The Integration Costs of Wind and Solar Power

An overview of the Debate on the Effects of Adding Wind energy and Solar Photovoltaic into Power Systems

D. Pescia, C. Redl

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Wind power and solar PV become key pillars of the European power system

IEA (2016), adapted from Hirth (2015), data for 2015 runs until 10/2015

Development of variable renewables in the 10 EU countries with shares above 10% in 2015

RES-E share in the EU generation mix 2030

Fraunhofer IWES (2015); Assumptions based on national energy strategies and ENTSO-E scenarios in line with EU 2030 targets

EU 2030
50% RES-E in the generation mix
30% Wind and PV in the generation mix
Project scope: generation costs alone (as captured e.g. by the LCOE) is not sufficient. A system perspective must be embraced in order to capture the economic challenges of power sector transformation.

Range* of levelized cost of electricity (LCOE) 2015

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Germany</th>
<th>International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind (onshore)</td>
<td>6 - 9 ct/kWh</td>
<td>6 - 13 ct/kWh</td>
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<tr>
<td>Solar PV (large scale)</td>
<td>8 - 9 ct/kWh</td>
<td>13 - 16 ct/kWh</td>
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<tr>
<td>Hard Coal</td>
<td>7 - 11 ct/kWh</td>
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<tr>
<td>Gas (CCGT)</td>
<td>7 - 12 ct/kWh</td>
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<tr>
<td>Hinkley Point C (UK)</td>
<td>11.3 ct/kWh</td>
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* based on varying utilization, CO₂-price and investment cost

Agora Energiewende (2015e)
“Integration costs“ is a concept used to compare the total costs of wind and solar energy with those of other technologies: it is controversial and varies tremendously depending on power systems, perspectives and methodologies.

<table>
<thead>
<tr>
<th>Area of discussion</th>
<th>Key controversy / difference of perspectives</th>
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<tr>
<td>Calculation of costs</td>
<td>Lost revenues vs. Cost to consumers</td>
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<tr>
<td>Attributed costs</td>
<td>Non-optimized approach vs. Optimized approach</td>
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<td>System boundaries</td>
<td>Legacy system vs. Adapted system</td>
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<tr>
<td>Context of the analysis</td>
<td>Integration costs of new technologies vs. Interaction costs between technologies</td>
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<td>Focus of the analysis</td>
<td>Low internalization of external costs vs. High internalization of external costs</td>
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<td></td>
<td>Marginal costs (scientific analysis) vs. Average costs (political debate)</td>
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<td>System in transition vs. System after transition</td>
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Own illustration
Three components are typically discussed under the term “integration costs”: grid costs, balancing costs and the cost effects of vRES on conventional power plants (so-called “utilization effect”)

Overview of components discussed under „integration costs“

- Grid cost
- Balancing cost
- Cost effect of interaction with other power plants

- "Backup"**
- "Utilization effect"

- Depending on system and perspective

*Average costs for the German power system with a penetration rate of 50 percent wind onshore and PV. Calculation based on a three technology system (ignite, combined cycle and open cycle gas turbines), with CO₂ costs ranging from 10 to 80 EUR/CO₂ and gas prices ranging from 15 to 30 EUR/MWh. Cost effects on conventional plants can be negative if the reduction of external cost outweighs the effect of lower utilization of conventional power plants.

Undisputed and rather low

Disputed: experts disagree on whether the cost effect of interaction with other power plants should be considered as „integration costs“

Agora Energiewende (2015)
While a definition of „integration“ may be challenging, an objective definition of „costs“ is likely to be impossible

Overview of possible system boundaries and types of costs and benefits

- Direct cost of electricity
  - Buying and using technical equipment and fuel

- External cost of electricity
  - Cost and price of CO₂ emission
  - Cost and price of insurance
  - Cost and price of land use

- Impact on economy
  - Payments to local and international suppliers
  - Competitiveness through technology leadership or through low power prices

- Impact on foreign policy
  - Securing resources by military and political action

Adapted from NEA (2012)
Grid and balancing costs
Certain costs for building grids and balancing can be attributed without much discussion to the addition of new capacities. Several challenges remain nevertheless in identifying these costs.

<table>
<thead>
<tr>
<th>Overview of grid costs (distribution and transmission grid) for different renewable technologies</th>
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<tbody>
<tr>
<td><strong>Wind offshore</strong></td>
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<td><img src="image" alt="Wind offshore diagram" /></td>
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<tr>
<td><strong>PV ground mounted</strong></td>
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<td><img src="image" alt="PV ground mounted diagram" /></td>
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<tr>
<td><strong>PV rooftop</strong></td>
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<tr>
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</tbody>
</table>

Own illustration
Calculating grid costs due to renewable energies must be separated from other grid (re)investments

Approaches for calculating grid costs by comparing two different futures (one with low RES and one with high RES)

Own illustration
Grid costs depend strongly on the specific case and variation can be large

Best-case and worst-case examples of grid costs for rooftop solar PV

Example PV rooftop

Best case

Small PV plants on rooftop in cities or on industrial buildings may not require any grid upgrade

Worst case

Large PV plants on rooftop of uninhabited buildings may require significant grid upgrade

Own illustration
In economic studies, grid and balancing costs for PV and wind onshore are often estimated at +5 to +13 EUR/MWh, even with high shares of renewables. Grid costs for wind offshore are higher.

Representative grid and balancing costs for wind and solar power

Agora Energiewende (2015), based on NEP, IAEW, Consentec, IC London, KEMA, NEA
The results for distribution grid costs from different EU studies are characterized by high variations, reflecting system specificities, different assumptions and calculation methods.

Quantification of distribution grid costs in Europe

Agora Energiewende (2015), based on IC London, KEMA, NEA
“State-of-the-art” grid planning, allowing for some punctual curtailment, can reduce grid cost very significantly.

Cost effects of curtailing maximum feed-in of solar power

* Based on data of a solar power plant located in southern Germany, provided by EEG TU Wien
Balancing costs are driven by imperfect forecast on power production of intermittent renewables

Forecasted and real power production by solar PV

Additional flexibility required – costs occur in ancillary services and intraday market
In economic literature, balancing costs for wind onshore are typically about 2-3 EUR/MWh. Studies on PV are much less common, with estimation around 1 EUR/MWh.

Balancing cost for wind estimates from the academic literature

Adapted from Hirth et al. (2015)
In Germany, balancing costs have declined over the last seven years: improvements on the balancing market have outweighed the impact of increasing renewables.

Balancing reserve and cost development in Germany since 2008

Since 2008, vRES capacity has been multiplied by three in Germany, while balancing costs have decreased by 50% over the same period. Other factors have overcompensated the VRE expansion (depressing the requirement for balancing reserve requirement):

- TSO cooperation
- More competitive balancing power markets
- Improvement of forecasts
- More liquid spot markets
- Economic recession (increase balancing power supply)

Adapted from Hirth et al. (2015)
“Reduced utilization effect” – the cost of “interaction” between vRES and other power plants
Adding new wind and PV or new baseload to a power system has a different impact on the residual generation, and its costs.

### Explaining the residual load duration curve: adding significant solar PV (150 GW ~ 25% of electricity demand) or baseload

#### new PV

<table>
<thead>
<tr>
<th>Electricity demand and generation by Solar PV (day, 24 hours)</th>
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<tbody>
<tr>
<td>Example with 150 GW solar PV in Germany*</td>
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#### new baseload

<table>
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<th>Residual load duration curve (year, 8760 hours)</th>
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<td>Results from sorting all hours of a year (8760) according to the residual demand (max. to min.)</td>
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Example Germany with (left) 150 GW solar PV, assuming non-optimized solar PV plant design based on real infeed data 2014 (~25% of electricity demand) or with (right) 18 GW new baseload power plants (~25% of electricity demand)
Wind and solar energy shift the residual demand towards more mid-merit and peaker power plants, without reducing the maximal residual demand.

<table>
<thead>
<tr>
<th>Residual load duration curve</th>
<th>Cost effective power plant mix</th>
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<tr>
<td>Adding wind and solar capacity*</td>
<td>Capacity (in GW)</td>
</tr>
<tr>
<td>1400</td>
<td>6000</td>
</tr>
<tr>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Adding new baseload capacity*</td>
<td>20 GW</td>
</tr>
<tr>
<td>1400</td>
<td>6000</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
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</table>

Adding 50% vRES in the power system leads – in most cases - to higher specific generation costs of the conventional power (lower utilization of installed capacity and higher use of mid- and peak-merit).

The quantification of this „utilization effect“ depends on:
- the structure of the conventional power plant mix: it is driven by the capital costs and the fuel costs
- the pricing of externalities: if externalities are valued at very high costs, the “utilization effect” effect can become negative (→ integration benefits)

Own illustration and calculation
The cost of “reduced utilization” is very system specific

Schematic representation of power production by thermal power plants, before and after adding solar PV

- **Summer day, System 1**
  - Production before PV
  - Production after PV (=residual load)
  - "Lost revenues": Fossil fuel generators loose sales revenues in times of highest prices
  - Less backup cost: Less power plants are needed in systems with high demand by air conditioner

- **Winter day, System 2**
  - Production before PV
  - Production after PV
  - Higher cost to serve load: Same amount of peak capacity needed, even at very high shares of solar power

Own illustration
System adaptation, flexibility and further electrification allows higher utilization rates of residual power plants, reducing considerably the integration costs.
Adding new baseload or new wind and PV to a power system have a different impact on the residual generation, and its cost

<table>
<thead>
<tr>
<th>Key differences</th>
<th>Cost drivers (residual generation)</th>
<th>Calculation approaches</th>
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<tbody>
<tr>
<td>1. Wind &amp; solar do not reduce maximum residual demand (in Germany)</td>
<td>1. Higher specific capital cost due to lower avg. utilization of installed capacity</td>
<td>“Backup”</td>
</tr>
<tr>
<td>2. Wind &amp; solar shift residual demand from baseload to mid-merit and peak load</td>
<td>2. Higher specific operational cost* due to higher use of mid-merit and lower use of baseload power plants</td>
<td>“Utilization effect”</td>
</tr>
</tbody>
</table>

*Assuming investment costs of 20 GW “back-up” at a cost of 20 EUR/kW/year (old depreciated CCGT) or 30-50 EUR/kW/year (new OCGT) when 300 TWh variable renewables are added

Approach NOT to follow

1-3 €/MWh
An approach for quantifying the „utilization effect“ is described in our report. This approach has nevertheless led to controversial debates.

An example of integration costs calculated from additional costs and **less than proportional** decreased costs.

![Diagram](image)

- **Total integration cost („utilization effect“) is 500 M€**
- **Specific integration costs is**
  - … per MWh renewables (50 TWh): 10 €/MWh
  - … per MWh added renewables (25 TWh): 20 €/MWh
  - … per MWh total power (100 TWh): 5 €/MWh

*example here: fully considering higher specific generation cost as integration cost, assuming that specific cost of conventional generation increase from 60 to 70 EUR/MWh, multiplied by 50 TWh (alternative calculation: 3,5 bn EUR – 4,5 bn EUR/ 75 TWh*50 TWh)*
Based on this method, calculations of the „utilization effect“ of 50% wind and PV in Germany could range between -6 and +13 EUR/MWh, depending on gas costs and CO2 cost (and the way it is internalized).

High CO2 and natural gas assumptions drive down the cost of „reduced utilization“

![Diagram showing the cost impact of reduced utilization with different CO2 and gas cost assumptions.]

- Lower share of baseload generation
  - Contribution in % of electricity (Example Germany, 50% penetration***)
  - Peak load 85%
  - Mid merit 14%
  - Baseload 11%
  - “old” residual load 4%
  - “new” residual load with wind & solar PV (or new baseload) 4%

- Generation cost of different technologies (assumptions*)
  - Cost for “reduced utilization”
    - Cost increase in specific generation cost:
      - 10 EUR/tCO2, gas 30 EUR/MWh +24% (from 54 to 67 EUR/MWh)
      - 50 EUR/tCO2, gas 20 EUR/MWh +2% (from 90 to 92 EUR/MWh)
      - 80 EUR/tCO2, gas 15 EUR/MWh -5% (from 118 to 111 EUR/MWh)**

- Own calculation

* Assumingignite, CCGT and OCGT as base/mid-merit and peak technologies, natural gas price of 30 EUR/MWh
** Illustrative calculation, assuming the same generation mix as above (ie cost for CO2 are not internalized and have no impact on power plant dispatch)
*** Optimized technology mix as 30 EUR/tCO2, gas 30 EUR/MWh

(Cost of “reduced utilization” can be negative if the reduction of external costs outweighs the cost effect of lower utilization of conventional power plants.)
Total system costs
A total system costs approach of different scenarios would be a more appropriate approach, avoiding the controversial attribution of system effects to specific technologies.

Total system cost approach for comparing different renewable energy penetration scenarios.

Own illustration
The total system cost approach must be subject to an intensive and transparent sensitivity analysis.

Overview of key sensitivity analysis and impact assessments to accompany total system cost comparison.

Comparison of total system cost

X bn EUR

Sensitivity analysis

| Assumptions about renewables (type and cost) | Assumptions about power system flexibility | Consideration of externalities (health, environment, risk of accident) | Assessment of economic impacts |
| High cost (biomass, wind offshore) | Legacy system | Not considered | |
| Low cost (wind onshore, solar) | Flexible electrification of heat & transport | Fully internalized | |

Own illustration

Different assumptions on the development of global industries: „nuclear renaissance“ vs. „renewable breakthrough“.
Key insights of the study “The Integration Costs of Wind and Solar Power”

1. Three components are typically discussed under the term “integration costs” of wind and solar energy: grid costs, balancing costs and the cost effects on conventional power plants (so-called “utilization effect”). The calculation of these costs varies tremendously depending on the specific power system and methodologies applied. Moreover, opinions diverge concerning how to attribute certain costs and benefits, not only to wind and solar energy but to the system as a whole.

2. Integration costs for grids and balancing are well defined and rather low. Certain costs for building electricity grids and balancing can be clearly classified without much discussion as costs that arise from the addition of new renewable energy. In the literature, these costs are often estimated at +5 to +13 EUR/MWh, even with high shares of renewables.

3. Experts disagree on whether the “utilization effect” can (and should) be considered as integration costs, as it is difficult to quantify and new plants always modify the utilization rate of existing plants. When new solar and wind plants are added to a power system, they reduce the utilization of the existing power plants, and thus their revenues. Thus, in most cases, the cost for “backup” power increases. Calculations of these effects range between -6 and +13 EUR/MWh in the case of Germany at a penetration of 50 percent wind and PV, depending especially on the CO2 cost.

4. Comparing the total system costs of different scenarios would be a more appropriate approach. A total system cost approach can assess the cost of different wind and solar scenarios while avoiding the controversial attribution of system effects to specific technologies.

Agora Energiewende
Thank you for your attention!

Questions or Comments? Feel free to contact me:

dimitri.pescia@agora-energiewende.de

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