20%	21%	22%	0.27	0.27	0.00	0.9	0.9	-1%
	doubleNTC	0.98	0.87	0.82	0.75	0.67	1.02	0.96	0.93	0.88	0.78	0.04	0.09	0.11	0.13	0.11	4%	11%	13%	18%	16%	0.31	0.23	0.07	1.0	0.8	23%
Nuclear	20% Nuc	0.98	0.89	0.84	0.76	0.65	1.00	0.97	0.94	0.88	0.78	0.03	0.08	0.10	0.12	0.12	3%	9%	12%	16%	19%	0.33	0.23	0.10	1.1	0.8	30%
	40% Nuc	0.98	0.89	0.82	0.68	0.56	1.01	0.96	0.91	0.81	0.74	0.03	0.07	0.08	0.13	0.17	3%	8%	10%	19%	31%	0.42	0.27	0.15	1.4	0.9	35%
	60% Nuc	0.99	0.86	0.75	0.56	0.44	1.00	0.94	0.88	0.70	0.59	0.01	0.08	0.13	0.14	0.15	1%	9%	17%	26%	34%	0.55	0.42	0.14	1.8	1.4	25%
Phase-Out	inv100	0.99	0.85	0.77	0.63	0.56	1.03	0.96	0.89	0.81	0.76	0.04	0.11	0.12	0.17	0.20	4%	13%	16%	27%	35%	0.43	0.27	0.16	1.4	0.9	37%
	Phase-Out20	0.98	0.89	0.84	0.77	0.71	1.00	0.97	0.94	0.90	0.82	0.02	0.08	0.10	0.13	0.12	2%	9%	13%	16%	16%	0.27	0.18	0.09	0.9	0.6	34%
	Phase-Out100	1.01	0.88	0.78	0.67	0.61	1.03	0.96	0.89	0.81	0.78	0.02	0.08	0.11	0.14	0.17	2%	9%	14%	21%	28%	0.40	0.25	0.15	1.3	0.8	38%
PriceCap	500€	0.97	0.90	0.84	0.77	0.71	1.00	0.97	0.94	0.89	0.82	0.04	0.07	0.10	0.12	0.11	4%	8%	12%	16%	16%	0.26	0.18	0.08	0.9	0.6	30%
	250€	0.96	0.90	0.84	0.78	0.72	1.00	0.97	0.95	0.90	0.82	0.03	0.08	0.10	0.12	0.11	4%	8%	12%	15%	15%	0.25	0.17	0.07	0.8	0.6	30%
	150€	1.00	0.92	0.86	0.80	0.73	1.03	1.00	0.97	0.92	0.85	0.03	0.08	0.10	0.12	0.12	3%	9%	12%	15%	16%	0.27	0.18	0.09	0.9	0.6	33%
Seasonality	both flat	1.03	0.93	0.86	0.78	0.71	1.01	0.97	0.92	0.88	0.81	-0.02	0.04	0.06	0.10	0.10	-2%	4%	7%	12%	14%	0.31	0.19	0.12	1.0	0.6	38%
	only gas seasona	1.04	0.94	0.87	0.79	0.72	1.02	0.96	0.91	0.87	0.81	-0.03	0.02	0.04	0.08	0.08	-3%	2%	5%	10%	11%	0.32	0.21	0.11	1.1	0.7	35%
	only avail sesao	0.97	0.88	0.83	0.76	0.70	1.00	0.97	0.94	0.91	0.83	0.04	0.09	0.12	0.15	0.13	4%	10%	14%	19%	19%	0.27	0.17	0.10	0.9	0.6	36%
Solar	5% solar	1.01	0.91	0.85	0.78	0.70	1.02	0.95	0.93	0.89	0.80	0.01	0.04	0.09	0.11	0.10	1%	5%	10%	14%	14%	0.31	0.22	0.09	1.0	0.7	28%
	10% solar	1.01	0.92	0.86	0.79	0.69	1.03	0.97	0.93	0.88	0.79	0.02	0.05	0.07	0.09	0.11	2%	6%	9%	12%	16%	0.33	0.24	0.09	1.1	0.8	27%
	15% solar	1.02	0.94	0.88	0.79	0.68	1.05	0.99	0.95	0.88	0.79	0.02	0.05	0.07	0.09	0.12	2%	5%	8%	12%	17%	0.35	0.25	0.09	1.2	0.8	27%
Storage	cheapSto	0.98	0.89	0.84	0.77	0.71	1.01	0.97	0.94	0.90	0.82	0.02	0.08	0.10	0.13	0.12	2%	9%	13%	16%	16%	0.28	0.18	0.10	0.9	0.6	34%
	todaySto	0.98	0.89	0.84	0.77	0.71	1.00	0.97	0.94	0.90	0.82	0.02	0.08	0.10	0.13	0.12	2%	9%	13%	16%	16%	0.27	0.18	0.09	0.9	0.6	34%
	zeroSto	0.97	0.89	0.84	0.76	0.67	1.00	0.97	0.94	0.89	0.81	0.03	0.08	0.11	0.13	0.14	3%	9%	13%	18%	21%	0.30	0.19	0.11	1.0	0.6	37%
	doubleSto	1.00	0.91	0.85	0.79	0.73	1.01	0.97	0.93	0.90	0.83	0.01	0.06	0.08	0.11	0.11	1%	6%	10%	15%	15%	0.27	0.18	0.09	0.9	0.6	35%
SuperFlex	very inflexible	0.97	0.89	0.84	0.76	0.67	1.00	0.97	0.94	0.89	0.81	0.03	0.08	0.11	0.13	0.14	3%	9%	13%	18%	21%	0.30	0.19	0.11	1.0	0.6	37%
	super flexible	1.00	0.93	0.85	0.79	0.74	1.00	0.97	0.93	0.90	0.85	0.00	0.05	0.08	0.11	0.12	0%	5%	10%	15%	16%	0.26	0.15	0.11	0.9	0.5	44%
ThermalFlex	noCHP	0.98	0.89	0.84	0.78	0.73	1.00	0.97	0.94	0.90	0.84	0.02	0.08	0.10	0.12	0.12	2%	9%	13%	16%	16%	0.25	0.16	0.09	0.8	0.5	36%
	noAS	0.98	0.89	0.84	0.78	0.72	1.00	0.97	0.94	0.90	0.83	0.02	0.08	0.10	0.12	0.11	2%	9%	13%	16%	16%	0.26	0.17	0.09	0.9	0.6	34%
	noAll	0.98	0.89	0.84	0.78	0.73	1.00	0.97	0.94	0.90	0.85	0.02	0.08	0.10	0.12	0.12	2%	9%	13%	16%	16%	0.25	0.15	0.09	0.8	0.5	38%
Years	2008	1.10	0.93	0.85	0.75	0.68	1.12	1.04	0.98	0.85	0.77	0.02	0.11	0.14	0.10	0.08	1%	12%	16%	13%	12%	0.42	0.35	0.07	1.4	1.2	16%
	2009	1.08	0.89	0.84	0.77	0.71	1.09	0.99	0.93	0.87	0.79	0.01	0.10	0.10	0.10	0.08	1%	12%	12%	14%	11%	0.37	0.30	0.07	1.2	1.0	18%
	2010	1.09	0.95	0.89	0.78	0.71	1.15	1.09	1.05	0.94	0.85	0.06	0.14	0.16	0.16	0.14	5%	15%	18%	21%	20%	0.38	0.29	0.09	1.3	1.0	23%
	2011	1.03	0.89	0.83	0.76	0.70	1.10	1.02	0.98	0.92	0.84	0.07	0.13	0.15	0.16	0.14	7%	15%	18%	21%	21%	0.33	0.26	0.07	1.1	0.9	22%
	2012	0.98	0.89	0.84	0.77	0.71	1.00	0.97	0.94	0.90	0.82	0.02	0.08	0.10	0.13	0.12	2%	9%	13%	16%	16%	0.27	0.18	0.09	0.9	0.6	34%
WindProfiles2	V90	0.98	0.88	0.82	0.75	0.67	1.00	0.96	0.93	0.89	0.81	0.03	0.08	0.11	0.14	0.13	3%	9%	14%	19%	20%	0.30	0.20	0.11	1.0	0.7	36%
	V110	0.99	0.93	0.87	0.80	0.77	1.00	0.98	0.96	0.93	0.90	0.00	0.05	0.09	0.13	0.13	0%	5%	10%	16%	17%	0.23	0.10	0.13	0.8	0.3	56%
	E70	0.97	0.87	0.80	0.73	0.63	1.00	0.96	0.92	0.87	0.77	0.03	0.09	0.12	0.14	0.14	3%	11%	16%	20%	22%	0.34	0.23	0.11	1.1	0.8	33%
	E82	0.98	0.87	0.81	0.74	0.66	1.00	0.96	0.93	0.88	0.79	0.03	0.09	0.12	0.14	0.14	3%	10%	15%	19%	20%	0.32	0.21	0.11	1.1	0.7	34%
	E115	0.99	0.92	0.86	0.79	0.75	1.00	0.98	0.95	0.93	0.89	0.01	0.06	0.10	0.14	0.14	1%	6%	11%	17%	18%	0.24	0.11	0.13	0.8	0.4	55%

Energiforsk

THE MARKET VALUE OF WIND ENERGY

Several studies shows that the revenues of wind power generators on spot markets – “market value” – decline with increasing deployment. This “value drop” is generally observed in power markets that are dominated by thermal power plants, such as in Germany.

This report assesses the market value of wind power for power systems with large amounts of large reservoirs in hydroelectric dams, such as in Sweden. The results indicate that when moving from 0 percent to 30 percent wind penetration, hydropower mitigates the value drop by a third. As a result, 1 MWh of electricity from wind is worth 18 percent more in Sweden than in Germany.

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