The Benefits of Flexibility: The Value of Wind Energy with Hydropower

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The Benefits of Flexibility: the Value of Wind Energy with Hydropower

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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, 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.

Key words – wind power, hydropower, system integration, market value

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1. Introduction

Renewable energy-based power generation is on the rise. By 2015, worldwide wind and solar power capacity exceeded 650 GW (Figure 1), nearly twice as much as total nuclear power capacity. 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 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.

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 (Grubb 1991a, IEA 2014), 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. 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. The most significant economic impact of wind power variability, however, is likely to be the reduced spot market value of wind energy (Ueckerdt et al. 2013, Hirth et al. 2015).

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2 On balancing requirements, see Ortega-Vazquez & Kirschen (2009), Holttinen et al. (2011) and Hirth & Ziegenhagen (2015).
3 For estimates of balancing costs, see Farahmand & Doorman (2012), Louma et al. (2014), and González-Aparicio & Zucker (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

\[ \bar{P}_{\text{wind}} = \frac{\sum_{t=1}^{T} W_t \cdot P_t}{\sum_{t=1}^{T} W_t} \]  

(1)

where \( t \in T \) 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 interpretation. Under perfect and complete markets, the increase in market value corresponds to the premium that consumers are willing to pay for generation from advanced VRE plants: 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” (Joskow 2011) is identical to the “system value” (Lamont 2008) or “marginal economic value” (Mills & Wiser 2012). The intersection of market value and levelized electricity costs defines the cost-optimal deployment level (Hirth 2015c).

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 1991b, Lamont 2008, Borenstein 2008, Joskow 2011, Mills & Wiser 2012, Gowrisankaran et al. 2015, Hirth et al. 2016, 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 \( VF_{\text{wind}} \) is defined as the ratio of the wind-weighted to the time-weighted average electricity price (base price),

\[ VF_{\text{wind}} \equiv \frac{\bar{P}_{\text{wind}}}{\bar{P}} \]  

(2)

where the base price \( \bar{P} \) is

\[ \bar{P} \equiv \frac{1}{T} \sum_{t=1}^{T} P_t. \]  

(3)

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 to 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.

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4 Other denominators exist. Hirth et al. (2016) use the load-weighted price. Here we follow the convention and use the time-weighted price (simple average).
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), and the model-based literature confirms this observation (Figure 4).

The value drop of wind (and solar) power potentially jeopardizes their long-term economic competitiveness; decarbonizing 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 (1991b), Lamont (2008), Hirth & Radebach (2016). 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 (2007), Sensfuß & Ragwitz (2011), Fripp & Wiser (2008), Hirth (2013, 2015a). 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.


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 Andrew Mills and Ryan Wiser (2012, 2013, 2014) 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. (2016) 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 (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 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, which reduces the market value of wind power. Some have called this the “self-cannibalization effect” (Delony 2015)\(^5\).

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5 This is not the “merit order effect” – the impact of wind power on the simple average electricity price (base price), see Sensfuß et al. (2008). 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 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. Førsund (2007) 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.

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 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
A 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.

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.6 It is open-source; the model code, as well as all input parameters and documentation, are freely available to the public.

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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.

#### Table 1: Hydropower capacity assumptions in EMMA

<table>
<thead>
<tr>
<th>Run of the river</th>
<th>Pumped hydro storage</th>
<th>Reservoir hydropower</th>
</tr>
</thead>
<tbody>
<tr>
<td>capacity</td>
<td>generation</td>
<td>capacity</td>
</tr>
<tr>
<td>Sweden</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Norway</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>France</td>
<td>12 GW</td>
<td>34 TWh</td>
</tr>
<tr>
<td>Germany</td>
<td>4 GW</td>
<td>20 TWh</td>
</tr>
<tr>
<td>NLD, BEL, POL</td>
<td>&lt; 1 GW</td>
<td>&lt; 1 TWh</td>
</tr>
</tbody>
</table>

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.

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.

### 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 equations (1) to (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.

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

The impact of the features not modeled (right column) is based on personal assessment.
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 Figure 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% 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 8. The market clearing price in a thermal power system with and without wind power.

Figure 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.

Figure 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.

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. Figure 11 and Figure 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.
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. Figure 13 reports the mean, 10%, and 90% quantiles for Germany. Figure 14 displays results for Sweden and Figure 15 for the value gap. As we lack information about the distribution of uncertain parameters, 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.
Figure 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% to 90%-quantile) with a mean of 13 points.

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 2008-12 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. Water inflow to hydro reservoirs, however, was not varied.

Figure 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 (Hirth 2013). In both countries, wind power also benefits from seasonal correlation with electricity consumption; winters tend to feature both stronger winds and higher electricity demand. Second, the German market value at high penetration is insensitive to choice of the year. Finally, the Swedish market value remains sensitive at high penetration. 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.

At 30% penetration, the wind value gap between the two countries varies between 8 and 14 percentage points, depending on the weather year (Figure 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 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 (Figure 18). The reason for the negative effect of higher CO\(_2\) prices on wind value lies in the effect of 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 (Figure 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. The wind value reduction is much lower in Sweden (Figure 20). At both higher and lower carbon prices, the wind value gap between hydro and thermal systems widens (Figure 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. 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 CO₂, we determine the cost-optimal quantity of wind power for different levels of reductions in wind generation costs (levelized electricity costs, LEC). Figure 18 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. 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 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 (Figure 28).

We interpret this finding as representing the following 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.

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 (IEA 2014, Brouwer et al. 2016), most obviously electricity storage (Zhao et al. 2015, Foley et al. 2015). These have been called “integration options” (Hirth & Ueckerdt 2013b) because they facilitate the integration of variable renewables into power systems, or “mitigation measures” (Mills & Wiser 2014) 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.

Pumped hydro storage. Figure 24 and Figure 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.

![Figure 24. Wind value in Germany without storage and with double the current storage capacity.](image)

![Figure 25. More storage narrows the gap to Swedish wind value.](image)

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 (2015b). Technological advances such as heat storage and batteries allow for constraints on power plant dispatch to be eased (Nuytten et al. 2013, Fang & Lahdelma 2016). Both countries have high CHP capacity, so relaxing these must-run constraints improves the wind value in both countries (Figure 26) without significantly affecting the value gap (Figure 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” (Chabot 2013). 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, in other words, have better system integration properties.

Hirth & Müller (2016) 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 emerges that low wind speed turbines mitigate the market value drop dramatically in both power systems (Figure 28, Figure 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 & Müller report 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 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.

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Hirth (2016): Wind market value in hydro systems

Figure 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.

Figure 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.

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 (Figure 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 & Wiser 2014). Clearly, hydropower is such a case.

Our model results indicate that hydropower benefits from wind deployment, albeit not much (Figure 31). At 30% wind penetration, 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 (Figure 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 is supportive.** 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:** 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.

- **Uncertainty and robustness:** 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 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 lever 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.

9. Conclusion

The investor and public policy decision on 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 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. 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.

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.
Literature


Gipe, Paul (2013): Low Wind Speed and Medium Wind Speed Turbines or New Large Diameter Turbines with Low Generator Ratings, www.windworks.org/cms/index.php?id=43&t_ttnews%5Btt_news%5D=2606&cHash=b989a0900b8d8a46a22f15376380a6f2


Mills, Andrew & Ryan Wiser (2013): “Changes in the economic value of wind energy and flexible resources at increasing penetration levels in the Rocky Mountain Power Area”, Wind Energy online.


Obersteiner, Carlo & Marcelo Saguan (2010): “Parameters influencing the market value of wind
power – a model-based analysis of the Central European power market”, European Transactions on Electrical Power 21(6), 1856-68.


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