

Integration Costs of Variable Renewable Energy Technologies in European Energy Systems

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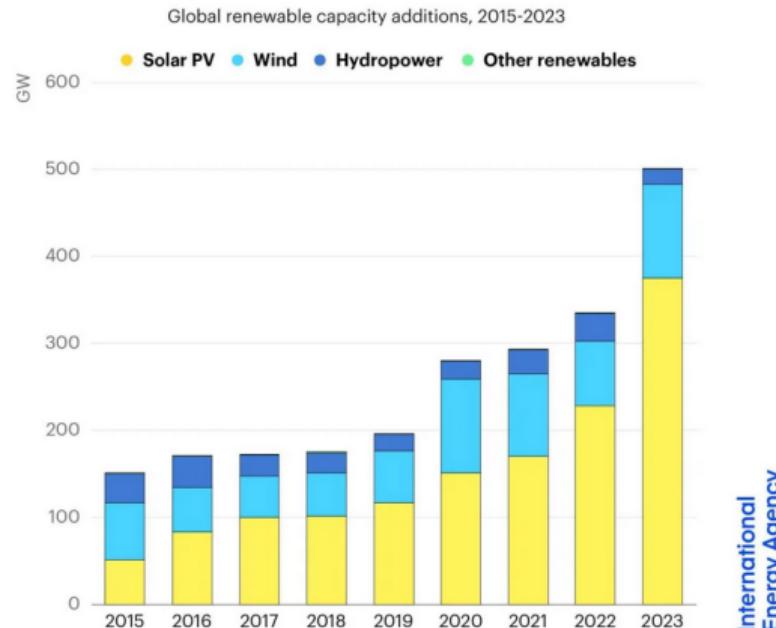
BEEES, Antwerp - January 20, 2026

Introduction

Introduction

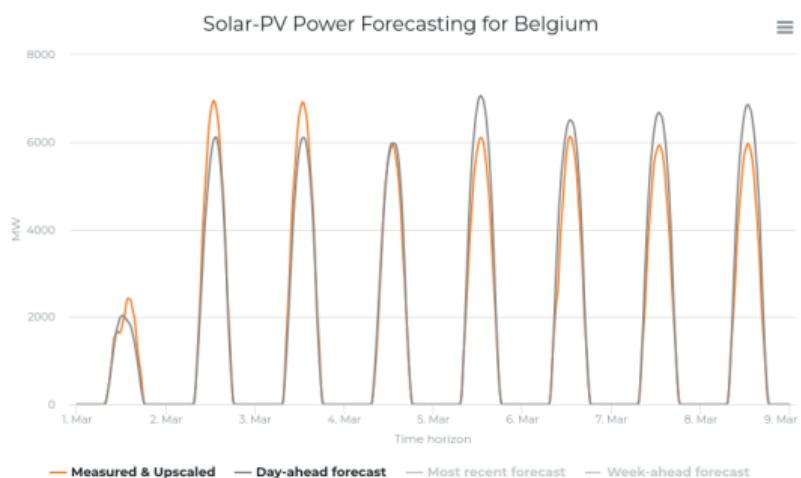
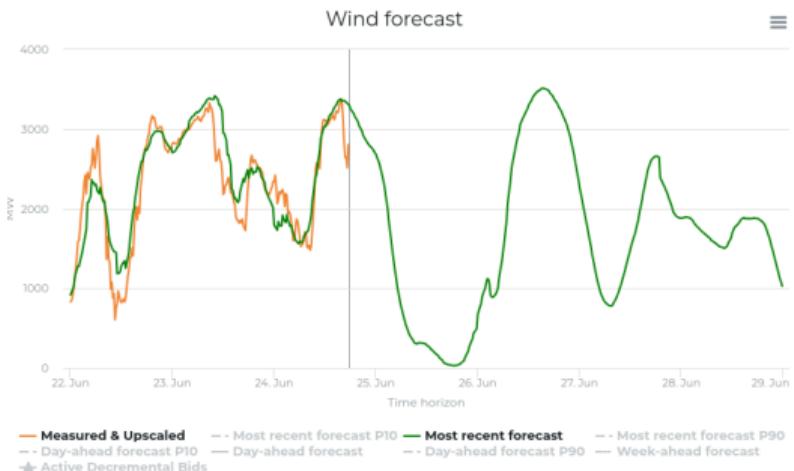


The world added a historic 510 GW of renewable capacity in 2023, equivalent to the entire power capacity of Germany, France & Spain combined



Introduction

Characteristics of VRE technologies! Uncertainty and Variability



A perfect forecast eliminates uncertainty, but variability remains



Introduction

challenges of managing the variability and uncertainty of VRE

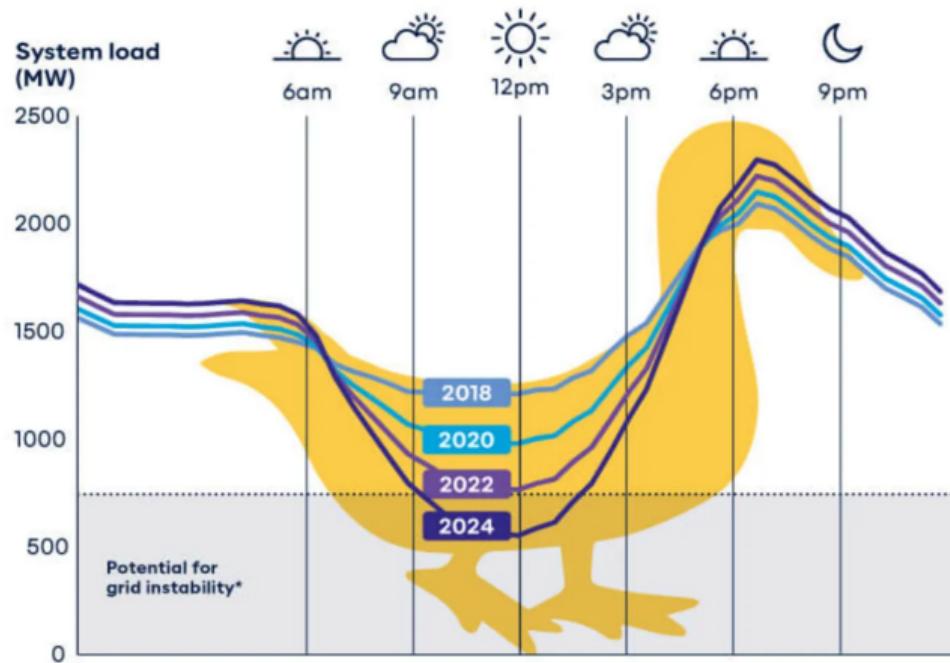


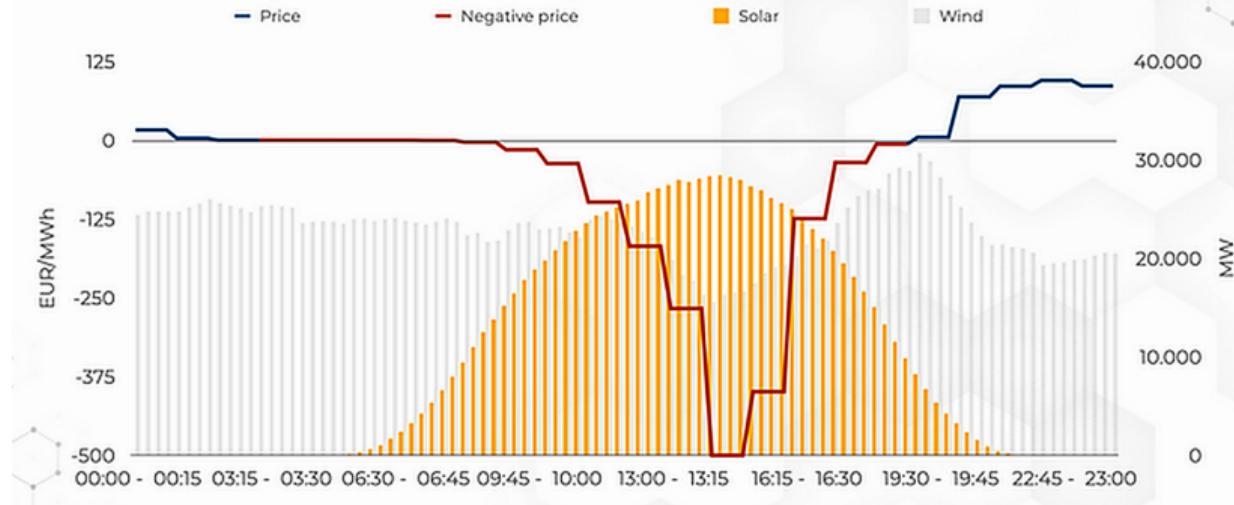
Image credentials: Jens C Thomsen

Introduction

Negative electricity prices with high solar generation



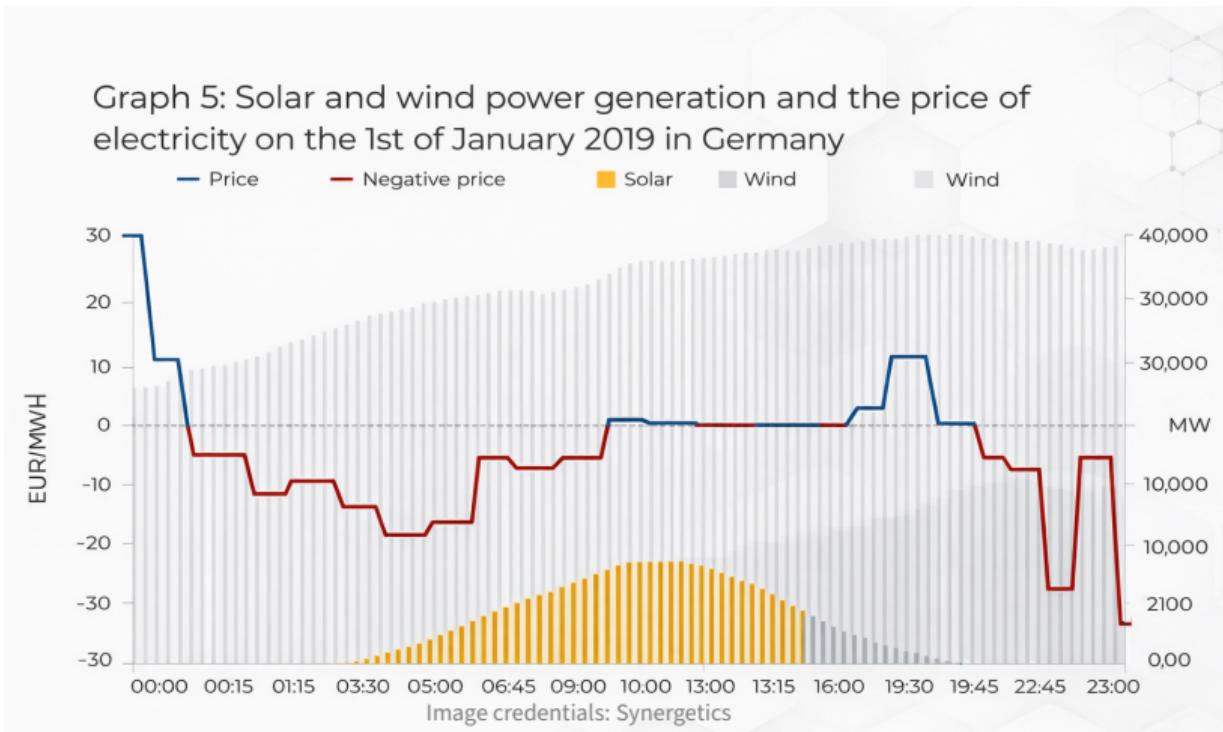
Graph 4: Solar and wind power generation and the price of electricity on the 2nd of July 2023 in Germany





Introduction

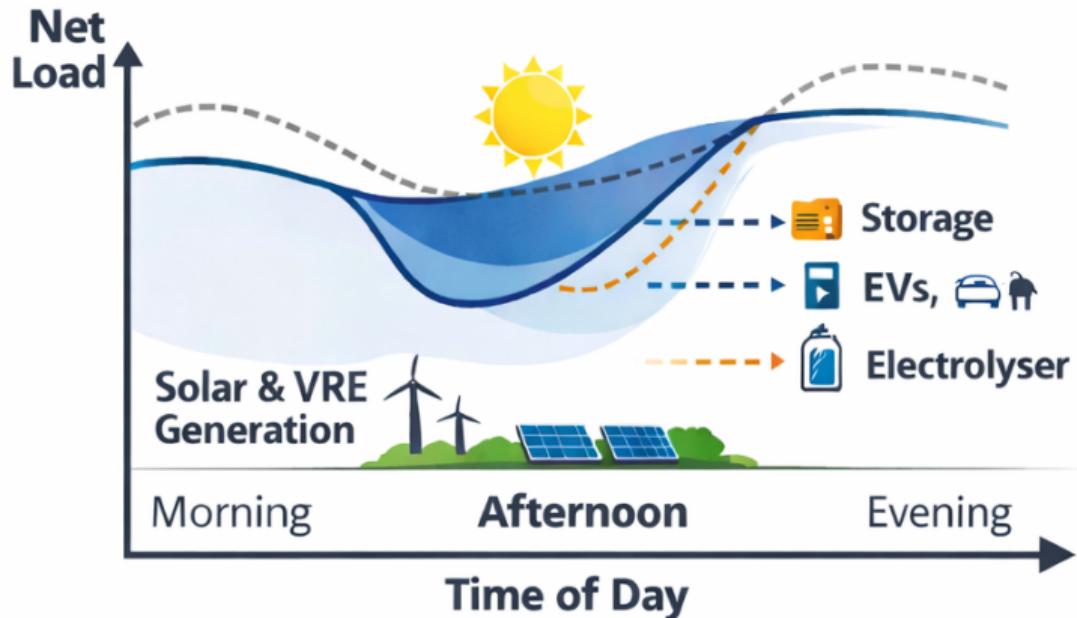
Negative electricity prices with high wind generation





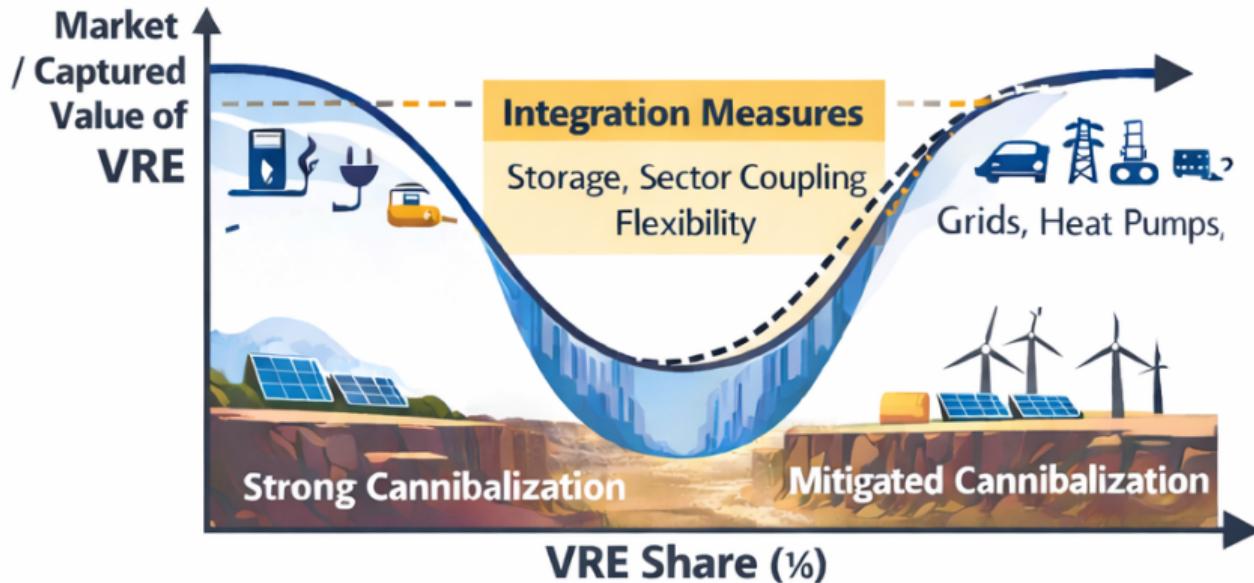
Introduction

Short-term operational challenges caused by VRE generation within a day



Introduction

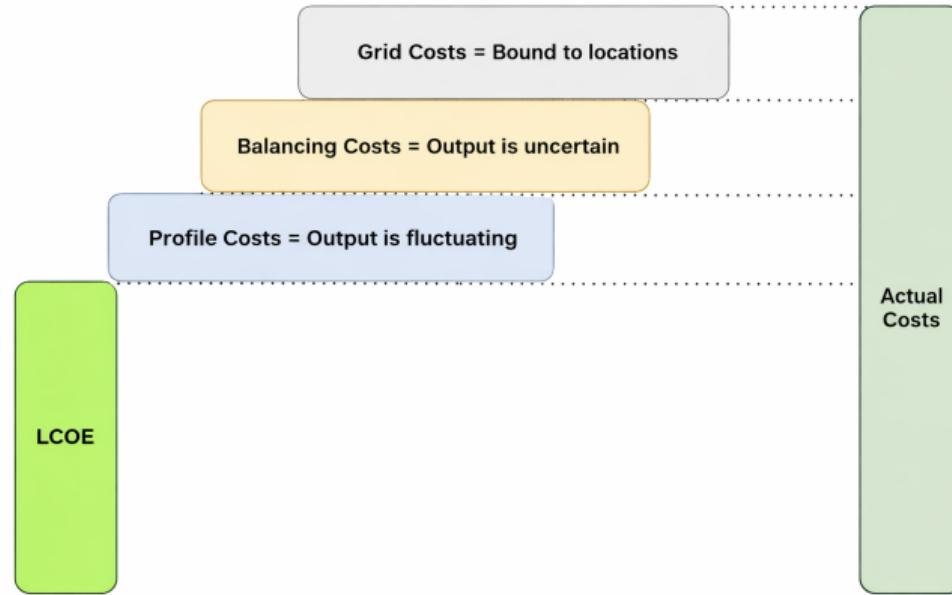
Long-term economic consequences of high VRE penetration





Introduction

Integration costs: the additional system cost when integrating VRE



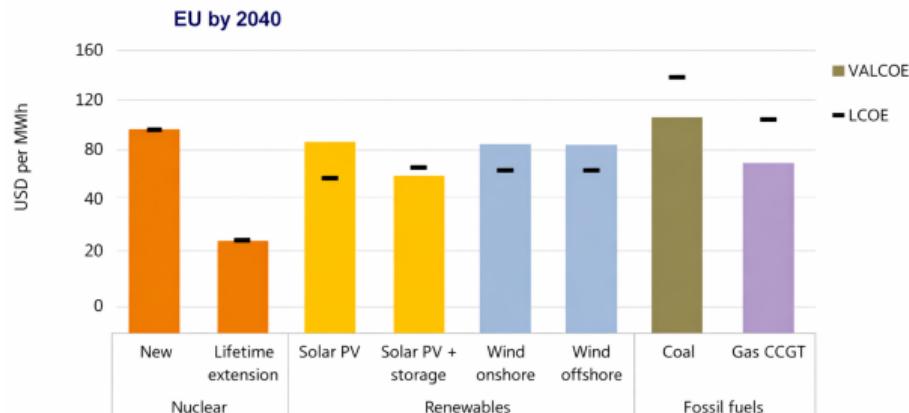
Addapted from Ueckerdt et al. 2013



Introduction

IEA- VALCOE: Assessing the true economic competitiveness of technologies

$$VALCOE_x = LCOE_x + \underbrace{[\hat{E} - E_x]}_{\text{Energy value}} + \underbrace{[\hat{C} - C_x]}_{\text{Capacity value}} + \underbrace{[\hat{F} - F_x]}_{\text{Flexibility value}}$$



A simplified economic model, not a full system analysis tool.

Image credentials: IEA

Methodology



Objective

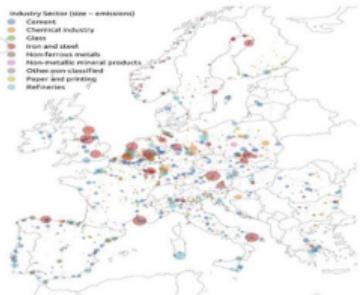
Compute the integration costs in a simple and straightforward way!

Utilize an energy system model

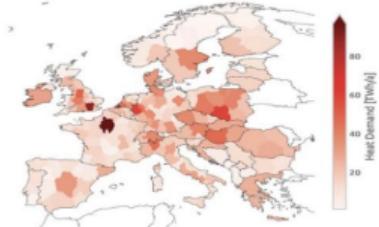
PyPSA-Eur



Industrial sector model

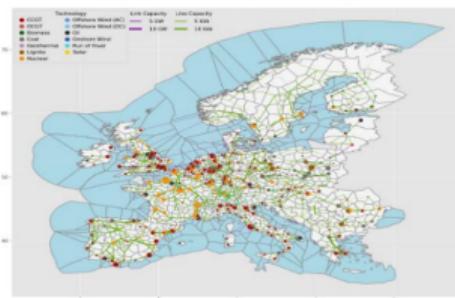


Heat demands

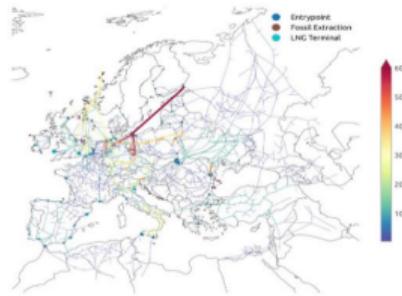


Workflows and scripts to extract
all demands, generation,
potentials, costs, ...

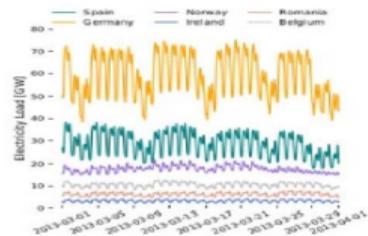
Existing grid and power plants



Detailed gas grid model



Hourly time series





Methodology

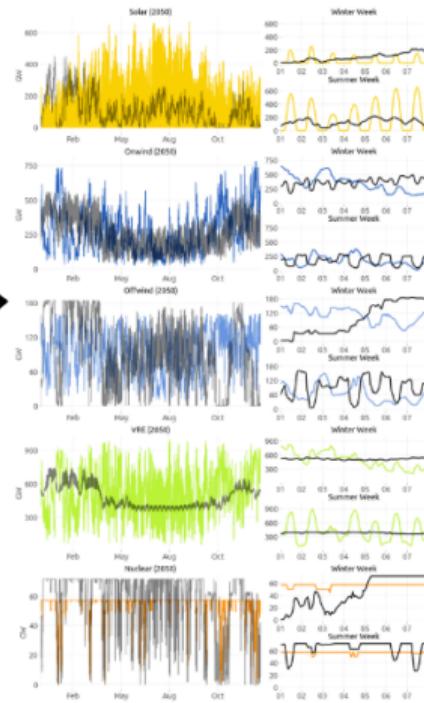
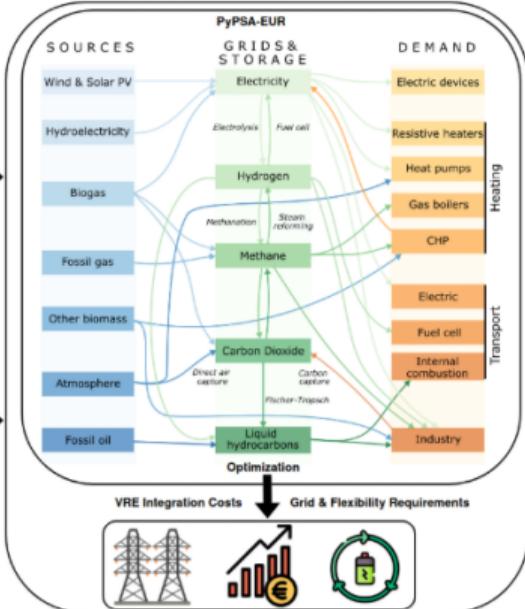
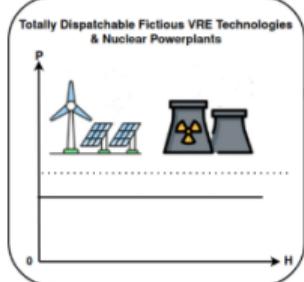
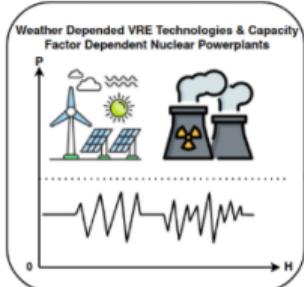
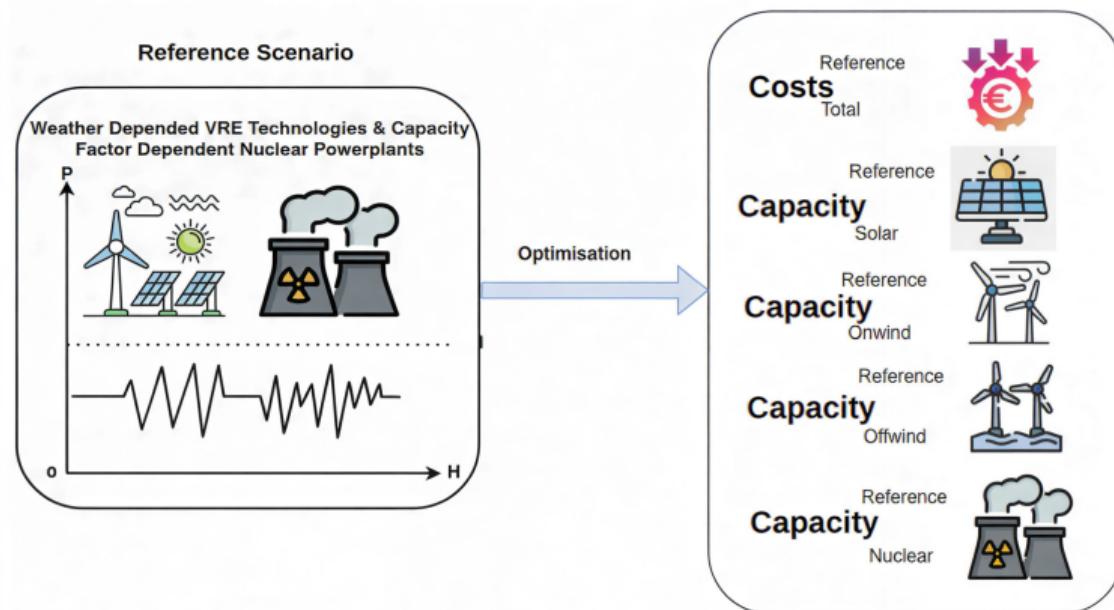


Image credentials: PyPSA-Eur



Methodology

Reference scenario computes the total annualised system costs and optimised capacities of renewable technologies





Methodology

Example: Solar integration costs

Equal Capacities



$$\text{Capacity}_{\text{Flexible solar}} = \text{Capacity}_{\text{Reference Solar}}$$



$$\text{Capacity}_{\text{Flexible onwind}} = \text{Capacity}_{\text{Reference Onwind}}$$



$$\text{Capacity}_{\text{Flexible offwind}} = \text{Capacity}_{\text{Reference Offwind}}$$

Generation Constraints



$$\sum_{i,t} \text{Generation}_{i,t}^{\text{Flexible solar}} \leq \sum_{i,t} \text{Generation}_{i,t}^{\text{Reference}}$$

Modified Capacity Factor



$$0 \leq \text{Capacity Factor}_{\text{Solar}} \leq 1$$



Methodology

Example: Solar integration costs



Costs
Total

=

Reference
Costs
Total

- Flexible solar
Costs
Total



Integration Costs
Solar

=

Costs
Total
Flexible solar
 $\sum_{i,t}$ Generation_{i,t}

LCOE
Adjusted
Solar

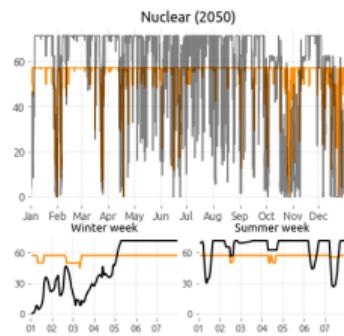
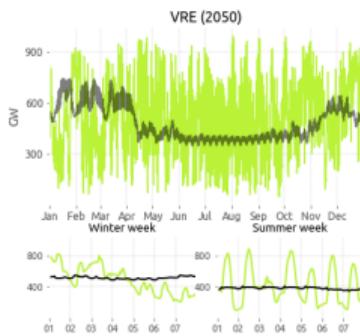
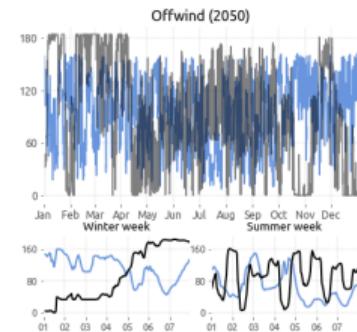
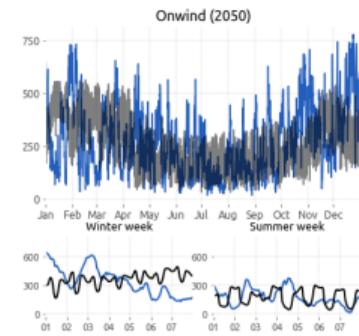
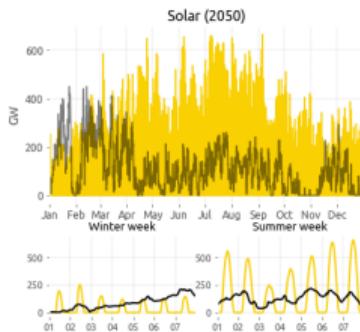
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LCOE
Solar + Integration Costs
Solar



Methodology

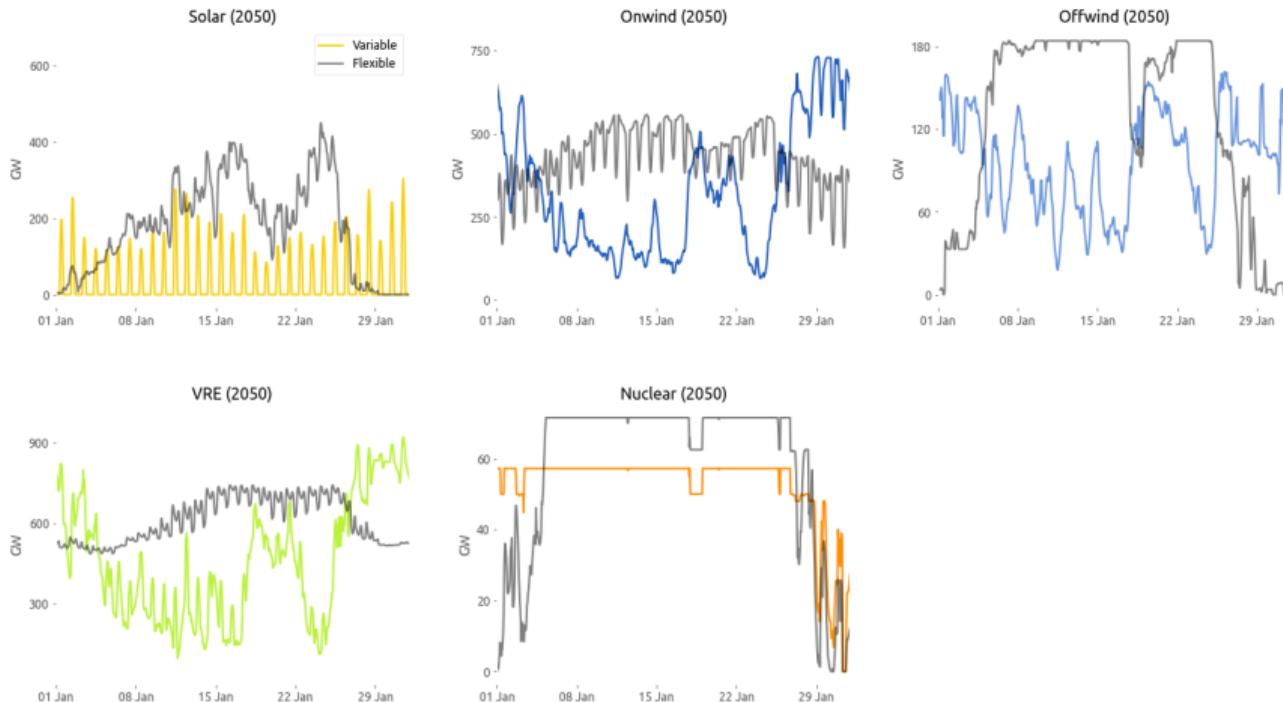
Dispatch profiles for whole year





Methodology

Dispatch profiles for a month



Scenarios

Scenario: net-zero by 2050



4 technologies considered for the integration cost assessment

Considered Nodes: BE, FR, NL, GB, DE

Optimisation: Greenfield

Configuration:

- ▶ Carbon budget: 2030 (-55%), 2040 (-85%), 2050 (net zero)
- ▶ Current demand projections + expected efficiency improvements
- ▶ Transmission lines expansion,max 50%
- ▶ Increased EV shares upto 85% by 2050
- ▶ CCS is allowed

Results



Results

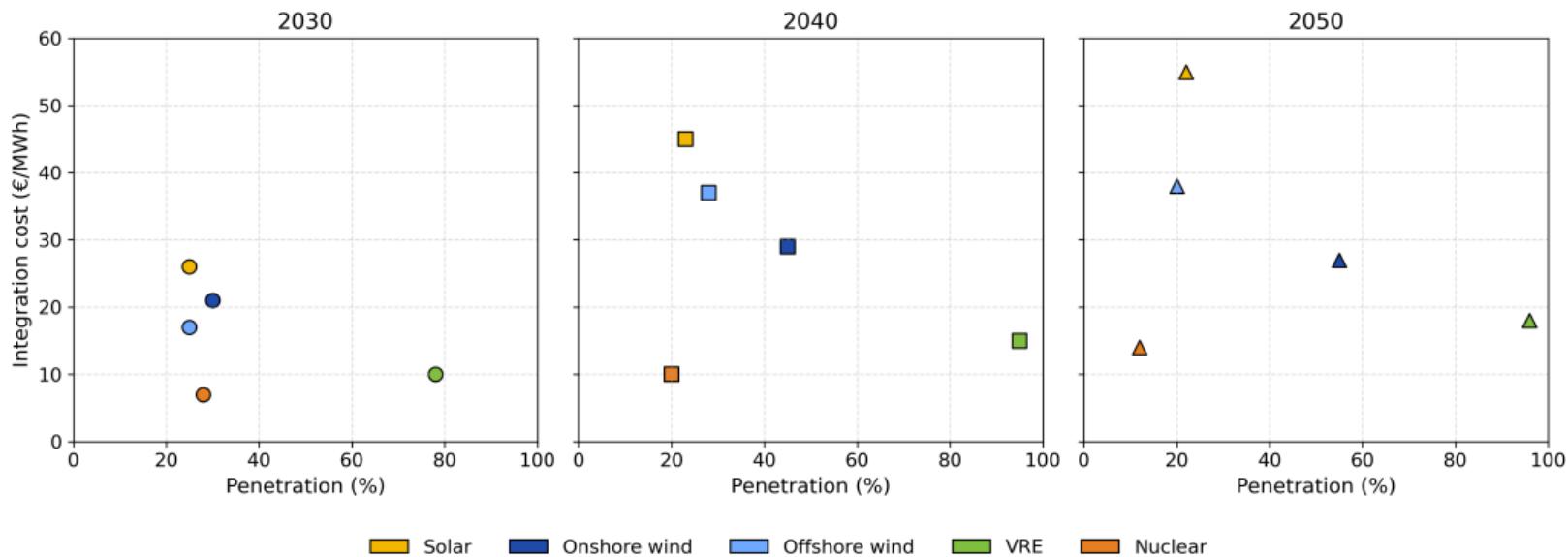
Integration costs





Results

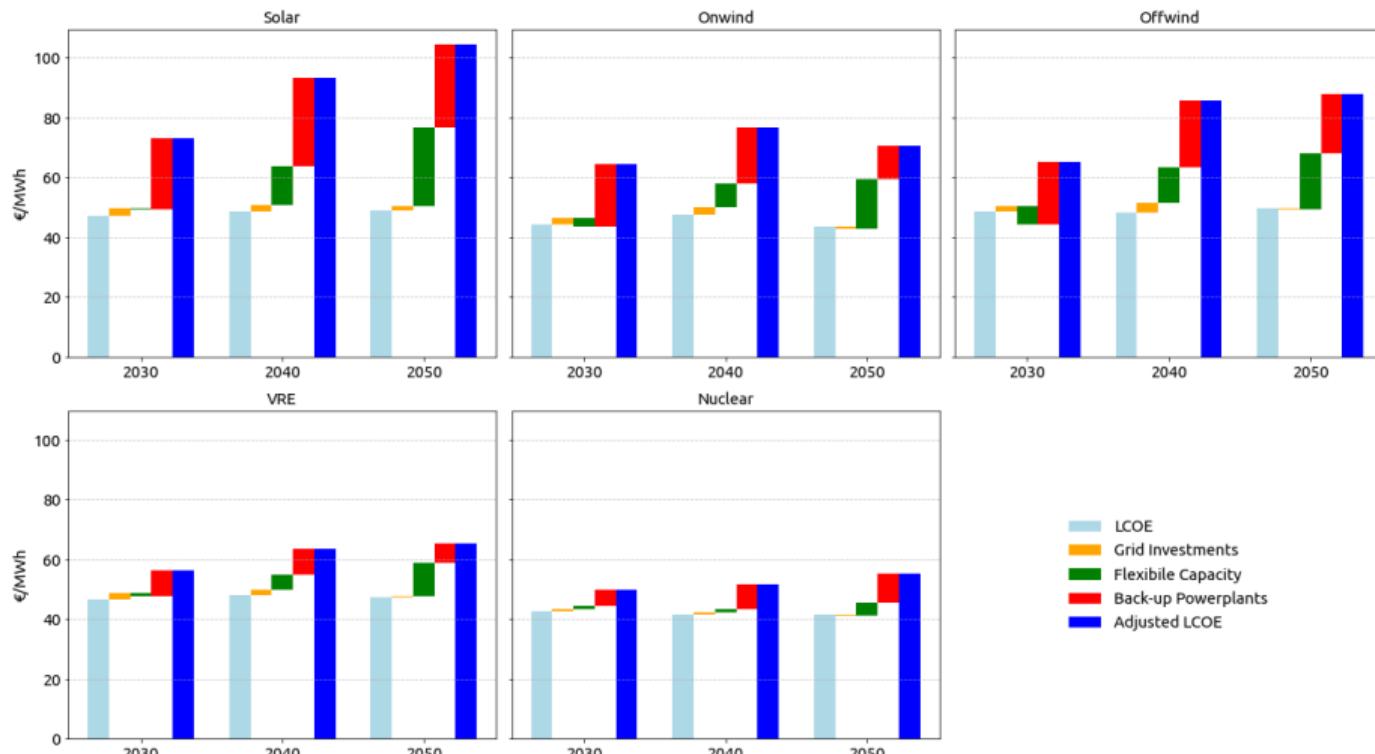
Integration costs with penetration level in power system





Results

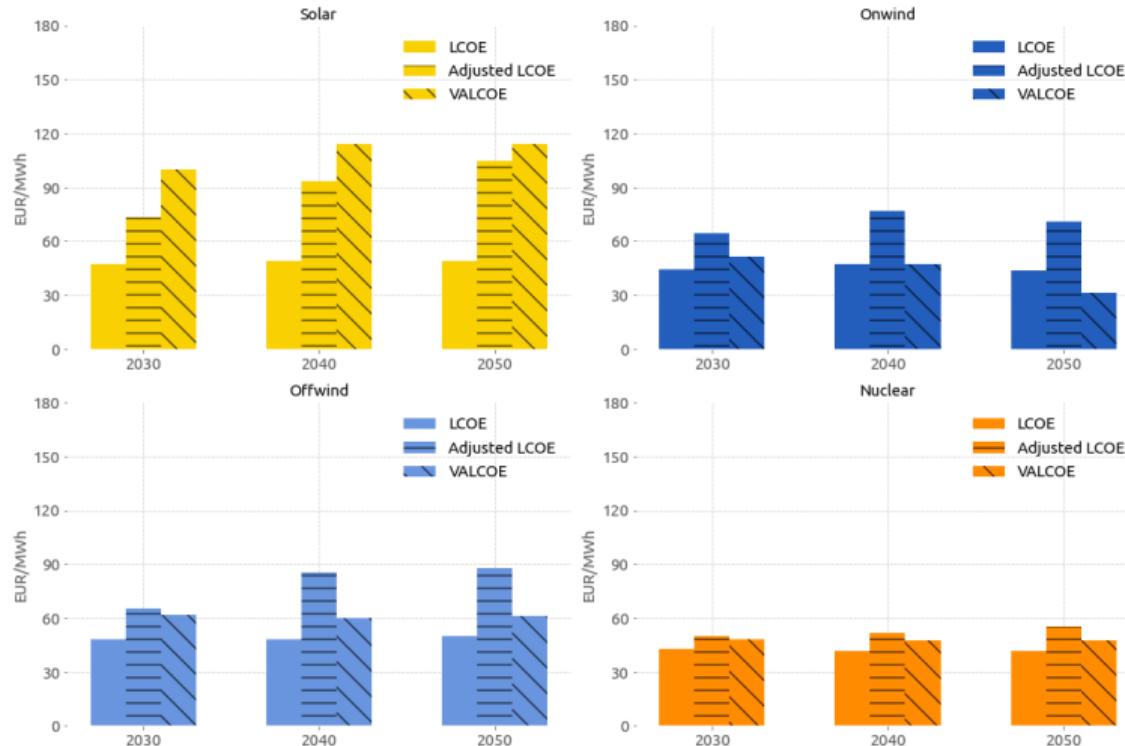
Distribution of integration costs





Results

Comparison with VALCOE



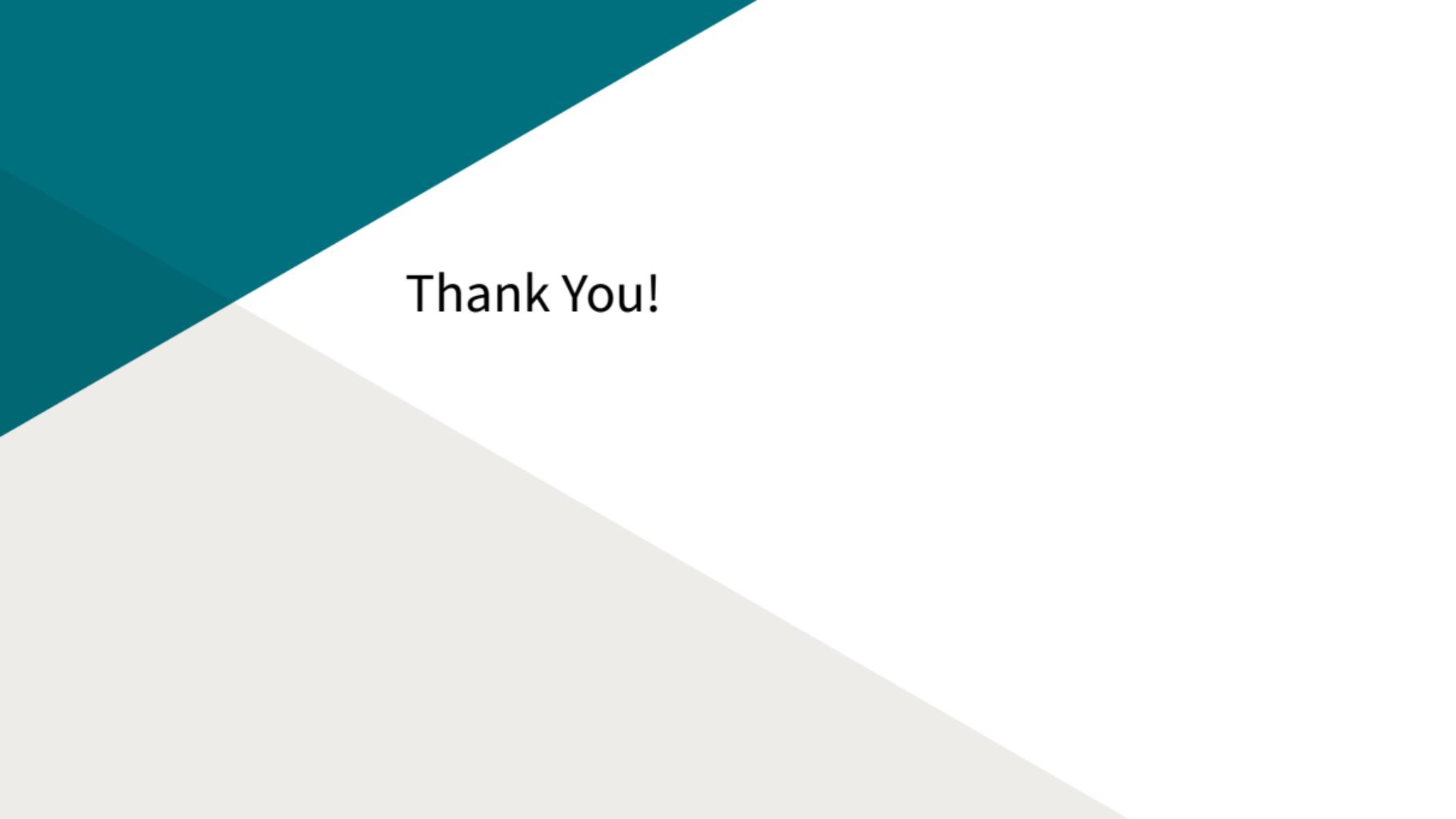
Conclusions

Conclusion



Conclusion:

- ▶ Integration costs computations can be made in a simple way using existing modeling tools.
- ▶ Solar integrations costs are 55 Euros/MWh compared to 13 Euros/MWh for nuclear by 2050.
- ▶ Complementarity and the diversity of different renewable energy sources; when combined, integration costs remain marginal even above 90% penetration.

The background features a large teal-colored triangle in the top-left corner and a light gray triangle in the bottom-right corner, both extending towards the center.

Thank You!



Extra slides



Extra slides

VALCOE Equations

$$VALCOE_x = LCOE_x + \overbrace{[\bar{E} - E_x]}^{\substack{\text{Value adjustments} \\ \text{Energy value}}} + \overbrace{[\bar{C} - C_x]}^{\substack{\text{Capacity value}}} + \overbrace{[\bar{F} - F_x]}^{\text{Flexibility value}}$$

$$\text{Energy value}_x \left(\frac{\$}{MWh} \right) = \frac{\sum_h^{8760} [\text{WholesalePrice}_h \left(\frac{\$}{MWh} \right) \times \text{Output}_{x,h} (\text{MW})]}{\sum_h^{8760} \text{Output}_{x,h} (\text{MW})}$$

$$\text{Capacity value}_x \left(\frac{\$}{MWh} \right) = \frac{\text{Capacity credit}_x \times \text{Basis capacity value} (\$/kW)}{(\text{capacity factor}_x \times \text{hours in year}/1000)}$$

$$\text{Flexibility value}_x \left(\frac{\$}{MWh} \right) = \frac{\text{Flexibility value multiplier}_x \times \text{Base flexibility value} \left(\frac{\$}{kW} \right)}{(\text{capacity factor}_x \times \text{hours in year}/1000)}$$