The Market Value of Wind and Solar Power: an Analytical Approach

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This is work in progress
Wind & sun deliver 15+% of electricity in some regions

Wind and solar power have been growing strongly, and are expected to continue to grow.

Wind and solar power combined now supply more than 10% of electricity in several power systems (and more than 20% in some) – they have become mainstream technologies.
In 2014, almost half of all new power generation capacity globally was based on renewables – of which wind and solar power captured the lion’s share of 70%.
Renewables are becoming cheaper and cheaper ...
Renewables are becoming cheaper and cheaper ...
Renewables are becoming cheaper and cheaper...

Residential small-scale rooftop solar PV costs in Germany

Economics has two sides: costs and value.
For economics, it matters *when* electricity is produced.

**German spot priced during four days**

German day-ahead spot price. 13-17 March 2014. On Sunday morning, the instantaneous wind penetration rate exceeded 50%.
**Value factor:** the relative price of wind power

<table>
<thead>
<tr>
<th>Wind in Germany</th>
<th>Base price (€/MWh)</th>
<th>Wind Revenue (€/MWh)</th>
<th>Value Factor (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>23.1</td>
<td>22.7</td>
<td>0.96</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>2014</td>
<td>35</td>
<td>30</td>
<td>.86</td>
</tr>
</tbody>
</table>

↑ Simple average of all hours of the year  
↑ Wind-weighted average  
↑ Ratio of these two
The relative value of electricity from wind and solar power is reduced as their market share grows. This has been called the “cannibalization effect”, but in fact it is simply diminishing returns. For solar power, the value drop is more pronounced.

Value Factor = Market value / base price

Each dot represents one year

Updated from Hirth (2013): Market value
The mechanics behind the value drop

Variable cost (€/MWh)

Market-clearing price

Reduced price

Capacity (MW)

Load

Residual load (net load)

Market-clearing price

30 €/MWh

20 GW Wind

Combined cycle (natural gas)

Open cycle

CHP

Nuclear

Lignite

Hardcoal

Reduced price

Combined cycle (natural gas)
At 30% penetration, the value factor of wind falls to 0.5 – 0.8 of the base price. In Germany, it has already fallen from 0.96 to 0.86 as penetration increased from 2% to 8%. The value drop jeopardizes power system decarbonization and transformation.
Market value research

Status quo of the literature

• Many quantitative studies based on numerical modelling

• Scatter literature, lack of synthesis

• Little theoretical understanding, in fact, Lamont (2008) might be the only one

Our contributions to the literature

1. Empirical: new data, new econometrics, better synthesis

2. Theoretical: an analytical expression for the value drop
A (linear) approximation of the value drop

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

\[ \bar{P}_{wind}(\Pi) = \beta_0 - \Pi \cdot \beta_1 \]

\[ \Pi = \frac{\sum_{t=1}^{T} W_t}{\sum_{t=1}^{T} L_t} \]
1. Econometrics
Quantitative Literature: overview

![Graph showing wind market share vs. wind value factor]

- $y = -1.02x + 1.00$

<table>
<thead>
<tr>
<th>Study Type</th>
<th># of Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed (realized) prices (&quot;market data&quot;)</td>
<td>4</td>
</tr>
<tr>
<td>Numerical dispatch model (&quot;short-term model&quot;)</td>
<td>8</td>
</tr>
<tr>
<td>Numerical investment and dispatch model (&quot;long-term model&quot;)</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18</strong></td>
</tr>
</tbody>
</table>
Within- and between study variation

Market value of wind power

Market share of wind power

study 1

study 2
Within- and between study variation

Market value of wind power

Market share of wind power

Pooled OLS estimator
Within- and between study variation

Market value of wind power

Market share of wind power

Two-way fixed effects estimator (?)
Clustering based on exogenous information

• We know not only results, also methodology of studies

• We can cluster studies into two groups
  • short-term approaches (ST)
  • long-term approaches (LT)
  • expectation: slope should be smaller in LT models, as they account for capital adjustments

• We can also cluster studies into three groups
  • short-term approaches based on numerical modelling (ST models)
  • econometric estimates based on observed market data (market)
  • long-term approaches based on numerical modelling (LT models)
Clustering estimates

# of subsamples  1  2  3  N

Pooled data; Within and between variance = OLS

ST & LT

ST, LT and market estimates

Within variance only = two-way fixed effects
Clustered and pooling

<table>
<thead>
<tr>
<th></th>
<th>1 cluster</th>
<th>2 clusters</th>
<th>3 clusters</th>
<th>N clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pooled (OLS)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Separated (2-way fixed effects)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
</tbody>
</table>

For separate model, we report mean coefficient estimates (model democracy, or rather: “study democracy”).
### Results: different estimates

<table>
<thead>
<tr>
<th>Slope estimate</th>
<th># of studies</th>
<th>OLS (within &amp; between)</th>
<th>FE (within only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pooled</td>
<td>18</td>
<td>-1.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>Short-term</td>
<td>12</td>
<td>-1.3</td>
<td>-1.9</td>
</tr>
<tr>
<td>Long-term</td>
<td>16</td>
<td>-0.7</td>
<td>-0.9</td>
</tr>
<tr>
<td>Market data</td>
<td>4</td>
<td>-0.9</td>
<td>-1.4</td>
</tr>
<tr>
<td>Short-term model</td>
<td>8</td>
<td>-1.2</td>
<td>-2.0</td>
</tr>
<tr>
<td>Long-term model</td>
<td>6</td>
<td>-0.7</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

- Short-term numerical models estimate steeper slope than market data suggests.
- Studies individually show steeper slope than pooled sample.
Conclusions and next steps

• New studies and more diverse econometric approaches confirm the established result: the value factor (relative price) of wind power drops as its market share increases

• Long-term models (accounting for changes in the capacity mix): drop of 0.7 – 0.9 percentage points per percentage point increase in market share

• Short-term models and market data estimates: 0.9 – 2.0

• What is the information value of between-model variation?

• Apply panel data techniques more rigorously?
2. Theory
A linearized supply curve (merit-order curve)

\[ P_t = \alpha \cdot \frac{R_t}{L_{max}} \quad \text{and} \quad R_t = L_t - W_t \]
The market value of wind power: analytically

- \( P_t = \alpha \cdot \frac{R_t}{L_{\text{max}}} \) (price, as above)
- \( \lambda_t = \frac{L_t}{L_{\text{max}}} \) (normalized load time series)
- \( \omega_t = \frac{W_t}{C} \) (normalized wind in-feed time series)
- \( \bar{P}_{\text{wind}} = \frac{\alpha}{L_{\text{max}}} \cdot \frac{\sum_{t=1}^{T} W_t \cdot R_t}{\sum_{t=1}^{T} W_t} \) (market value definition, as above)
- \( \bar{P}_{\text{wind}} = \frac{\alpha}{L_{\text{max}}} \cdot \left\{ L_{\text{max}} \cdot \frac{\sum_{t=1}^{T} \omega_t \cdot \lambda_t}{\sum_{t=1}^{T} \omega_t} - C \cdot \frac{\sum_{t=1}^{T} \omega_t^2}{\sum_{t=1}^{T} \omega_t} \right\} \)
- \( C = \Pi \frac{\bar{L}}{\bar{\omega}} = \Pi \frac{\bar{\lambda} \cdot L_{\text{max}}}{\bar{\omega}} \)
- \( \bar{P}_{\text{wind}} = \alpha \cdot \left\{ \frac{\sum_{t=1}^{T} \omega_t \cdot \lambda_t}{\sum_{t=1}^{T} \omega_t} - \Pi \cdot \frac{\bar{\lambda}}{\bar{\omega}} \cdot \frac{\sum_{t=1}^{T} \omega_t^2}{\sum_{t=1}^{T} \omega_t} \right\} \)
Market value in terms of (co-) variances

Using the fact that:

- \( \text{cov}(\omega_t, \lambda_t) = \frac{1}{T} \sum_{t=1}^{T} \omega_t \cdot \lambda_t - \bar{\omega} \bar{\lambda} \)  (definition of covariance)
- \( \text{var}(\omega_t) = \frac{1}{T} \sum_{t=1}^{T} \omega_t^2 - \bar{\omega}^2 \)  (definition of variance)
- \( c_v(\omega_t) = \frac{\sqrt{\text{var}(\omega_t)}}{\bar{\omega}} \)  (def. of coefficient of variation)

We derive:

- \( \bar{P}_{\text{wind}} = \alpha \cdot \bar{\lambda} \cdot \left\{ (1 + \frac{\text{cov}(\omega_t, \lambda_t)}{\bar{\lambda} \bar{\omega}}) - \Pi \cdot \left(1 + \frac{\text{var}(\omega_t)}{\bar{\omega}^2}\right) \right\} \)
- \( \bar{P}_{\text{wind}} = \alpha \cdot \bar{\lambda} \cdot \left\{ (1 + \frac{\text{cov}(\omega_t, \lambda_t)}{\bar{\lambda} \bar{\omega}}) - \Pi \cdot (1 + c_v(\omega_t)^2) \right\} \)
Interpreting: intercept and slope

\[
\bar{P}_{\text{wind}} = \alpha \cdot \bar{\lambda} \cdot \left\{ \left( 1 + \frac{\text{cov}(\omega_t, \lambda_t)}{\bar{\lambda} \bar{\omega}} \right) - \Pi \cdot (1 + c_v(\omega_t)^2) \right\}
\]

**Intercept: a function of ...**

\[
\lim_{\Pi \to 0} \bar{P}_{\text{wind}} = \bar{P} \cdot \left( 1 + \frac{\text{cov}(\omega_t, \lambda_t)}{\bar{\lambda} \bar{\omega}} \right)
\]

- ... the covariance btw load & wind
- ... the “capacity factors” of both time series

**Slope: a function of ...**

\[
\frac{\partial \bar{P}_{\text{wind}}}{\partial \Pi} = -\alpha \cdot \bar{\lambda} \cdot (1 + c_v(\omega_t)^2)
\]

- ... the capacity factor of load
- ... the variance of wind generation, expressed as it’s coefficient of variation

<table>
<thead>
<tr>
<th>Wind</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02</td>
<td>1.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.25</td>
<td>-2.47</td>
</tr>
</tbody>
</table>
Conclusions and next steps

• To the best of our knowledge, this is the first expression of the market value of wind power as a function of its statistical properties and those of load

• Lamont (2008) provides the only other expression, but assumes prices to be given

• It is the covariance between load and wind that determines the wind value initially

• *It is the variance of wind that determines the value drop* – independent of the correlation with load

• Constant wind generation would also lead to dropping value, but the slowest drop possible

• “More constant” wind generation is more robust against value loss: wind turbines with a higher capacity factor and lower coefficient of variation ⇒ Hirth & Müller (forthcoming)
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