Surrogate models to predict the adequacy and flexibility of large-scale power systems: case-study with the EU power system

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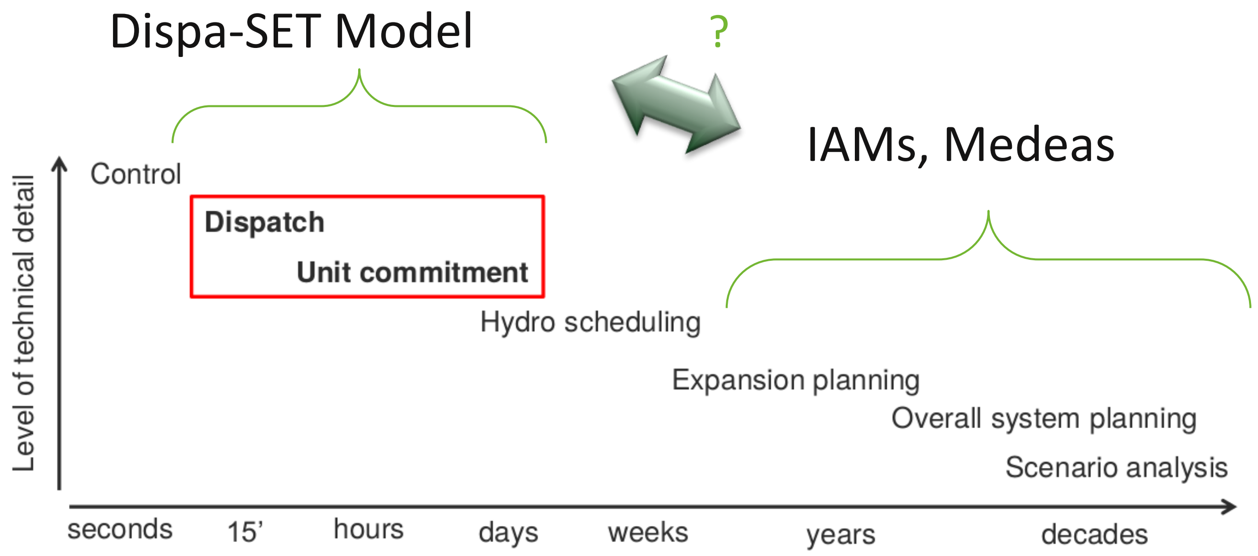
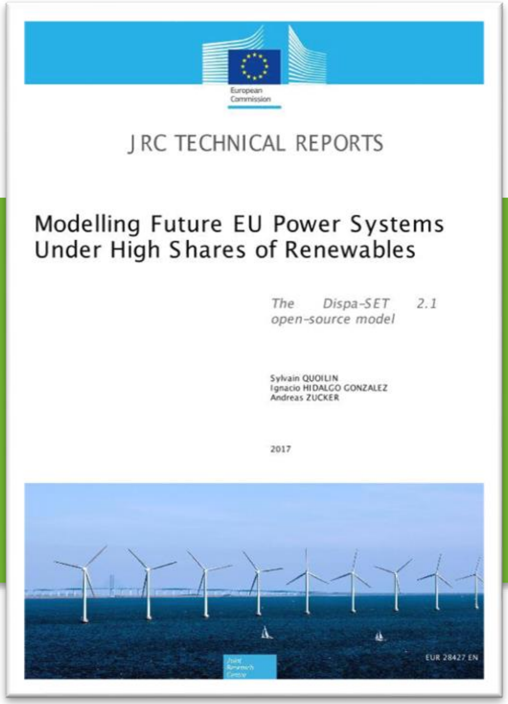
LIÈGE université Sciences Appliquées

KU LEUVEN

Flexibility assessment in integrated assessment models

- Main challenge: integrate flexibility contraints into low time-resolution models
- Should be expressed by a simple equation
- Focus on high shares of renewables




European Commission

JRC TECHNICAL REPORTS

Modelling Future EU Power Systems Under High Shares of Renewables

The Dispa-SET 2.1 open-source model

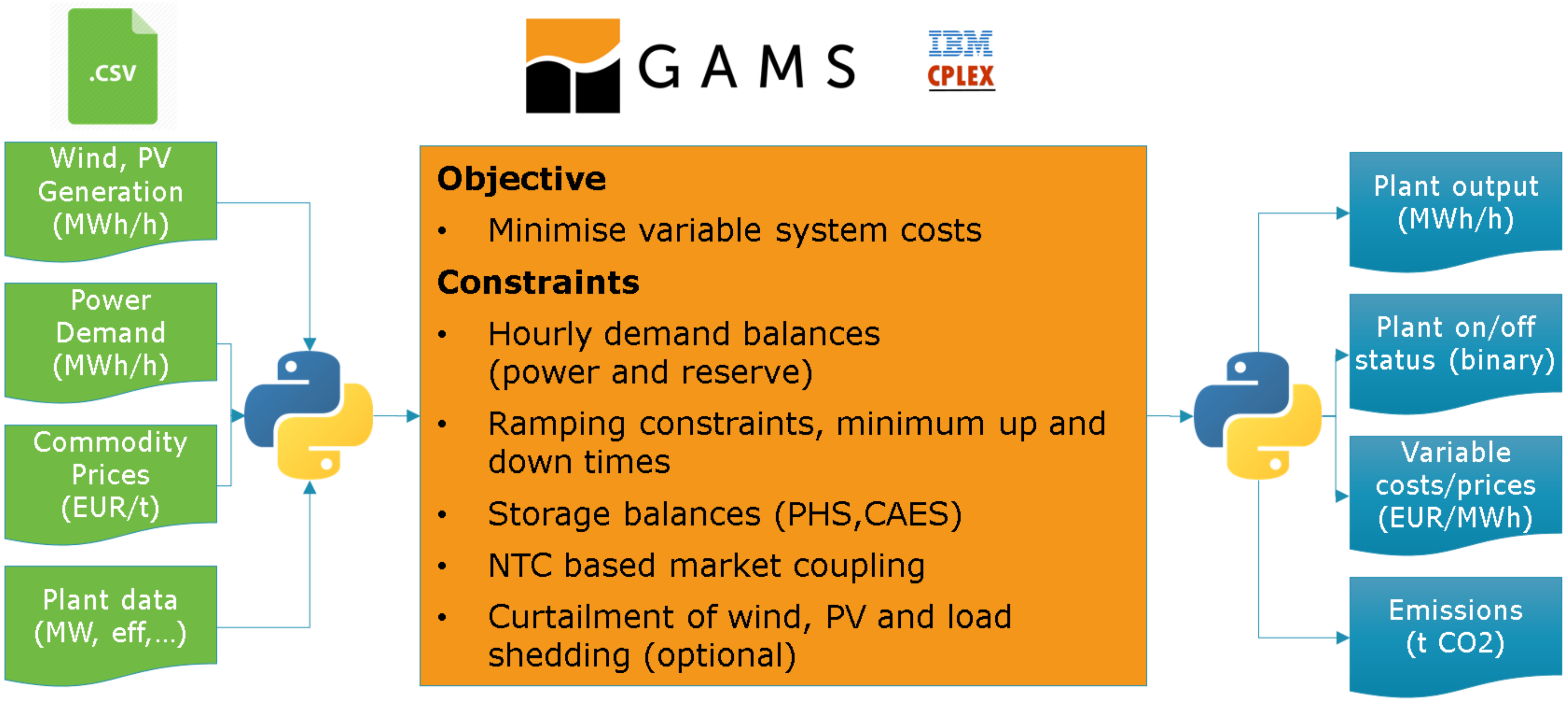
Sylvain QUOILIN
Ignacio HIDALGO GONZALEZ
Andreas ZUCKER

2017

EUR 28427 EN

The Dispa-SET model

Dispa-SET 2.3: unit commitment and dispatch model



- Formulated as a tight and compact mixed integer program (MILP)
- Implemented in Python and *GAMS*, solved with *CPLEX*

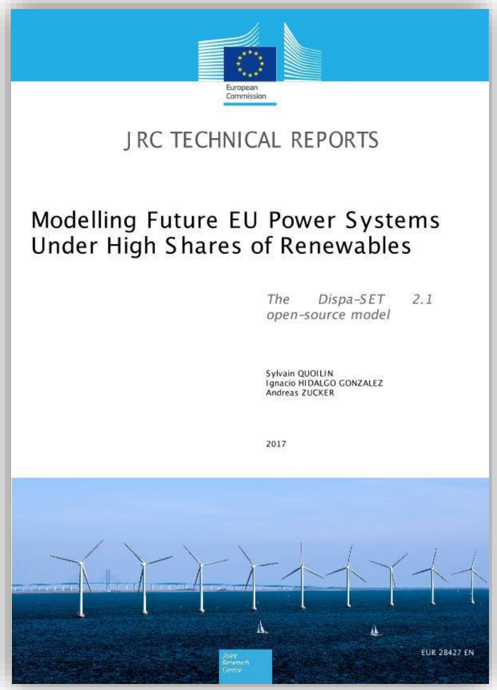
Dispa-SET in a nutshell

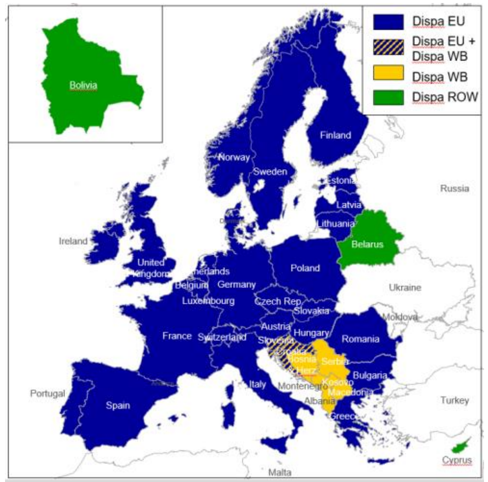
What Dispa-SET is:

- A unit commitment and dispatch model of the European power system
- Two successive optimizations:
    - Mid-term scheduling of power stations
    - Short-term unit commitment (rolling horizon)
- Probabilistic assessment of system adequacy and flexibility needs of power systems, with growing share of renewable energy generation
- Easily “pluggable” to the outputs of long-term planning models

What Dispa-SET is <u>not</u>:

- An expansion planning model
    - Only operational costs are optimized
    - No investments





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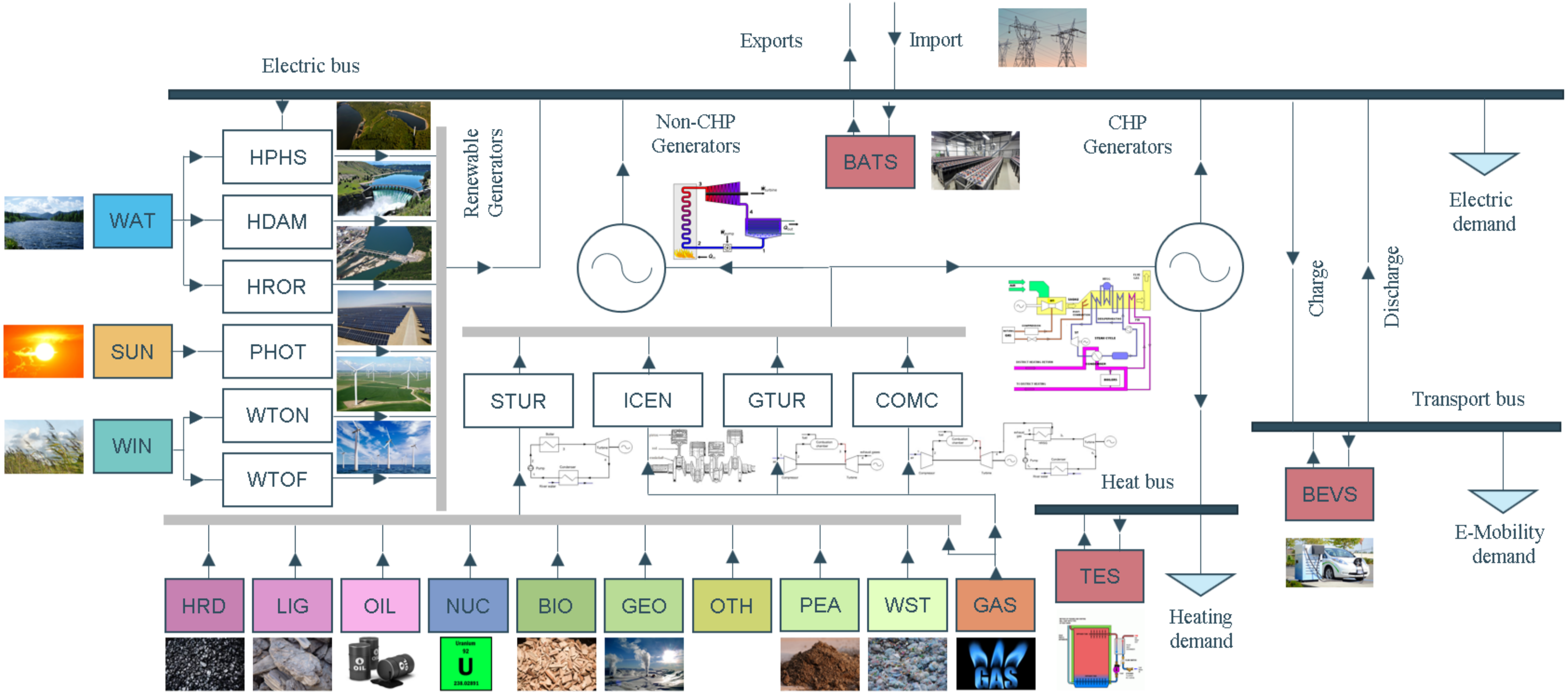
Dispa-SET 2.3: System structure & technology overview in a single node

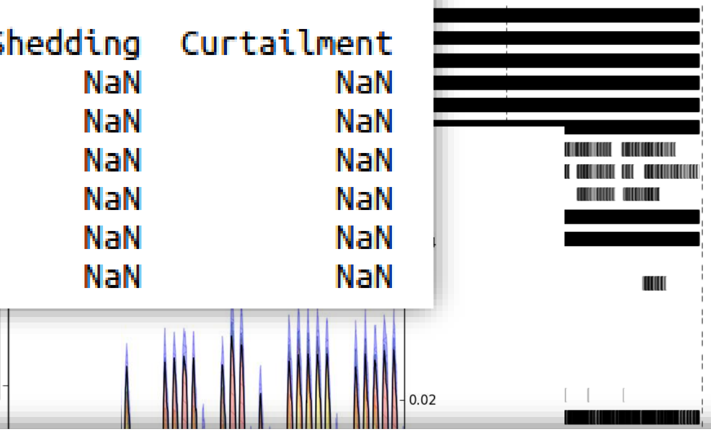


- Sector coupling options: P2H, P2V, P2P…

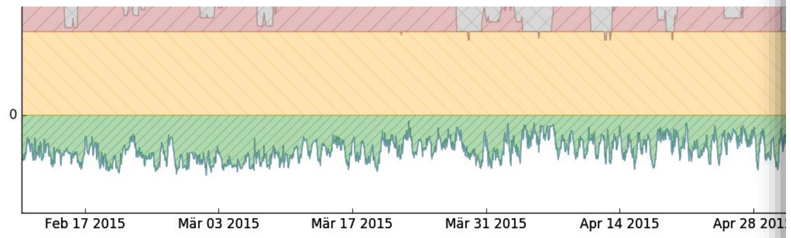
Dispa-SET 2.1: typical outputs

Country-Specific values (in TWh or in MW):

	Demand	PeakLoad	NetImports	LoadShedding	Curtailment
AT	59.375448	10144.000000	5.144132	NaN	NaN
BE	86.971154	13632.250000	8.911190	NaN	NaN
CH	44.694098	7794.262468	7.199527	NaN	NaN
DE	478.030824	76212.250000	-17.260122	NaN	NaN
FR	470.075612	90588.000000	-51.878128	NaN	NaN
NL	87.925973	16285.500000	5.682672	NaN	NaN




```
Aggregated statistics for the considered area:
Total consumption:1227.07310992 TWh
Peak load:203182.461067 MW
Net importations:-42.20072928 TWh
```



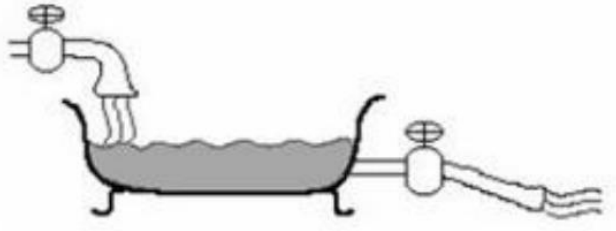

```
Number of hours of congestion on each line:
{'AT -> CH': 5917,
 'AT -> DE': 430,
 'BE -> FR': 62,
 'BE -> NL': 344,
 'CH -> AT': 720,
 'CH -> DE': 15,
 'CH -> FR': 56,
 'DE -> AT': 1522,
 'DE -> CH': 4378,
 'DE -> NL': 2803,
 'FR -> BE': 2689,
 'FR -> CH': 7665,
 'NL -> BE': 1403,
 'NL -> DE': 60}
```

The Medeas model

The MEDEAS models

System dynamics and EROI

Hydraulic Metaphor



Stock-Flow Diagram

Integral Equation

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0)$$

Differential Equation

$$d(Stock)/dt = Net\ Change\ Rate = Inflow(t) - Outflow(t)$$

Source: Sterman, 2000

‘We need to ‘spend’ energy to ‘make’ energy’

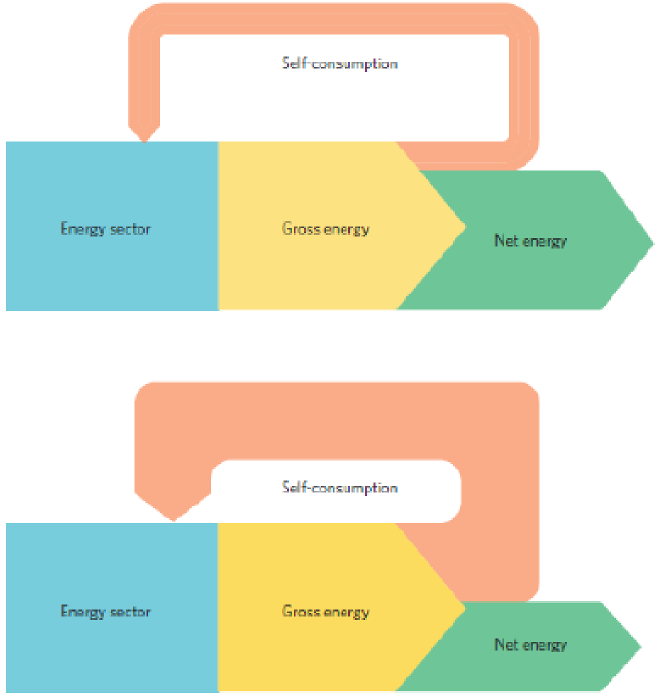


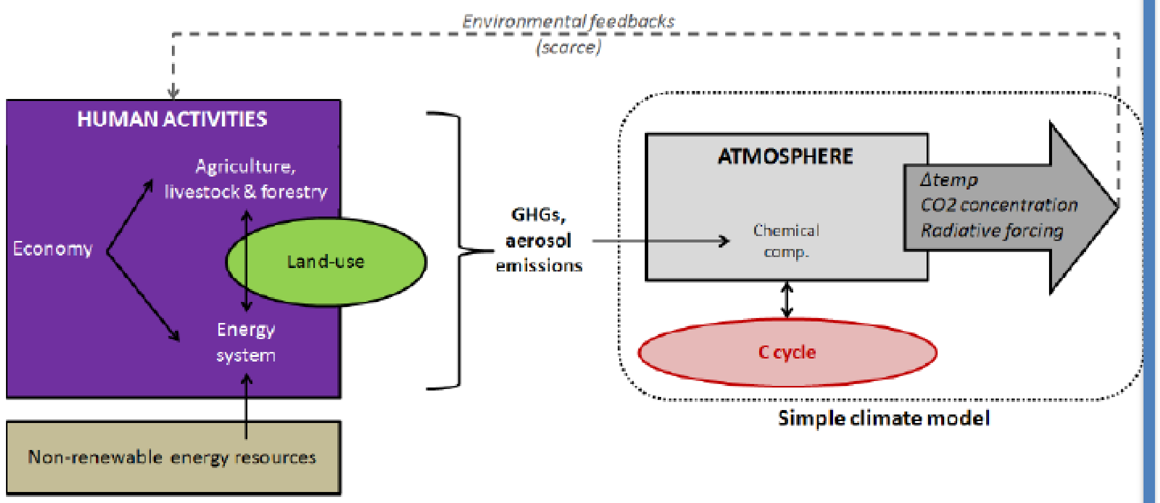
Figure 1 | Net energy analysis (NEA) studies the net output of energy-producing technologies, accounting for the energy consumed, directly and indirectly, by the energy sectors, in contrast to the gross energy production measured by the International Energy Agency and US Energy Information Administration in their analyses. Only net energy is available for end uses within society. As net energy output from a system declines (top to bottom), less energy is available to society per unit of total energy consumption, increasing investment requirements and environmental impacts of final energy use.

Source: Carbajales-Dale et al. 2014.

Energy Ville

MEDEAS vs. classic IAM models

IAMs vs MEDEAS



Notes: In practice, IAMs usually focus on the interactions between processes and systems within the "Human Activities" box of Figure 1.1, including the energy system, the agriculture, livestock and forestry system and the other human systems. Some also include Land-use, while environmental feedbacks are scarce in the literature.

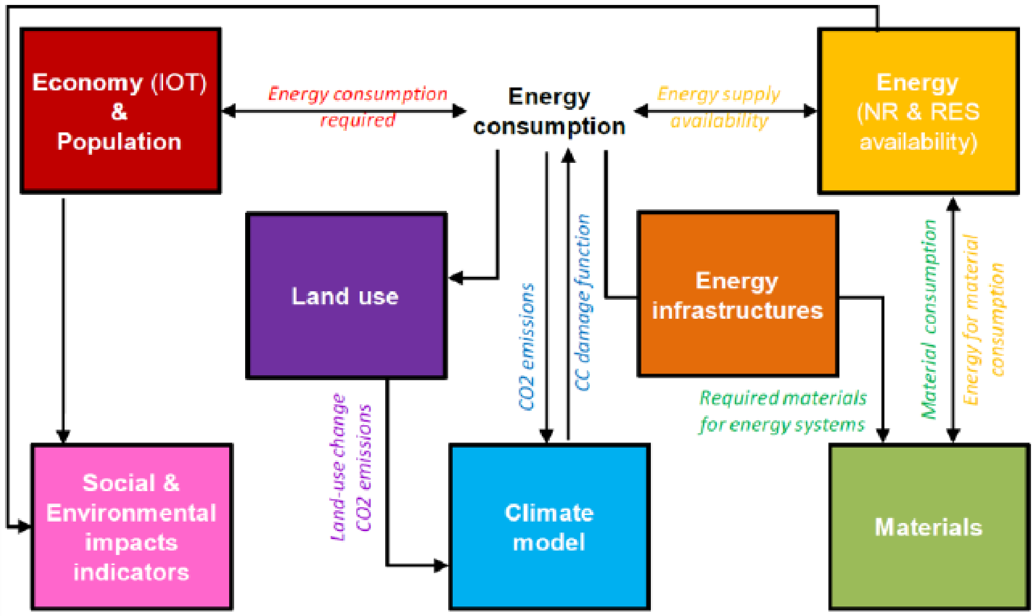
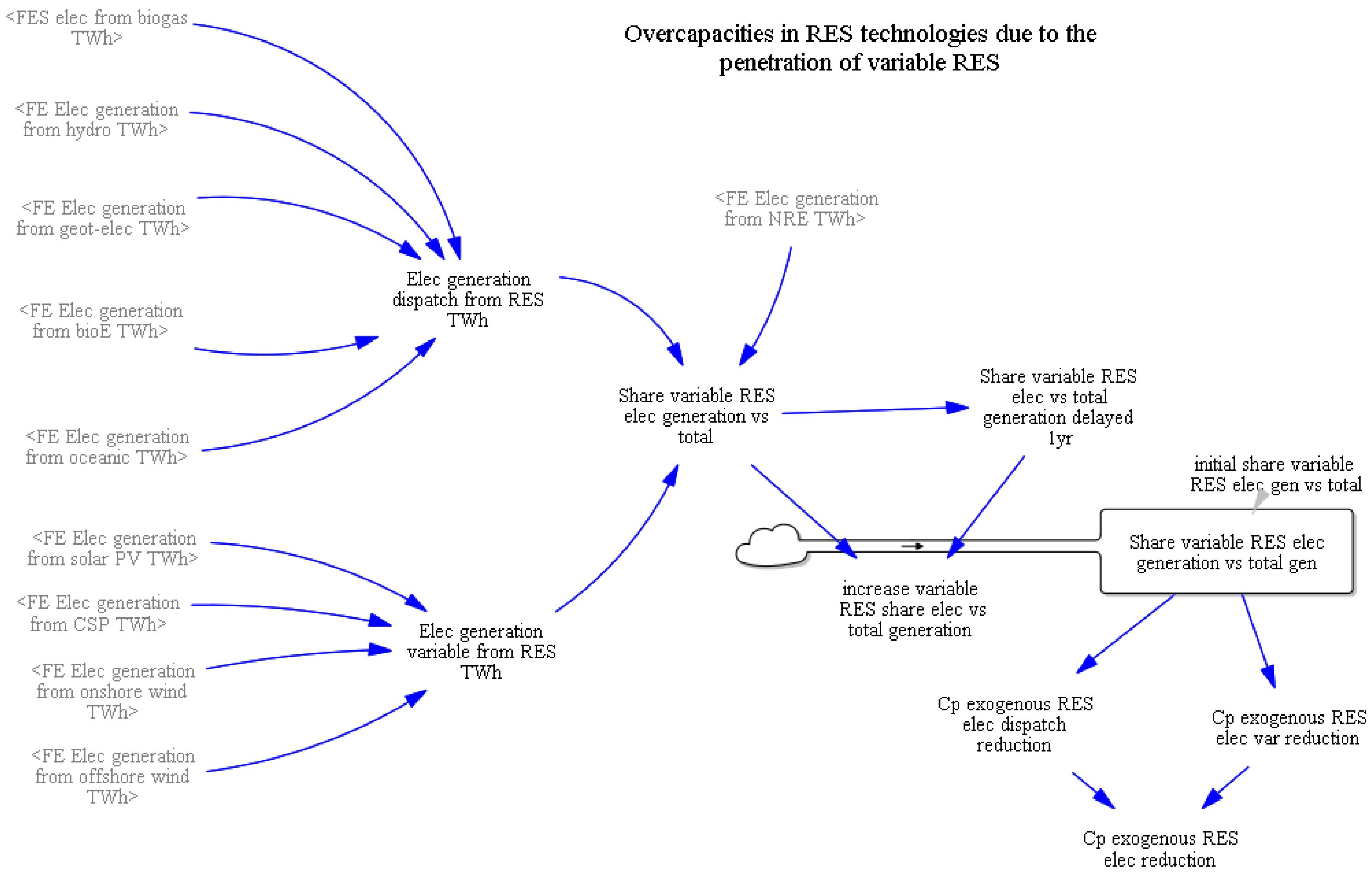


Figure 2: Overview of MEDEAS-World by modules and the modelled linkages between them

IAMs vs MEDEAS

MEDEAS limitation: calculating excess energy



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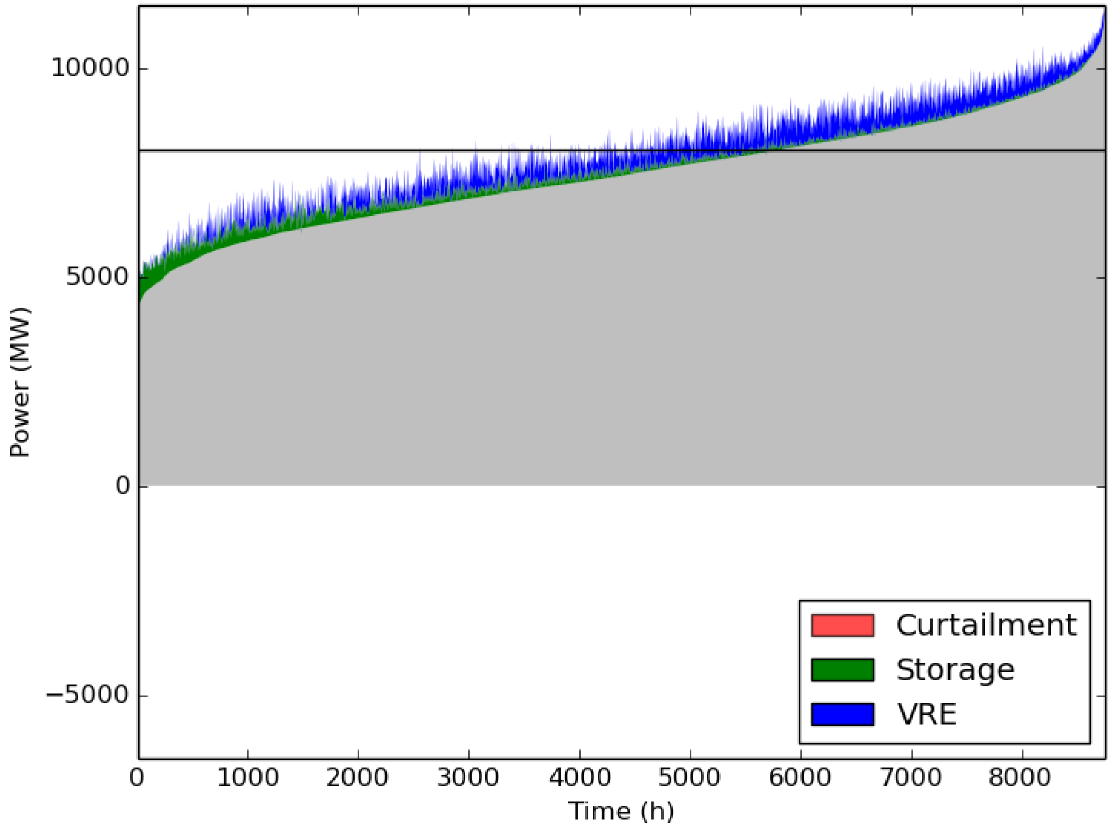
Excess energy calculation in Dispa-SET

MEDEAS limitation: calculating excess energy

- Excess energy appears when increasing the VRE penetration



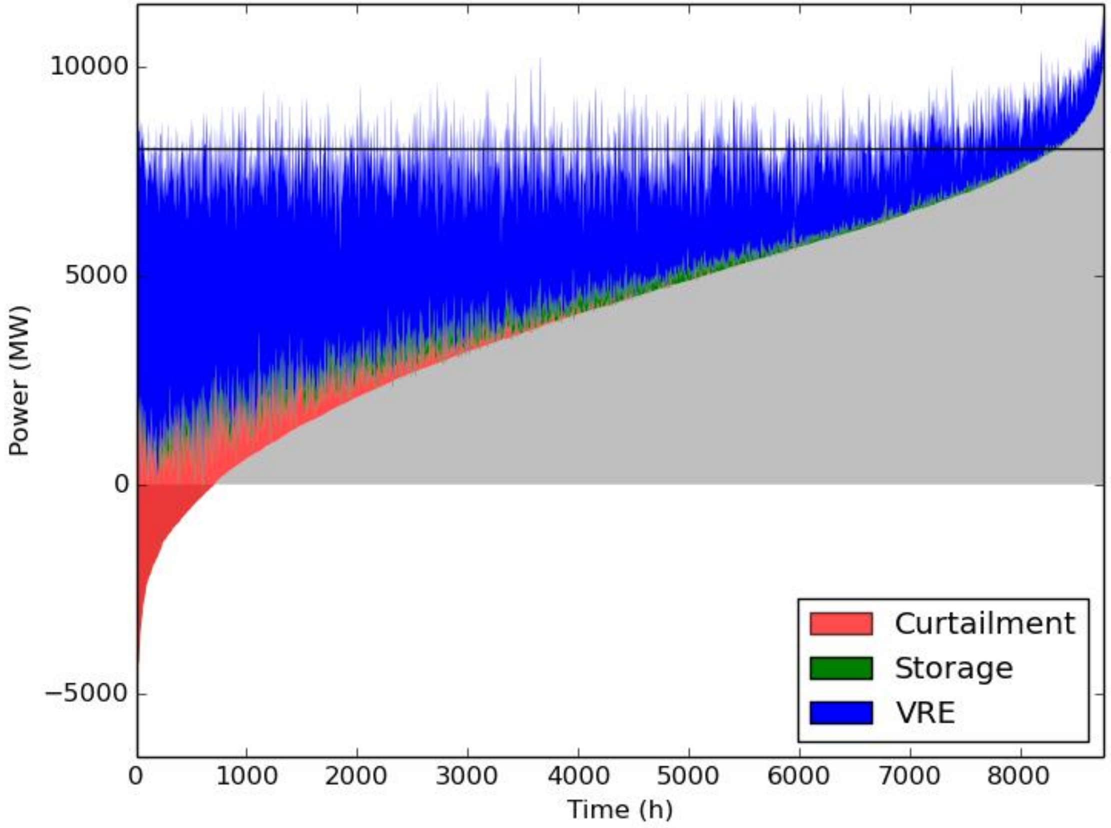
Peak load: 11 GW

VRE: 2.6 GW
7% of demand

VRE: 23 GW
49% of demand

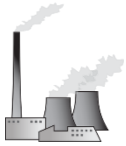
MEDEAS limitation: calculating excess energy

- Effect of the generation fleet flexibility



Nuclear

6 GW

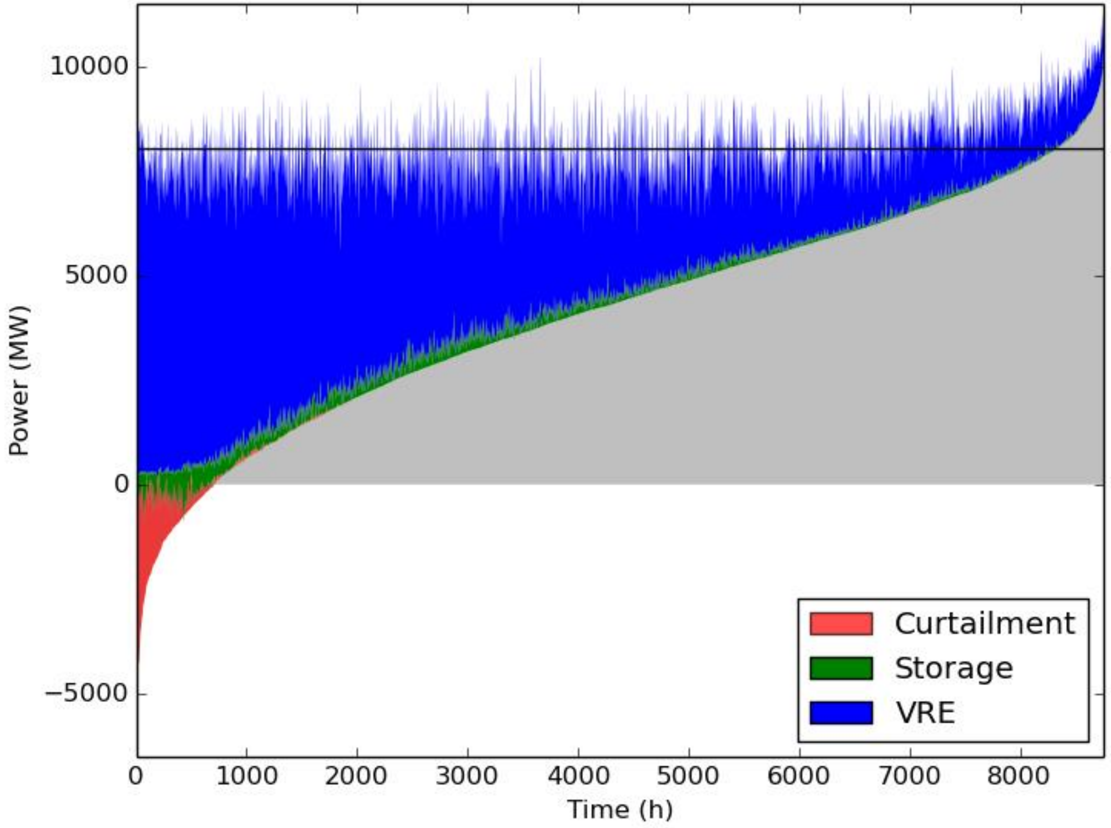


CCGT

5 GW

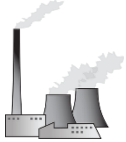
Increasing power plant flexibility

- Effect of the generation fleet flexibility



Nuclear

0 GW

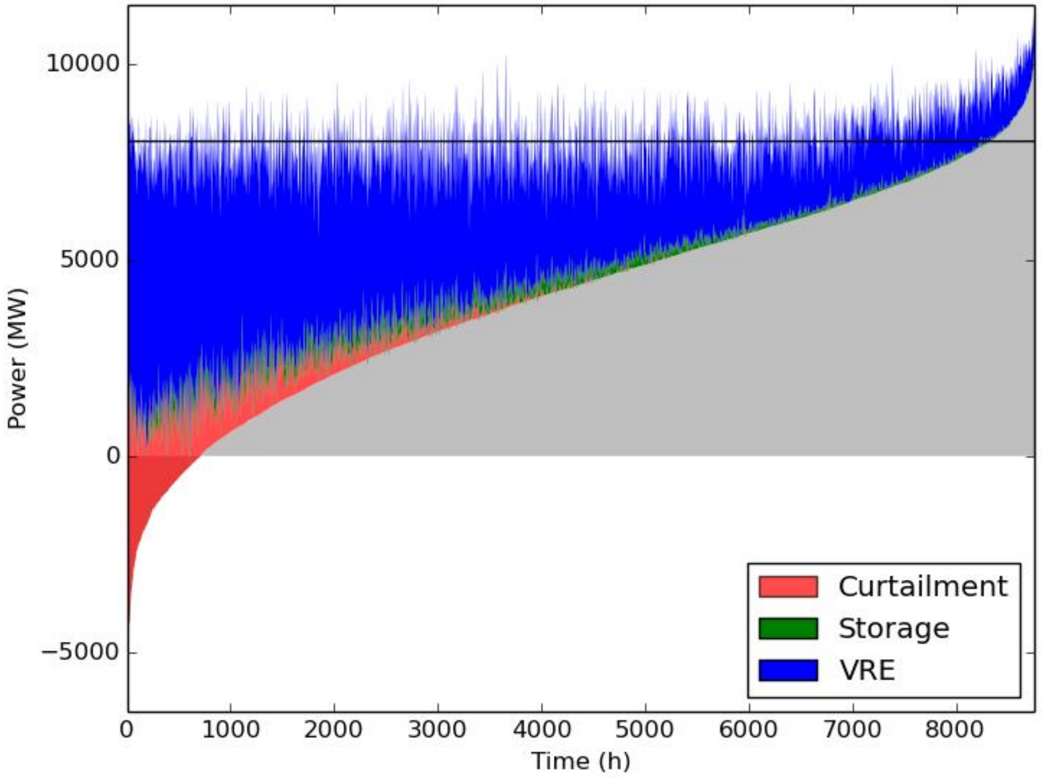


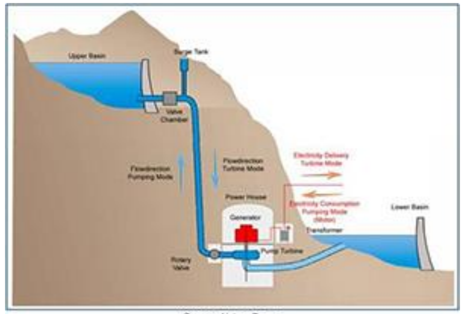
CCGT

11 GW

MEDEAS limitation: calculating excess energy

- Effect of the storage capacity



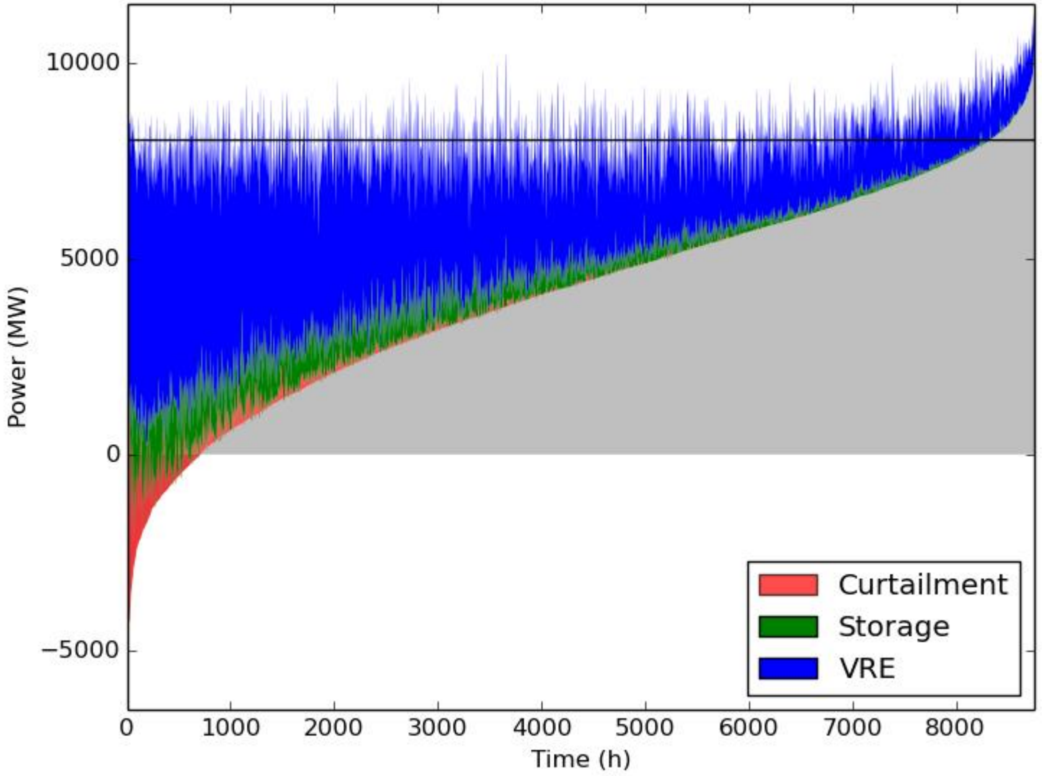


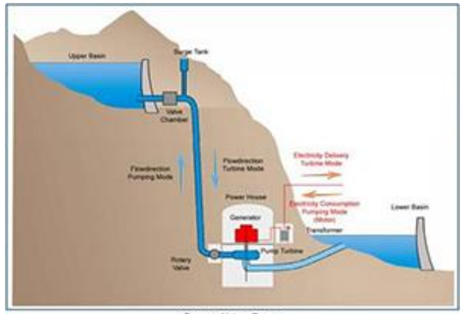
Source: Alstom Power

Power: 1.3 GW
Capacity: 4.5h

MEDEAS limitation: calculating excess energy

- Effect of the storage capacity



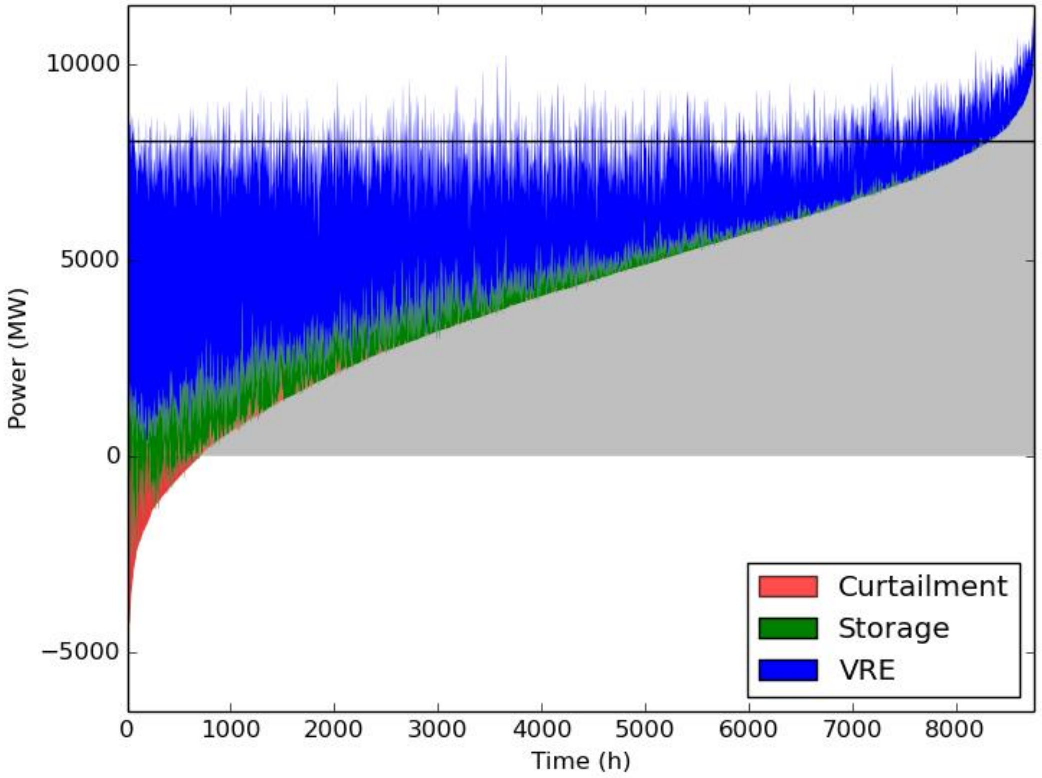


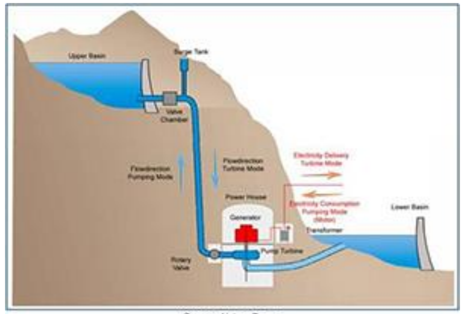
Source: Alstom Power

Power: 4 GW
Capacity: 4.5h

MEDEAS limitation: calculating excess energy

- Effect of the storage capacity





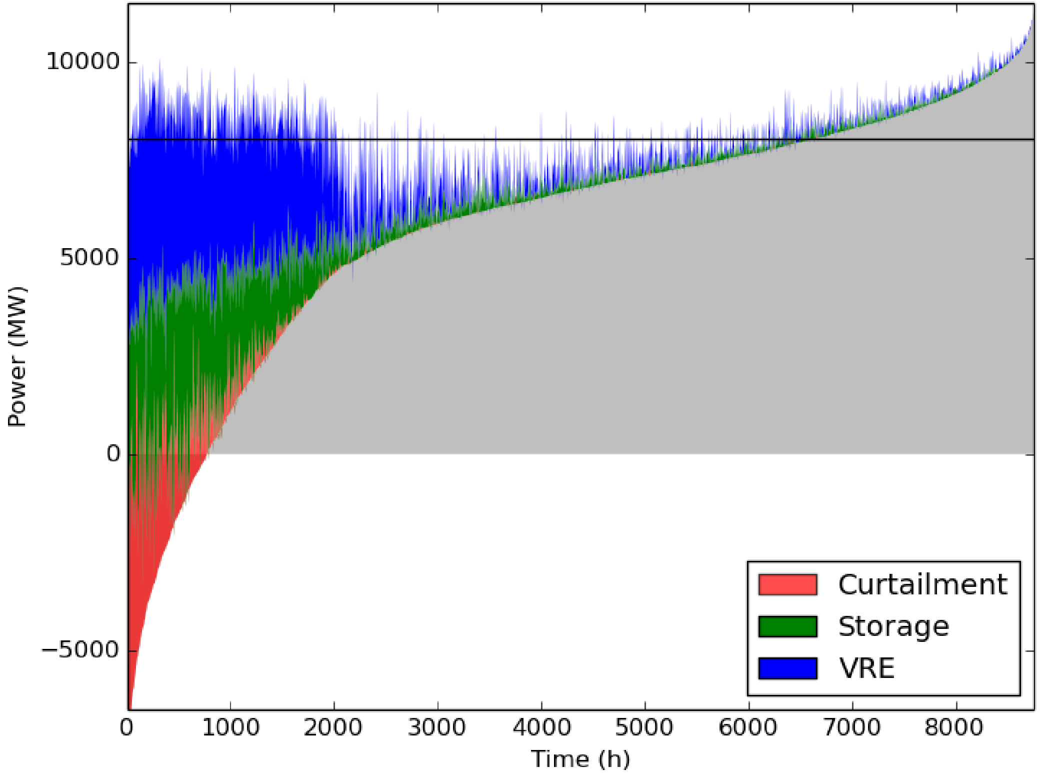
Source: Alstom Power

Power: 6.3 GW

Capacity: 4.5h

MEDEAS limitation: calculating excess energy

- Effect of the wind/solar share



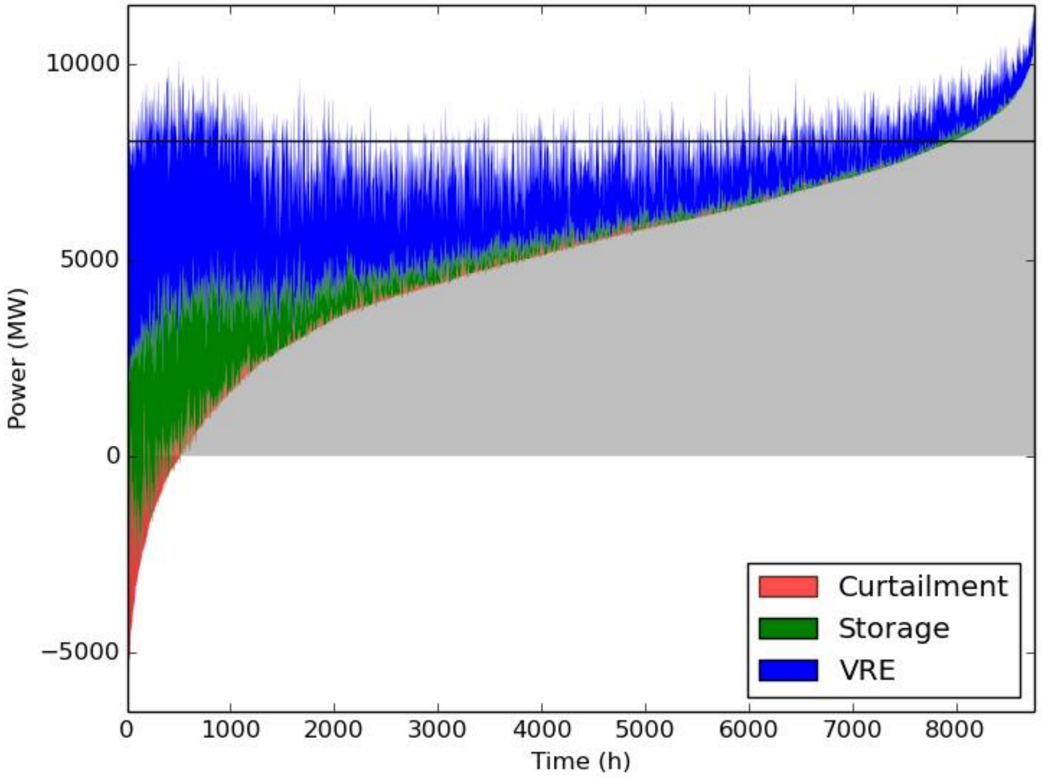
0%

100%

Total: 20GW

MEDEAS limitation: calculating excess energy

- Effect of the wind/solar share



25%

75%

Total: 20GW

MEDEAS limitation: calculating excess energy

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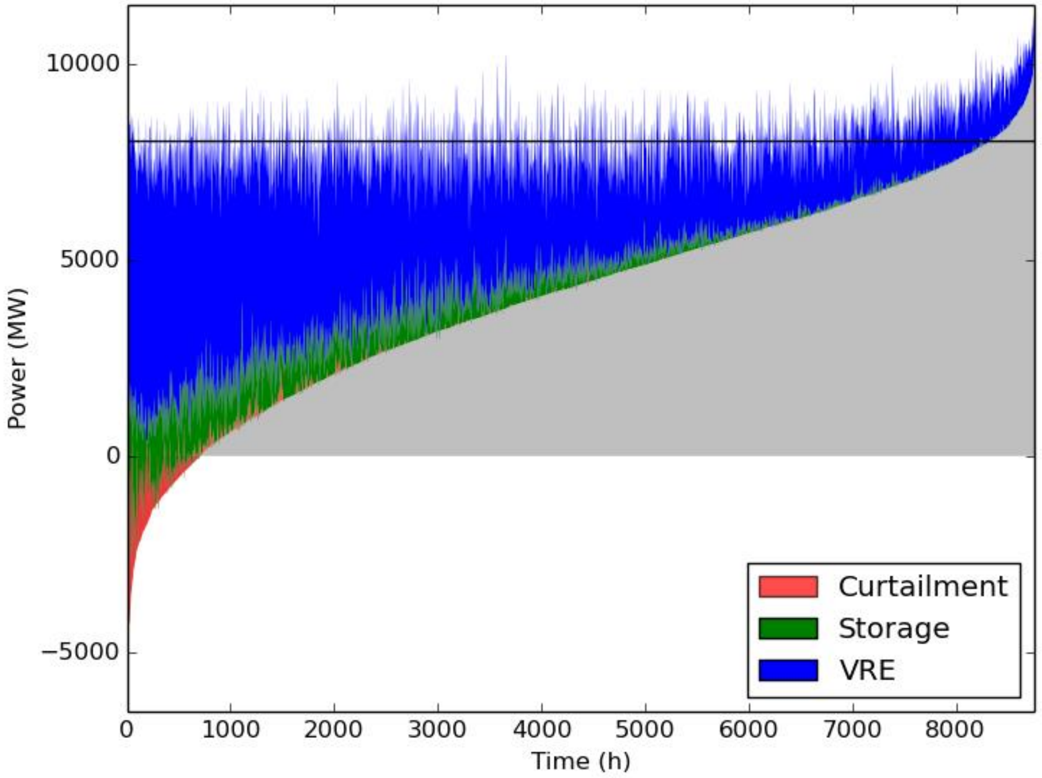

50%

50%

Total: 20GW

MEDEAS limitation: calculating excess energy

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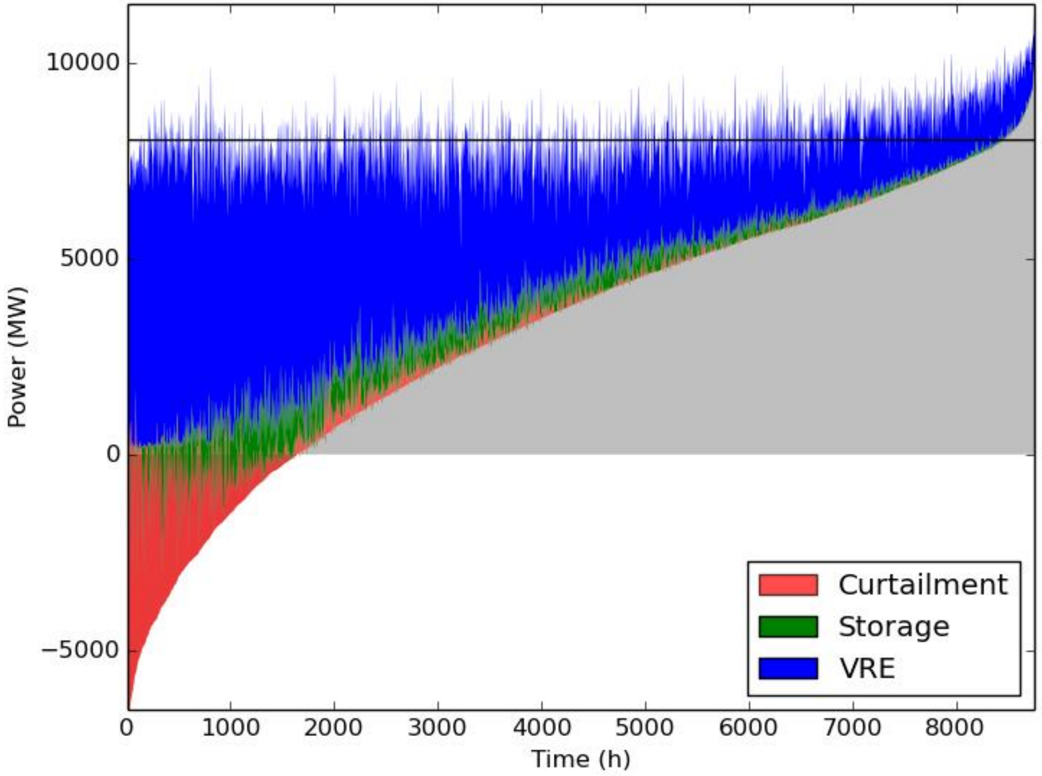

75%

25%

Total: 20GW

MEDEAS limitation: calculating excess energy

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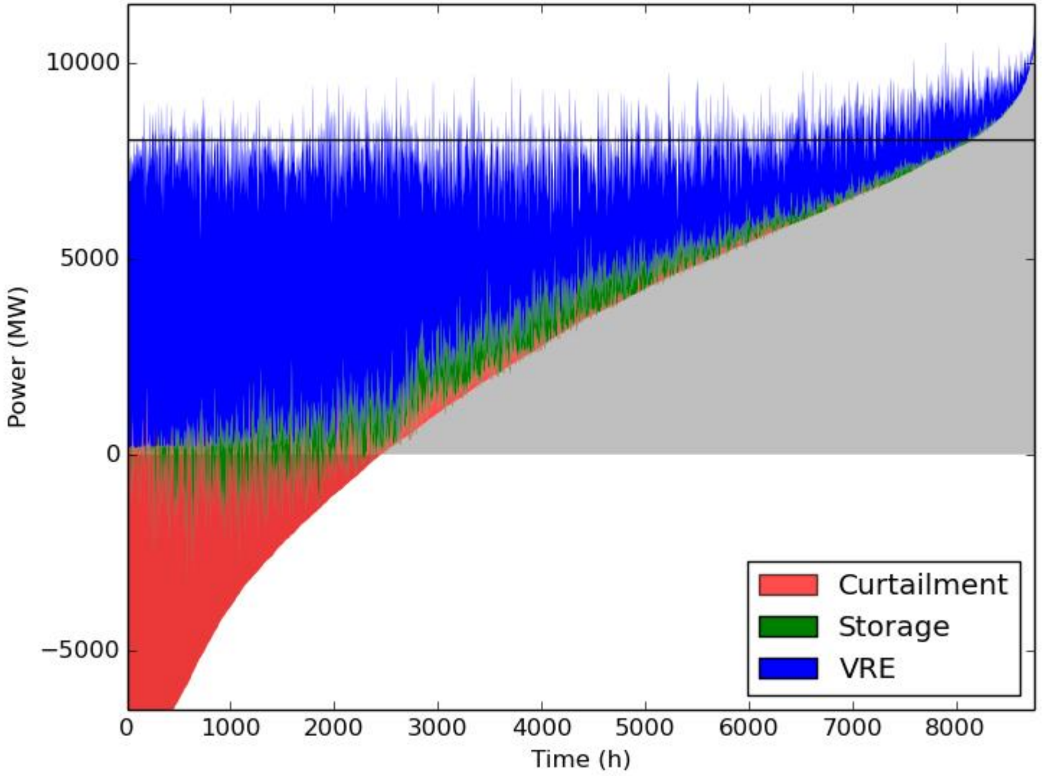

100%

0%

Total: 20GW

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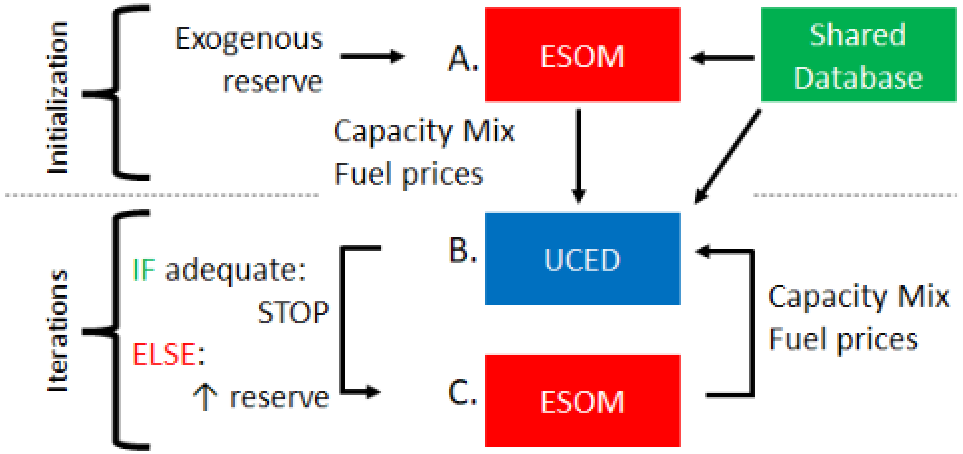
Linking models

Linking models

- Soft-linking:
  - Run both models iteratively
  - Convergence not ensured
  - Low computational efficiency
- Hard-linking
  - Connect the variables of the model
  - Solve in a single run
  - Lower computational tractability
  - Not applicable to models with diverging formulations
- Proposed method: surrogate models
  - Running the most detailed model over a large range of inputs
  - Train a surrogate model over this dataset
  - Implement into the least-detailed models

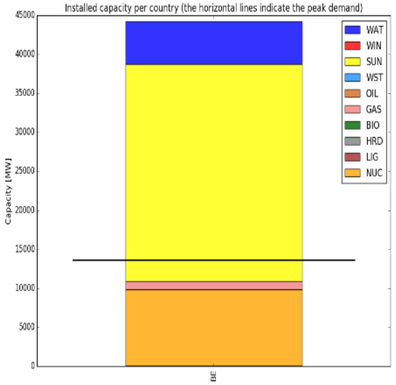


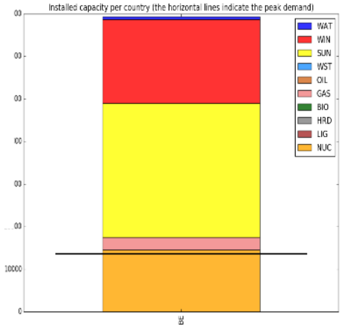
Bidirectional soft-linking between UCED and ESOM models. Source: Pavicevic et al, 2022

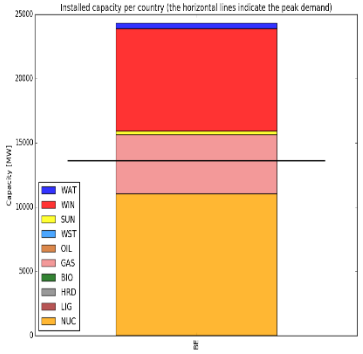
Methodology

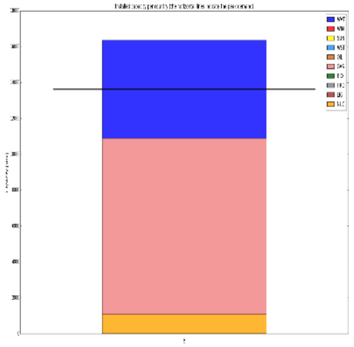
Input parameters of the simulations:

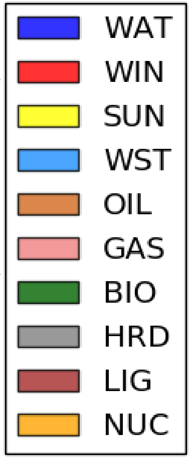
- Thermal capacity margin
- Share of flexible capacity (CCGT vs Nuclear)
- Storage Power [MW]
- Storage Capacity [MWh]
- Wind penetration
- PV penetration











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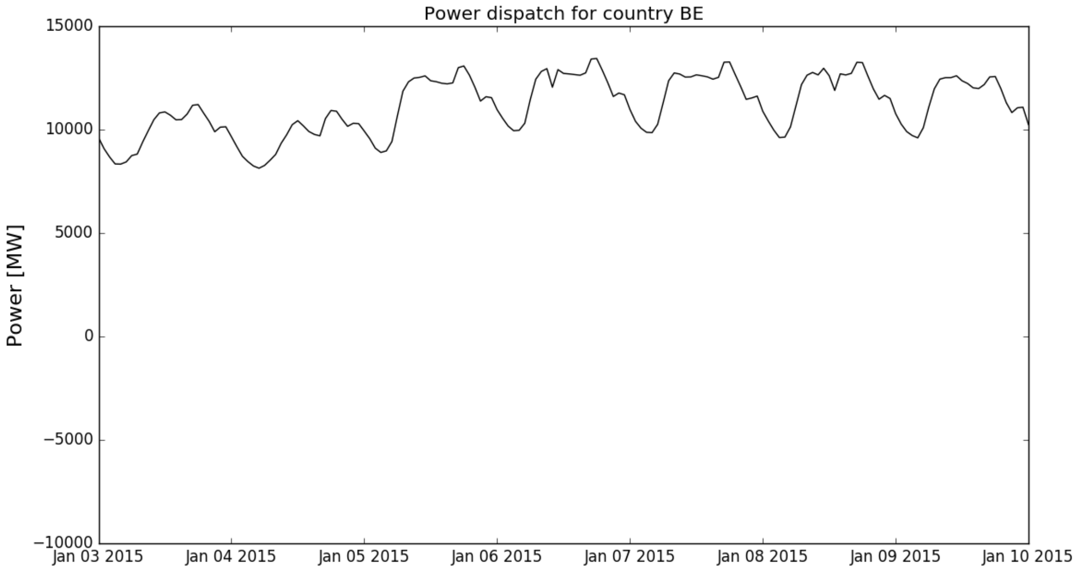
Latin hypercube: Definition of 4096 Runs

Simulation in Dispa-SET



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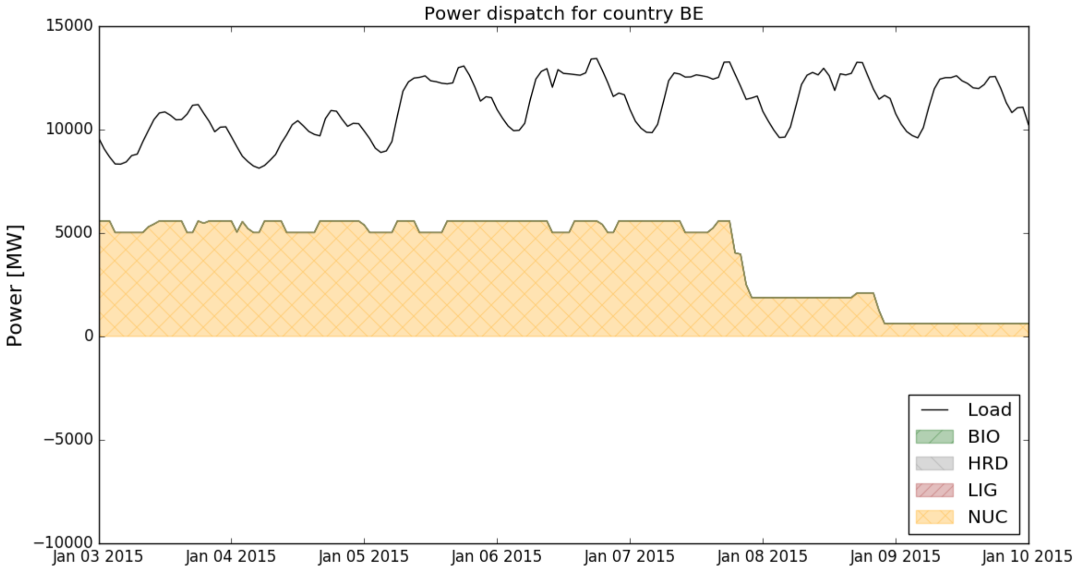

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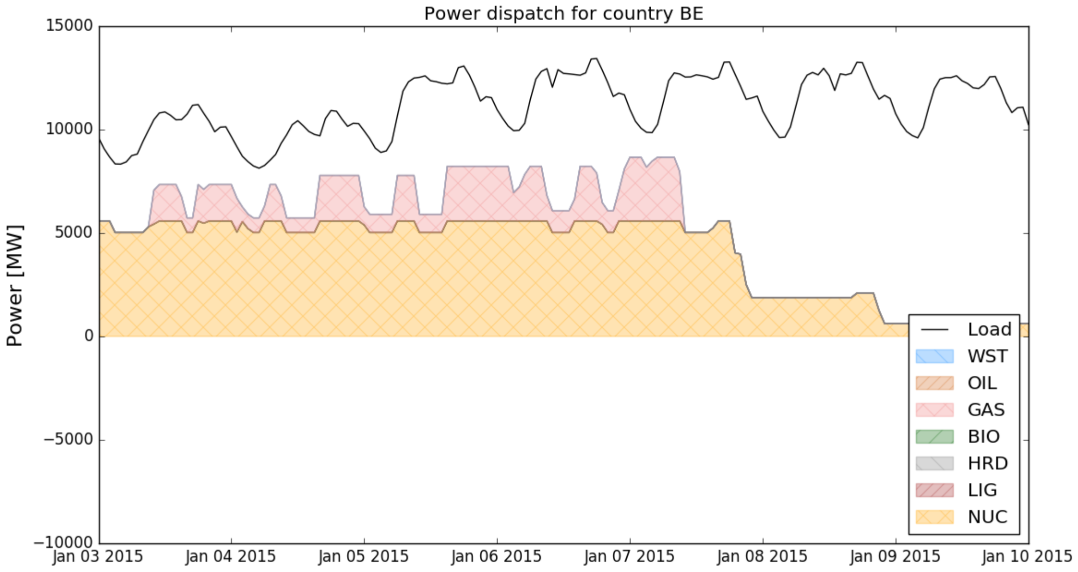

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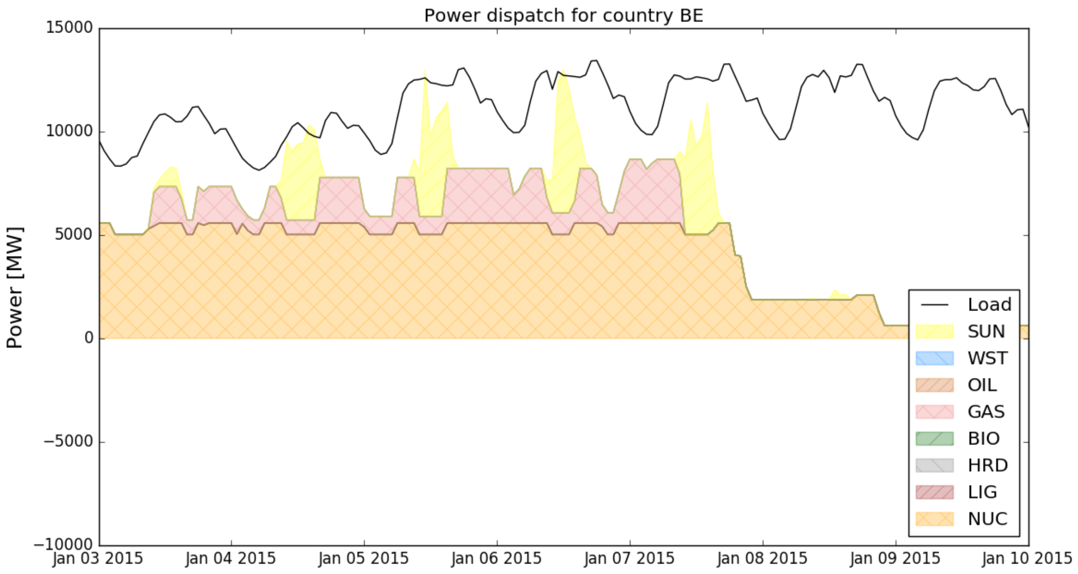

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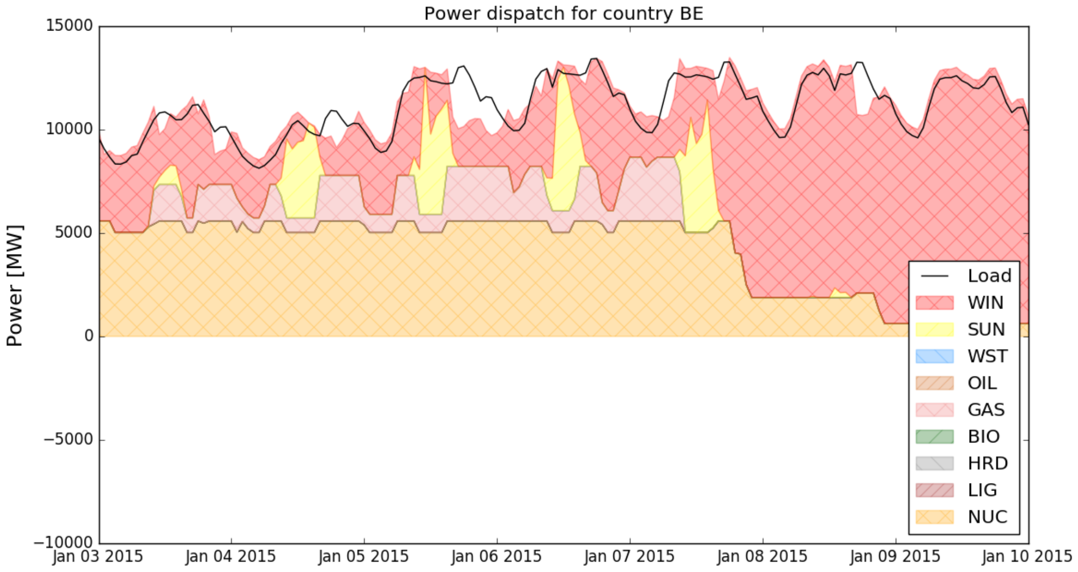

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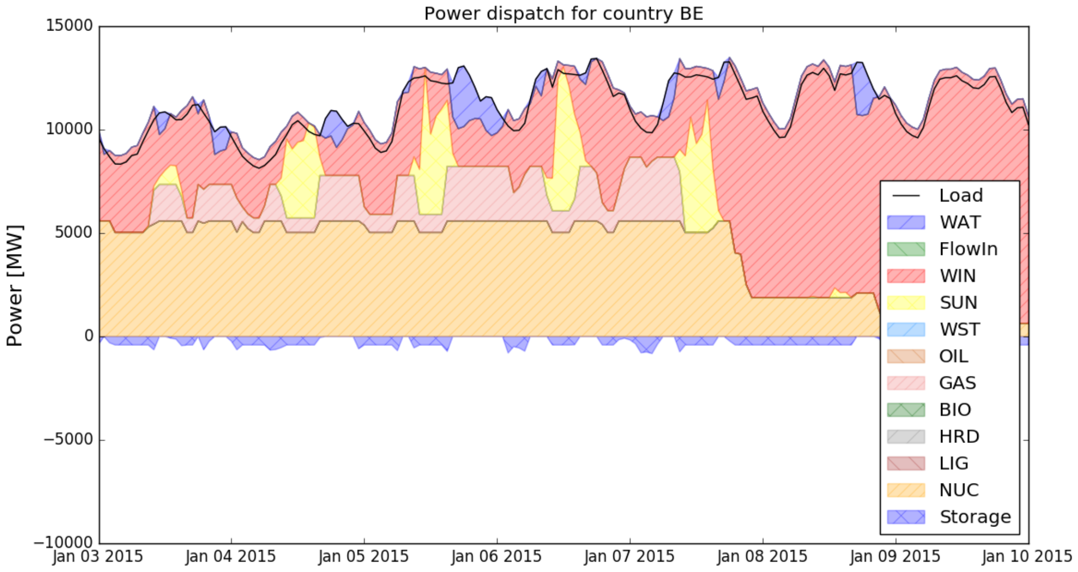

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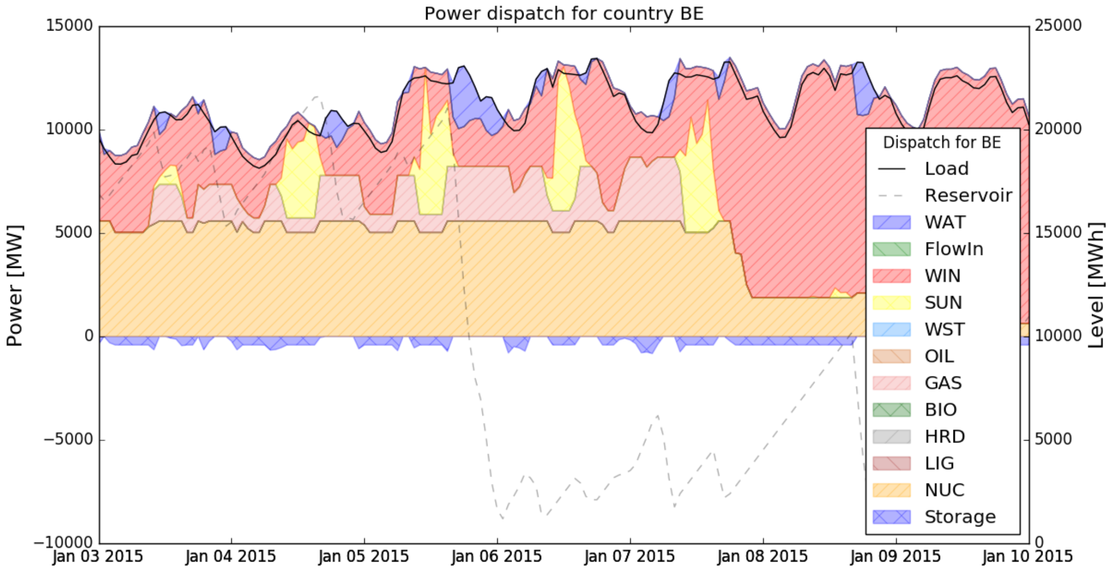

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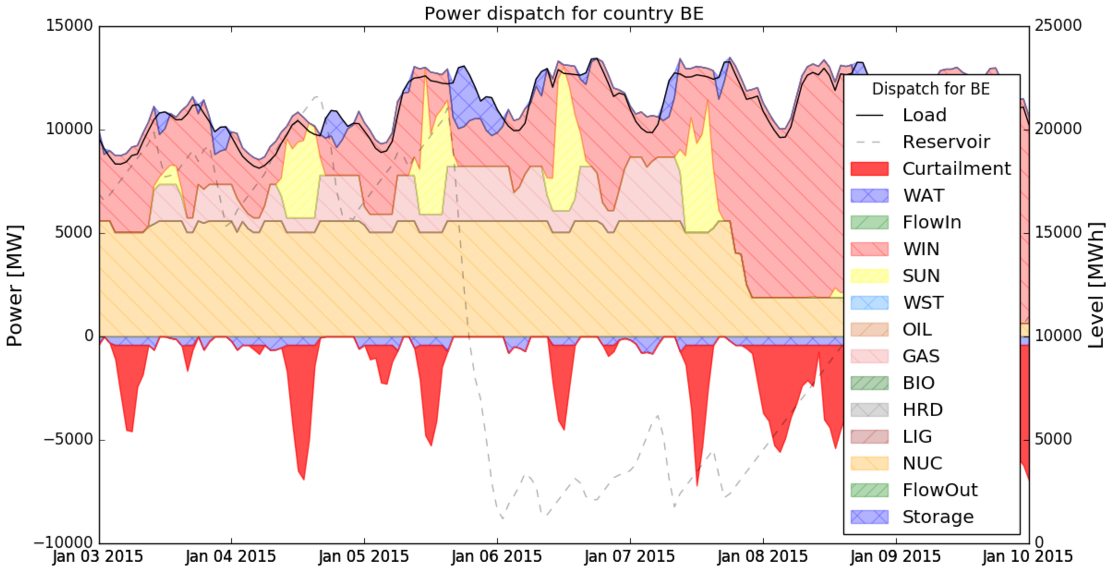

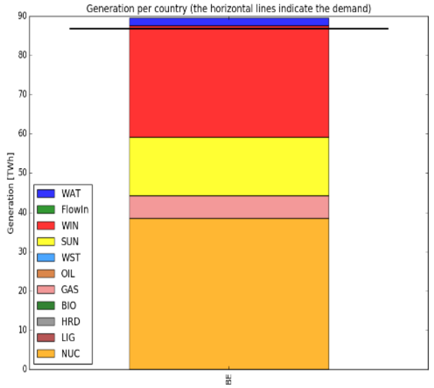

Energy Ville

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Latin hypercube: Definition of 4096 Runs

Simulation in Dispa-SET

→

Cleaning up: discarding simulations with lost load

Methodology

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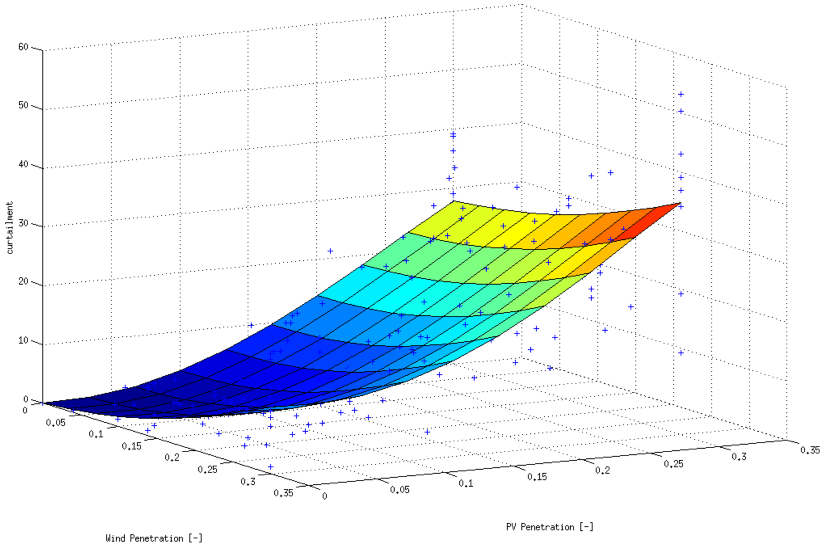
Latin hypercube: Definition of 4096 Runs

Simulation in Dispa-SET

Cleaning up: discarding simulations with lost load

Gaussian Processes interpolation of the results to build the most likely response surface



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→

Latin hypercube: Definition of 4096 Runs

Simulation in Dispa-SET

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Cleaning up: discarding simulations with lost load

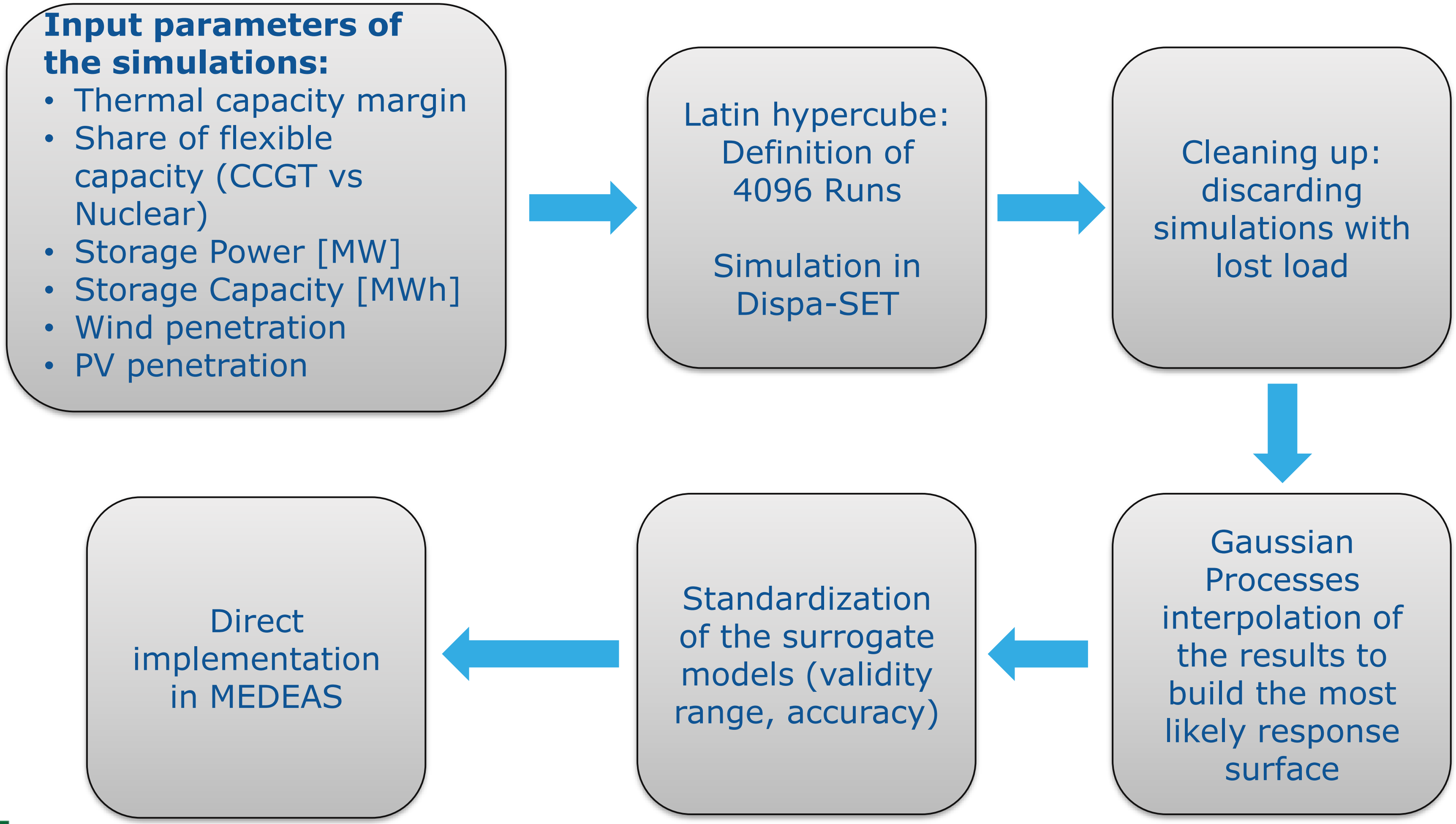
↓

Gaussian Processes interpolation of the results to build the most likely response surface

←

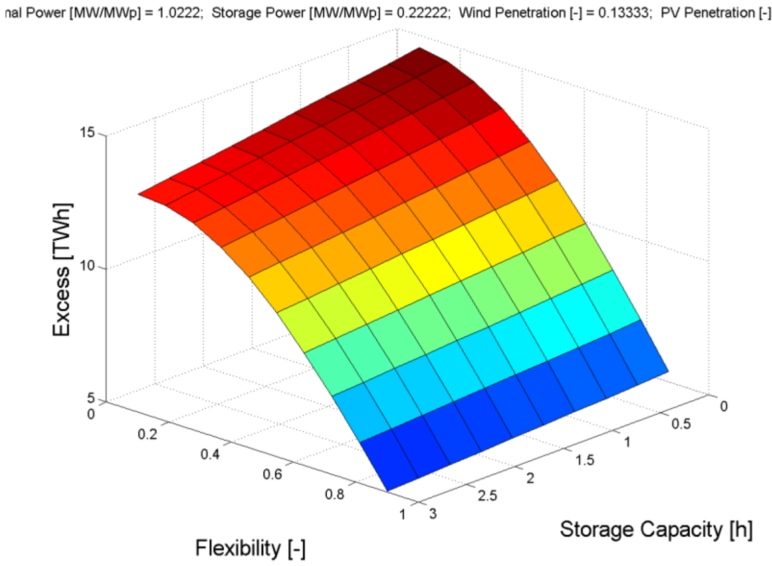
Standardization of the surrogate models (validity range, accuracy)

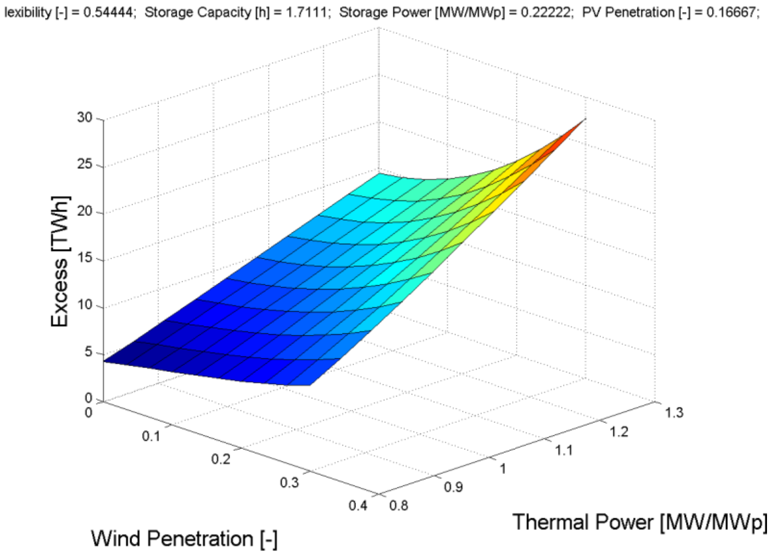
Methodology

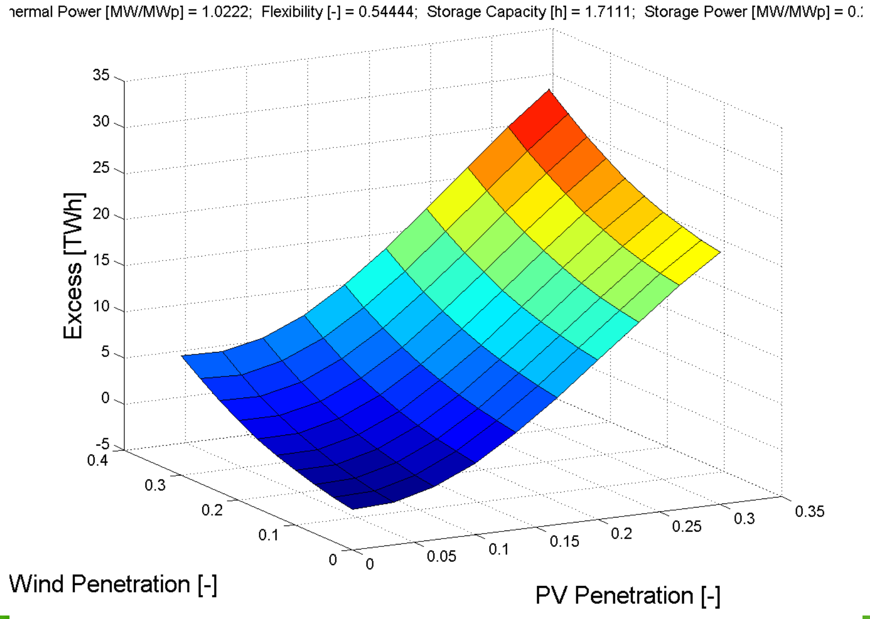


EnergyVille

Regression results (examples)







Conclusions

- A methodology has been defined to extract simplified flexibility constraints from a large number of runs from a power system model
- Demonstrated for the excess power, but also used to limit the dispatch of baseload generation
- Could be an alternative to soft or hard-linking, or to the increase of the simulation time-resolution
- Work in progress! Future work will focus on:
  - Implementation and extensive testing in the MEDEAS model
  - Robustness of the approach in other conditions
- All methods and models are released as open-source

Dispa-SET
Power system modelling

GitHub

zenodo

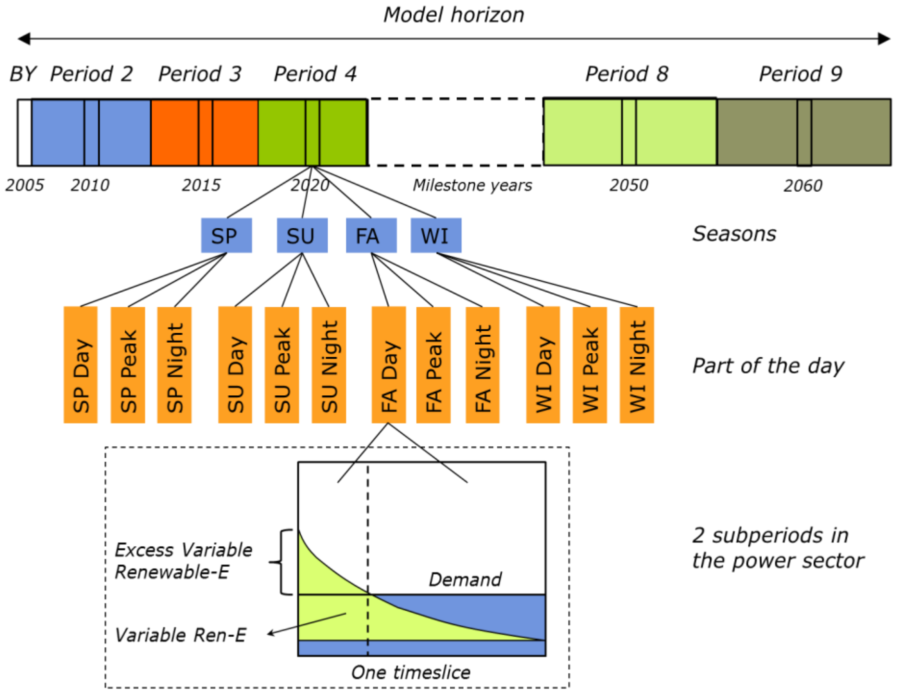
Energy Ville

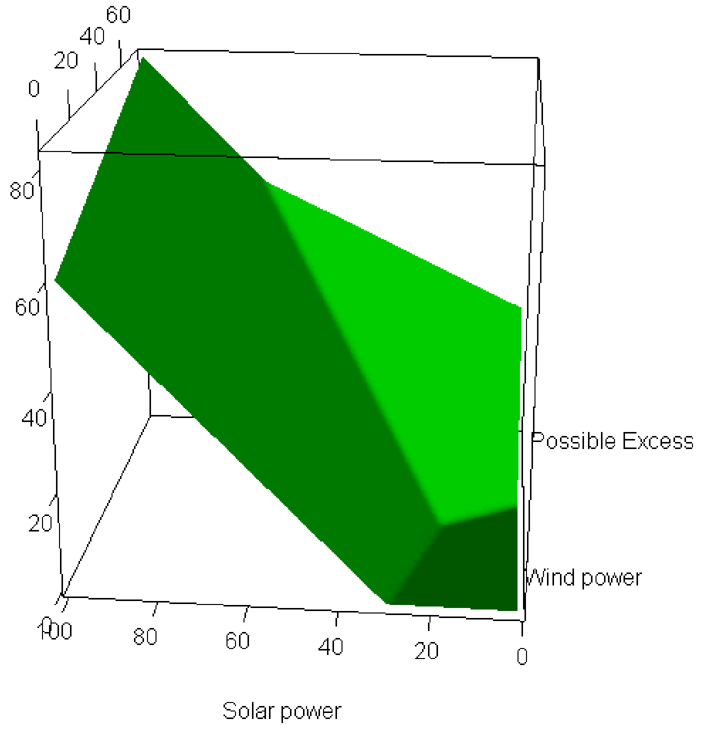
http://www.dispaset.eu

Thank you!

JRC-EU-TIMES Variable Renewable Energy (VRE)

- Parametrization based on detailed analysis outside JRC-EU-TIMES
- Applied to all timeslices



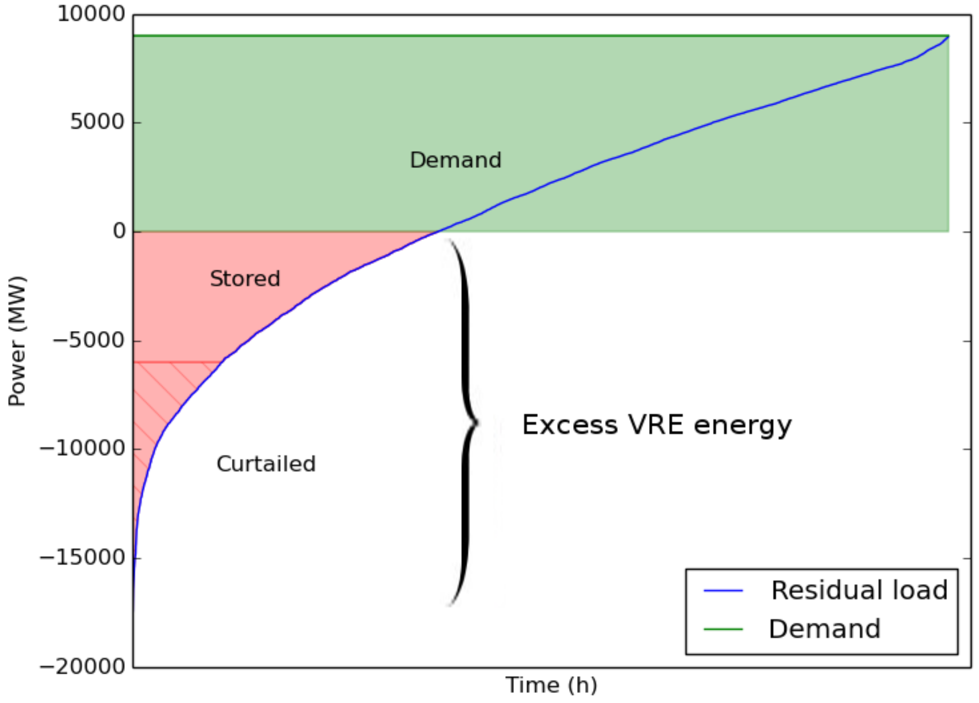


Excess energy characterization

- Focus on high shares of renewables

- Approach:

1. Simulation of the power system
2. Identification of the curtailed energy
3. Express the curtailed amount as a function of the power system characteristics



Dispa-SET 2.3

$$\min \sum_{i} SystemCost_{i}$$

$$\sum_{u} (P_{u,i} \cdot Location_{u,n}) + \sum_{l} (Flow_{l,i} \cdot LineNode_{l,n})$$
$$= Demand_{DA,n,h} + \sum_{r} (StorageInput_{s,h} \cdot Location_{s,n}) - ShedLoad_{n,i}$$
$$-LostLoadMaxPower_{n,i} + LostLoadMinPower_{n,i} \qquad (2)$$