System Effects and electricity generation costs in low-carbon electricity systems

Marco Cometto, CFA
Nuclear Energy Analyst,
OECD/NEA Division of Nuclear Development
Outline of the presentation

A. COP 21 and decarbonisation scenarios

B. Main findings from the NEA study on System Effects

C. Coexistence of nuclear and variable renewables: technical challenges

D. Coexistence of nuclear and variable renewables: economic challenges

E. Take away messages
NDCs are not sufficient to achieve climate objectives, leading to a 2.7°C increase.
Challenges to achieve 2°C are immense, road to 1.5°C goes to uncharted territories.
Colossal investments for energy sector: 40 trillion USD + 35 in energy efficiency (2°C).
A complete reconfiguration of the electricity generation system is needed by 2050.

- Trends: rise of nuclear, a complete phase-out of coal and oil, a decrease of gas, large development of CCS and a massive increase of renewable energies.

**Coexistence of ≈40% of VRE, 40% of low-C dispatchable capacity, 20% of hydro.**
Current nuclear capacity of 390 GW to more than double by 2050 to reach over 900 GW, share of nuclear electricity would increase from 11% to 16%.

China sees largest increase in installed capacity and becomes largest nuclear power producer.

Formidable challenge: multiply current capacity by 2.3 in 35 years and increase investments in nuclear up to USD 110 billion/year over the period 2016-2050 (21 USD billion in 2015).

IEA WEO sees a nuclear capacity for 2040 of 600 GW (NewPolicies Scenario) and 820 GW (450 ppm scenario). IAEA says 385 or 632 GW by 2030 (low or high growth).
Outline of the presentation

A. COP 21 and decarbonisation scenarios

B. Main findings from the NEA study on System Effects

C. Coexistence of nuclear and variable renewables: technical challenges

D. Coexistence of nuclear and variable renewables: economic challenges

E. Take away messages
Background

Share of intermittent sources (solar and wind) in OECD countries generation

Source: IEA Electricity monthly reports
It was the first large quantitative study on SE

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 at low-marginal cost 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.

Uncertainties in the results.

Seminar on “Electricity Systems within the energy transition”, Brussels, 19 November 2016
Introduction

Recent fast deployment of subsidised Variable Renewable Energy (VRE) had a significant impact on the whole electricity systems in many OECD countries.

- Increasing needs for T&D infrastructure, challenges for balancing.
- Significant impacts on the mode of operation and flexibility requirements of conventional power plants in both the short- and long-run.
- Large effects on the electricity markets (lower prices, higher volatility) and on the economics of existing power plants.

- *Interconnected power systems yields effects that cannot be explained by considering its components in isolation.*
- Need to look at the electricity system as a whole and not at each component.
- Traditional metrics such as the LCOE are not sufficient anymore to adequately characterise and compare different generation sources.

Increasing attention has been given to the definition, analysis and quantification of system effects and costs in the scientific literature and in the policymaking areas.
Characteristics and Challenges of VRE

Wind does not always blow

Difficult to predict

Good sites are distant from load centers

- Grid-level system costs are very difficult to model and estimate. Also there is not an "all-inclusive" model.

- System costs are country-specific, strongly inter-related and depend on penetration level. Different cost categories influence each others.

- System effects can be understood and quantified only by comparing two systems.
Impact on the Residual Demand Load

Quantitative analyses performed by IER Stuttgart based on German electricity system

50% Renewables scenario (35% of VRE)

80% Renewables scenario (62% of VRE)

Significant number of hours in which Renewables fully meet the demand.

Residual demand load is determined more by the production of VRE than by demand.

Residual demand load loses its characteristics seasonal and daily patterns.

- More difficult to plan a periodic load-following schedule.
- Loss of predictable peak/off-peak pattern (ex: impact of PV on hydro-reservoir economics).

Need for more flexibility in the system (generation, electricity storage, interconnection and market integration, demand side management).
Assessing System Effects: The Short-Run and the Long-Run

Crucial importance of the time horizon, when assessing economical cost/benefits and impacts on existing generators from introducing new capacity.

Two scenarios describe the time effects of the introduction of new generation.

- **Short-term**
  - The introduction of new capacity occurs instantaneously and has not been anticipated by market players.
  - In the short-term physical assets of the power system cannot be changed. Investment occurred are sunk.
  - New capacity is simply added into a system already capable to satisfy a stable demand with a targeted level of reliability. No back-up costs for new VRE capacity.

- **Long-term**
  - The analysis is situated in the future where all market players had the possibility to adapt to new market conditions.
  - In the long-run, the country electricity system is considered as a green field, and the whole generation stock can be replaced and re-optimised.
  - VRE due to its low capacity credit requires dedicated back-up.

**Issue for investors and researchers: when does short-run become long-run?**

Impacts of VRE deployment depends on the degree of system adaptation and thus the speed of their deployment as well as on evolution of electricity demand.
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 the average electricity price on wholesale power markets (merit order effect).

<table>
<thead>
<tr>
<th></th>
<th>10% Penetration level</th>
<th>30% Penetration level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind</td>
<td>Solar</td>
</tr>
<tr>
<td>Load losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine (OCGT)</td>
<td>-54%</td>
<td>-40%</td>
</tr>
<tr>
<td>Gas Turbine (CCGT)</td>
<td>-34%</td>
<td>-26%</td>
</tr>
<tr>
<td>Coal</td>
<td>-27%</td>
<td>-28%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>-4%</td>
<td>-5%</td>
</tr>
<tr>
<td>Profitability losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine (OCGT)</td>
<td>-54%</td>
<td>-40%</td>
</tr>
<tr>
<td>Gas Turbine (CCGT)</td>
<td>-42%</td>
<td>-31%</td>
</tr>
<tr>
<td>Coal</td>
<td>-35%</td>
<td>-30%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>-24%</td>
<td>-23%</td>
</tr>
<tr>
<td>Electricity price variation</td>
<td>-14%</td>
<td>-13%</td>
</tr>
</tbody>
</table>

- Together this means declining profitability especially for OCGT and CCGT (nuclear is less affected).
- No sufficient economical incentives to built new power plants.
- Security of supply risks as fossil plants close.
• New investment in the presence of renewable production will change generation structure.
• Renewables will displace base-load on more than a one-to-one basis, especially at high penetration levels: base-load is replaced by wind and gas/coal (more carbon intensive).
• Cost for residual dispatchable load rises as technologies more expensive per MWh are used.
• No change in electricity prices for introducing VaRen at low penetration levels.
• These effects (and costs) increase with the penetration level.
Quantification of profile costs

We compare two situations: the residual load duration curve for a 30% penetration of fluctuating wind (blue curve) and 30% penetration of a dispatchable technology (red curve).

[Graph showing the comparison of load duration curves with and without wind.]
Auto-correlation and declining market values of VRE

- The *auto-correlation* of VRE production reduces the its effective contribution to the system and thus its **market value** at increasing penetration level.
- Self-sustaining, market-based finance of VRE even bigger challenge than for nuclear.

The marginal value should be taken into account in investment decision making!

Will VRE always need to be subsidised?

Is their LCOE declining faster than their value?
A study from EdF on VRE integration

- Very detailed study at an European scale performed by the French utility EdF.
- Scenario with high VRE penetration: 60% RES and 40% VRE (700 GW) and 85 GW of nuclear.
- Looking at technical and economic feasibility of large deployment of Wind & Solar.

**Key results**

- Geographical diversity helps, but there is still significant variability at EU level.
- Operational requirements on NPP are not different from those currently achieved in France.
- Despite large VRE capacity, the system needs **back-up capacity for security of supply**. The conventional mix requires less conventional base-load units and more peaking.
- Also **VRE will have to contribute to balancing** (downward flexibility), **ancillary services** and provide **new services** such as **fast frequency response (synthetic inertia)**.
- The **system need increased operating margins** to handle exposure to climate conditions.
- The average carbon emission is 125 gr/kWh (73 gr/kWh if gas replaces coal). **Full decarbonisation** can only be achieved with a significant share of **carbon free base-load**.
- Above a certain share of VRE, the **marginal efficiency** on CO₂ reduction decreases, and the marginal cost of these reductions increases.
- Integrating large share of VRE requires a **coordinated development of RES and network**.
- The **pace of RES deployment should be optimised** to limit total system costs and curtailment.
A new NEA study: Dealing with System Costs (mid 2017)

The NEA is undertaking a new study on the interaction between VRE, nuclear and the whole electricity system: “Dealing With System Costs In Decarbonising Electricity Systems: Policy Options”.

- Review and synthesise literature that has been published since 2012
- Calculate on the basis of rigorous cost optimisation model the total system costs for electricity systems with a common carbon constraint but different shares of variable renewables, nuclear and other generating technologies;
- Discuss the policy instruments available to internalise system costs.

Estimate the system costs of electricity systems with identical demand and carbon emission target in scenarios with different shares of VRE and nuclear.

- A CO₂ emissions target is fixed at 50 gr/kWh.
- Provide a realistic representation of a large, well interconnected power system, with abundant hydro resources and flexibility options (DSM, storage).
- Analysis performed with state-of-the-art modelling tools by team from MIT.
- Additional analysis to look at the impact of a system with (i) less interconnections, (ii) lower flexible hydro resources and (iii) more flexible nuclear capacity.

Final publication is expected for mid-2017.
Outline of the presentation

A. COP 21 and decarbonisation scenarios

B. Main findings from the NEA study on System Effects

C. Coexistence of nuclear and variable renewables: technical challenges

D. Coexistence of nuclear and variable renewables: economic challenges

E. Take away messages
Flexibility of nuclear power plants: an example from France

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

Power history of a French PWR reactor

- For 2/3 of the cycle the load fluctuates between 85% and 100%, while in the last third of the cycle the plant is operated in a base load mode.
- Daily load following, with power reductions up to 35%-40% of nominal power.
- “Stretch” can be observed in the last few days of operation.
Contribution to reduce system effects: flexibility of nuclear power plants

- Flexibility of nuclear power plants has constantly improved over time.
  - Several Gen II plants were already built with sufficient manoeuvring capabilities or have been already upgraded.
  - Strong flexibility is required by utilities and already implemented in the design of new Gen III NPPs.

<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>

- Economic impact of significant flexibility from NPPs
  - No proven impacts on fuel failures and major components.
  - Studies have shown correlation between load following and increased maintenance needs, but were unable to quantify the related costs.
  - EdF has observed a reduction in availability factor due to extended maintenance (1.2-1.8%).
  - The main economic consequence of load following is the reduction in load factor.
A. COP 21 and decarbonisation scenarios

B. Main findings from the NEA study on System Effects

C. Coexistence of nuclear and variable renewables: technical challenges

D. Coexistence of nuclear and variable renewables: economic challenges

E. Take away messages
Generation cost structure for nuclear: at 7% Discount Rate

**Nuclear energy is capital intensive**
- 70% capital costs (up-front)
  - 20% of which are interests.
- 85% of Fixed Costs
- 15% of Variable Costs
- Decommissioning costs are negligible (*discounting*).

**Impact of discount rate**
- Capital costs represent:
  - 50% at 3% discount rate.
  - 80% at 10% discount rate.

The cost structure of all low carbon technologies is very similar (high CAPEX, low OPEX), and they have similar “economic” characteristics.
- Economics strongly depends on total investment costs (*overnight, lead time, discount rate*).
- All capital intensive technologies are highly sensitive to discount rate (*project risk*).
- Variable costs of low-C electricity production are low, stable and well predictable over time.
Financing new generation capacity under current market conditions

- Electricity wholesale prices are very low in Europe, well below long-term average generation cost for all technologies.

- Several power plants in Europe are unable to recup variable generation costs:
  - Peaking and mid-load plants (OCGT and CCGT).
  - More surprisingly also capital intensive plants.

- The financial situation of several utilities has strongly deteriorated, jeopardising their ability to take on new investments.

- Utilities are not perceived anymore as part of a low-risk business (low β, favourable ratings, low cost of capital).

- Under these conditions, no Power Plant can be financed on a pure market basis.

- Still need to finance a large electricity infrastructure:
  - Generation infrastructure is ageing
  - Need to go toward a low-C generation mix
  - Transmission and Distribution
Current electricity markets and challenges ahead

Electricity markets in many OECD countries are based on **marginal cost pricing**:  
- Successfully enhanced competition and effectiveness in the electricity sector.  
- Effective in providing appropriate signals for short-term dispatch.  
- Does not provide appropriate long-term investment signal ("missing money" and SoS) and implicitly favour carbon intensive fossil fuel technologies.

**Current market designs are not well suited for investments in capital intensive technologies and won’t deliver a low-C mix.** Forcing low carbon technologies on a pure market basis would require very high CO₂ prices and entail some risk for SoS.

- A low-carbon mix with large quantity of VRE, will inevitably lead to high variability of electricity prices, with a high number of hours at VOLL and 1000s of hours at zero price, with a very skewed distribution of revenues for all generation capacities.  
- Electricity price will be strongly dependent on annual weather conditions (high/low wind production, high/low hydro production), with large fluctuations for VRE and base-load.  
- Electricity market risk (and political risk) will have an impact on the cost of capital.  
- Decreasing value of VRE generation and increased market risk will make full market finance for solar and wind very challenging.
New Market design for low-C technologies

1. High levels of low-carbon investments will need new market arrangements and a robust CO₂ price.

2. Low-Carbon technologies need a **long-term price signal**: price stability can be provided through long-term power purchase agreements (PPAs), feed-in premiums (FIP) or feed-in-tariffs (FITs) / contracts-for-difference (CfDs).
   - This does not mean the end of competition. However, it means proceeding from competing on marginal costs to competing on average costs through competitive auctions.
   - Regulated markets have their own challenges but provide the price and revenue stability that low carbon technologies require.

3. **Flexibility provision** through demand response, storage and improved interconnections are part of the new market design.

4. The **system costs** of all technologies must be allocated fairly and transparently:
   - Back-up power and increased “profile costs”
   - Balancing needs
   - Connection and reinforcement of transport and distribution costs
Outline of the presentation

A. COP 21 and decarbonisation scenarios

B. Main findings from the NEA study on System Effects

C. Coexistence of nuclear and variable renewables: technical challenges

D. Coexistence of nuclear and variable renewables: economic challenges

E. Take away messages
Decarbonising the energy sector is an immense challenge for all OECD countries.

Achievement of climate targets inevitably requires the full-decarbonisation of electricity sector by 2040/2050.

- Electrification of transport.
- Complete reconfiguration of the generation mix, with the coexistence of all available low-C sources.
- Massive investments are needed on generation, transmission and distribution.

New market design are needed to achieve this transition at the lowest cost.

Increasing attention is given on the topic of system effects

- Work at the IEA on the integration of VRE; NEA is undertaking a follow-up of the System Cost study.
- An in-depth analysis of the large VRE integration at an EU scale from the French utility EdF.

Key points on the integration of VRE

- Different effects in the short-run and the long-run
- System costs are country-specific, strongly interrelated and depend on penetration level
- The value of VRE generation decreases drastically with penetration level.
- System costs are large and need to be appropriately accounted for and internalised.
Thank you
For your attention

The NEA reports are available on-line


Contacts: Marco Cometto and Jan Horst Keppler
Marco.Cometto@oecd.org and Jan-Horst.Keppler@oecd.org
LCOE is the constant unit price of output ($/MWh) that would equalise the sum of discounted costs over the lifetime of a project with the sum of discounted revenues.

- Nuclear is the lowest cost options for all countries at 3% discount rate.
- Median cost of nuclear is slightly lower than coal or gas at 7% discount rate, but is higher at 10%.

Note: Assumes region specific fuel prices for US, Europe, Asia; 85% load factor; CO2 price of 30 USD/tonne.
- Cost of Renewables (in particular solar PV) has declined substantially since the last EGC and they are no longer cost outliers. Further cost reductions are expected.
- Plant-level costs are becoming of lesser importance. What is needed is the ability to ensure secure and cost-efficient supply at the system level.
Methodology and Challenges in defining and quantifying system costs

- Grid-level system costs are difficult to quantify (*externality*) and are a *new area of study*.
  - There is not yet a clear definition, nor a common methodology used and accepted internationally.
  - Knowledge and understanding of the phenomena is still in progress.
  - Each study makes its own assumptions, specific objectives and has a different level of detail.
  - Modelling and quantitative estimation is challenging and there is no “all-inclusive” model.
  - Strong difference between *short-term* and *long-term* effects and difficulties in seeing it recognised and acknowledged in the studies.

- Grid-level costs are country-specific, strongly inter-related and depend on penetration level. Different cost categories influence each others:
  - **Larger balancing areas**: balancing costs, cheaper optimal generation mix;
  - **More flexible mix, storage**: balancing costs, generally is more expensive.

- What we observe in electricity markets results from many factors, not only system effects.
- System effects also create demand for new markets and services (capacity, flexibility…).

**However, a consensus is emerging for considering as System Costs:**

- Grid cost (including distribution and transmission).
- Balancing costs.
- Utilisation costs (*profile costs or back-up costs*) including adequacy.
- **Still connection costs are substantial and should be considered.**

Seminar on “Electricity Systems within the energy transition”, Brussels, 19 November 2016
Another approach: the market value of variable renewables

Different methodologies robust findings: value drops

- Wind value factor drops from 1.1 at zero market share to about 0.5 at 30% (*merit-order* effect)
- Solar value factor drops even quicker to 0.5 at only 15% market share
- Existing capital stock interacts with VRE: systems with much base load capacity feature steeper drop

Courtesy of Lion Hirth
System Value of VRE generation: Consistent with findings from SC1

- Value of the average MWh generated by VRE
- Value of the 'marginal' MWh generated by VRE

No interconnections

Electricity value (% of a flat band)

Penetration level (%)

Electricity value - dispatchable
Electricity value - wind
Marginal electricity value - wind
Electricity value - solar
Marginal electricity value - solar
Estimating System Effects

• System effects can be understood and quantified only by comparing two different systems.

• Grid-level system costs are difficult to quantify (externality) and are a new area of study.
  o There is not yet a common methodology as understanding of the phenomena is still in progress.
  o Modelling and quantitative estimation is challenging and there is no “all-inclusive” model.
  o Difference between short-term and long-term effects, often not acknowledged in the studies.

• What we observe in electricity markets results from many factors, not only system effects.

• Grid-level costs depend strongly on country, context and penetration level

• Grid-level costs for variable renewables at least one level of magnitude higher than for dispatchable technologies
  o Grid-level costs are in the range of 15-50 USD/MWh for renewables (wind-on shore lowest, solar highest)
  o Average grid-level costs in Europe about 50% of plant-level costs of base-load technology (33% in USA)
  o Nuclear grid-level costs 1-3 USD/MWh
  o Coal and gas 0.5-1.5 USD/MWh.
Risk is function of technology and time

Nuclear

- Large uncertainty in the construction phase
- Once a NPP is operating, rather stable and predictable production costs

Risk premium of different power plants once operating

During operation, the revenues risk of a NPP is lower than that of a power plant with higher operational costs (CCGT, coal), and of a Variable Renewable Plant (solar, wind).

Source: John Parsons and Fernando de Sisternes, MIT