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

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HIGHLIGHTS

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

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ABSTRACT

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

1. Introduction

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

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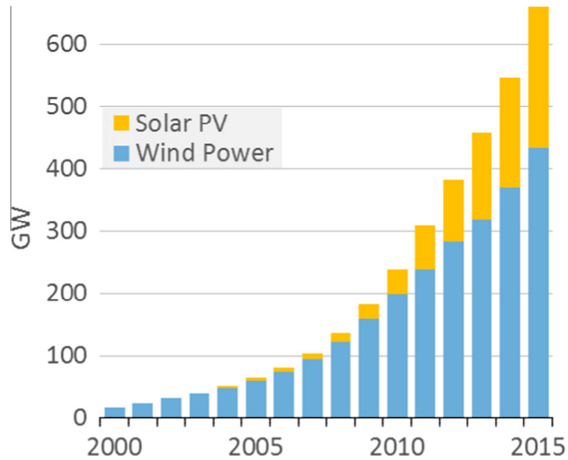

Fig. 1. Wind and solar power capacity installed globally. Own illustration based on data from REN21 [64].

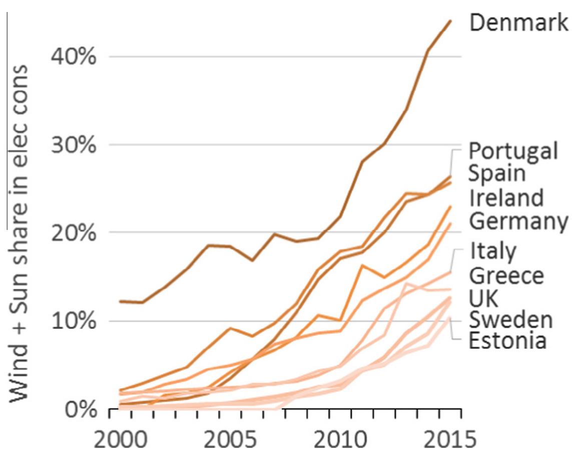

Fig. 2. In a number of countries, wind and sun supply more than 15% of power demand. Own illustration based on data from IEA Electricity Statistics.

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

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

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

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

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

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

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

$$VF_{wind} \equiv \frac{\overline{P}_{wind}}{\overline{P}}, \quad (2)$$

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

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

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

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

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

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

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

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