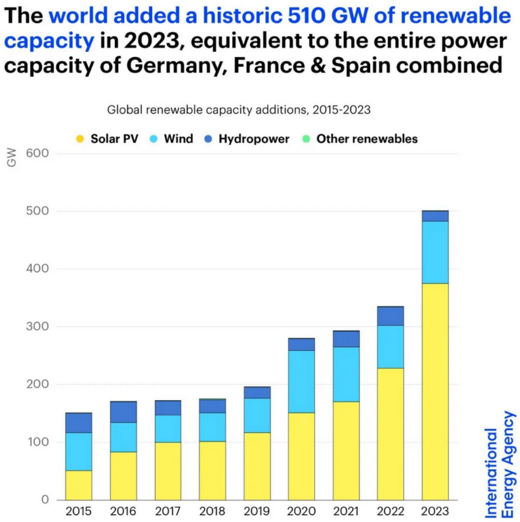
Quantifying Integration Costs of Variable Renewable Energy Technologies in European Energy Systems

Muhammad Umair Tareen, Sylvain Quoilin

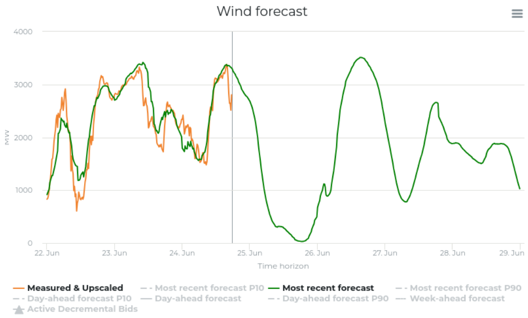
ECOS, Paris - June 30, 2025

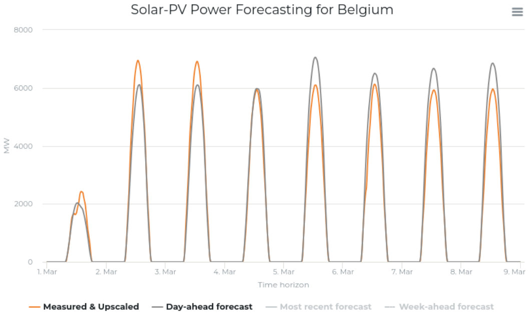
Introduction

Introduction



Introduction
Characteristics of VRE technologies! Uncertainty and Variability



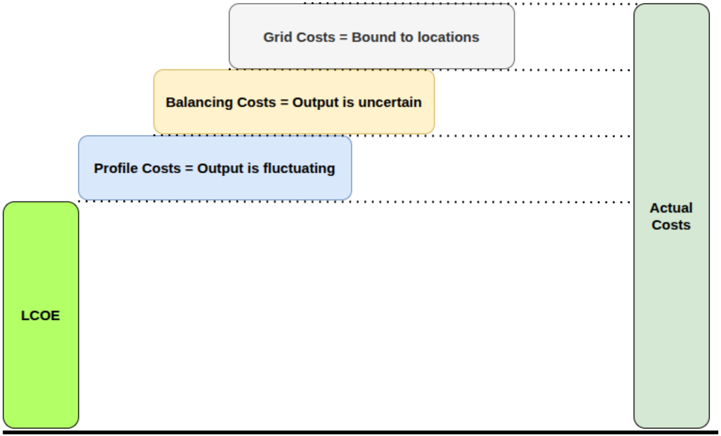


A perfect forecast eliminates uncertainty, but variability remains

Courtesy: Elia Dashboard

Introduction

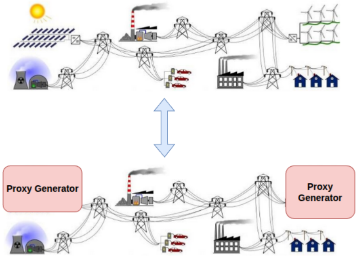
Integration costs: the additional system cost when integrating VRE



Addapted from Ueckerdt et al. 2013

Introduction
Methodologies used to compute integration costs (literature review)

Cost production model method



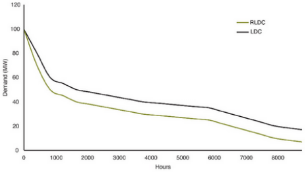
Different Metrics

VALCOE

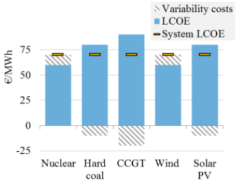
ACOE

LACE

Load duration curves method



System LCOE method



Methodology

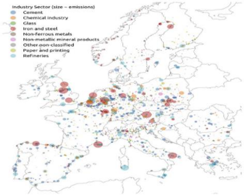
Objective

Compute the integration costs in a simple and straightforward way!

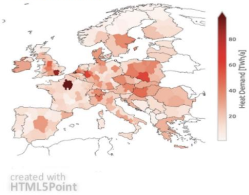
Utilize an energy system model

Why PyPSA-Eur?

Industrial sector model

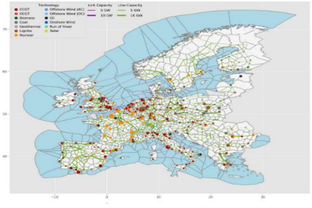


Heat demands

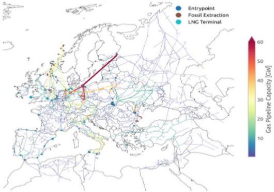


Workflows and scripts to extract all demands, generation, potentials, costs, …

Existing grid and power plants



Detailed gas grid model



Hourly time series

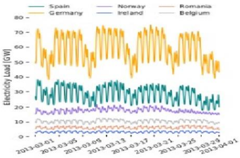


Image credentials: PyPSA-Eur

Methodology

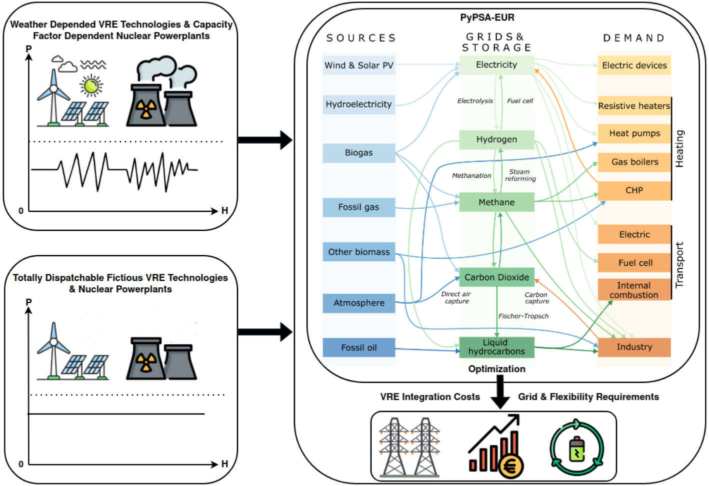
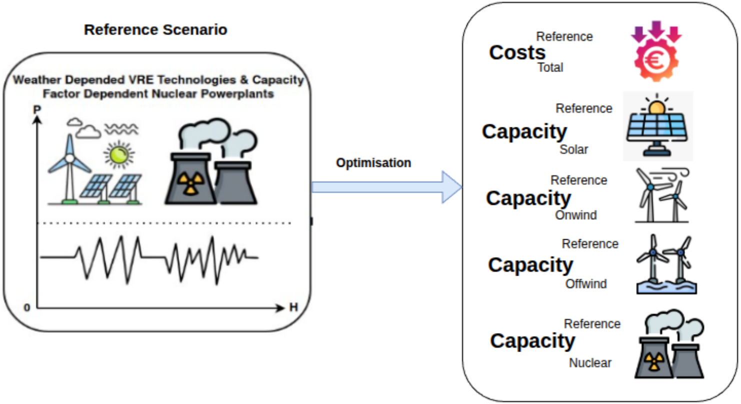


Image credentials: PyPSA-Eur

Methodology

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



Methodology
Example: Solar Scenario

Capacity Constraints

$$\text{Capacity}_{\text{Solar}}^{\text{Solar Scenario}} \leq \text{Capacity}_{\text{Solar}}^{\text{Reference}}$$

$$\text{Capacity}_{\text{Onwind}}^{\text{Solar Scenario}} \leq \text{Capacity}_{\text{Onwind}}^{\text{Reference}}$$

$$\text{Capacity}_{\text{Offwind}}^{\text{Solar Scenario}} \leq \text{Capacity}_{\text{Offwind}}^{\text{Reference}}$$

Generation Constraints

$$\sum_{i,t} \text{Generation}_{i,t}^{\text{Solar Scenario}} \leq \sum_{i,t} \text{Generation}_{i,t}^{\text{Reference}}$$

Modified Capacity Factor

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

Methodology
Example: Solar Scenario

$$\text{Costs}_{\text{Total}} = \text{Costs}^{\text{Reference}}_{\text{Total}} - \text{Costs}^{\text{Solar Scenario}}_{\text{Total}}$$

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

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

Straight forward computation of integration costs

Scenarios

Scenarios

5 Scenarios: Solar, Onshore Wind, Offshore Wind, VRE, Nuclear

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

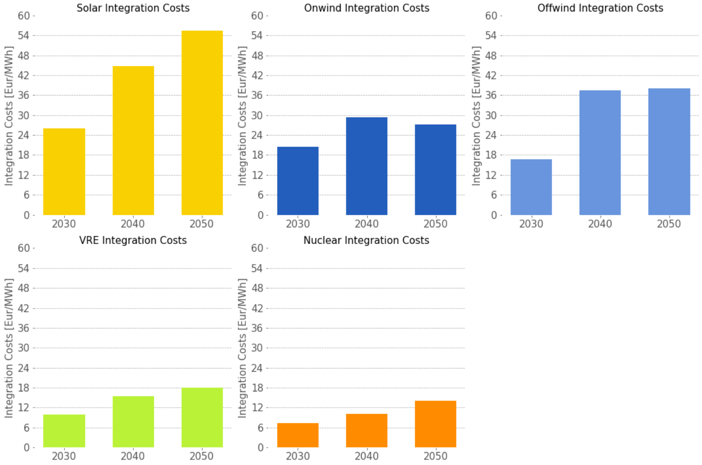
Optimisation: Greenfield and brownfield

Configuration:

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

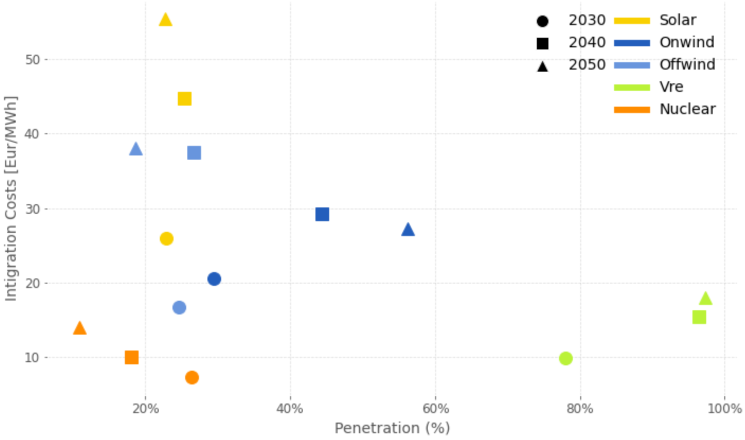
Results

Results
Integration costs in all scenarios

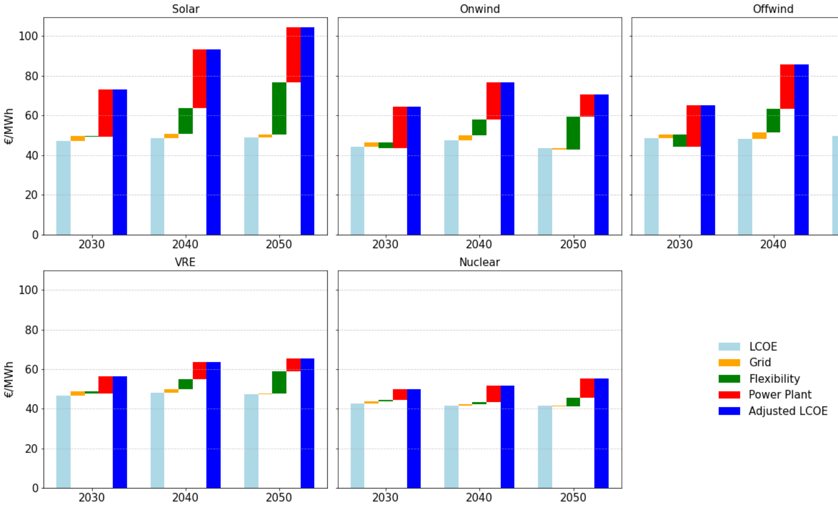


Results

Integration costs with penetration level in power system



Results
Distribution of integration costs



IEA- VALCOE

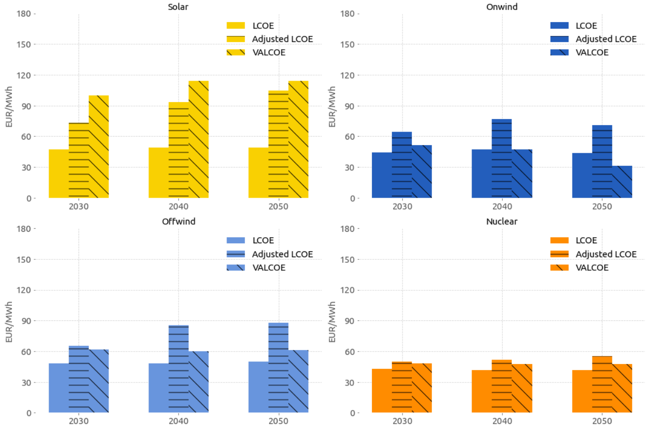
$$VALCOE_x = LCOE_x + \overbrace{\overbrace{[\bar{E} - E_x]}^{Energy\ value} + \overbrace{[\bar{C} - C_x]}^{Capacity\ value} + \overbrace{[\bar{F} - F_x]}^{Flexibility\ value}}^{Value\ adjustments}$$

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

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

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

Results
Comaprison with VALCOE



Conclusions

Conclusion and Future Work

Conclusion:

- Integration costs computations can be made in a simple way using existing modeling tools.
- Individually, these costs can be very high for some VRE technologies like solar.
- Policy measures have a big impact on VRE integration; when combined, integration costs remain marginal even above 80% penetration.

Future Work:

- Extending the study on regional level.
- Considering the operational constraints of powerplants.
- Comparison of results with other studies.
- Sensitivity analysis.

Thank You!