Nuclear Energy and Renewables: System Effects in Low-Carbon Electricity Systems

Evidence from a Recent NEA Publication

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1. Interaction between variable renewables, nuclear power and the electricity system

2. Quantitative estimation of system effects of different generating technologies
   - Costs imposed on the electricity system above plant-level costs
   - Total system-costs in the long-run
   - Impact of intermittent renewables on nuclear energy and other generation sources

3. Institutional frameworks, regulation and policy conclusions to enhance the sustainability, flexibility and security of supply of power generation and enable coexistence of renewables and nuclear power in decarbonising electricity systems
“System costs are the total costs above plant-level costs to supply electricity at a given load and given level of security of supply.”

- **Plant-level costs**
- **Grid-level system effects (technical externalities)**
  - Grid connection
  - Grid-extension and reinforcement
  - Short-term balancing costs
  - Long-term costs for maintaining adequate back-up capacity
- **Impact on other electricity producers (pecuniary externalities)**
  - Reduced prices and load factors of conventional plants in the short-run
  - Re-configuration of the electricity system in the long-run
- **Total system costs**
  - Take into account not only the costs but also the benefits of integrating new capacity (variable costs and fixed costs of new capacity that could be displaced)
  - Other externalities (environmental, security of supply, cost of accidents, ...)

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The Contribution of Nuclear to Reduce System Effects

• In some countries (France, Germany, Belgium) significant flexibility is required of NPPs:
  o Primary and secondary frequency control
  o Daily and weekly load-following.

• Good load-following characteristics
  o No proven impacts on fuel failures and major components
  o Availability factor reduction due to extended maintenance (1.2 – 1.8%)
  o Economical consequences of load-following mainly due to reduction in load factors

<table>
<thead>
<tr>
<th>Power Plant Type</th>
<th>Start-up Time</th>
<th>Maximal change in 30 sec</th>
<th>Maximum ramp rate (%/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open cycle gas turbine (OGT)</td>
<td>10-20 min</td>
<td>20-30 %</td>
<td>20 %/min</td>
</tr>
<tr>
<td>Combined cycle gas turbine (CCGT)</td>
<td>30-60 min</td>
<td>10-20 %</td>
<td>5-10 %/min</td>
</tr>
<tr>
<td>Coal plant</td>
<td>1-10 hours</td>
<td>5-10 %</td>
<td>1-5 %/min</td>
</tr>
<tr>
<td>Nuclear power plant</td>
<td>2 hours - 2 days</td>
<td>up to 5%</td>
<td>1-5 %/min</td>
</tr>
</tbody>
</table>

• Nuclear fleet management
  o Performing outages when electricity is less valuable minimises private and social losses Economical benefit is in the range of 0.5 – 1 USD/MWh (1-2% of LCOE) for the whole nuclear park.
  o Also reduces the residual demand balance and the need for additional capacity
• Crucial importance of the time horizon, when analyzing **adequacy back-up costs** and **impacts on dispatchable generators** (no issue for grid costs or balancing costs):

• **Adequacy and back-up costs:**
  
  o In the **short run** (*ex post*), in a system where existing capacity reliably covers peak demand, there are no back-up costs for new variable renewable capacity.
  
  o In the **long run** (*ex ante*), variable renewable capacity due to its low « capacity credit » demands dedicated back-up, which is not commercially sustainable on its own.

• **Impacts on dispatchable generators**
  
  o In the **short run**, the pecuniary externalities of subsidized, variable renewables (reduced electricity prices and load factors) will over-proportionally affect technologies with high fixed costs such as CCGTs.
  
  o In the **long run**, the structural re-composition of residual dispatchable capacity will over-proportionally affect technologies with high fixed costs such as nuclear.
  
  o Issue for investors and researchers: when does the short-run become the long-run?
In the short-run, renewables with zero marginal costs replace technologies with higher marginal costs, including nuclear as well as gas and coal plants. This means:

- Reductions in electricity produced by dispatchable power plants (lower load factors, compression effect).
- Reduction in average electricity prices on wholesale power markets (by 13-14% and 23-33%).

Together this means declining profitability especially for gas (nuclear less affected).
- Carbon emissions are reduced
- Security of supply risks as fossil plants close (borne out by reality, 30 GW in past two years).
• Renewable production will change generation structure also for back-up.
• Without countervailing measures (carbon taxes), nuclear power will be displaced by a more carbon-intensive mix of renewables and gas.
• Cost for residual dispatchable load will rise as more expensive technologies are used.
• No change in electricity prices for penetration levels < 25%.
• Capacity credit is calculated using complex probabilistic techniques (LOLP) and requires a sophisticated modeling of the electricity system.
• Residual load duration curves allow for simple and reliable estimation of the capacity credit

![Diagram showing capacity credit calculation](image)
Comparison of the residual load duration curve for a 30% penetration of fluctuating wind (blue curve) and 30% penetration of a dispatchable technology (red curve).
The auto-correlation of VaREN production reduces the effective contribution of variable resources to covering electricity demand.

“Grid parity” based on plant-level cost no indicator of costs for equivalent contribution to supply at the system level.

The marginal value should be taken into account in investment decision making!
Six countries, Finland, France, Germany, Korea, United Kingdom and USA analyzed

Grid-level costs for variable renewables at least one level of magnitude higher than for dispatchable technologies

- Grid-level costs depend strongly on country, context and penetration level
- Grid-level costs are in the range of 15-80 USD/MWh for renewables (wind-on-shore lowest, solar highest)
- Average grid-level costs in Europe about 50% of plant-level costs of base-load technology (33% in USA)
- Nuclear grid-level costs 1-3 USD/MWh
- Coal and gas 0.5-1.5 USD/MWh.

### System Costs at the Grid Level (average of 6 countries - USD/MWh)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Nuclear</th>
<th>Coal</th>
<th>Gas</th>
<th>On-shore wind</th>
<th>Off-shore wind</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration level</td>
<td>10%</td>
<td>30%</td>
<td>10%</td>
<td>30%</td>
<td>10%</td>
<td>30%</td>
</tr>
<tr>
<td>Back-up Costs (Adequacy)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.05</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Balancing Costs</td>
<td>0.53</td>
<td>0.35</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Grid Connection</td>
<td>1.71</td>
<td>1.71</td>
<td>0.94</td>
<td>0.94</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>Grid Reinforcement and Extension</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total Grid-Level System Costs</td>
<td>2.24</td>
<td>2.05</td>
<td>0.99</td>
<td>0.99</td>
<td>0.51</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Total Costs of Electricity Supply for Different Renewables Scenarios

- Comparing total annual supply costs of a reference scenario with only dispatchable technologies with six renewable scenarios (wind ON, wind OFF, solar at 10% and 30%)
  - Takes into account also fixed and variable cost savings of displaced conventional PPs

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th></th>
<th>UK</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ref.</td>
<td>10% penetration level</td>
<td>30% penetration level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conv. Mix</td>
<td>Wind on-shore</td>
<td>Wind off-shore</td>
<td>Solar</td>
</tr>
<tr>
<td>Total cost of electricity supply</td>
<td>80.7</td>
<td>86.6</td>
<td>91.3</td>
<td>101.2</td>
</tr>
<tr>
<td>Increase in plant-level cost</td>
<td>-</td>
<td>3.9</td>
<td>7.8</td>
<td>16.9</td>
</tr>
<tr>
<td>Grid-level system costs</td>
<td>-</td>
<td>1.9</td>
<td>2.8</td>
<td>3.6</td>
</tr>
<tr>
<td>Cost increase</td>
<td>-</td>
<td>5.8</td>
<td>10.5</td>
<td>20.4</td>
</tr>
<tr>
<td>Total cost of electricity supply</td>
<td>98.3</td>
<td>101.7</td>
<td>105.6</td>
<td>130.6</td>
</tr>
<tr>
<td>Increase in plant-level cost</td>
<td>-</td>
<td>1.5</td>
<td>3.9</td>
<td>26.5</td>
</tr>
<tr>
<td>Grid-level system costs</td>
<td>-</td>
<td>1.9</td>
<td>3.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Cost increase</td>
<td>-</td>
<td>3.4</td>
<td>7.3</td>
<td>32.3</td>
</tr>
<tr>
<td>Total cost of electricity supply</td>
<td>72.4</td>
<td>76.1</td>
<td>78.0</td>
<td>88.2</td>
</tr>
<tr>
<td>Increase in plant-level cost</td>
<td>-</td>
<td>2.1</td>
<td>4.2</td>
<td>14.3</td>
</tr>
<tr>
<td>Grid-level system costs</td>
<td>-</td>
<td>1.6</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Cost increase</td>
<td>-</td>
<td>3.7</td>
<td>5.6</td>
<td>15.7</td>
</tr>
</tbody>
</table>

- Total costs of renewables scenarios are large, especially at 30% penetration levels:
  - Plant-level cost of renewables still significantly higher than that of dispatchable technologies.
  - Grid-level system costs alone are large, representing up to 67% of the increase in unit electricity costs.
The integration of large amounts of variable generation and the dislocation it creates in electricity markets requires institutional and regulatory responses in at least three areas:

A. Markets for short-term flexibility provision
For greater flexibility to guarantee continuous matching of demand and supply exist in principle four options that should compete on cost:
  1. Dispatchable back-up capacity and load-following
  2. Electricity storage
  3. Interconnections and market integration
  4. Demand side management
So far dispatchable back-up remains cheapest.

B. Mechanisms for the long-term provision of capacity
There will always be moments when the wind does not blow or the sun does not shine. Capacity mechanisms (payments to dispatchable producers or markets with supply obligations for all providers) can assure profitability even with reduced load factors and lower prices.

C. A Review of Support Mechanisms for Renewable Energies
Subsidising output through feed-in tariffs (FITs) in Europe or production tax credits (PTCs) in the United States incentivises production when electricity is not needed (including negative prices). Feed-in premiums, capacity support or best a substantial carbon tax would be preferable.
Lessons Learnt

The integration of large shares of intermittent renewable electricity is an important challenge for the electricity systems of OECD countries and for dispatchable generators such as nuclear.

- Grid-level system costs for variable renewables are large (15-80 USD/MWh) but depend on country, context and technology (Wind ON < Wind OFF < Solar PV)
- Grid-level and total system cost increase over-proportionally with the share of variable renewables
- System effects of nuclear power exist but are modest compared to those of variable renewables
- Lower load factors and lower prices affect the economics of dispatchable generators: difficulties in financing capacity to provide short-term flexibility and long-term adequacy need to be addressed.

Policy Conclusions

1. **Account for system costs and ensure transparency of power generation costs.**
2. **New regulatory frameworks are needed to minimize and internalize system effects.**
   - (1) Capacity payments or markets with capacity obligations,
   - (2) Oblige operators to feed stable hourly bands of capacity into the grid,
   - (3) Allocate costs of grid connection and extension to generators,
   - (4) Offer long-term contracts (contracts for difference, feed-in-tariffs) to dispatchable base-load capacity.
3. **Recognize the role of dispatchable low-carbon technologies such as nuclear**
4. **Develop flexibility resources to enable the co-existence of nuclear and variable renewables in low carbon electricity systems.**