LIÈGE université

Integration Costs of Variable Renewable Energy Technologies in European Energy Systems

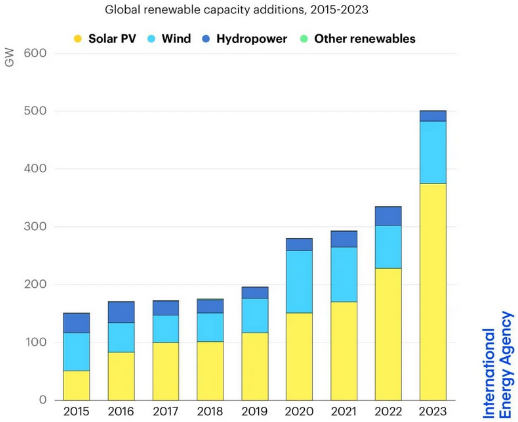
Muhammad Umair Tareen, Sylvain Quoilin

BEEES, Antwerp - January 20, 2026

Introduction

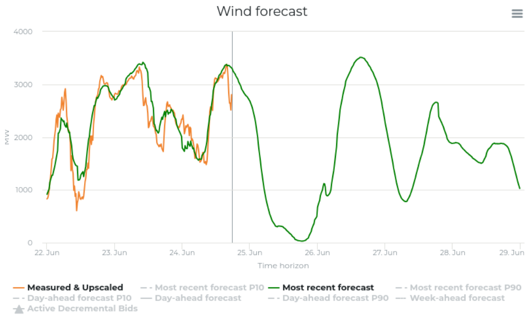
Introduction

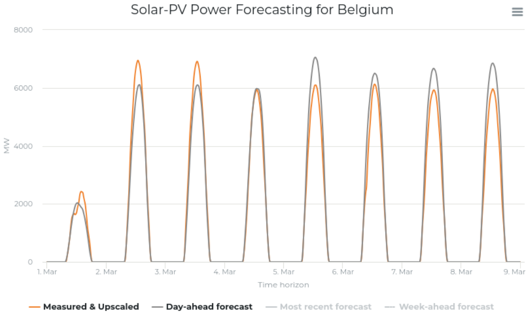
The world added a historic 510 GW of renewable capacity in 2023, equivalent to the entire power capacity of Germany, France & Spain combined



Introduction

Characteristics of VRE technologies! Uncertainty and Variability





A perfect forecast eliminates uncertainty, but variability remains

Courtesy: Elia Dashboard

Introduction
challenges of managing the variability and uncertainty of VRE

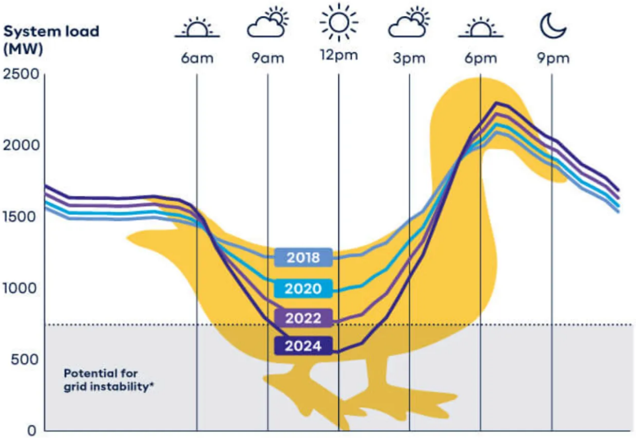


Image credentials: Jens C Thomsen

Introduction
Negative electricity prices with high solar generation

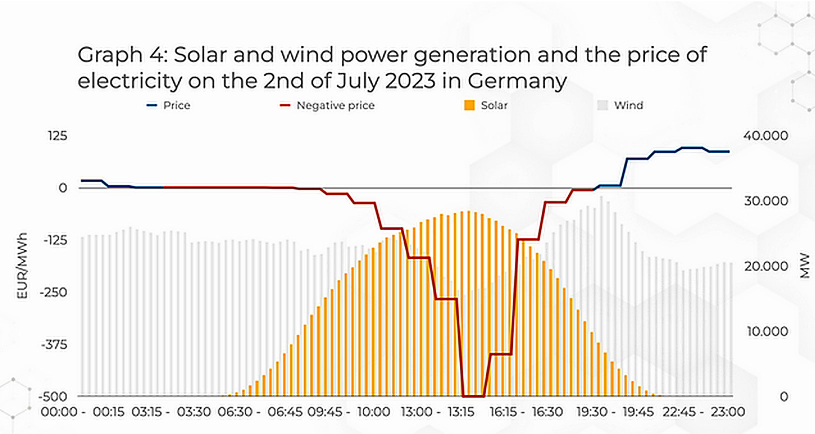


Image credentials: Synergetics

Introduction
Negative electricity prices with high wind generation

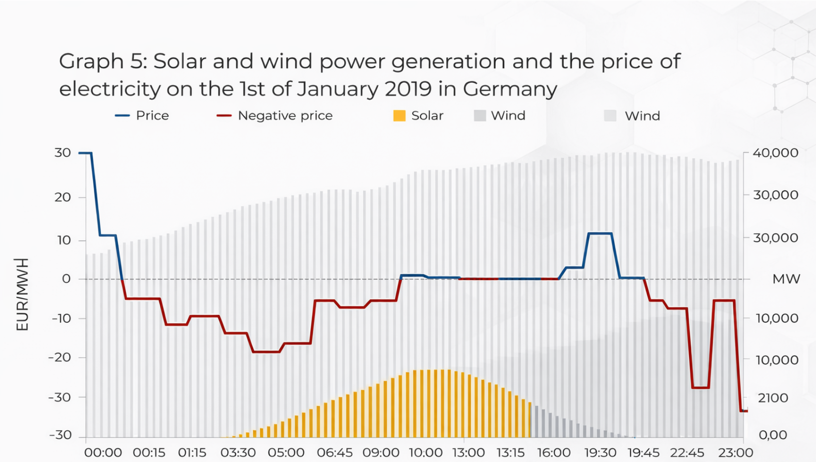
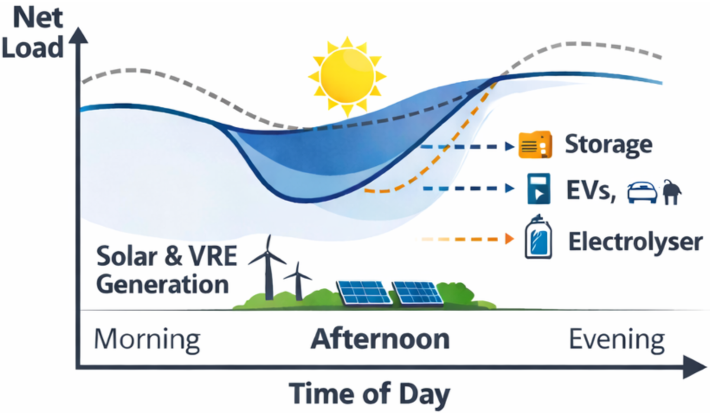


Image credentials: Synergetics

Introduction

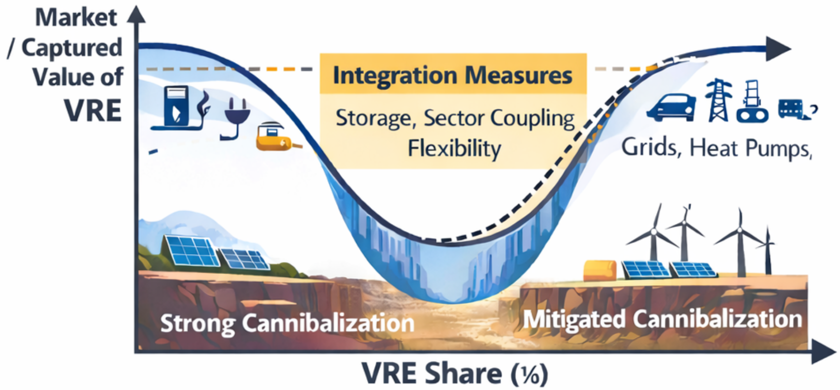
Short-term operational challenges caused by VRE generation within a day



AI generated image

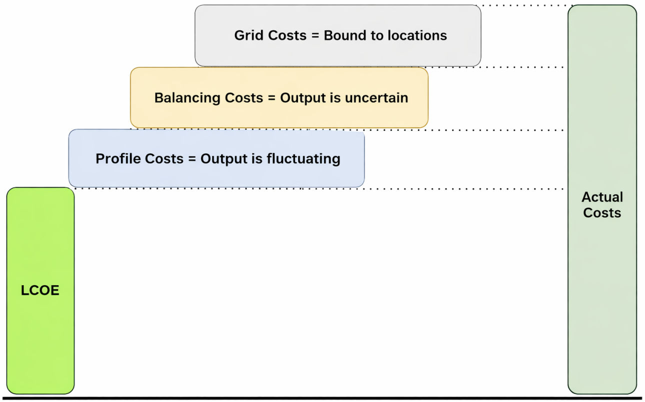
Introduction

Long-term economic consequences of high VRE penetration



AI generated image

Introduction
Integration costs: the additional system cost when integrating VRE

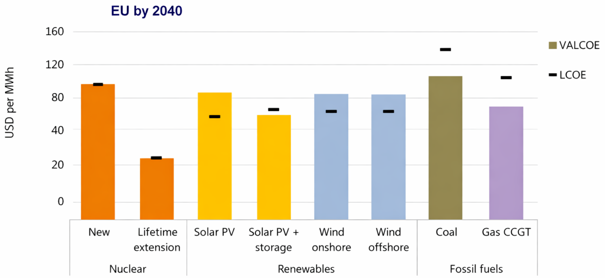


Addapted from Ueckerdt et al. 2013

Introduction

IEA- VALCOE: Assessing the true economic competitiveness of technologies

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



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

Image credentials: IEA

Methodology

Objective

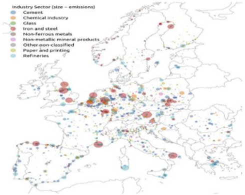
Compute the integration costs in a simple and straightforward way!

Utilize an energy system model

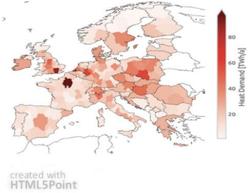
Image credentials: IEA

PyPSA-Eur

Industrial sector model

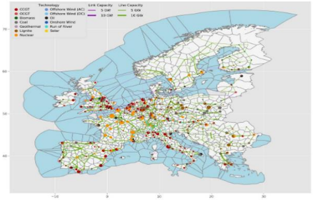


Heat demands

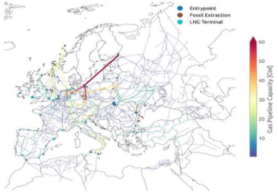


Workflows and scripts to extract all demands, generation, potentials, costs, …

Existing grid and power plants



Detailed gas grid model



Hourly time series

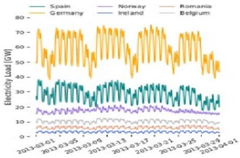


Image credentials: PyPSA-Eur

Methodology

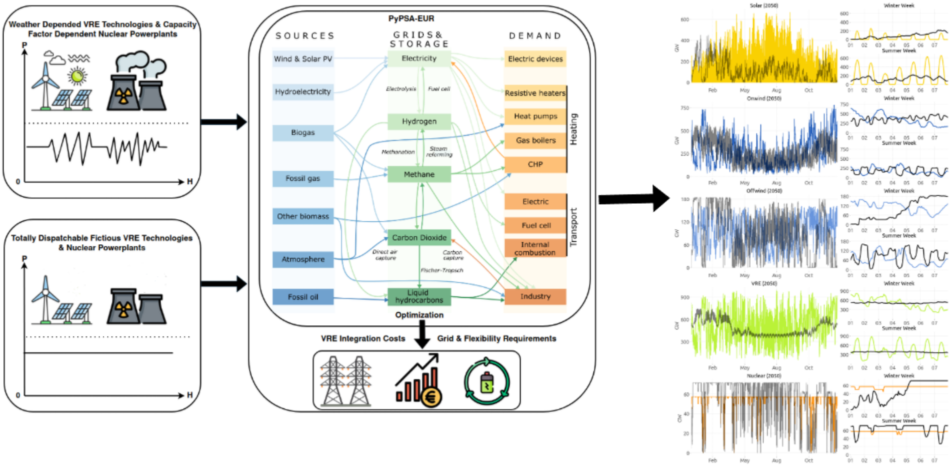
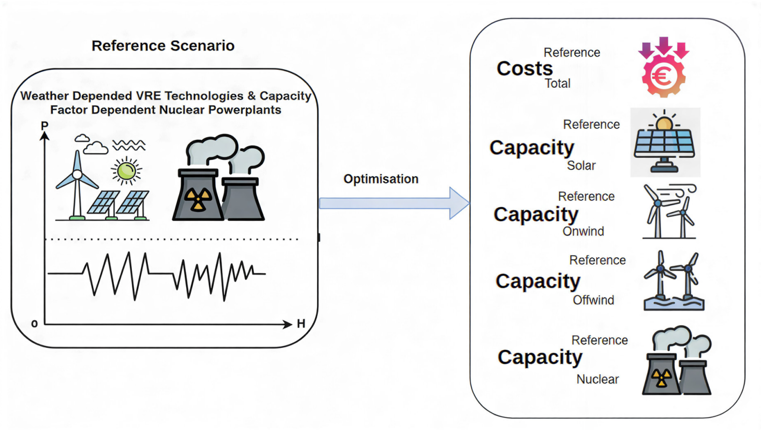


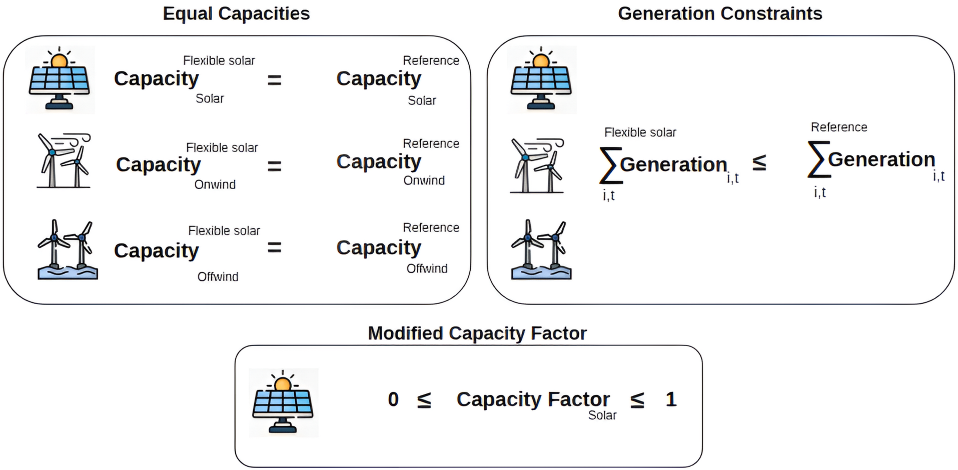
Image credentials: PyPSA-Eur

Methodology

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



Methodology
Example: Solar integration costs



Methodology

Example: Solar integration costs

$$\text{Costs}_{\text{Total}} = \text{Costs}^{\text{Reference}}_{\text{Total}} - \text{Costs}^{\text{Flexible solar}}_{\text{Total}}$$

$$\text{Integration Costs}_{\text{Solar}} = \frac{\text{Costs}_{\text{Total}}}{\sum_{i,t}^{\text{Flexible solar}} \text{Generation}_{i,t}}$$

$$\text{LCOE}^{\text{Adjusted}}_{\text{Solar}} = \text{LCOE}_{\text{Solar}} + \text{Integration Costs}_{\text{Solar}}$$

Scenarios

Scenario: net-zero by 2050

4 technologies considered for the integration cost assessment

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

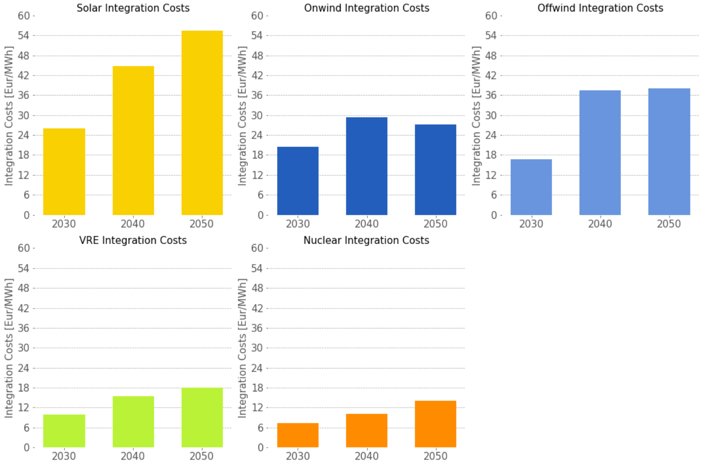
Optimisation: Greenfield

Configuration:

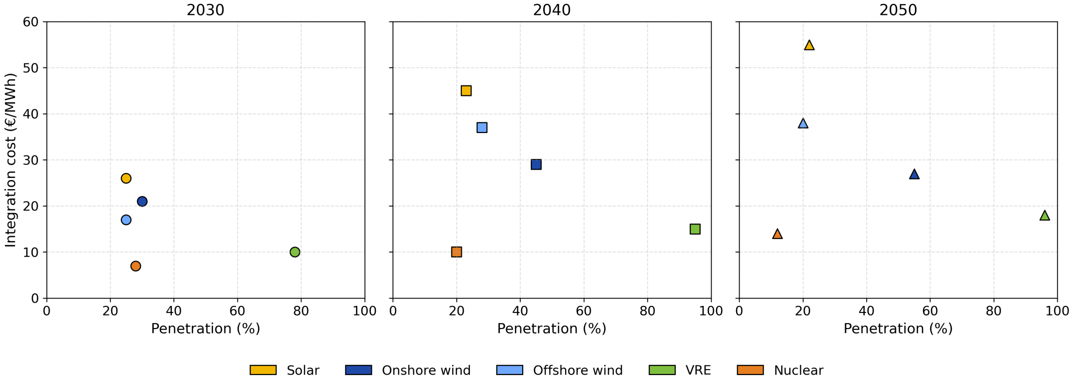
- Carbon budget: 2030 (–55%), 2040 (–85%), 2050 (net zero)
- Current demand projections + expected efficiency improvements
- Transmission lines espansion,max 50%
- Increased EV shares upto 85% by 2050
- CCS is allowed

Results

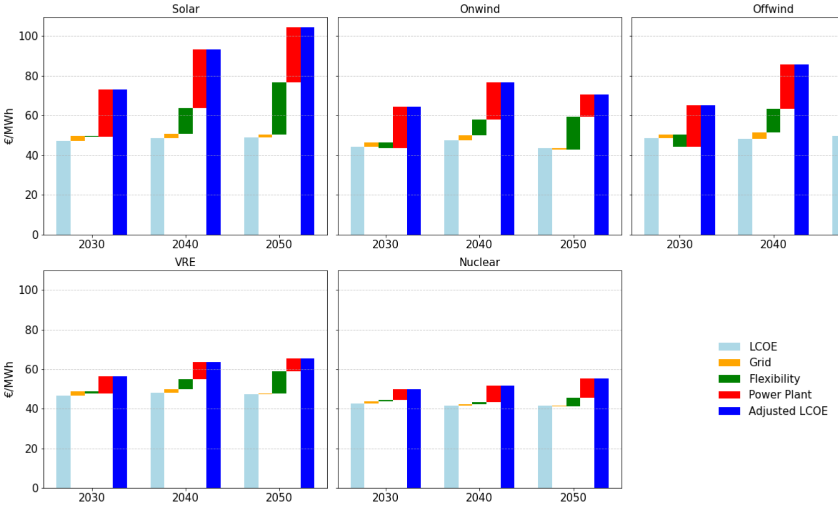
Results
Integration costs



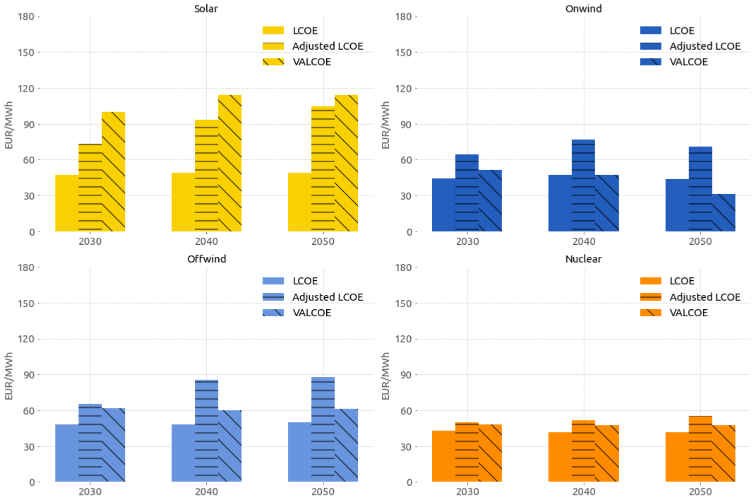
Results
Integration costs with penetration level in power system



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.

Thank You!

Extra slides

Extra slides

VALCOE Equations

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

$$Energy\ value_x\left(\frac{\$}{MWh}\right) = \frac{\sum_h^{8760}\left[WholesalePrice_h\left(\frac{\$}{MWh}\right)\ x\ \ Output_{x,h}\,(MW)\right]}{\sum_h^{8760} Output_{x,h}\,(MW)}$$

$$Capacity\ value_x\left(\frac{\$}{MWh}\right) = \frac{Capacity\ credit_x\ \ x\ \ Basis\ capacity\ value\ (\$/kW)}{(capacity\ factor_x\ \ x\ \ hours\ in\ year/1000)}$$

$$Flexibility\ value_x\left(\frac{\$}{MWh}\right) = \frac{Flexibility\ value\ multiplier_x\ \ x\ \ Base\ flexibility\ value\left(\frac{\$}{kW}\right)}{(capacity\ factor_x\ \ x\ \ hours\ in\ year/1000)}$$