Nuclear energy and renewables in low-carbon energy systems: costs and technical implications.

A synthesis of OECD/NEA studies

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Outline of the presentation

A. **Few words on the OECD/NEA**

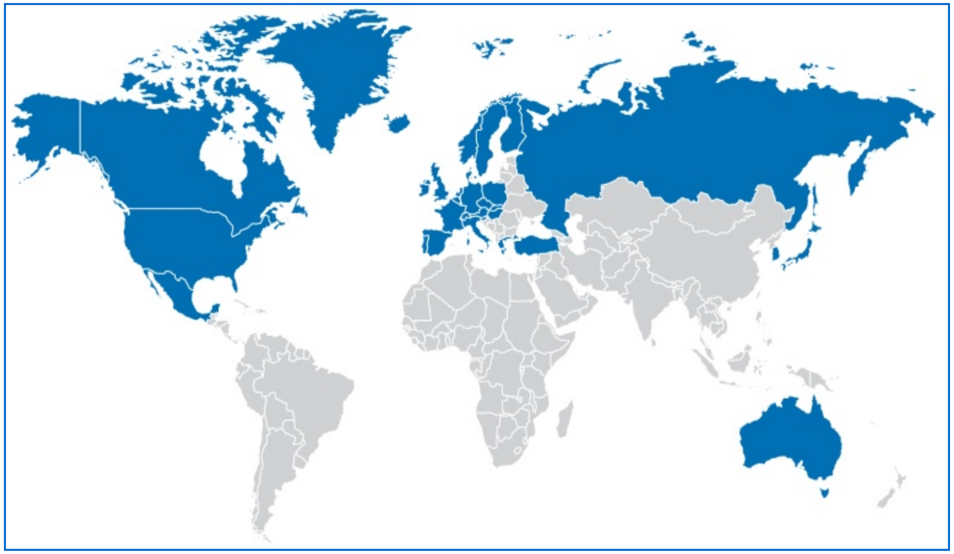
B. **Variable Renewables in low-carbon electricity systems**

- Deployment of VRE: past trends and future vision.
- Specificities of VRE electricity generation.
- NEA work on System Effects and on integration of VRE and nuclear.

C. **Some insights from the NEA study on System Effects II**

- Introduction on the NEA study on "System Effects".
- Impact on the net load.
- Flexibility needs.
- Cost of electricity generation and system costs.
- Impact on electricity markets.
- Policy implications.

OECD / NEA: a forum for cooperation



OECD founded in 1948

OECD Nuclear Energy Agency founded in 1958

33 member countries including Argentina and Romania which joined in 2017

88% of global nuclear electricity capacity

[China 4.8%, Ukraine 3.5%, India 1.2%]

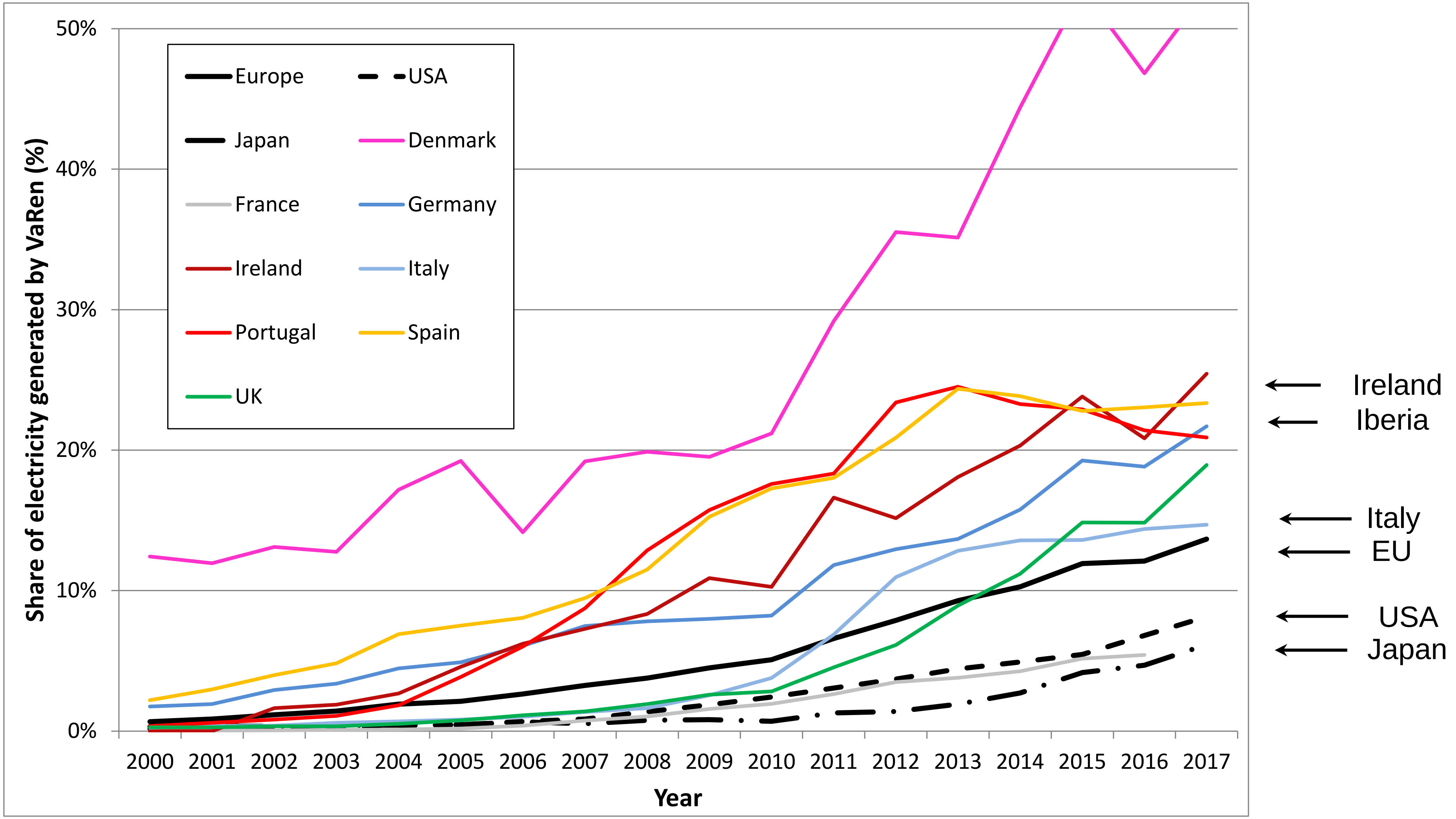
NEA Mission

- To assist its member countries in maintaining and further developing, through international co-operation, the **scientific, technological and legal bases** required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes.
- To provide authoritative assessments and to forge common understandings on key issues, as **input to government decisions on nuclear energy policy**, and to broader OECD policy analyses in areas such as energy and sustainable development.

- **7 standing technical committees**
- **70+ working parties and expert groups**
- **20+ international joint projects**
- **Technical secretariat of GIF, IFNEC and MDEP**

Deployment of Variable Renewables: Historical trend

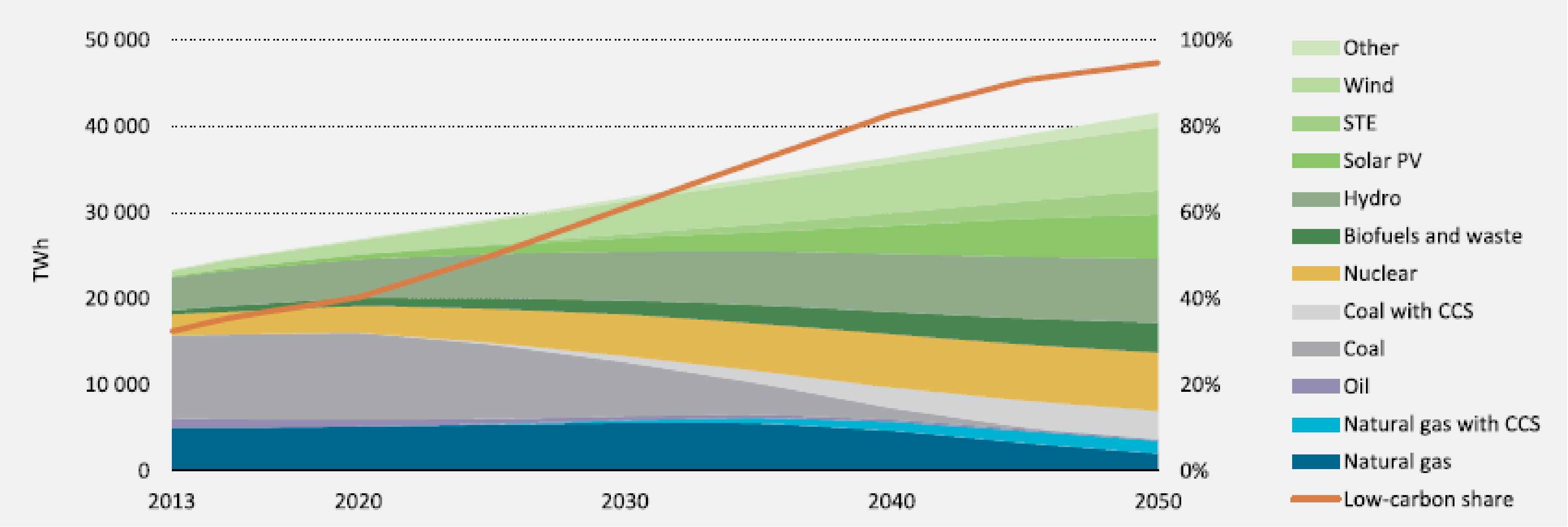
Share of electricity produced by intermittent sources (solar and wind)



Source: IEA Electricity monthly reports

Power sector almost completely decarbonised in the IEA 2DS

Global electricity production and technology shares in the IEA 2DS



Source: IEA, ETP2016

68% fossil fuels
22% renewables
11% nuclear

533 gCO_2/kWh

17% fossil fuels
67% renewables
16% nuclear

40 gCO_2/kWh

- A **complete reconfiguration** of the electricity generation system is needed by 2050.
- Rise of nuclear is accompanied by a *complete phase-out* of coal and oil, a drastic decrease of gas, development of CCS and a massive increase of renewable energies.
- **What are the implications for nuclear power plants operations, economics and overall competitiveness?**

Introduction

Recent fast deployment of significant amounts of **fluctuating** electricity at **low marginal cost** in many OECD countries had a profound impact on the whole electricity system both in a technical and economic dimension.

Technical

- Increasing needs for the transmission and distribution infrastructure.
- Challenge in short-term balancing and additional flexibility needs.
- Significant impacts on the mode of operation and flexibility requirements of thermal power plants in both the short- and long-run.

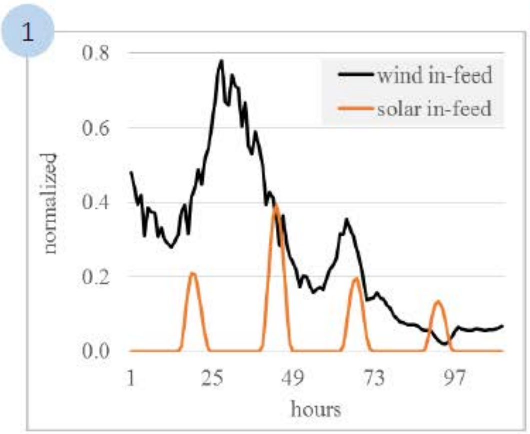
Economic

- Large effects on the electricity markets (lower prices, higher volatility) and on the economics of existing power plants.
- Investment issues in financing new capacity and adequacy concerns.
- Long-term impact on the "optimal" generation structure.
- Significant increase in total costs for electricity supply.
- Need to look at the electricity system as a whole and not at each component in isolation.

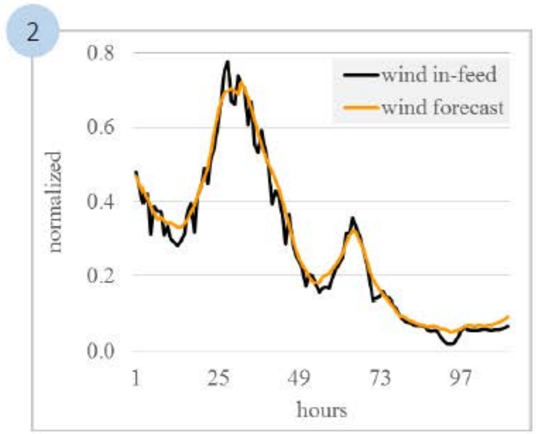
➡ **Large impact on baseload technology, i.e. on nuclear power**

VRE Characteristics and Three Main System Effects

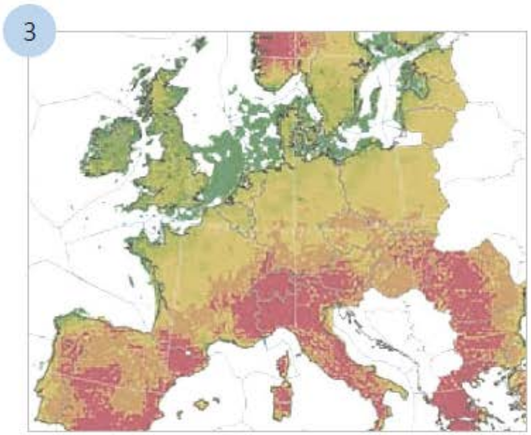
System effects are mainly due to some characteristics that are intrinsic to VRE.



Wind does not always blow



Difficult to predict

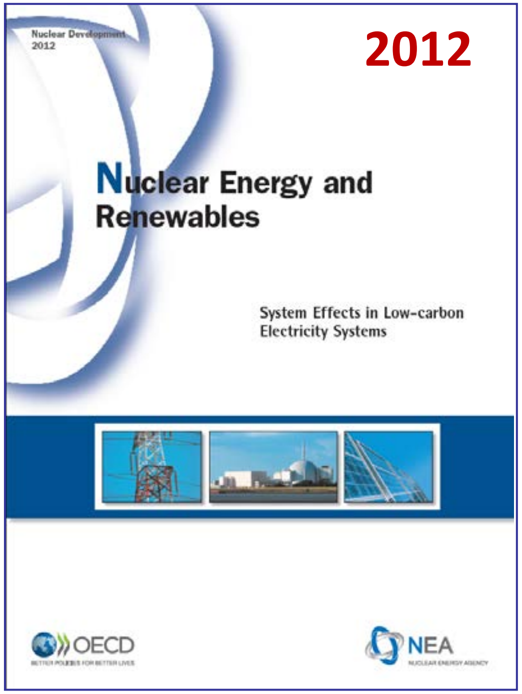


Sites distant from load and may be dispersed

Source: L. Hirth

- System effects are technology- and country-specific, and depend on penetration level.
- Crucially important is the time horizon, when assessing economical cost/benefits and impacts on existing generators from introducing new capacity.
- The costs of grid-level system effects remain difficult to assess and can be understood and quantified only by comparing two systems.

The two NEA System Effects Studies



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**

First quantitative study on System Eff. → Uncertainties in the results.

New NEA Study

Dealing With System Costs In Decarbonising Electricity Systems: Policy Options

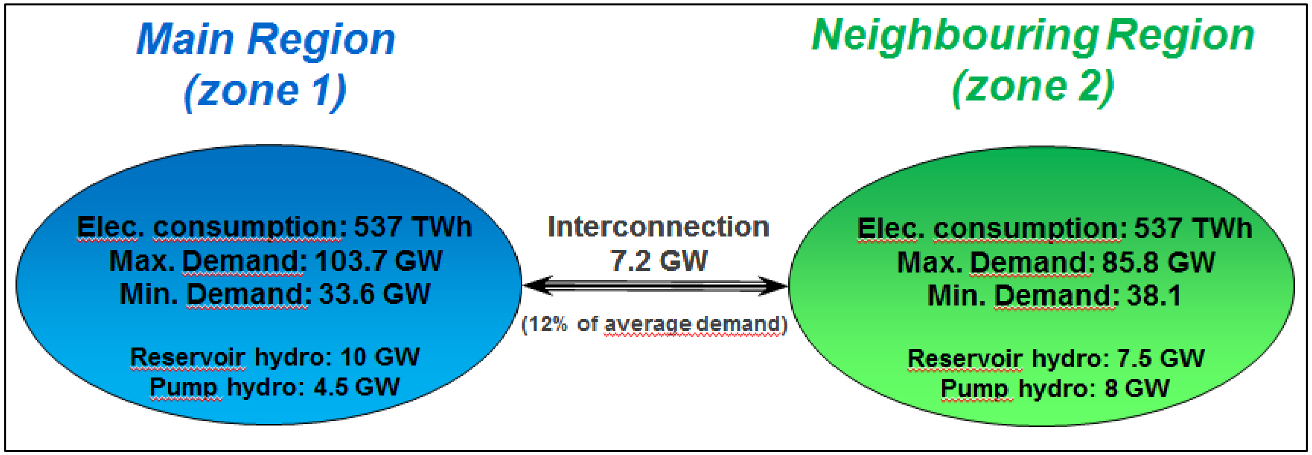
To be published
In Autumn **2018**

a) **Review and synthesize literature published since 2012.**

b) **Calculate on the basis of rigorous cost optimization model the total system costs for electricity systems with a common carbon constraint but different shares of variable renewables, nuclear and other generating technologies** (0%, 10%, 30%, 50% and 75% VRE)**.**

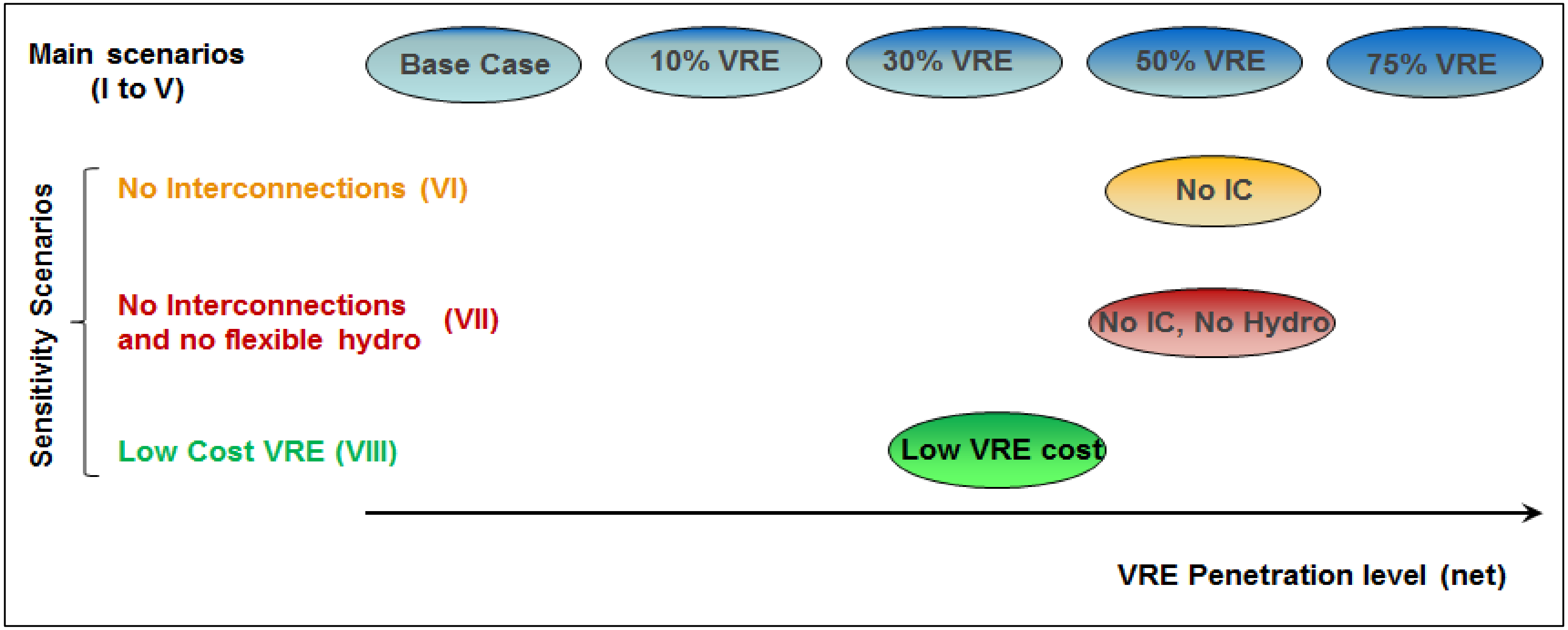
c) **Discuss policy instruments available to internalise system costs.**

The new NEA System Cost II study: Objectives of modelling effort



- Study the system costs of electricity systems with identical total demand and carbon emission target in scenarios with different shares of VRE and nuclear.
  - A CO_2 emissions objective is fixed at 50 g/kWh . This is compatible with carbon emission requirements in IEA 2DS or 450 ppm scenarios.
- Provide a realistic representation of a large, well interconnected power system.
  - It represent a large (continental scale), well interconnected system, with **abundant hydro resources** (reservoir and pumped) and different regimes of VRE generation.
  - Use of actual data from 2015 (demand, realised production from hydro resources and real water inflows, observed VRE load factors).
  - Quantitative analysis performed with **state-of the art** modelling tools by a group of modellers from MIT.

Definition of case studies



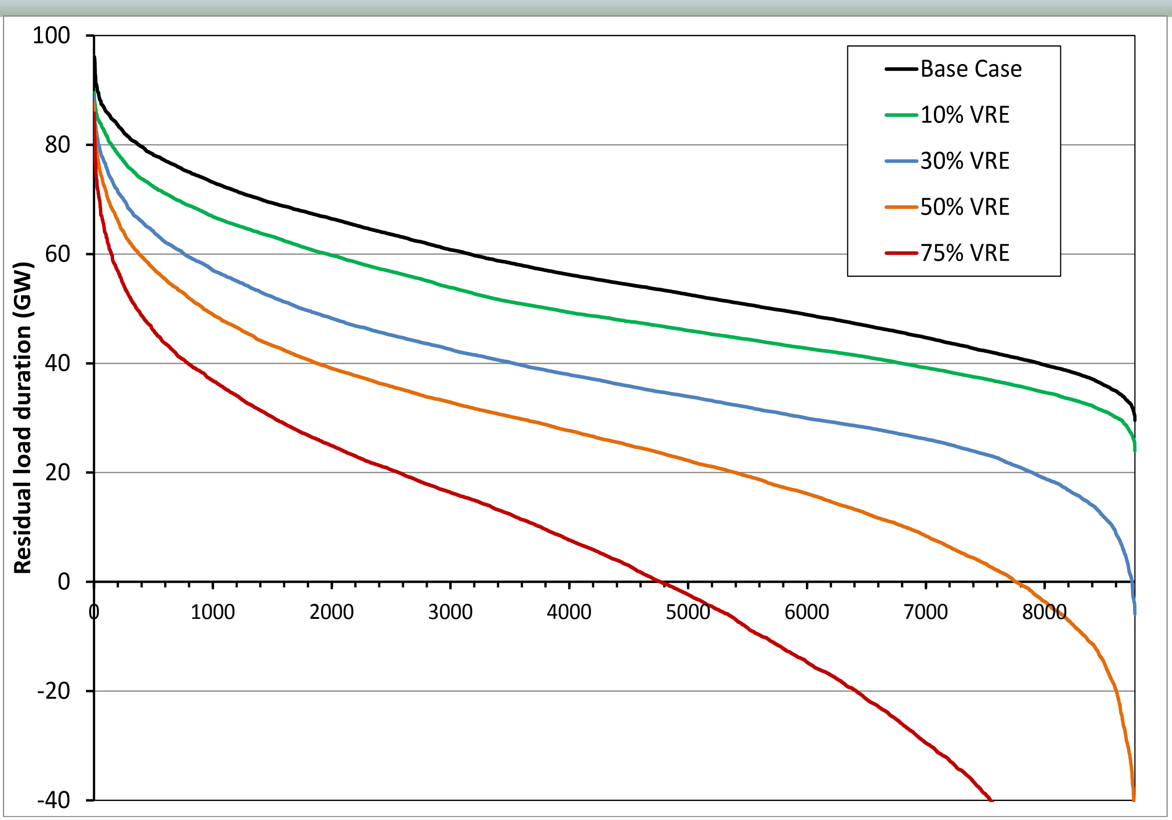
- 5 Main scenarios with different shares of VRE imposed exogenously into the system.

  Base case with an imposed carbon price (leading to similar carbon emissions).

- The case studies "No interconnections" will help to quantify the impact of having a isolated system, with limited potential for exchange with neighbouring countries (ex. Japan, Korea).

- A scenario "Low cost of VRE technologies" assess a situation with favourable conditions for deployment of VRE: significant cost reduction for VRE technologies and availability of cheaper options for flexibility

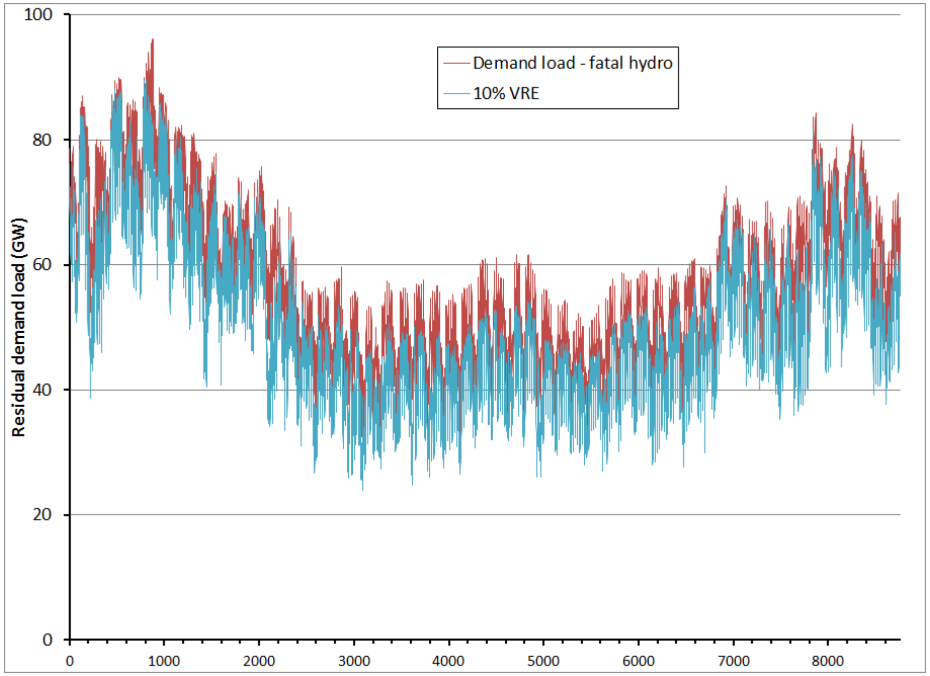
Residual Load Duration Curves



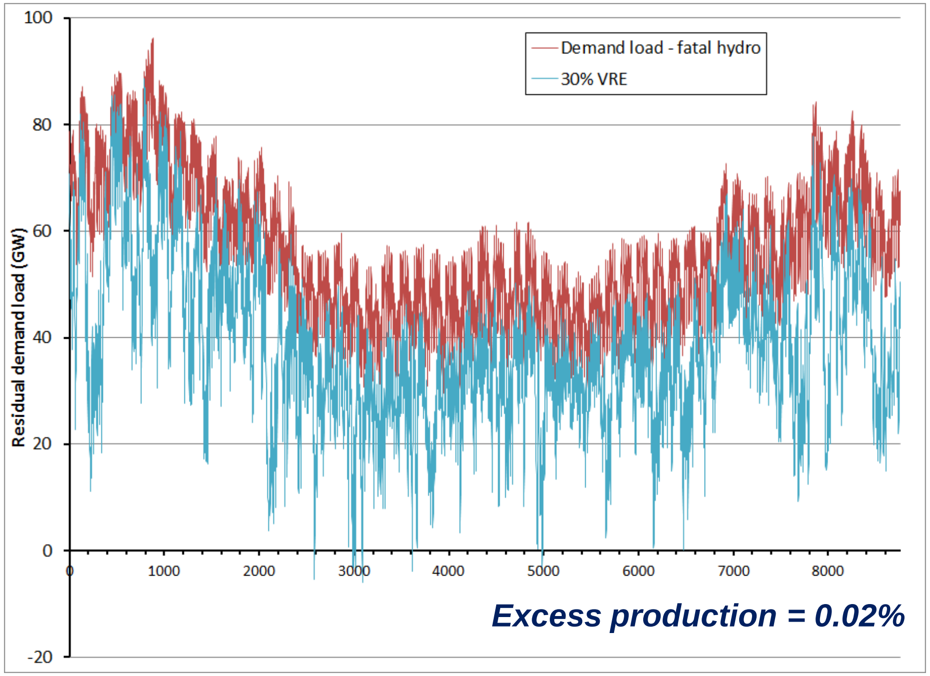
- At high PL, significant number of hours where VRE and fatal hydroelectric fully meet demand.
- Little contribution of VRE to peak demand.
- Non-parallel shift on the load duration curve: VRE generation occurs more on the right side (lower value of electricity)
- Significant changes in the composition of the generating mix (proportionally more peak- and medium-load capacity, less baseload) . ➡ Providing the residual load is more expensive.

Residual Load

10% Variable Renewables scenario

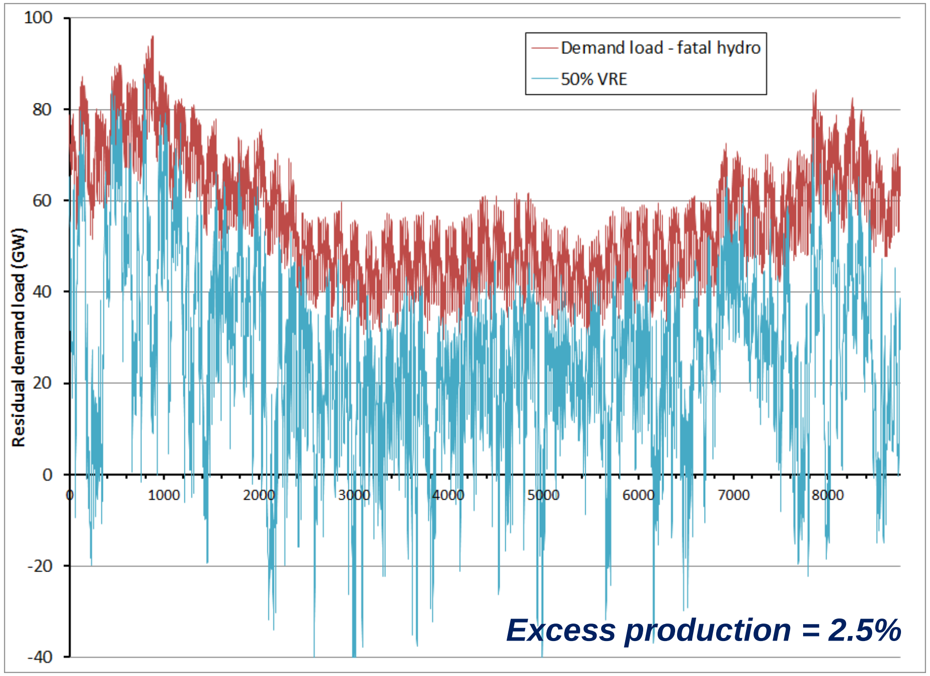


30% Variable Renewables scenario

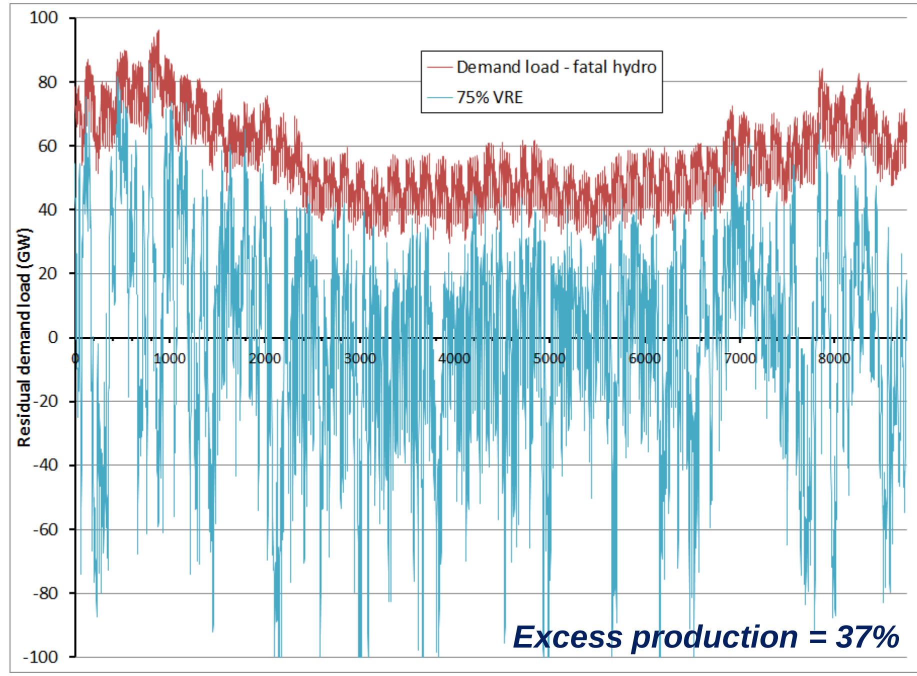


Residual Load

50% Variable Renewables scenario



75% Variable Renewables scenario

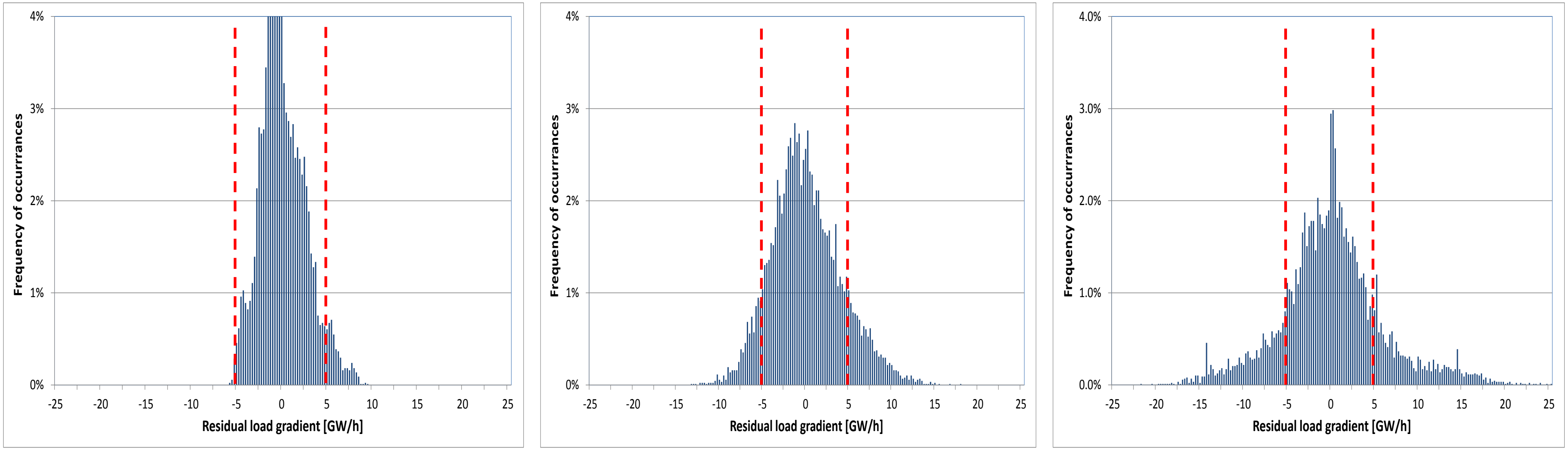


- Residual demand is determined more by VRE production than by the demand and loses its characteristics daily, weekly and seasonal patterns.
- Residual demand becomes more volatile and more unpredictable.
  - More difficult to plan a periodic load-following schedule.
  - Loss of predictable peak/off-peak pattern.

➡ A more variable residual load is favourable to electricity storage.

Ramping Rates Requirements

10% VRE Scenario / 50% VRE Scenario / 75% VRE Scenario



- No significant changes at 10% VRE penetration level and small changes at 30% (not shown)
- High gradient of change in residual load (more than +20/-25 GW/h, about 25% of max load!)
- Frequency of occurrence of large positive and negative gradients increases.
- Those changes must be assured by a reduced number of dispatchable generators.
- The unpredictability of those changes adds an additional difficulty to the challenge.

VRE and Flexibility Needs

More and more flexibility will be required from all components of the system

There are essentially 4 dimensions:

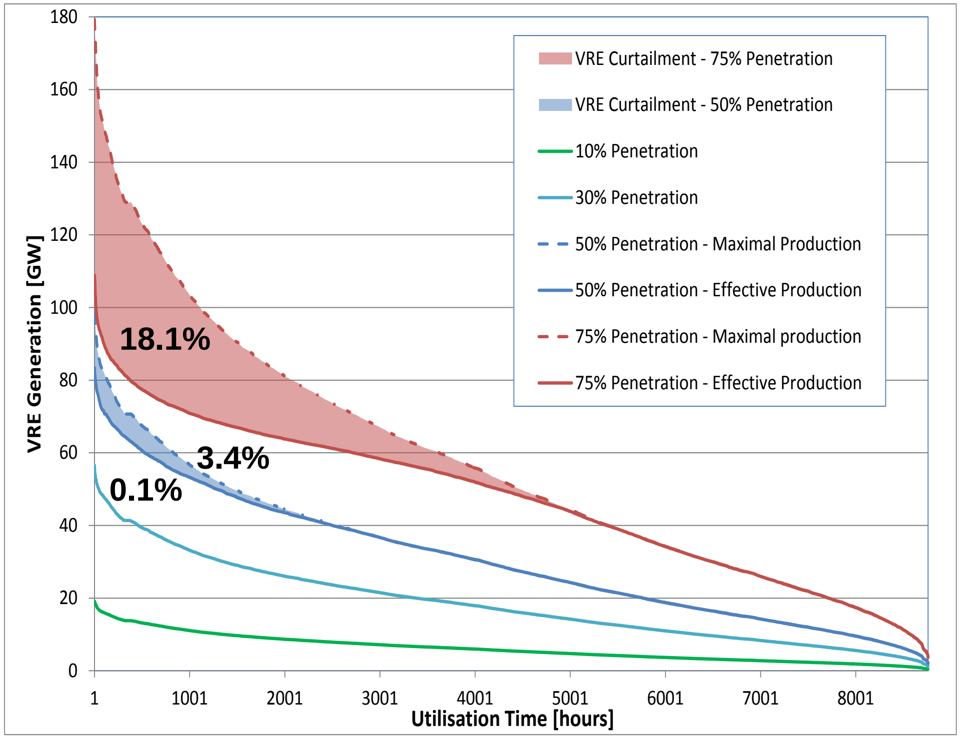
- Interconnections and market extensions
- Demand-side Measures/ Demand-side Management
- Electricity and energy storage
- Flexibility provided by power generation units
  - Thermal power plants.
  - Curtailment of VRE.

At the moment, DSM and flexibility from existing power plants are the most economic solutions.

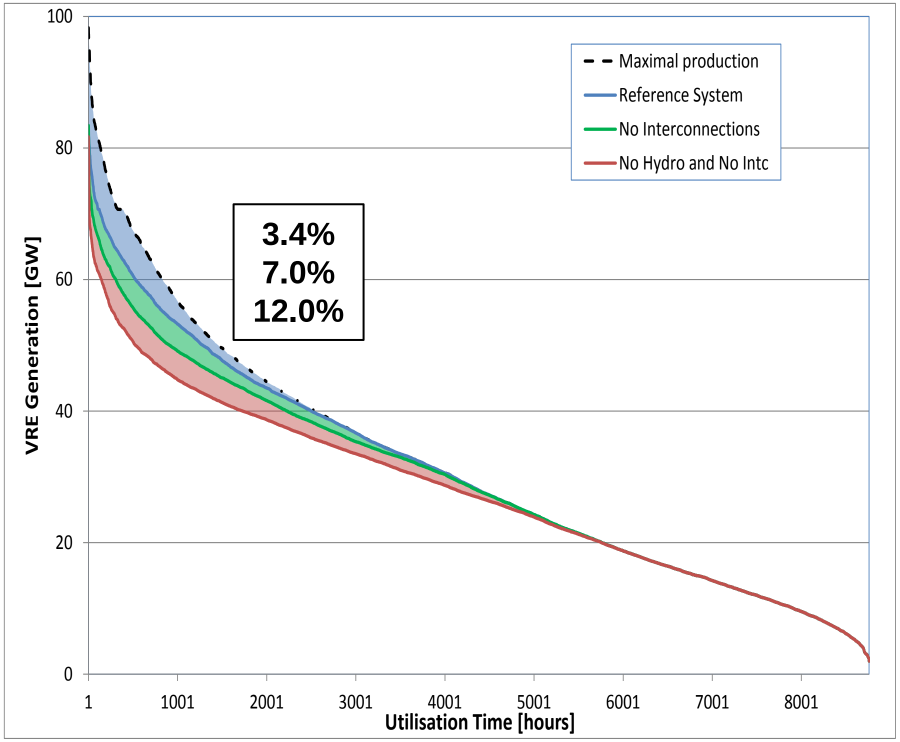
➡ **All sources of flexibility will be needed in the future low-carbon systems**

VRE Curtailment

Main scenarios

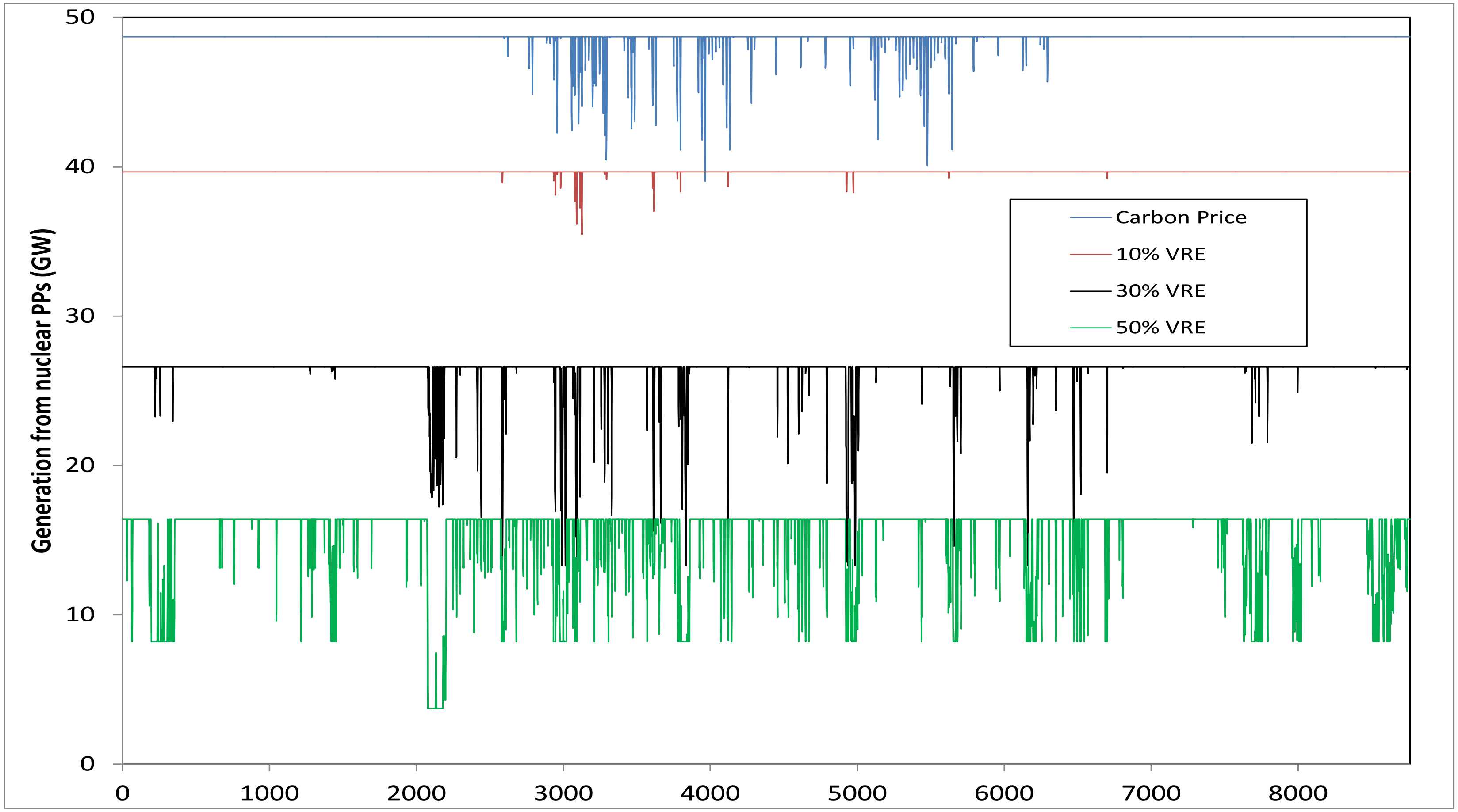


50% VRE: sensitivity analysis



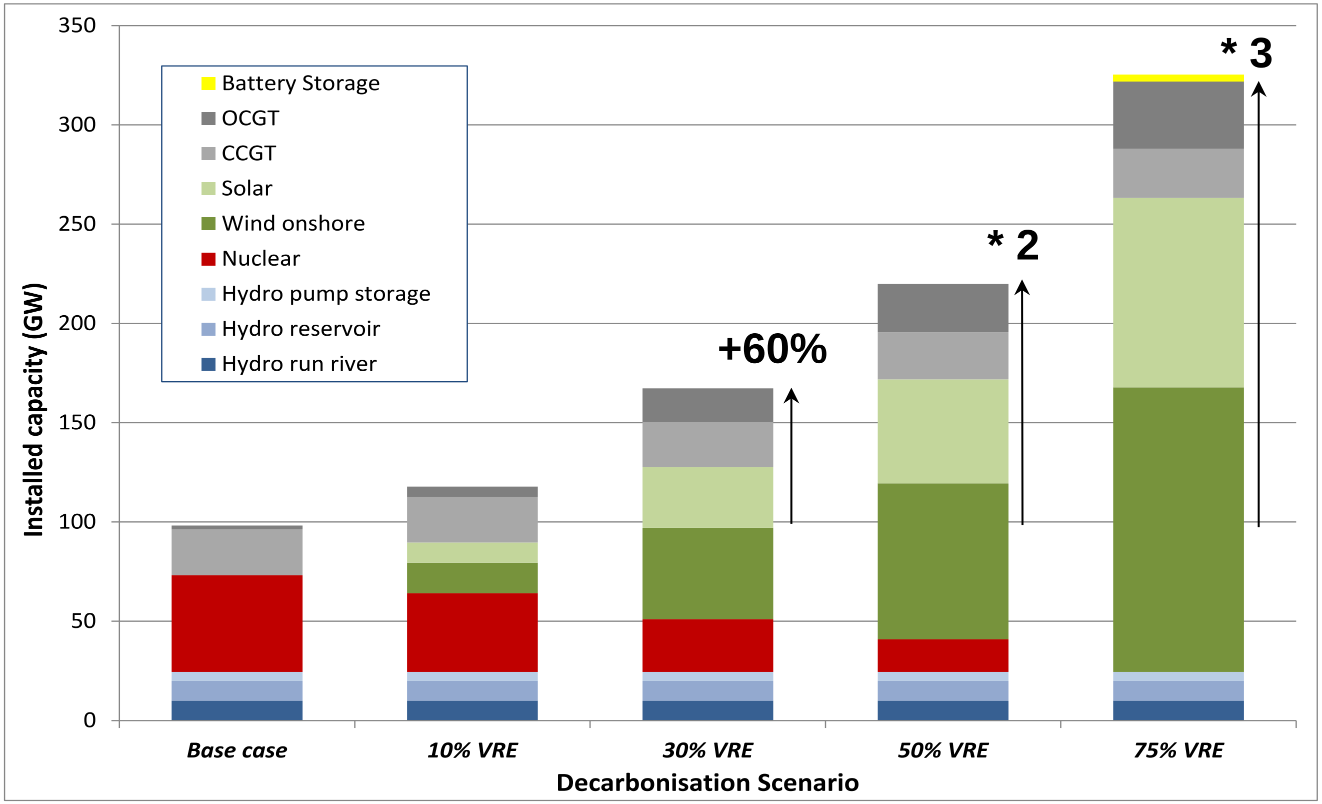
- Curtailment of VRE starts to be noticeable at 50% penetration level and then increases significantly.
- Curtailment of the marginal unit is much higher (0.6%, >18% and >36%).
- Interconnections, flexible hydro (and cheap storage) help reducing VRE curtailment ane ease the integration of VRE.

Flexibility requirements for nuclear power plants



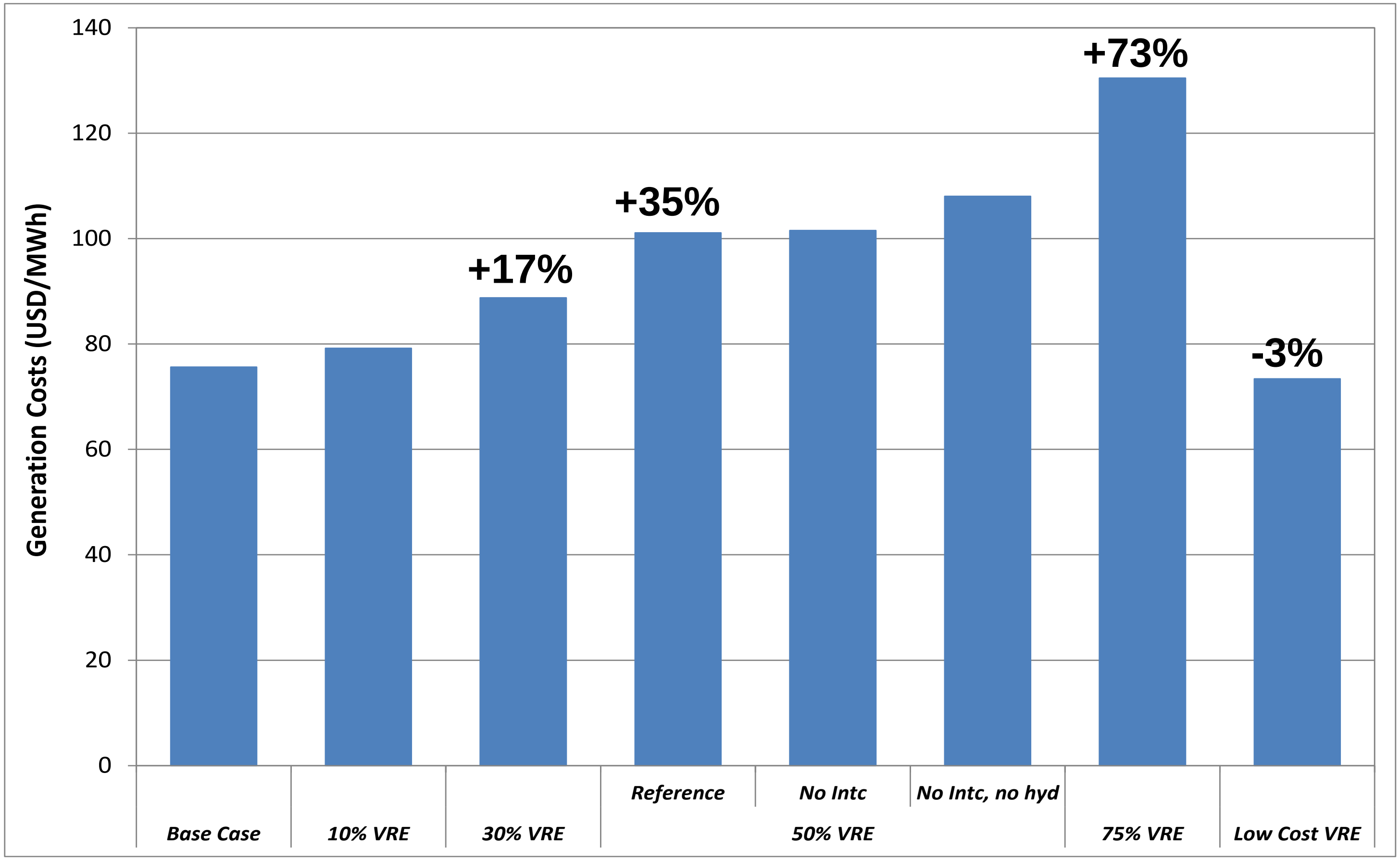
- VRE deployment: less nuclear capacity and more cycling (NOT between 0% and 10%).
- Cycling becomes important at 30% VRE penetration and is large at 50%.
- At 50% VRE extended periods of production at minimal rate and nuclear must ramp up and down by +30%/-35% of the total capacity per hour.

Optimal generation mixes



- Under cost assumptions, carbon price leads to a deployment of nuclear and no VRE.
- Larger amount of total capacity installed as VRE targets increase.
- Nuclear capacity is displaced by VRE to meet the carbon constraint.
- High VRE penetration requires more OCGT capacity, CCGT operating at low LF.
- Battery storage is deployed only at very high VRE penetration levels.

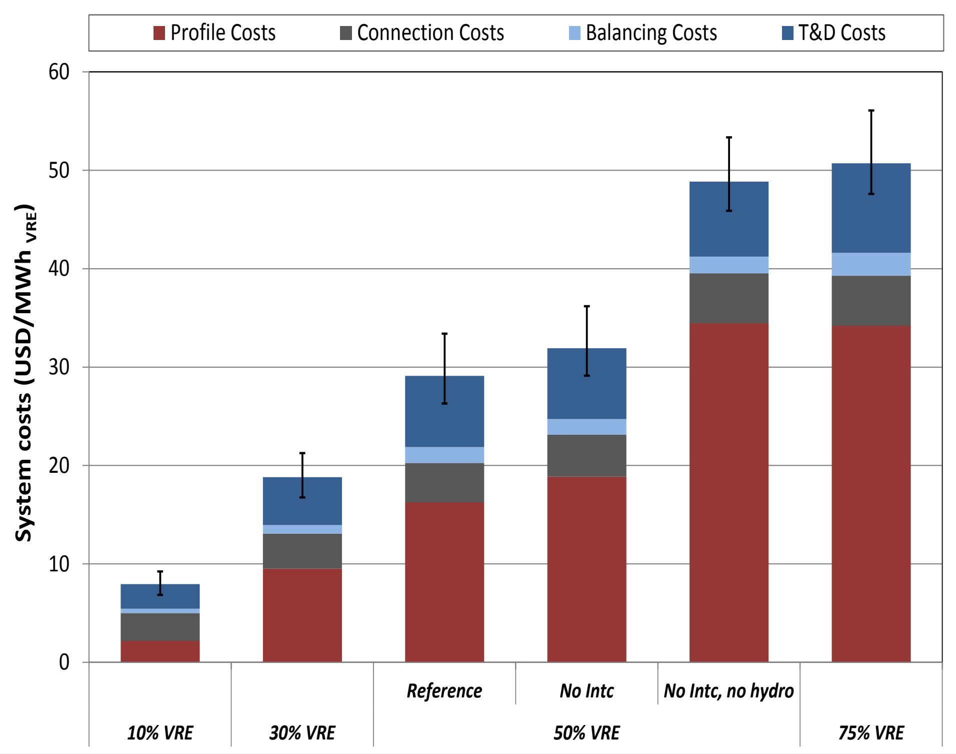
Total costs of electricity generation



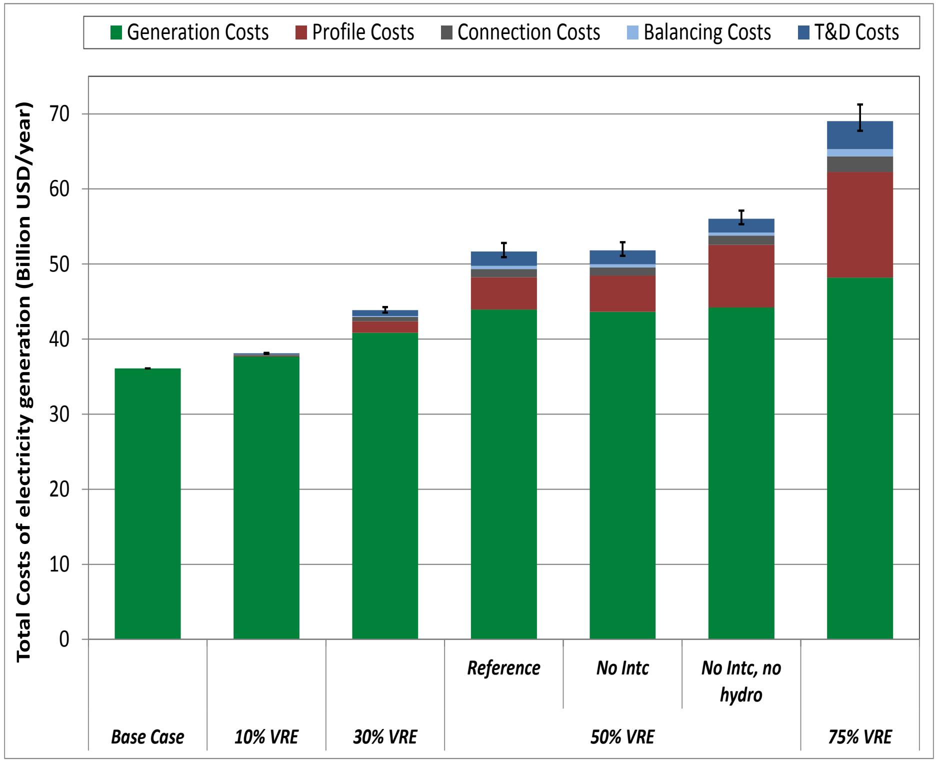
- The cost of generation increase with the share of VRE deployed in the system.
- Similar trends are observed also for the second region of this study
- The most efficient policy measure to achieve carbon emission targets is the adoption of a carbon tax, without selecting specific technologies.

Total costs of electricity provision including all system costs

Total system costs of VRE

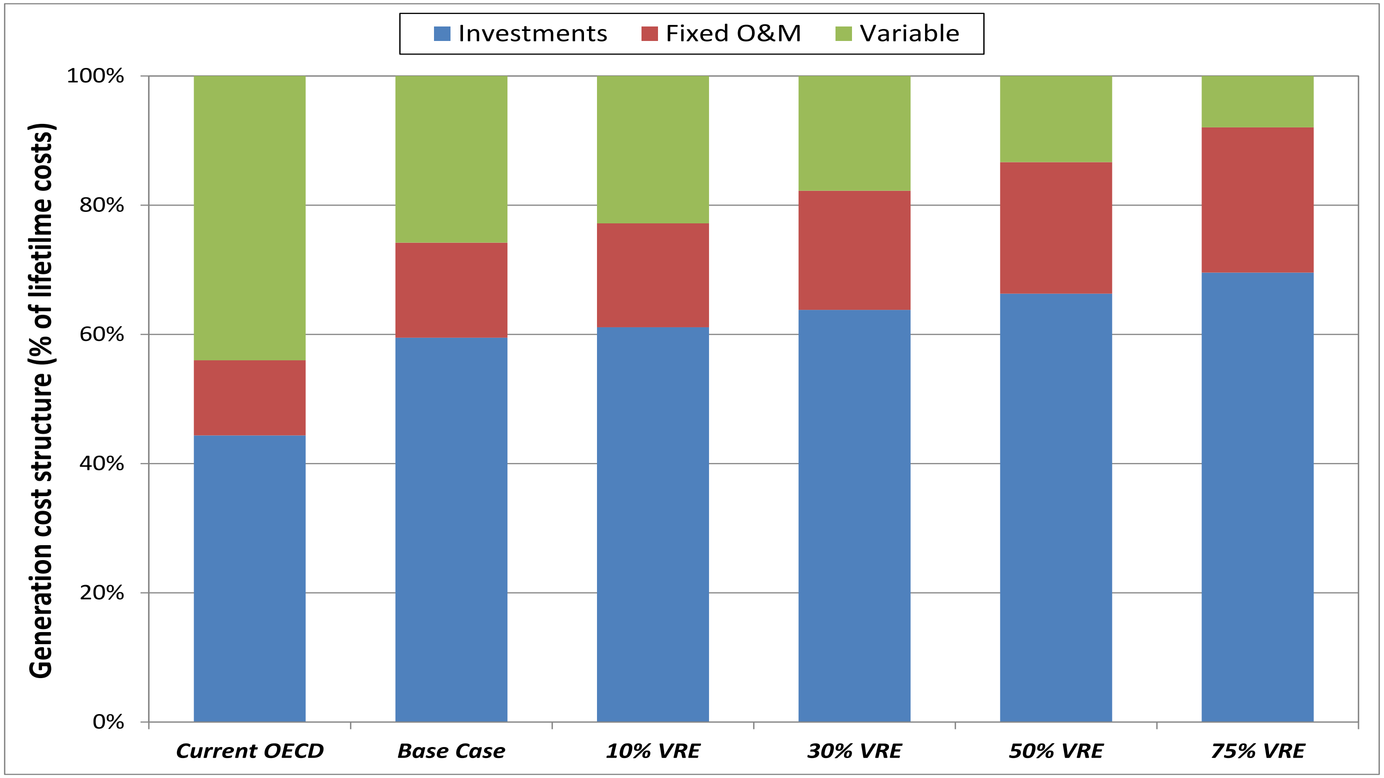


Total cost of electricity provision



- Estimate of total cost of electricity provision, including other components of system costs from literature (T&D, connection and balancing).
- System costs increase substantially with penetration level.
- The main component of system costs are profile costs.

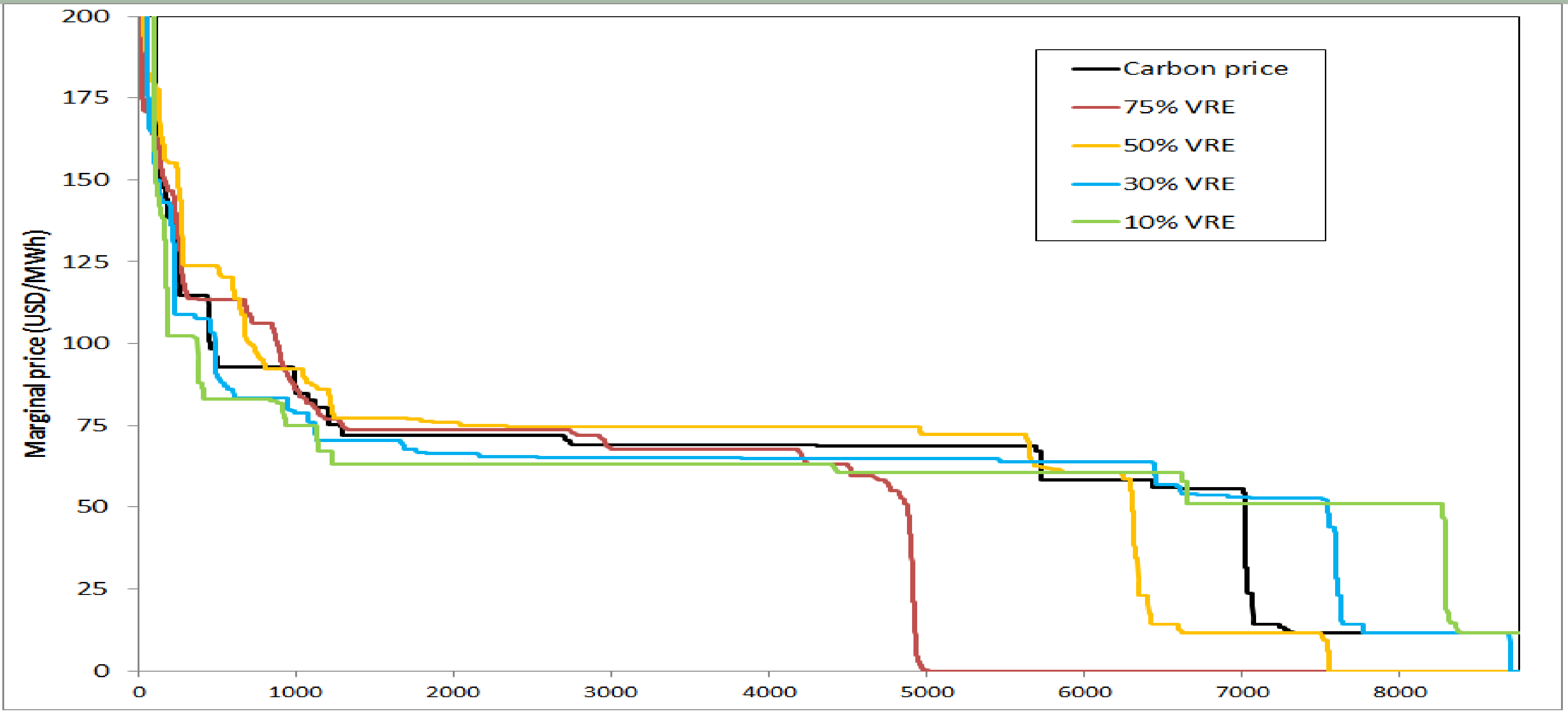
Towards a more capital intensive generation mix



- A low-carbon generation mix is inevitably more capital intensive than current mix.
- The choice of low-carbon technology has impact on the ratio fixed/variable costs.
- Ratio fixed to variable costs has an impact on the financial risk faced by investors and on the structure and volatility of electricity prices

Price duration curve

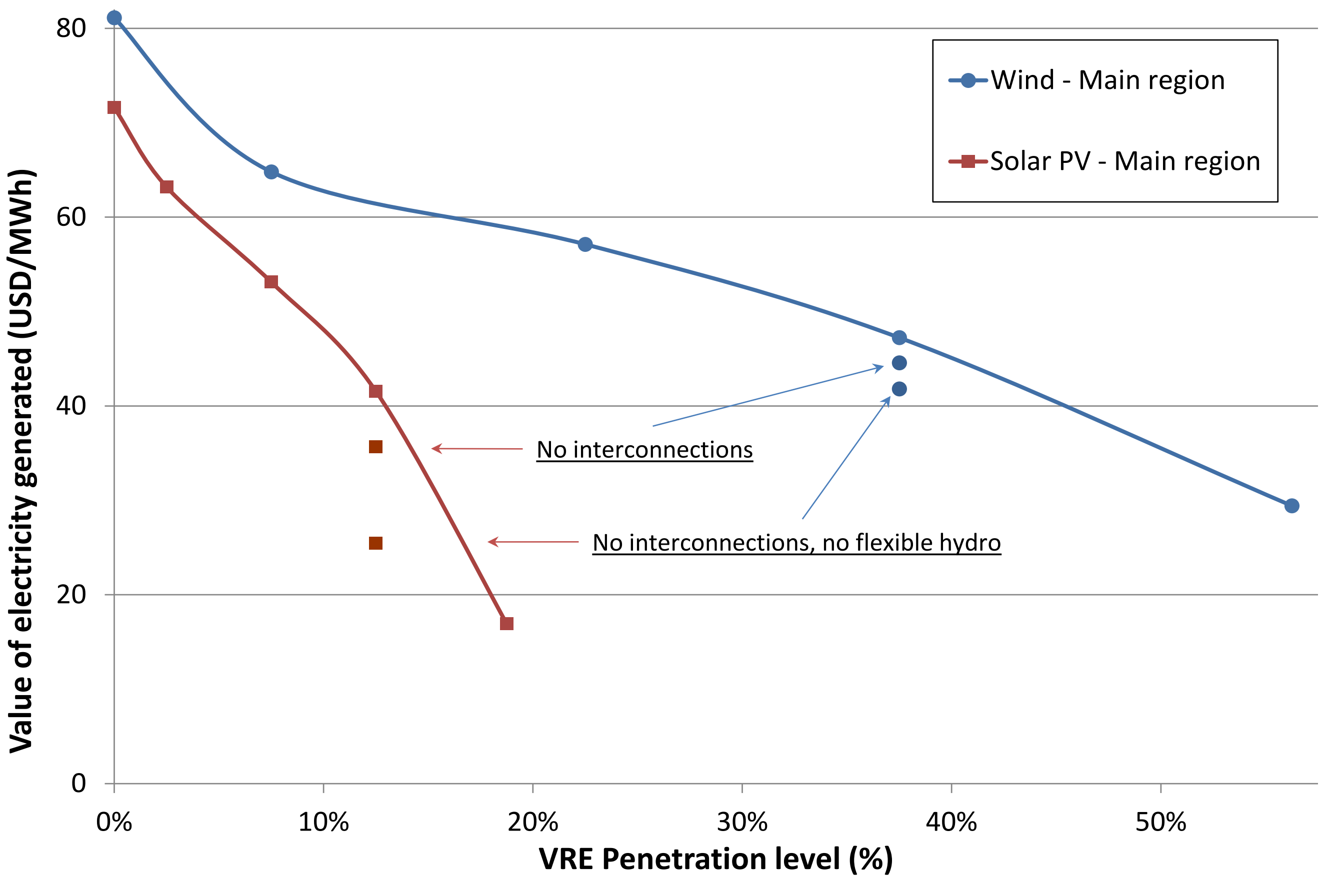
Locational marginal price



- More demanding VRE targets increase the number of hours with zero price.
  - No hours with zero price at low penetration levels, appear at 30% penetration level.
  - Over 1200 hours at 50% VRE and over 3750 hours at 75% VRE.
- Compensated by an increase of hours with high electricity prices (>100 USD/MWh).
- Increase in the volatility and unpredictability of electricity market prices.
- All this creates good conditions for storage technologies.

➡ Impact on the **electricity market risk** for all technologies, in particular far baseload.

System Value of VRE generation: Consistent with findings from SC1



- Value of the first MW of wind and solar PV is >1 (good correlation with demand).
- Drop in value is more pronounced for solar PV than for wind.
- Interconnections and storage improve the value of VRE.
- Results are consistent with literature and findings from System Cost 1 study.

Main technical findings

- The total cost of electricity supply increase significantly with VRE penetration level (from 36 ➡ 38 ➡ 44 ➡ 52 ➡ 71 billion USD/year).
- System costs increase over-proportionally with VRE (+8, 20, 30, 50 USD/MWh_{VRE})
- Under same carbon constraint, nuclear capacity declines with VRE targets: (49 GW ➡ 40 GW ➡ 27 GW ➡ 16 GW ➡ 0 GW at 75% VRE penetration).
- Flexibility needs from thermal plants (and from NPPs) increase with VRE penetration
- Imposing stringent carbon target shifts the cost structure of electricity provision toward more fixed costs and less variable costs, whatever is the low-carbon mix (more nuclear or more VRE).
- Increase of the hours at zero price with higher VRE targets (1000 and 3750 hours !).
- Market value of solar PV and wind is significantly reduced (autocorrelation).
- System costs are large and should be internalised to the maximal extent possible.

Policy Implications

Deployment of low-carbon technologies requires specific policy measures:

1. **A first best policy framework for maximum efficiency consists of two pillars**
   a) ***The Internalisation of System Costs***
   b) ***Carbon Pricing***
      - **Carbon taxes (CT)** are economically efficient and provide price certainty for investors; but they pose distributional issues as environmental rent is transferred from electricity sector to government; they ensure that most cost-efficient LowC technologies are selected.
      - **Emissions trading (ET)** is alternative but makes for uncertain prices; ET with free allocation of quotas allows for alternative rent distributions.

2. **If political constraints pose obstacles, alternative instruments exist :**
   a) ***Feed-in tariffs (FIT) for low carbon technologies with auctioning***
   b) ***Feed-in premiums (FIP) for low carbon technologies with auctioning***
   c) ***Zero emission credits (ZECs) or production tax credits (PTC)***
   d) ***Capital cost support and capacity remuneration mechanisms (CRMs)***
   e) ***Better remuneration of flexibility and system services***

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 CO_2 prices and entail some risk for SoS.

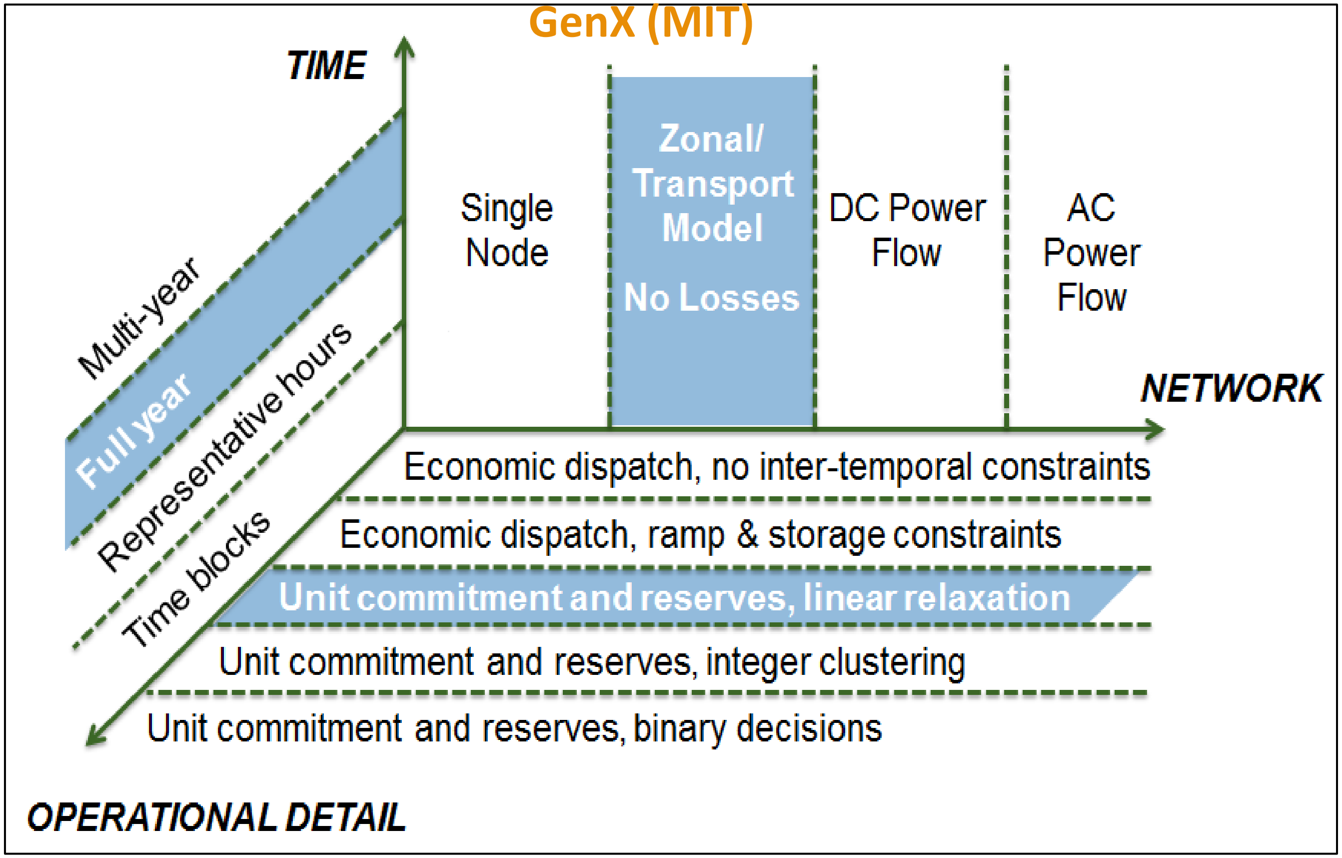
- A low-carbon mix with large quantity of VRE, will inevitably lead to high variability of electricity prices, with a high number of hours at VOLL and 1000s of hours at zero price, with a very skewed distribution of revenues for all generation capacities.
- Electricity price will be strongly dependent 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.

Key points and takeaway 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.
- **Current market designs are not well suited for investments in capital intensive technologies and won't deliver a low-C mix.**
- **New market design are needed to achieve this transition at the lowest cost.**
  - ✓ A robust carbon price is the most effective policy .
  - ✓ 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).
  - ✓ Flexibility provision through demand response, storage and improved interconnections are part of the new market design.
  - ✓ **System costs** of VRE are large and must be allocated fairly and transparently.

Reserve slides

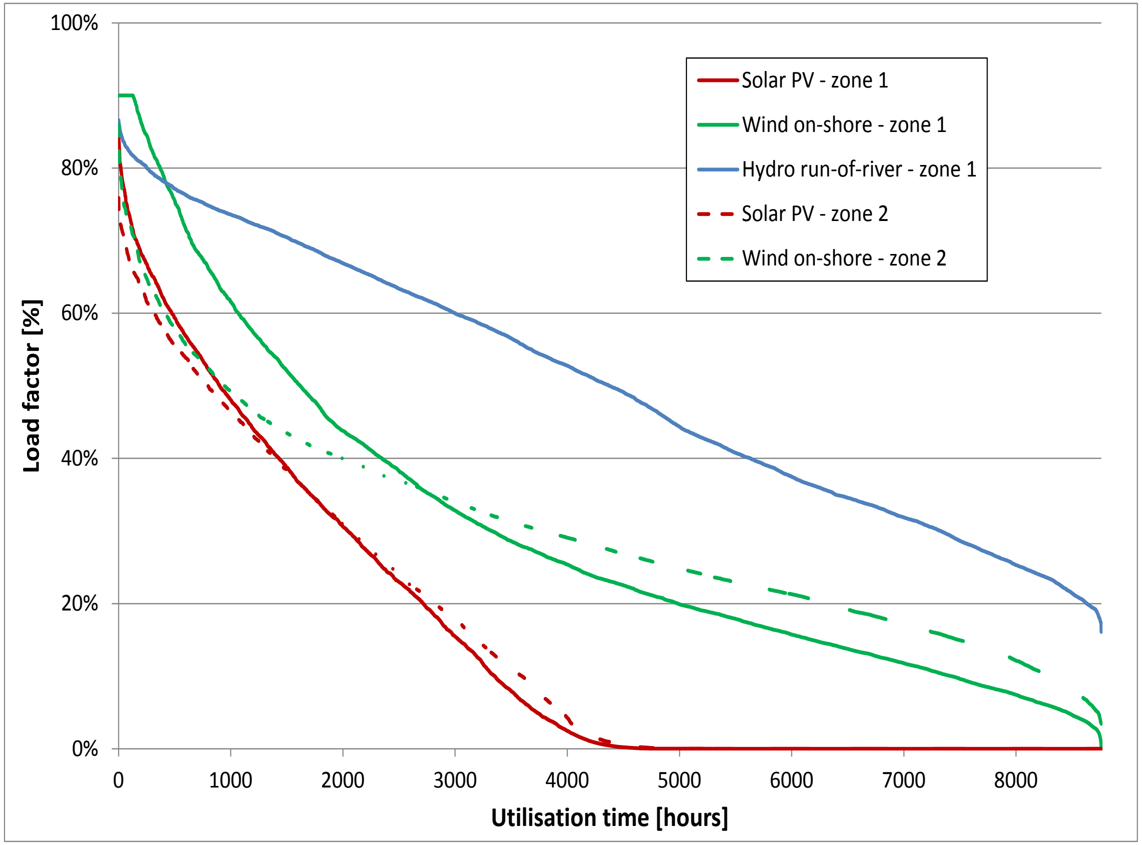
Modelling choices



Economic data for generation technologies are derived from IEA/NEA Projected Cost of Electricity Generation: 2015 Edition, using a 7% real discount rate.

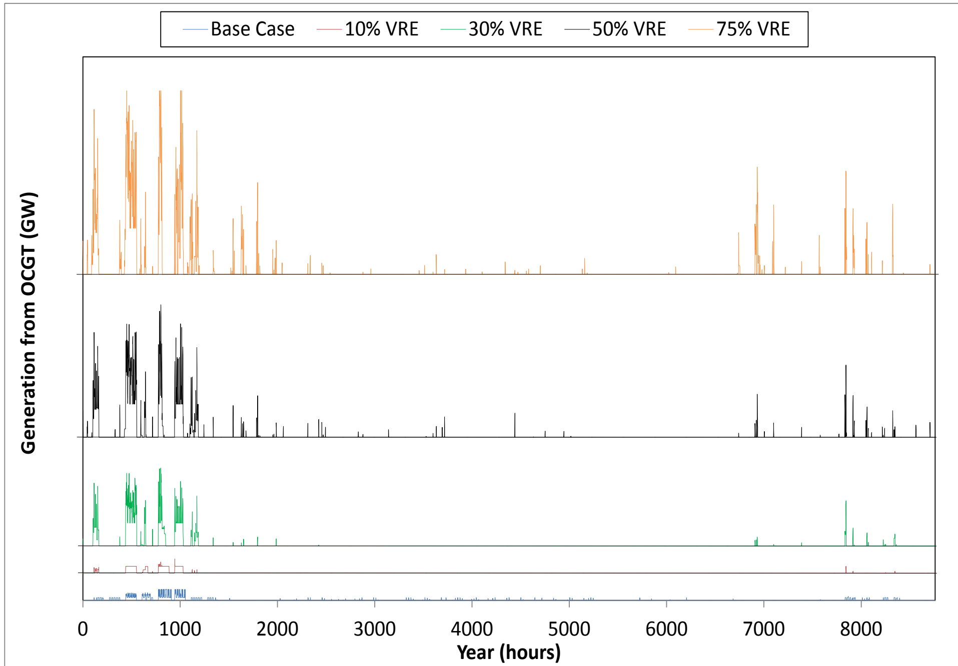
- Cost represent the average of submitted data for OECD countries.
- In the low cost VRE scenario, the cost of wind is decreased by 33% and the cost of solar by 60% with respect to the baseline case.

Load factor duration curves: solar PV and wind



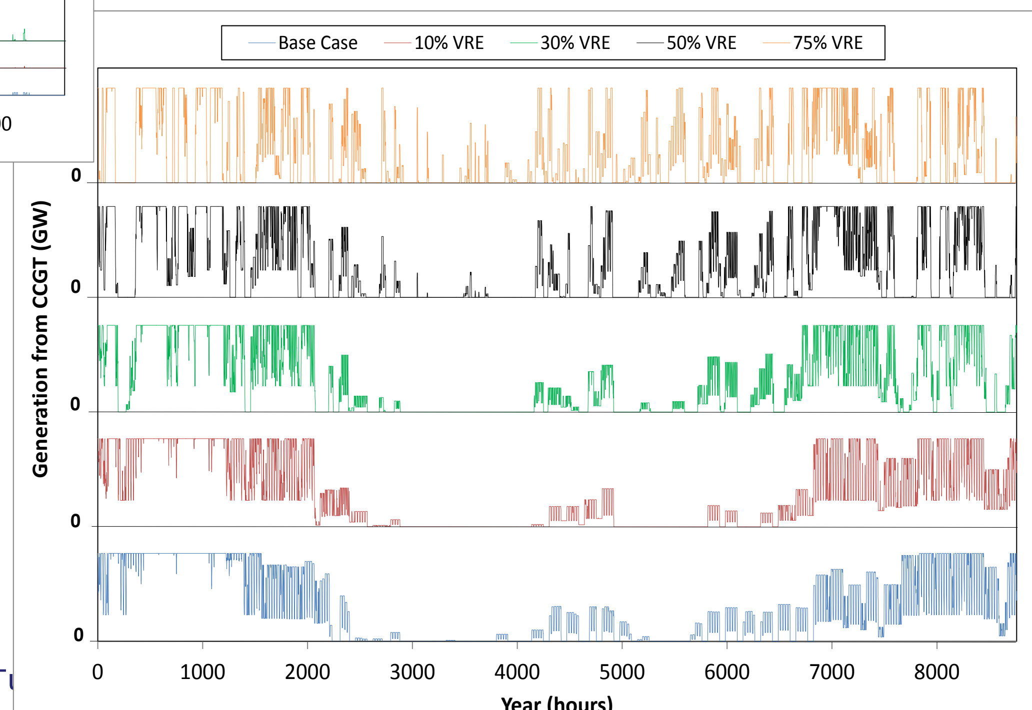
- Solar PV features the steeper curve, followed bay wind-on shore and wind off-shore.
- Geographical diversification helps (region 2 is flatter than region 1).

Flexibility requirements for gas power plants



- Capacity of CCGT is almost constant in all scenarios
- Their load factor decreases with VRE penetration.
- CCGT undergo more cycling and steeper ramping rates. (especially at 75% VRE penetration)

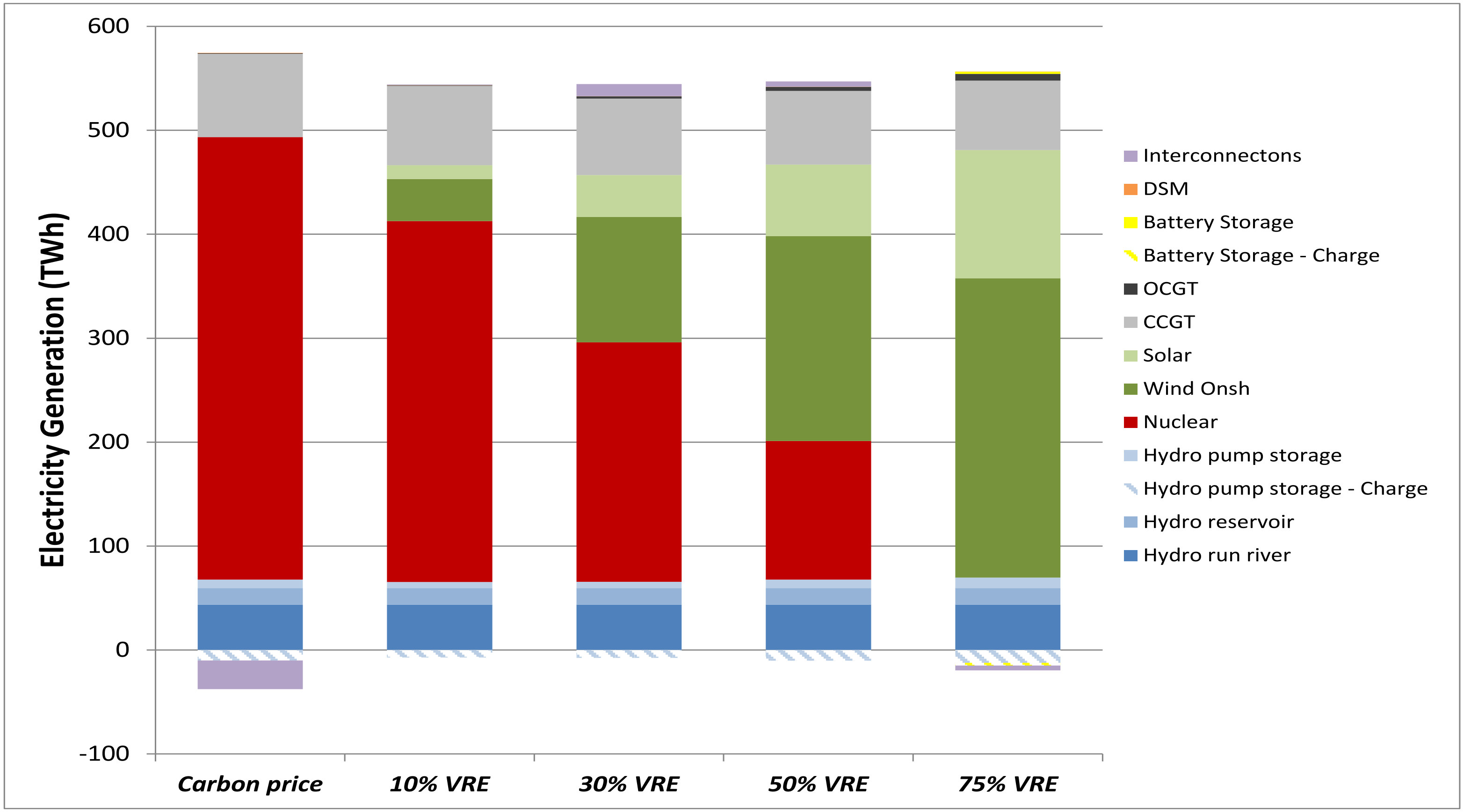
CCGT



OCGT

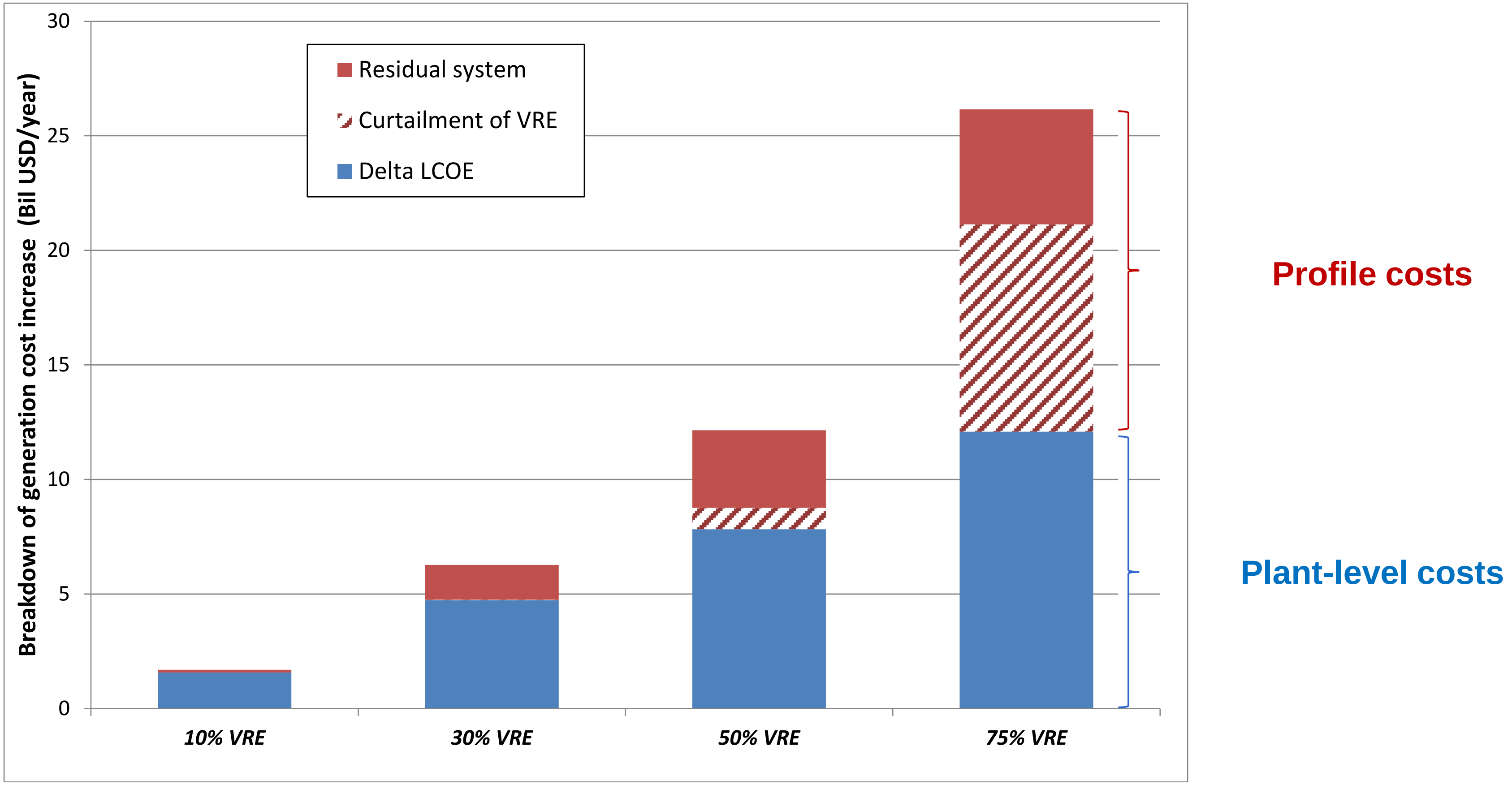
- Large increase in OCGT capacity. (from 2 to 30 GW)
- OCGT Load factor actually increases.
- OCGT undergo steeper and steeper ramping rates. (from 1.5/-1.7 GW/h to 20/-17 GW/h)

Electricity generation



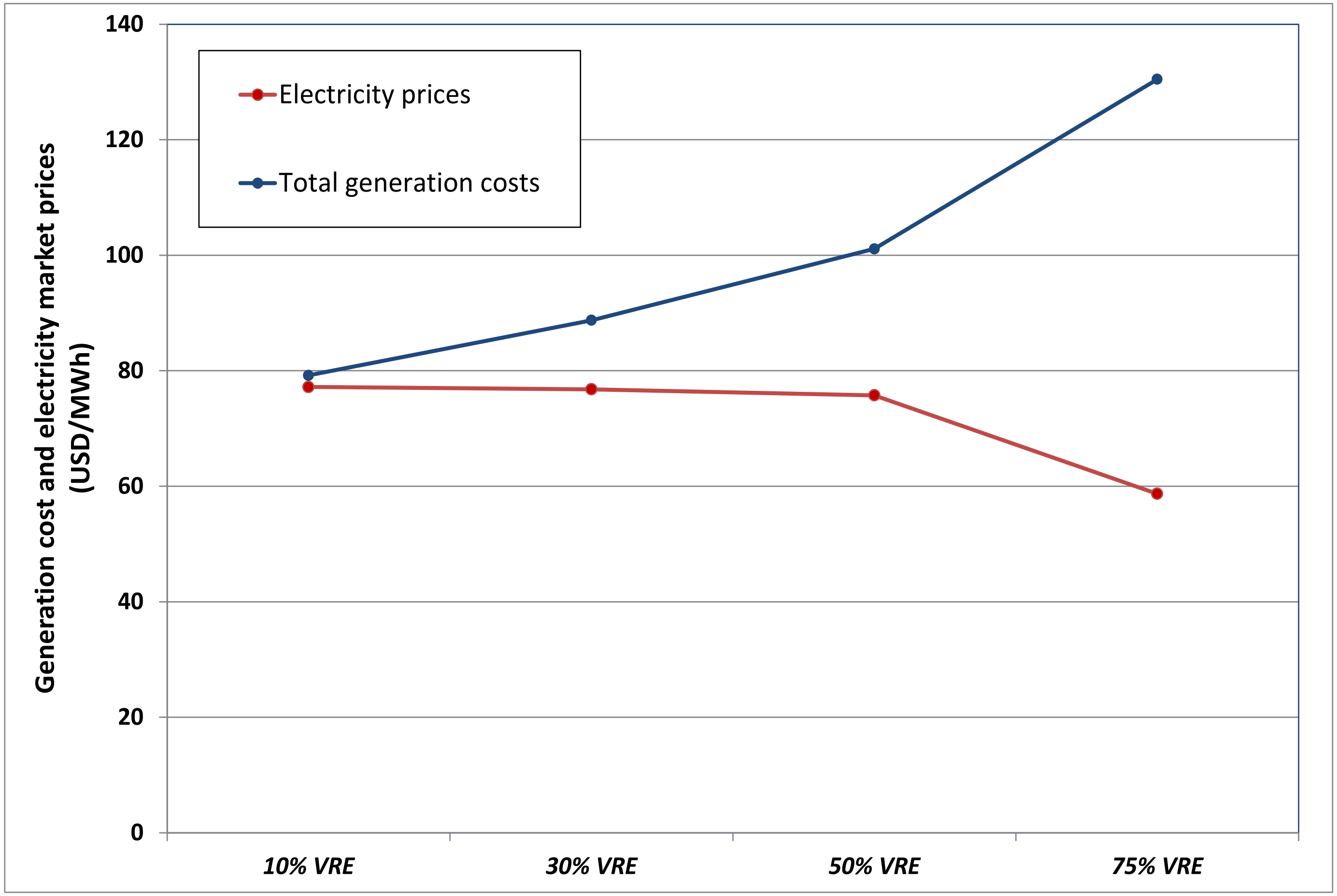
- Nuclear generation is displaced by VRE as their targeted penetration level increases.
- The combined share of gas-fuelled plants is almost constant as limited by the carbon constraint.
- A shift from more efficient CCGT to less capital intensive OCGT is observed.

Total costs of generation: a breakdown



- Increase in cost of generation can be attributed to three different components:
  - The LCOE of VRE is still higher than that of the alternative low-carbon technology.
  - At high Penetration Level, the curtailment of VRE increases its costs.
  - The residual system becomes more expensive.

Price and costs of electricity generation

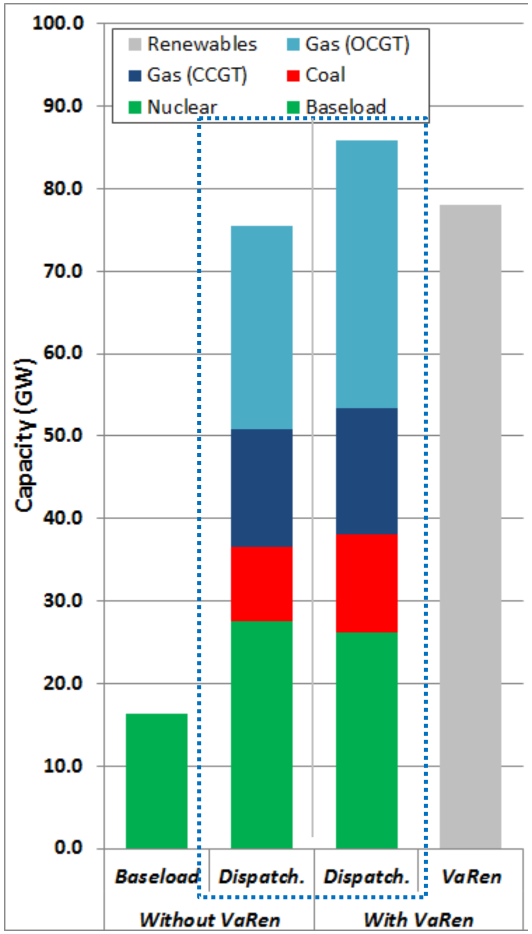


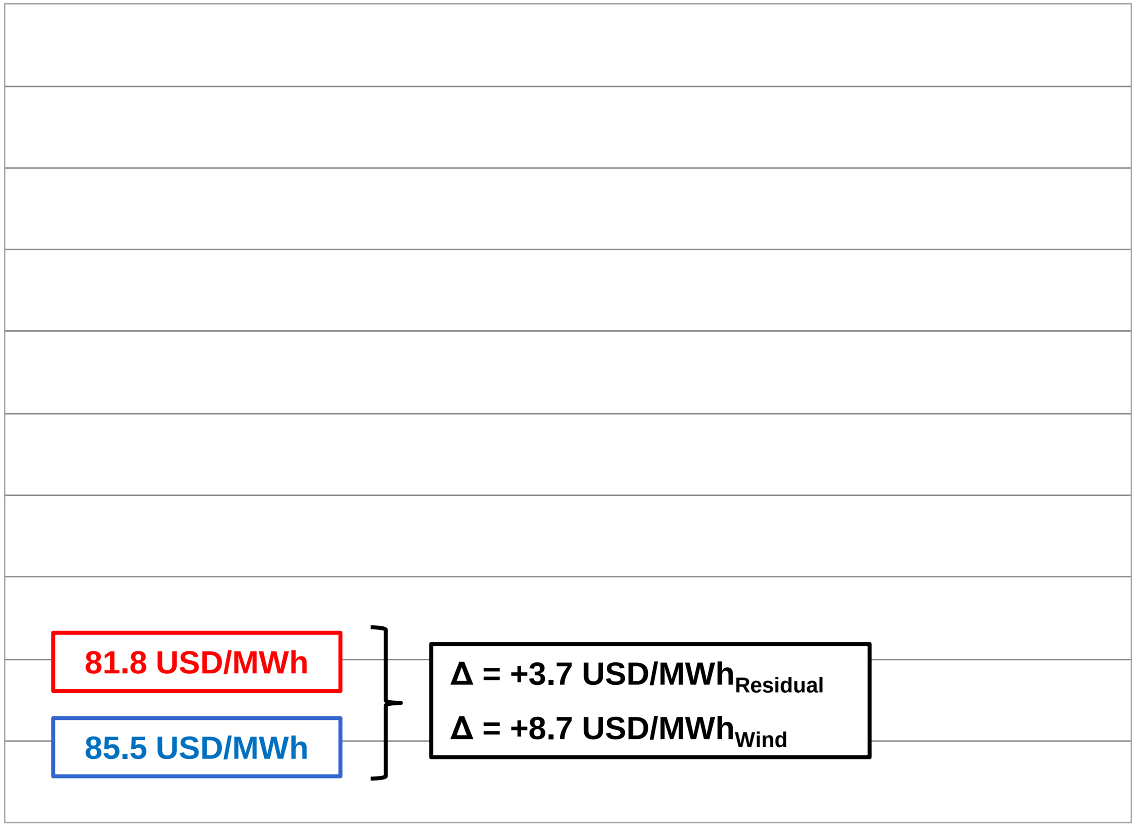
- There is a divergence between average cost and average price as a result of not taking into account the subsidies necessary to achieve the renewable target in the price and the price of reserves.

An example: Quantification of profile costs

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

Profile costs are calculating comparing the residual load duration curve for a 30% penetration of fluctuating wind (blue curve) and 30% penetration of a dispatchable technology (red curve).





Economics of generation alternatives

Economic data for generation technologies are derived from IEA/NEA Projected Cost of Electricity Generation: 2015 Edition, using a 7% real discount rate.

- Cost represent the average of submitted data for OECD countries.

Technology	*Discount rate*	*Size*	*Electrical efficiency*	*Load factor*	*Construction time*	*Lifetime*	*Overnight Cost (incl. contingency)*	*O&M Costs*		*LCOE (NEA Methodology)*
								Fixed	*Variable*	*Total*
	[%]	*[MWe]*	*[%]*	*[%]*	*[years]*	*[years]*	*[USD/kW]*	*[USD/MW]*	*[USD/MWh]*	*[USD/MWh]*
Nuclear	7%	1000.0	33.0%	85.0%	7	60	4700.0	100000.0	1.50	81
Gas - CCGT	7%	500.0	58.0%	85.0%	2	30	1050.0	26000.0	3.50	82
Gas - OCGT	7%	300.0	38.0%	85.0%	2	30	700.0	20000.0	15.30	123
Coal	7%	845.0	45.0%	85.0%	4	40	2200.0	37000.0	5.00	80
Wind - Onshore	7%	50.0		30.0%	1	25	2000.0	62000.0	0.00	89
Wind - Offshore	7%	250.0		40.0%	1	25	5000.0	175000.0	0.00	172
Solar	7%	1.0		15.0%	1	25	1600.0	36000.0	0.00	132
Hydro - run of the river	7%	10.0		50.0%	5	80	4300.0	65000.0	0.00	94
Hydro - reservoir	7%	10.0		20.0%	5	80	3250.0	50000.0	0.00	179
Hydro- pump storage	7%	10.0		na	5	80	4450.0	65000.0	0.00	na
Wind - Onshore - Low cost Scenario	7%	50.0		30.0%	1	25	1500	46500	0	67
Wind - Offshore - Low cost Scenario	7%	250.0		40.0%	1	25	2500	87500	0	86
Solar - Low cost Scenario	7%	1.0		15.0%	1	25	800	18000	0	66

- In the low cost VRE scenario, the cost of wind is decreased by 25% and the cost of solar by 50%with respect to the baseline case.

Economics of flexibility options

- The cost of Non Served Energy is set at 10000 USD/MWh. And cost for unmet reserves at 5000 USD/MWh.
- DSM (demand curtailment) of 4% of the demand at a cost of 500 USD/MWh.
- Possibility to further develop pumped hydro (up to adding 5 additional GW in zone 1) if economically sustainable.
- Battery storage available (Li-Ion) with a cost of 760 USD/kWh (in the low cost VRE scenario storage cost is reduced by 30%).

  Battery storage is developed if economically sustainable without limit in capacity.
- Flexibility characteristics and cost of conventional power plants has been derived from literature review and expert estimates.

		Gas-OCGT	*Gas- CCGT*	*Coal*	*Nuclear*
Minimal Power	[%]	25%	30%	40%	50%
Ramping Rate	[%Pmax/h]	100%	70%	30%	20%
Minimal up-time	[h]	1	4	8	8
Minimal down time	[h]	1	6	8	24
Cost of start-up	[USD/MW/start]	15000	75000	211250	500000