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Empowering Generation Adequacy: The Impact of Energy Storages Evaluated with a System-wide Least-Squares Monte Carlo Approach

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Project workshop (VeSiMa)

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Adequacy assessments have to address stochastic fluctuations

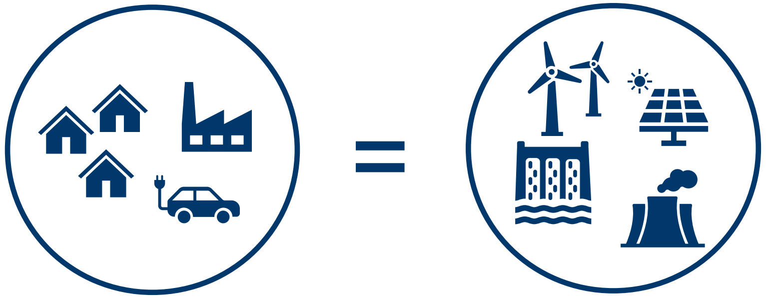
Increasing uncertainties in the European power system

& Increased integration of European electricity markets

- Raising shares of variable renewable generation
- Decreasing conventional power plant capacities
  Especially in Germany: nuclear phase out, coal phase out
- Uncertain availability of gas
  New concern since about two years
- Aging conventional power plant fleet with increasing availability concerns
  Notably French nuclear power plants, partly also other causes

Generation adequacy is the ability of the power system generation to meet the power demand at all points in time

(European Commission, 2017).



➡ Traditional assessment using deterministic capacity balances provide unsatisfactory answers

➡ Need for probabilistic analyses considering stochastic events

European Commission, 2017. Identification of appropriate generation and system adequacy standards for the internal electricity market: final report

Modeling storage operations appropriately is crucial to determine flexibility during scarcity events

- Renewable dominated energy systems have a **large need for flexibility** to balance **fluctuations** from **renewable infeed** and **power demand**
- **Energy storages**, e.g., battery or hydro storages or PtX technologies are **flexible** and can **reduce supply shortages** by shifting energy – but **limited** by their amount of **stored energy**
  - Battery and hydro storages: High efficiency, quick response, no carbon emissions, usually no fuel costs
  - PtX technologies: Flexible energy carriers,
- Flexible operation of storages more difficult to determine than for thermal power plants – due to energy restrictions
  - Opportunity costs (“water value”) determine storage operation
  - depend on future developments → comparison of continuation value (future revenues) and current revenues to determine optimal storage operation

➡ Appropriate modeling of storage operations is crucial to determine available discharging capacities during supply shortages

Traditionally: Storage operation is optimized based on system costs & depending on intertemporal effects

Thermal power plants: **constant** in time and **exogenously given**

Thermal power plants: **merit-order based** determination per timestep

Objective function minimizes system costs

- System costs are calculated as the product of **operational costs** and **power generation** per power plant

Storages: **opportunity costs** determine **storage operation** over the entire time period

Assumptions

- Perfect foresight
- Perfect competition
- Storage provides optimal arbitrage
- No investments

Constraints

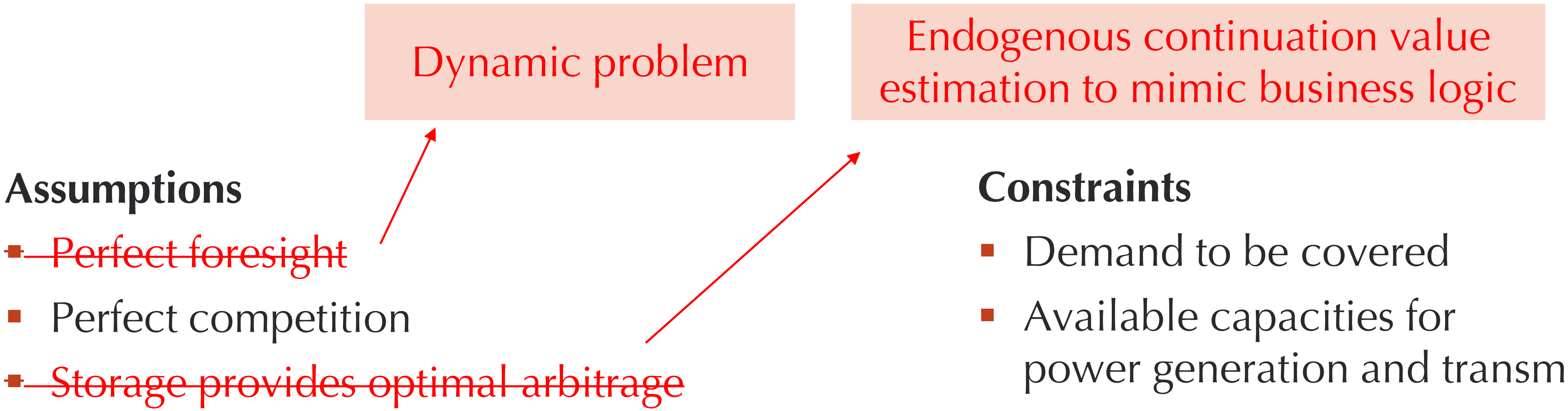
- Demand to be covered
- Available capacities for power generation and transmission
- Storage filling level restrictions
- …

Traditionally: Storage operation is optimized based on system costs & depending on intertemporal effects

? How can we determine the **available discharging capacities** of **multiple large-scale energy storages** in each time step for a large number of Monte-Carlo paths?

Objective function minimizes system costs

- System costs are calculated as the product of **operational costs** and **power generation** per power plant



Dynamic problem

Endogenous continuation value estimation to mimic business logic

Assumptions

- ~~Perfect foresight~~
- Perfect competition
- ~~Storage provides optimal arbitrage~~
- No investments

Constraints

- Demand to be covered
- Available capacities for power generation and transmission
- Storage filling level restrictions
- …

Least-Squares Monte Carlo: Conceptional introduction

Background and Usage

- Developed in finance for valuation of so-called American options by Longstaff and Schwartz (2001) to determine optimal execution of options
- Approximate continuation value (CV) as the value of not exercising the option
  - Option to charge or discharge storage
  - Least-squares regression to estimate CV
- Combination of stochastic modeling in Monte Carlo simulation and least-squares regression
- Previously used to evaluate individual storages based on exogeneous prices
- Here extension to multiple storages in a system context

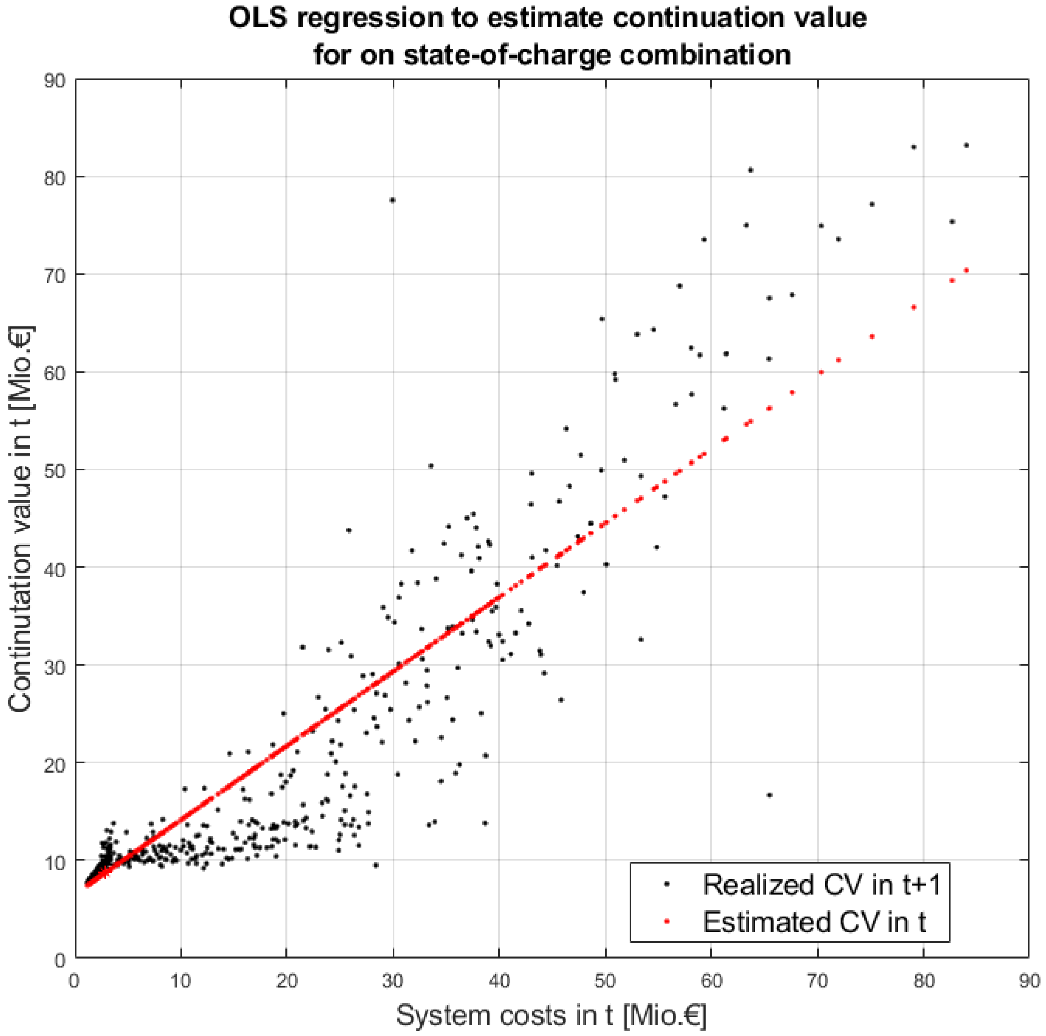
① **Estimate future value (of storage)** with an ordinary **least-squares (OLS) regression** based on a large number of **Monte-Carlo paths**

② **Determine storage operations** for all Monte Carlo paths in a temporal forward propagation

Least-Squares Monte Carlo: Estimate future system costs

Estimate future storage value with an OLS regression over all MC paths in a temporal **backward propagation**

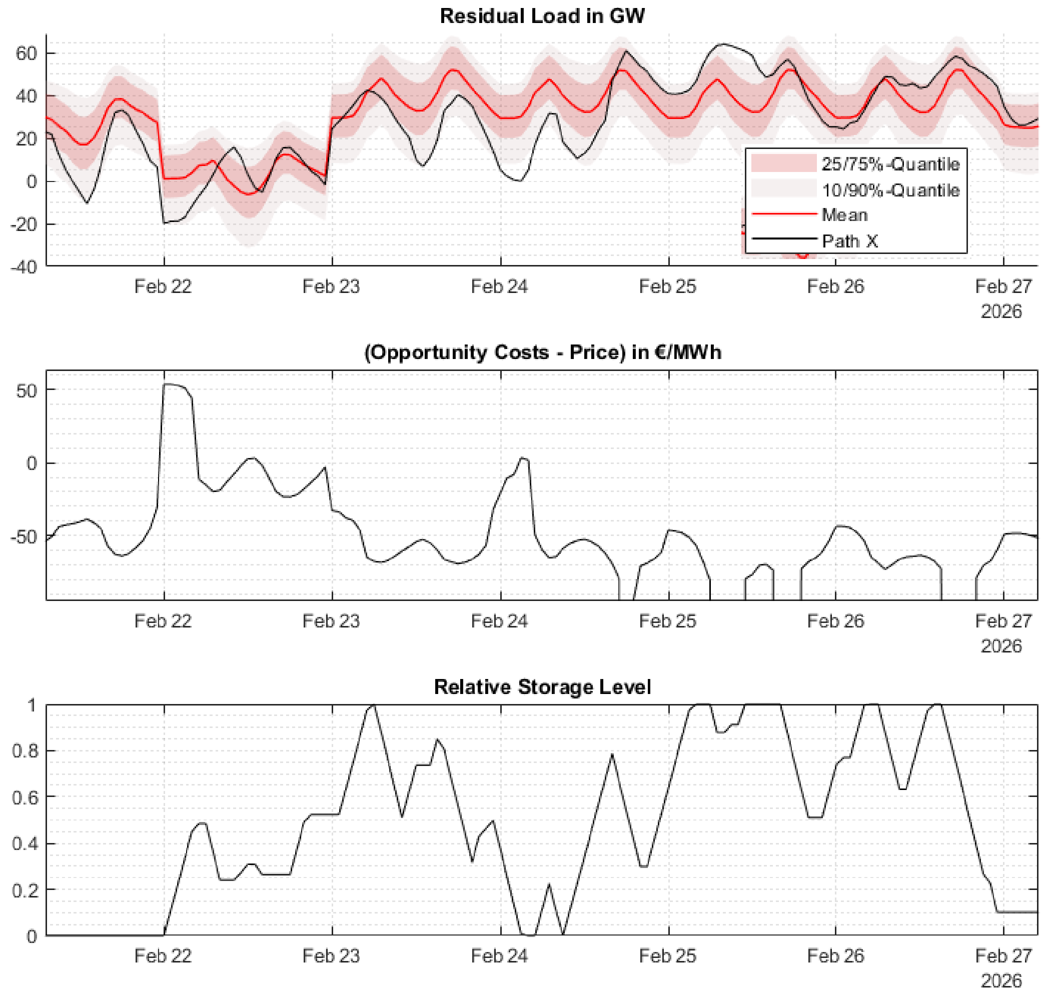
```
for t = T-1 to 0 do
    B1: Load simulations, i.e., residual load $D_t$
    B2: Determine system costs excl. storage actions $C_t^{MR}(D_t)$
    B3: Estimate CV for all state-of-charge (SOC) combinations
        based on $C_t^{MR}(D_t)$ and save regression coefficient $\hat{\beta}_{t,s}$
    B4: Interpolate continuation values (CV) for all SOC
        combinations and possible actions $\mathbb{E}[C_{t+1,s'(o)}(D_t)]$
    B5: Re-determine system costs incl. storage actions $C_{t,s}^{MR}(o, D_t)$
    B6: Minimize total costs to determine optimal storage actions
        $\min_{o \in O^{Feas}(s)} C_{t,s}(o, D_t) = \underbrace{C_{t,s}^{MR}(o, D_t)}_{\text{Current system costs}} + e^{-\delta \Delta t}\, \underbrace{\mathbb{E}[C_{t+1,s'(o)}(D_t)]}_{\text{Expected future system costs}}$
end for
```



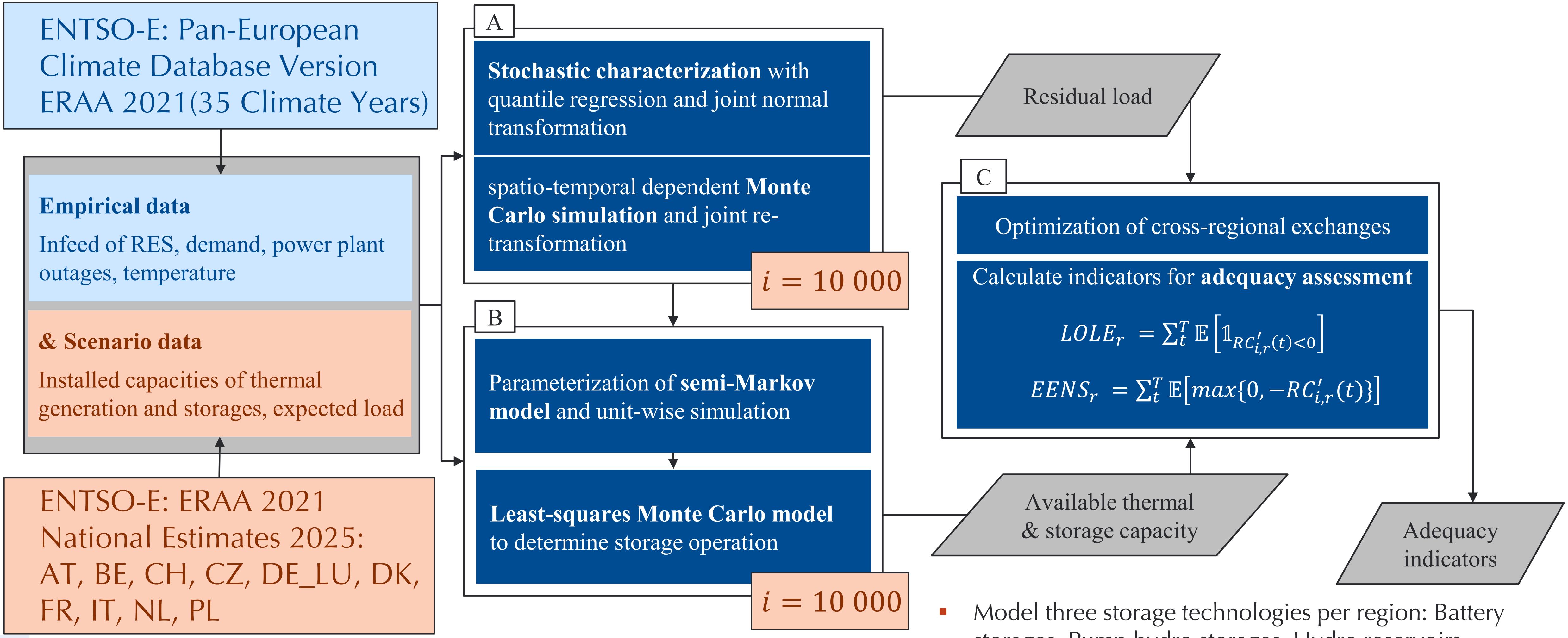
Least-Squares Monte Carlo: Incorporate expected future system costs to determine storage operations

Determine storage operations in all MC paths in a temporal **forward propagation**

```
for t = 1 to T do
    F1: Load simulations, i.a. residual load $D_t$
    F2: Determine possible storage actions $o$
    F3: Determine system costs excl. storage actions $C_t^{MR}(D_t)$
    F4: Estimate CV for all SOC combinations based on $C_t^{MR}(D_t)$
        and regression coefficients $\widehat{\beta}_{t,s}$
    F5: Interpolate CVs for all possible actions $\mathbb{E}[C_{t+1,o}(D_t)]$
    F6: Re-determine system costs incl. storage actions $C_t^{MR}(o, D_t)$
    F7: Minimize total costs to determine optimal storage actions
        $\min_{o \in O^{Feas}(s)} C_t(o, D_t) = \underbrace{C_t^{MR}(o, D_t)}_{\text{Current system costs}} + \underbrace{e^{-\delta \Delta t}\, \mathbb{E}[C_{t+1,o}(D_t)]}_{\text{Expected future system costs}}$
end for
```



Case Study: ERAA 2021 National Estimates 2025



ENTSO-E: Pan-European Climate Database Version ERAA 2021(35 Climate Years)

Empirical data

Infeed of RES, demand, power plant outages, temperature

& Scenario data

Installed capacities of thermal generation and storages, expected load

ENTSO-E: ERAA 2021 National Estimates 2025: AT, BE, CH, CZ, DE_LU, DK, FR, IT, NL, PL

A

Stochastic characterization with quantile regression and joint normal transformation

spatio-temporal dependent **Monte Carlo simulation** and joint re-transformation

$i = 10\,000$

B

Parameterization of **semi-Markov model** and unit-wise simulation

Least-squares Monte Carlo model to determine storage operation

$i = 10\,000$

Residual load

C

Optimization of cross-regional exchanges

Calculate indicators for **adequacy assessment**

$$LOLE_r = \sum_t^T \mathbb{E}\left[\mathbb{1}_{RC'_{i,r}(t)<0}\right]$$

$$EENS_r = \sum_t^T \mathbb{E}\left[max\{0, -RC'_{i,r}(t)\}\right]$$

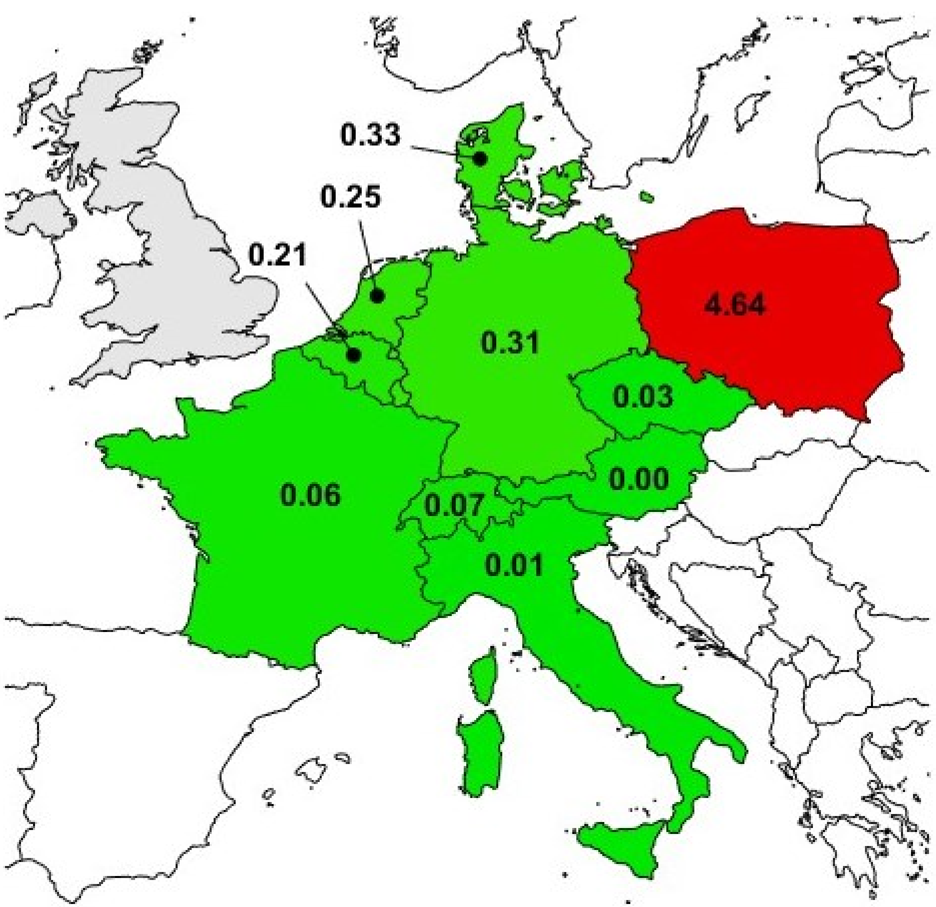
Available thermal & storage capacity

Adequacy indicators

- Model three storage technologies per region: Battery storages, Pump hydro storages, Hydro reservoirs
- Estimate net imports using a generalized linear model

Case Study: Loss of load expectation

- Scenario: ERAA 2021 National Estimates 2025 – **No EVA & No CM**



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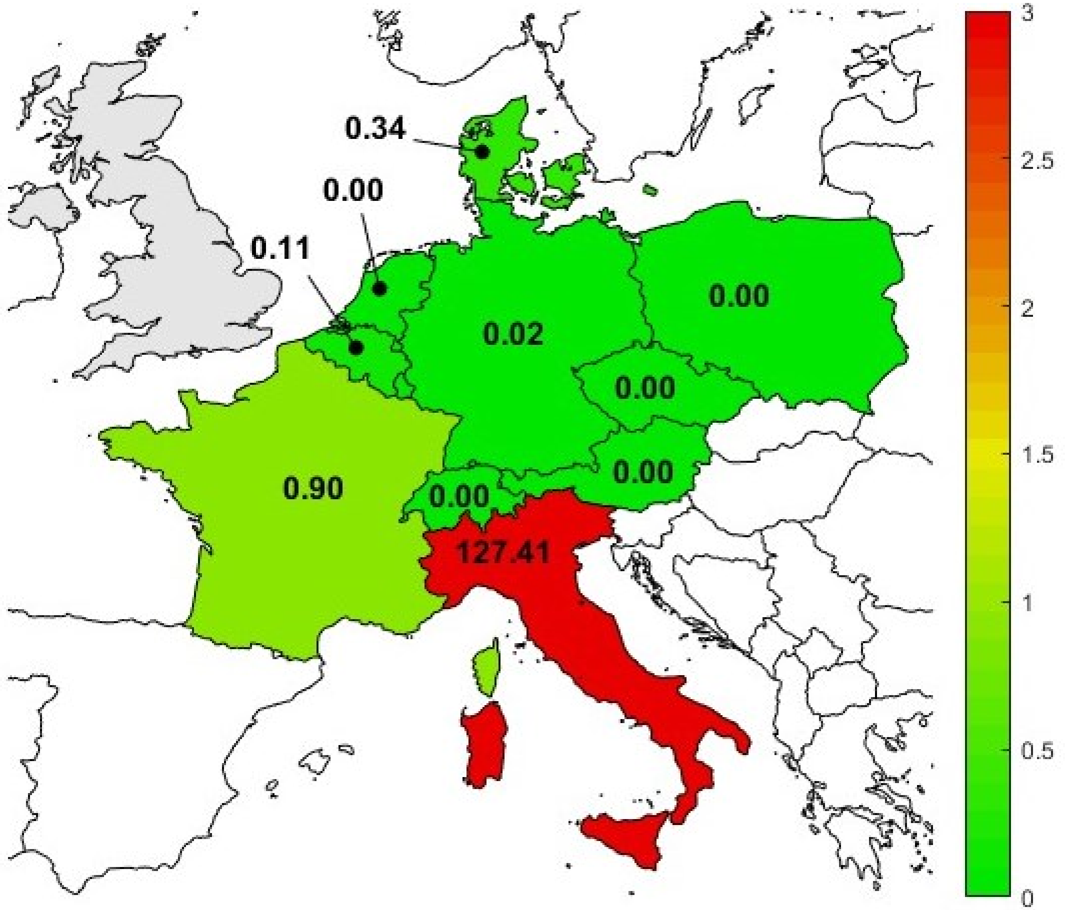
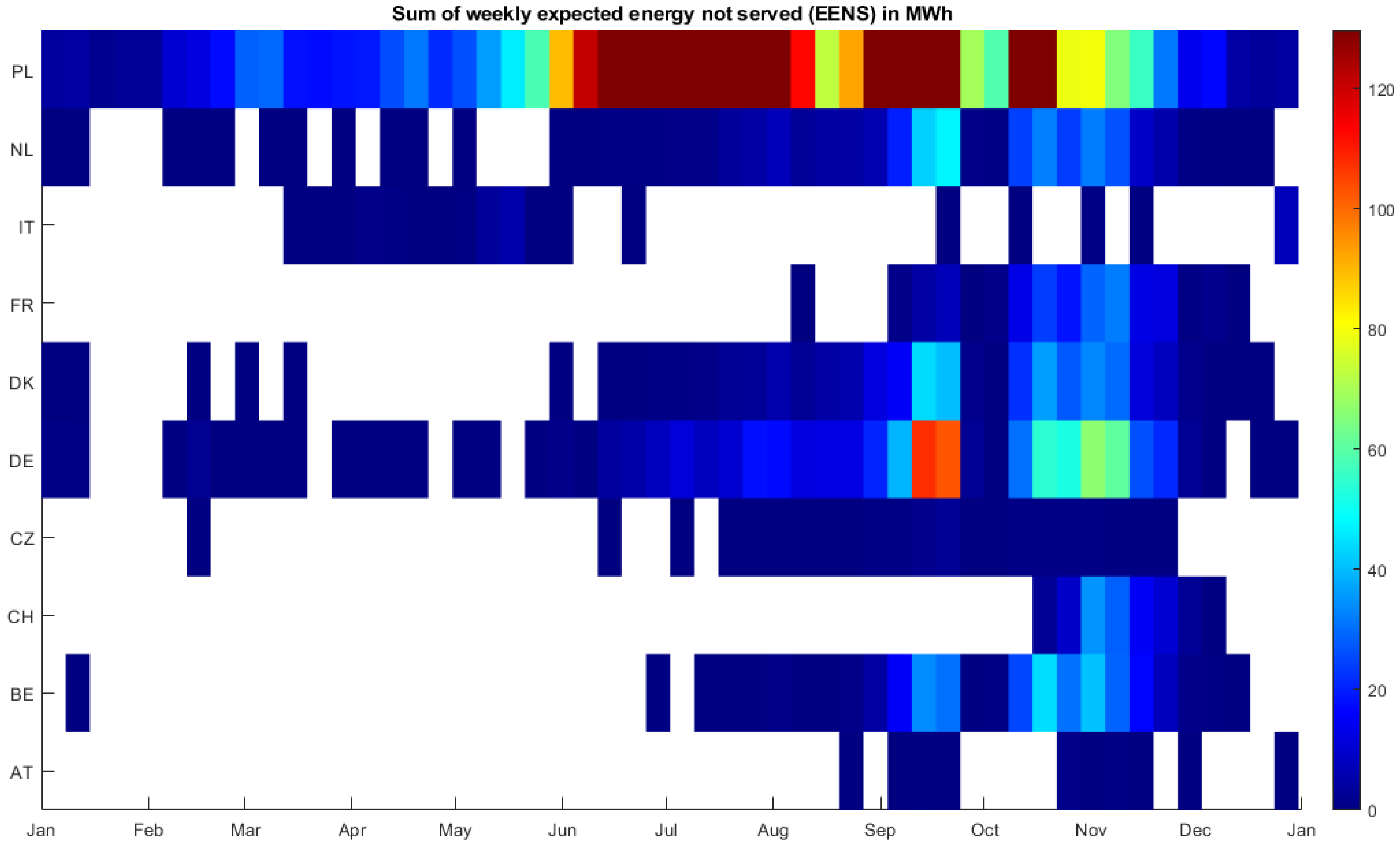


ERAA 2021

Mean national reliability standard: $LOLE \leq 3\ h/a$

Case Study: Expected energy not served indicate seasonal differences

- Scenario: ERAA 2021 National Estimates 2025 – **No EVA & No CM**



Conclusion

System-wide least-squares Monte Carlo approach

- Stochastic determination of storage operations in without perfect foresight
- Computational feasibility restricts model scope: Trade-off between assumptions and stochastics
- Challenging to interpret interplay of storage technologies
- Potential to model flexibility of system components e.g., demand side management, …

Adequacy Assessment

- Comprehensive stochastic modeling that provides a robust assessment of resource adequacy
- Insights in detailed simulation valuable for subsequent studies

Thank you for your attention!

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