Artificial intelligence for assessing the security of electricity supply

Short study – Nuclear Power Plants in Germany (2023)

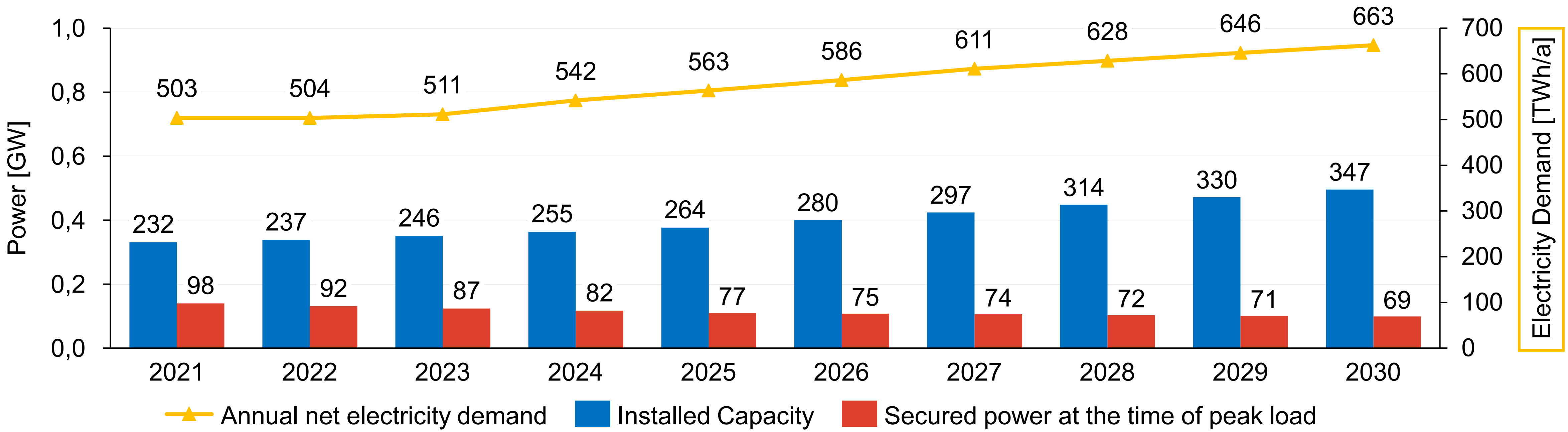
Philipp Daun, Marius Tillmanns, Jan Priesmann and Aaron Praktiknjo
Chair for Energy System Economics (FCN-ESE), RWTH Aachen University, Germany

IAEE 2023

European Conference, Milan, Italy
July 26th, 2023

The energy transition: a challenge for the future security of supply ?

Forecast development of the electricity system in Germany



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Philipp Daun, Marius Tillmanns, Jan Priesmann, Aaron Praktiknjo; Chair for Energy System Economics (FCN-ESE)
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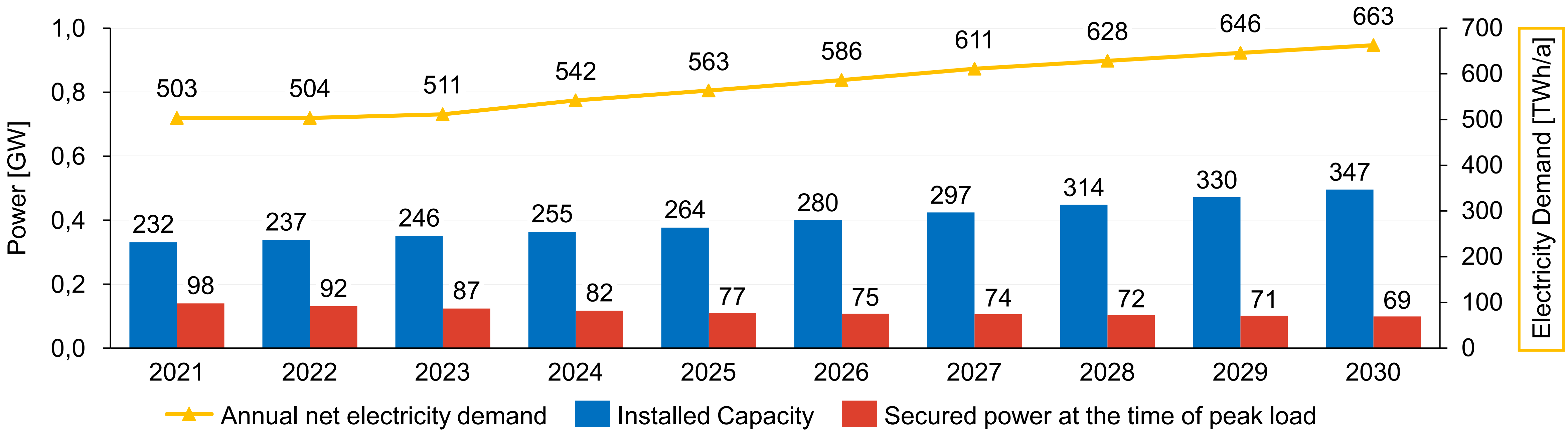

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- **Non-availability** of conventional generation plants as well as renewables, an increase in **electricity demand** as well as a lack of **flexibilities** can lead to **bottlenecks in the security of supply**
- The **assessment of the security of electricity supply** is therefore becoming increasingly important

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Assessment of the security of electricity supply

Complexity vs. scenario scope

- Requirement for **probabilistic** assessment of security of supply *(ACER 2020, ERAA - European Resource Adequacy Assessment)*
- According to ERAA, only a **greatly reduced consideration of uncertainties in** generation, storage, grids and consumption is necessary

➢ **Uncertainty space** is only represented to **a very limited extent** due to the high **model complexity**

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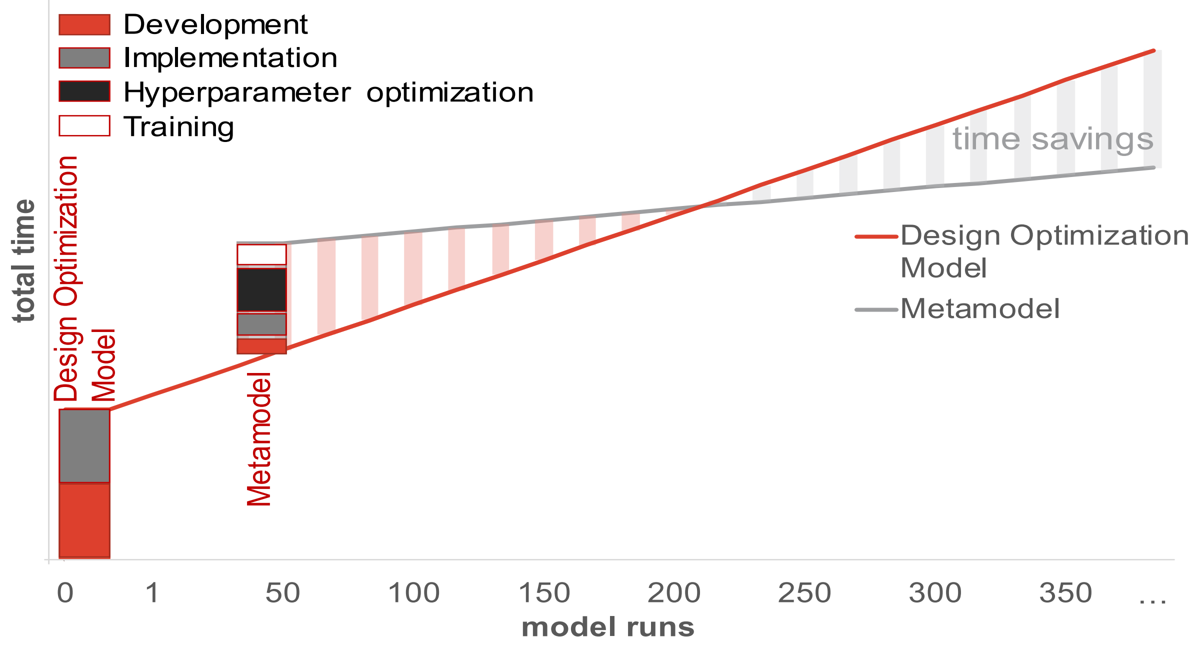
A solution? Meta-modeling



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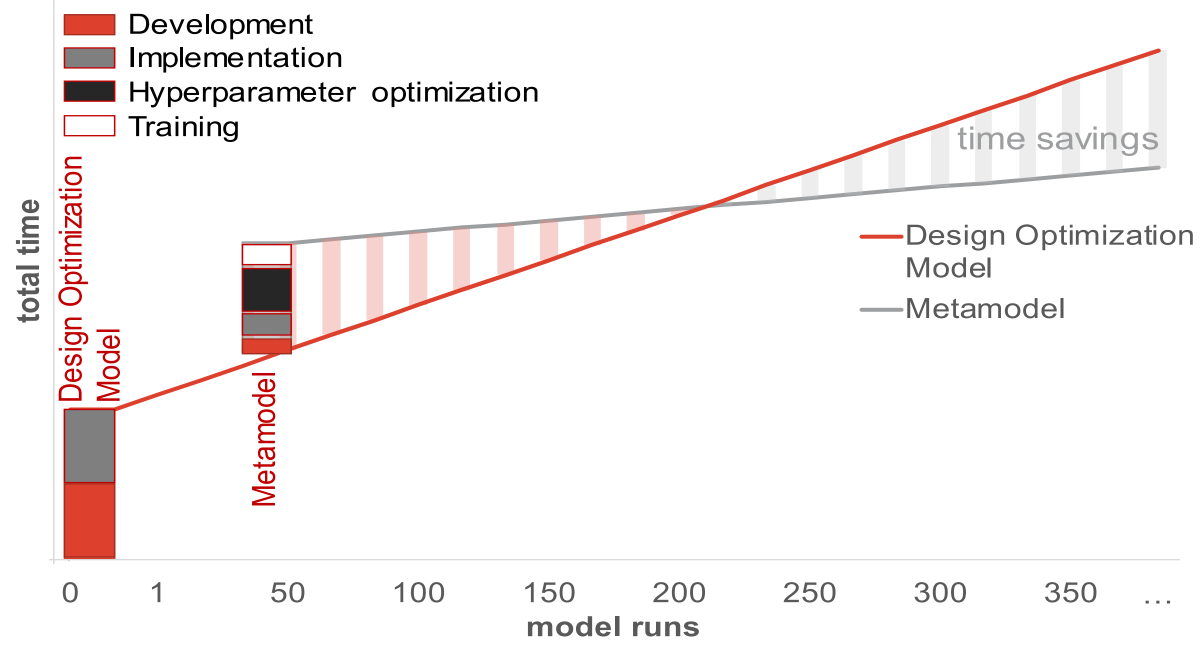

Research questions

- To what extent can **metamodeling** help to reduce the **runtime** in the assessment of security of supply?
- And at what **cost**? Does the **accuracy of the model** remain sufficiently intact?
- **Case study:** Does the **extension of the operating lives** of the remaining **nuclear power plants in Germany** until 15 April 2023 improve the security of electricity supply?

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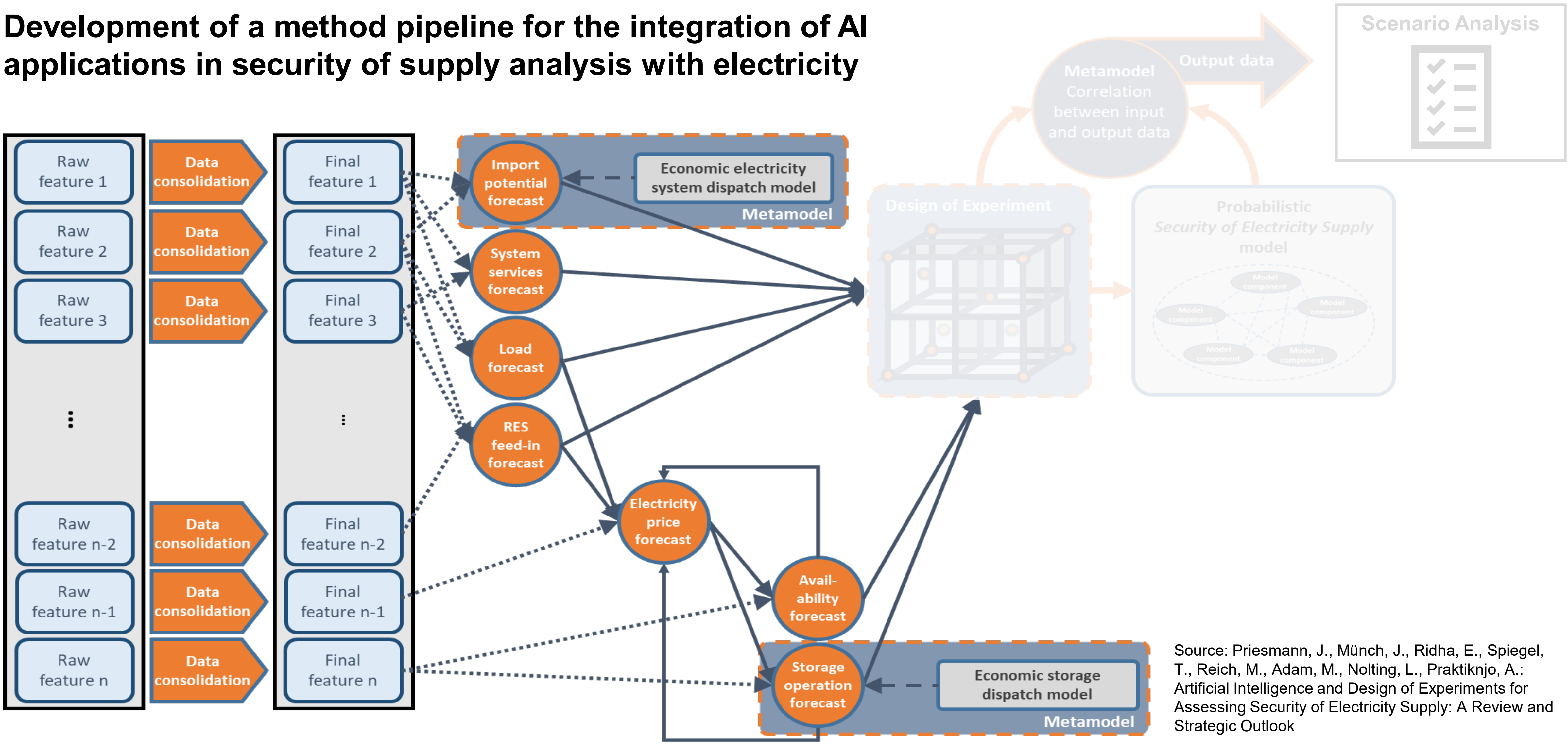
Method pipeline and meta-modeling

Development of a method pipeline for the integration of AI applications in security of supply analysis with electricity



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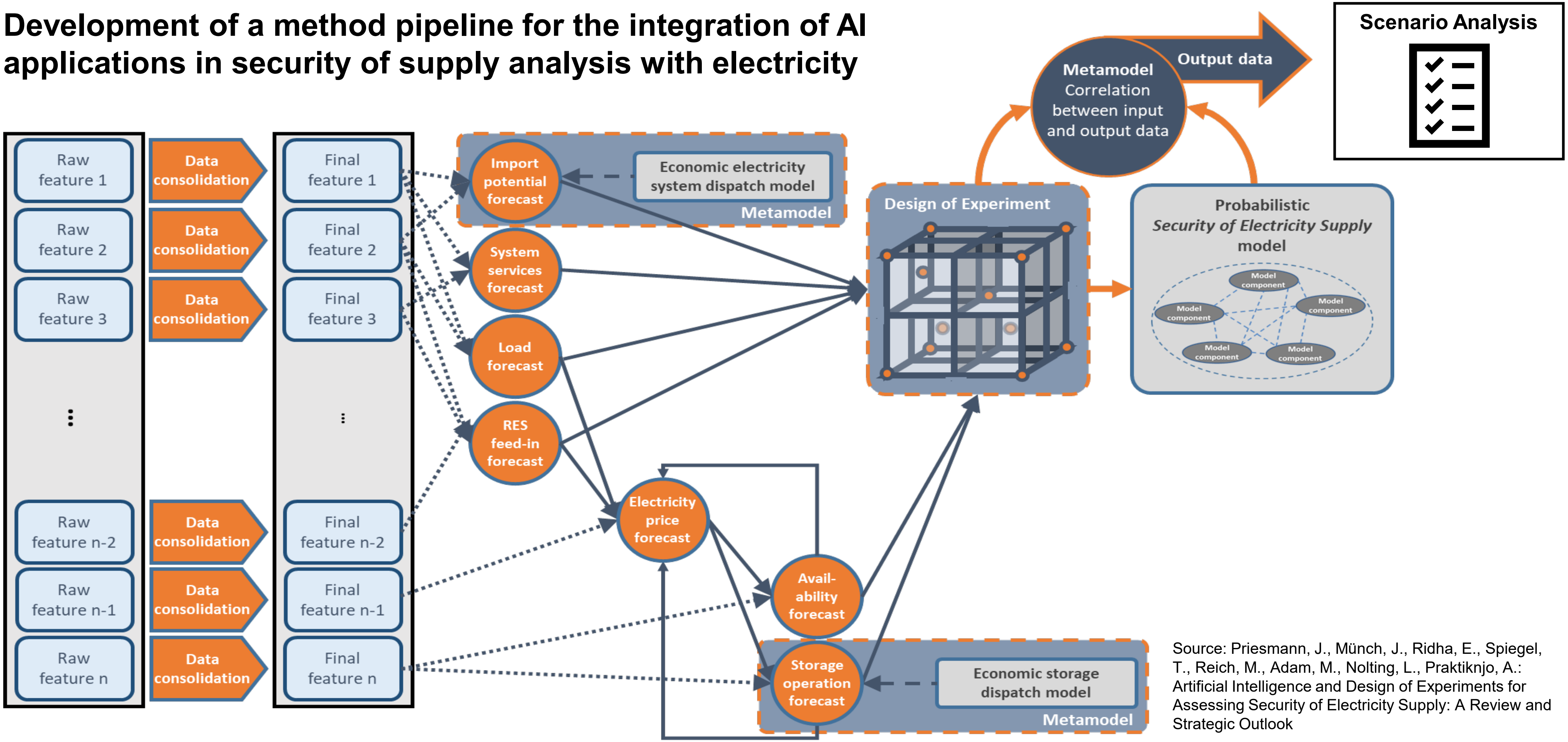

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Second approach of meta-modeling

Direct prediction of key figures of security of supply

Input data

- Conventional Power plant park (controllable)
- Renewable Power plant park (conditionally controllable)
- Import potential from neighbouring countries
- Electrical load (*net electricity demand*)
- (Sector coupling) EV, heat pumps

Output data

Loss of Load Probability (LoLP)
(Probability that the load cannot be met in one hour)

$$LoLP(t) = 1 - Pr_{Load\ coverage}(t)$$

Loss of Load Expected (LoLE)
(expected duration of the load interruption in hours)

$$LOLE = \sum_{t=1}^{t=8.760} LOLP(t) \cdot 1\frac{h}{a}$$

Expected Energy not Served (EEnS)
(Electricity demand in MWh/h or MWh/a that is not expected to be met)

$$EEnS(t) = \int_{P=0\ GW}^{P=P_{res}(t)} (1 - Pr_{available}(t))\, dP$$

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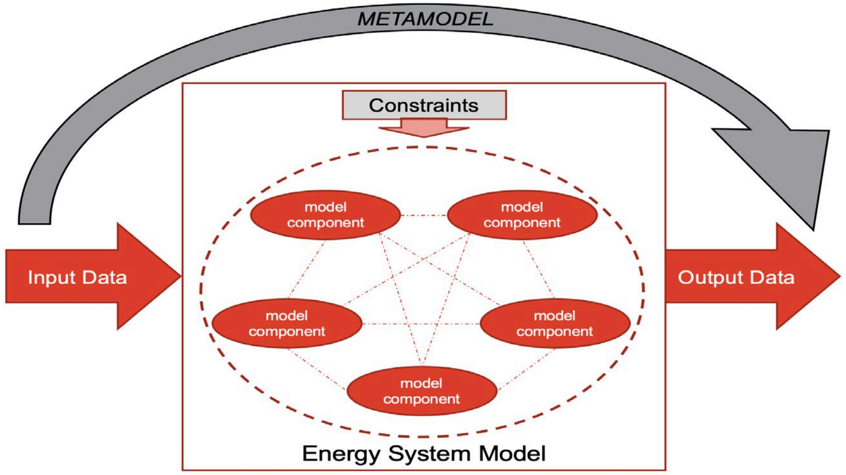

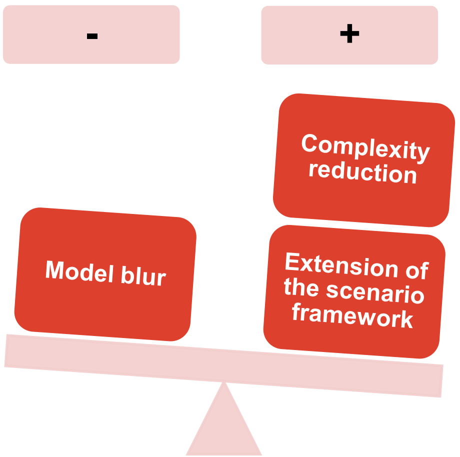

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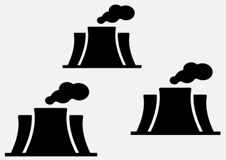
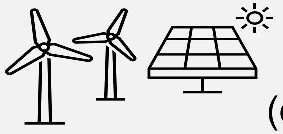


Conventional
Power plant park
(controllable)



Renewable
Power plant park
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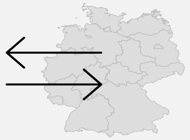
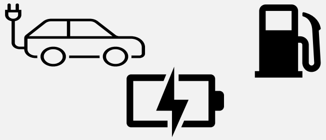
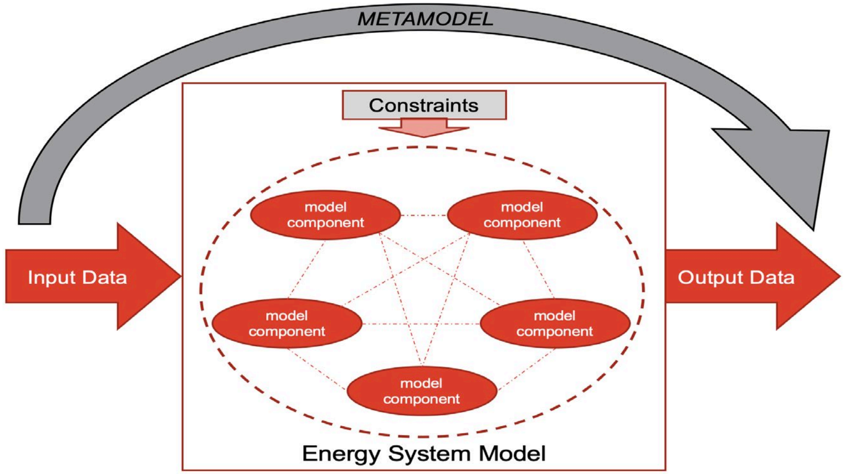


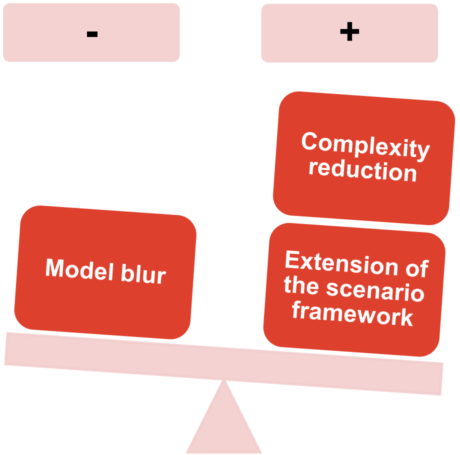
Import potential from
neighbouring countries

Electrical load
(*net electricity demand*)



(Sector coupling)
EV, heat pumps





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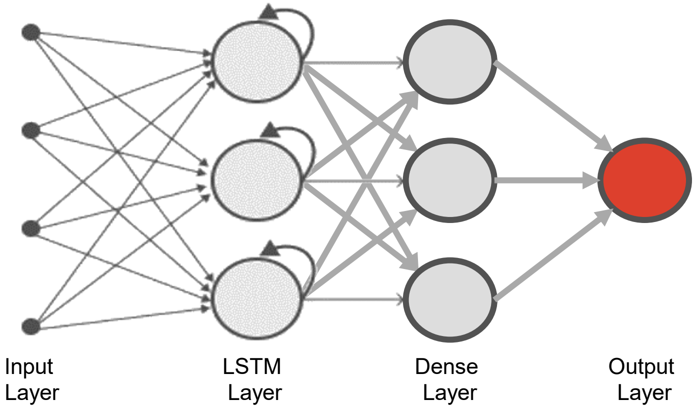
Meta-modeling: artificial neuronal network

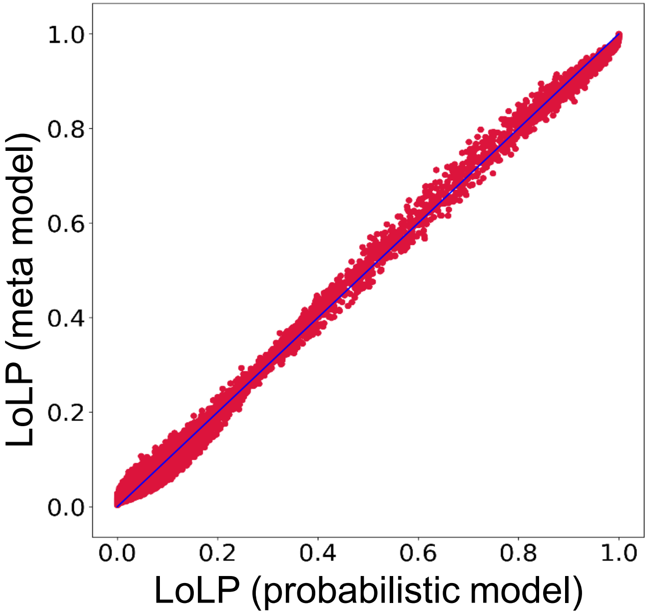
The simulation results: key figures of the training data

Metamodel

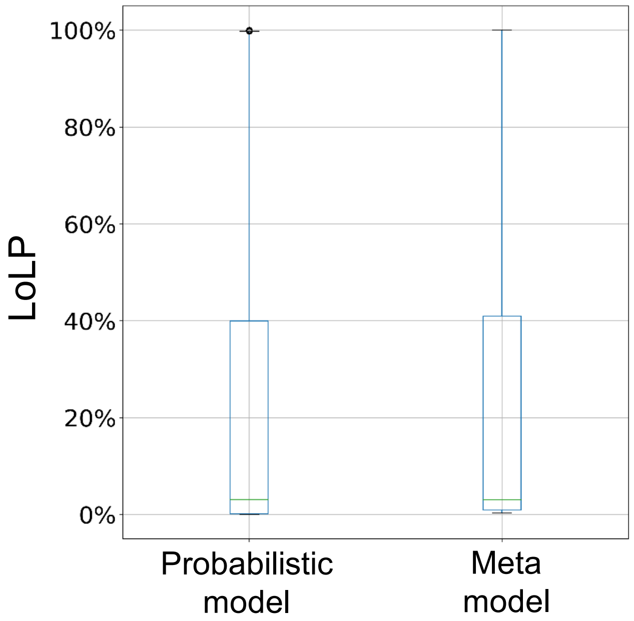


- **4 layers:** Input, LSTM, Dense and Output layers
- **3,081 Training weights,** trained with **262,800 input-output relations**

Forecast accuracy



Distribution of the LoLPs



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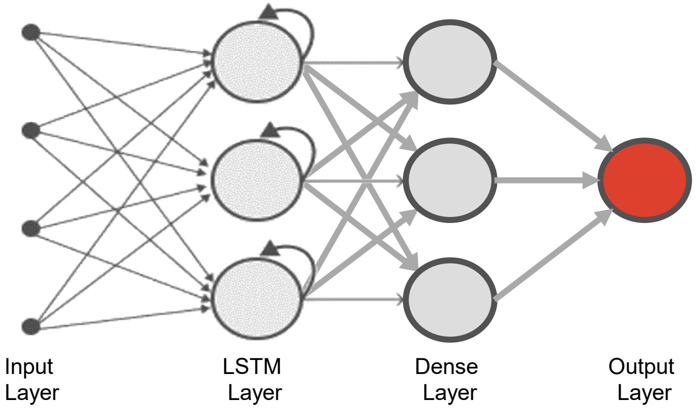

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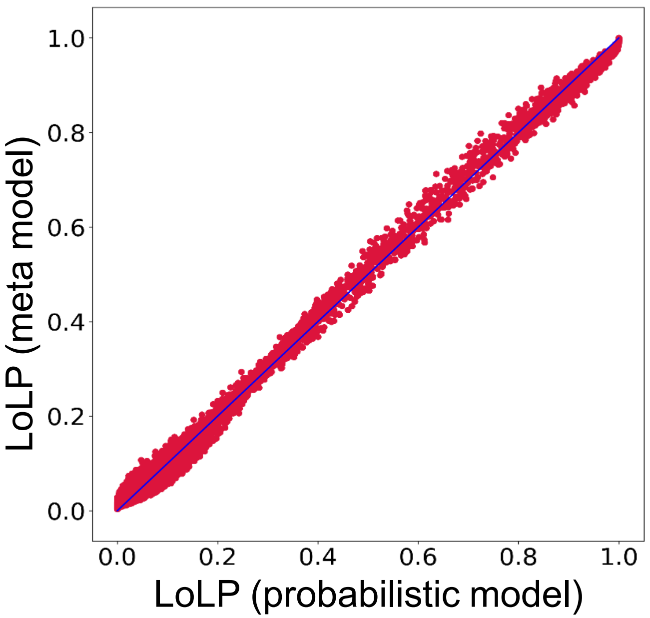

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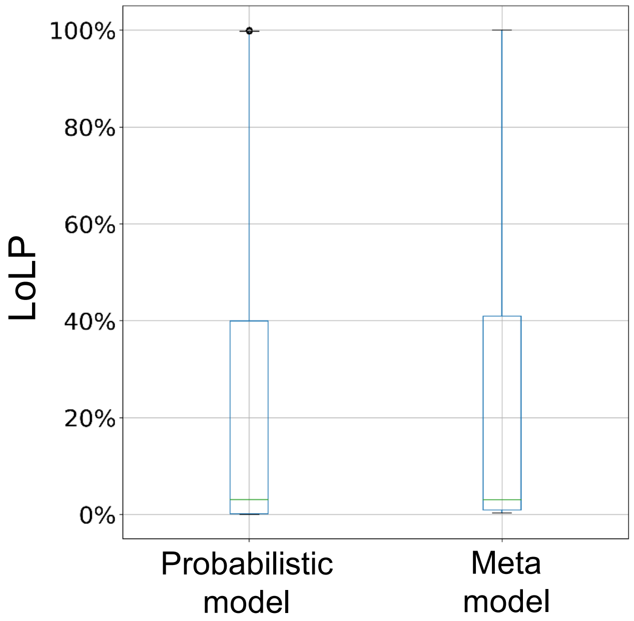

- Spread of errors is an important indicator of metamodel weaknesses
- **Best metamodel:** LSTN-NN (Long short-term memory-neuronal network)
- **The model approximates the simulation data with a coefficient of determination of R^2 = 99,86 % and a mean absolute error of MAE = 1 %**

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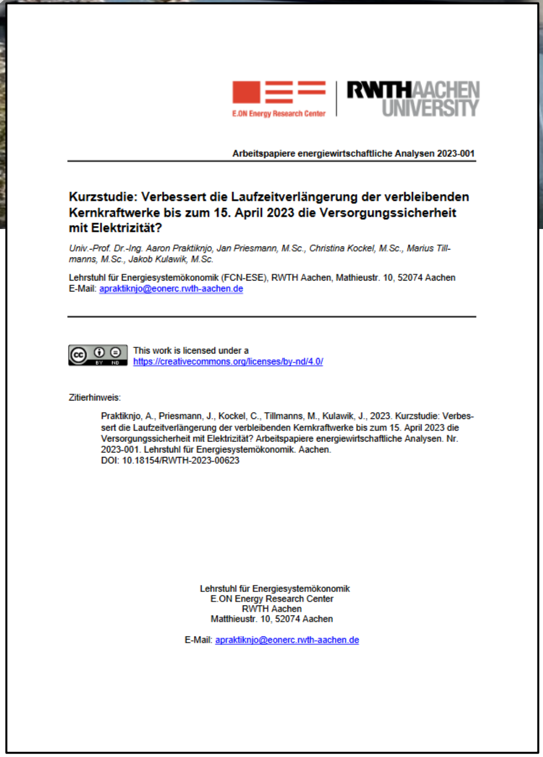
Does the extension of the operating lives of the remaining nuclear power plants until 15 April 2023 improve the security of electricity supply?

Aaron Praktiknjo, Jan Priesmann, Christina Kockel, Marius Tillmanns, Jakob Kulawik



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Arbeitspapiere energiewirtschaftliche Analysen 2023-001

Kurzstudie: Verbessert die Laufzeitverlängerung der verbleibenden Kernkraftwerke bis zum 15. April 2023 die Versorgungssicherheit mit Elektrizität?

Univ.-Prof. Dr.-Ing. Aaron Praktiknjo, Jan Priesmann, M.Sc., Christina Kockel, M.Sc., Marius Tillmanns, M.Sc., Jakob Kulawik, M.Sc.

Lehrstuhl für Energiesystemökonomik (FCN-ESE), RWTH Aachen, Mathieustr. 10, 52074 Aachen
E-Mail: apraktiknjo@eonerc.rwth-aachen.de

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Zitierhinweis:

Praktiknjo, A., Priesmann, J., Kockel, C., Tillmanns, M., Kulawik, J., 2023. Kurzstudie: Verbessert die Laufzeitverlängerung der verbleibenden Kernkraftwerke bis zum 15. April 2023 die Versorgungssicherheit mit Elektrizität? Arbeitspapiere energiewirtschaftliche Analysen. Nr. 2023-001. Lehrstuhl für Energiesystemökonomik. Aachen.
DOI: 10.18154/RWTH-2023-00623

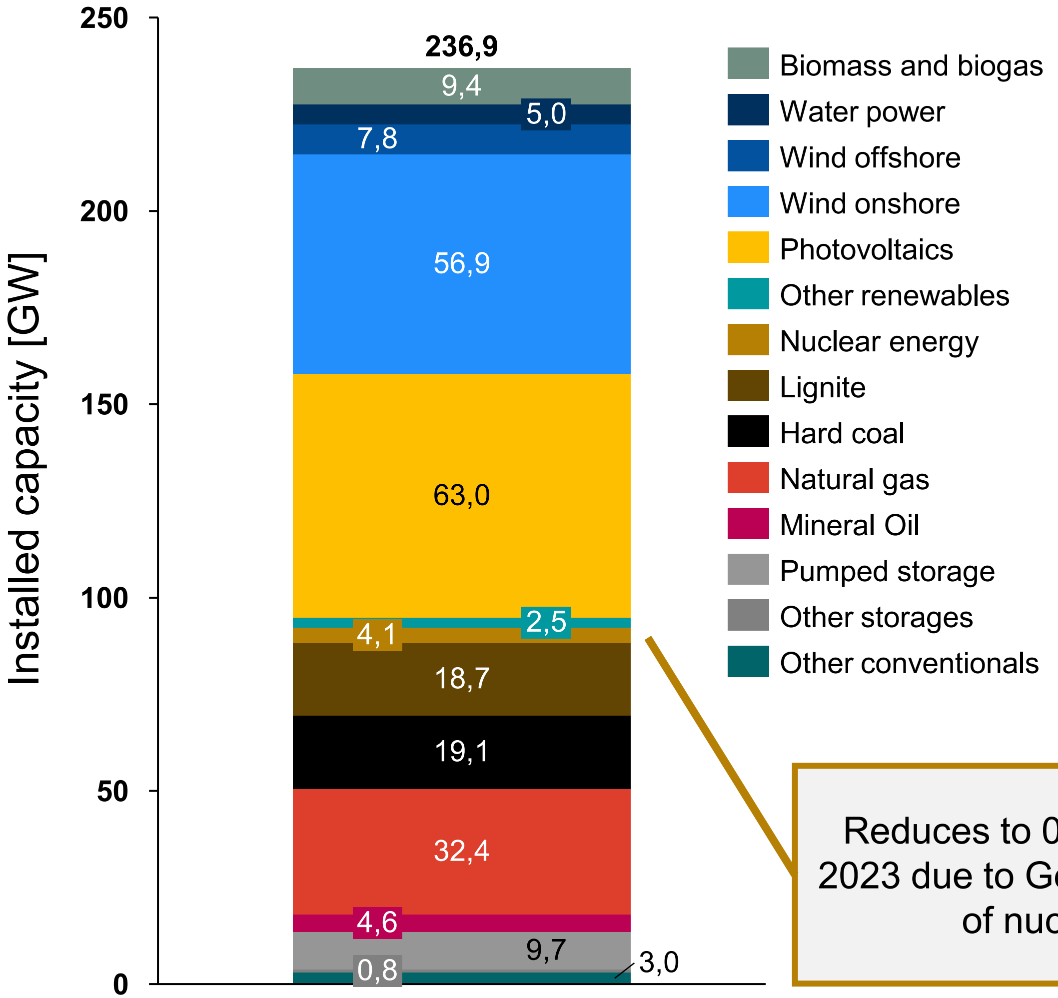
Lehrstuhl für Energiesystemökonomik
E.ON Energy Research Center
RWTH Aachen
Matthieustr. 10, 52074 Aachen

E-Mail: apraktiknjo@eonerc.rwth-aachen.de

DOI: 10.18154/RWTH-2023-00623

Scenario framework for the calendar year 2023

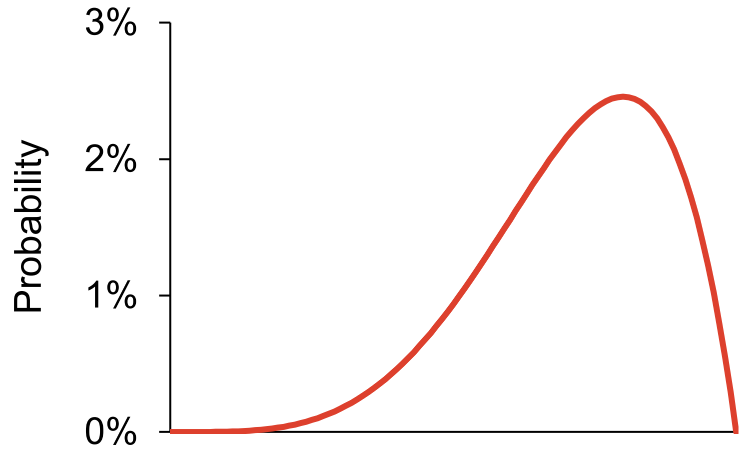
Power plant park in Germany *(based on Federal Network Agency power plant list of 25 November 2022)*



Reduces to 0 GW after 15 April 2023 due to Germany‘s phase-out of nuclear power

Further uncertainties considered

- Reduction of available **gas capacities** due to supply bottlenecks
- Reduction of **import potentials**
- Reduction of **electricity demand**



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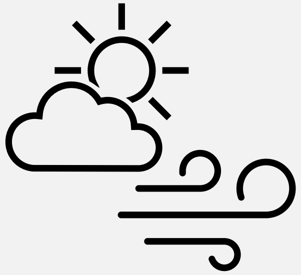
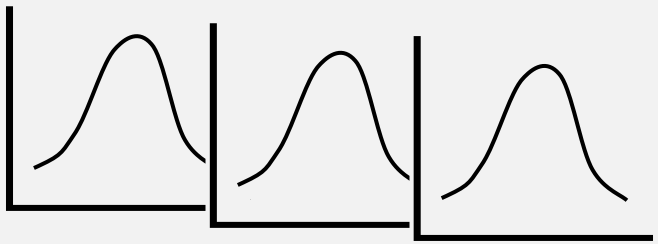
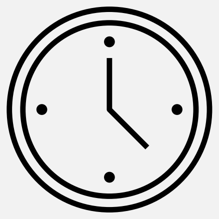
Scope of simulation and comparison of runtime to probabilistic model

Weather years	Monte Carlo simulation of the further uncertainties	Hourly resolution
		

Variants

30 x 1000 x 8760

= 30,000 simulated years = 262.8 million simulated hours

Comparison of Running times

Probabilistic Model	Trained metamodel
~4,000 – 8,000 hours (HPC)	~30 minutes (PC)

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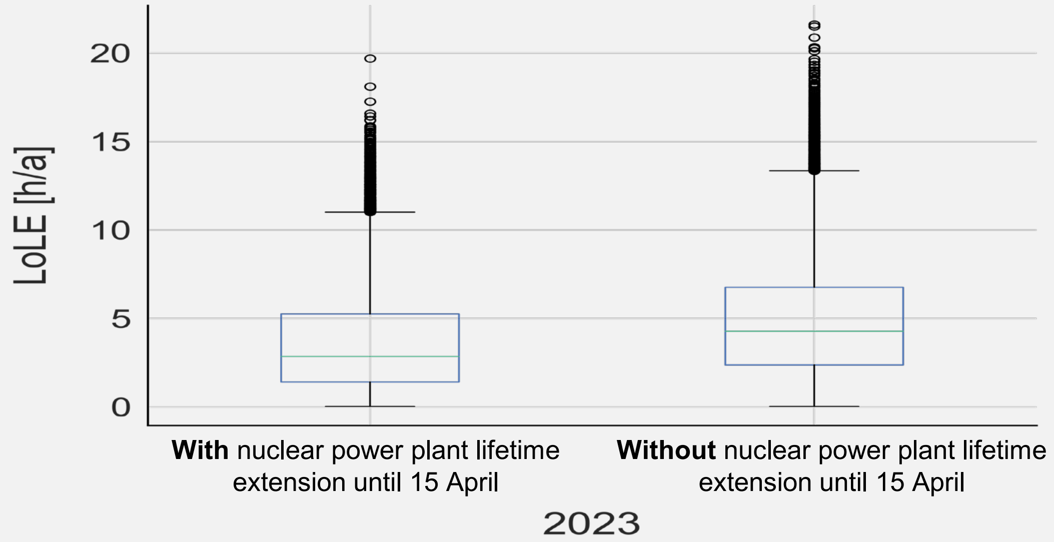
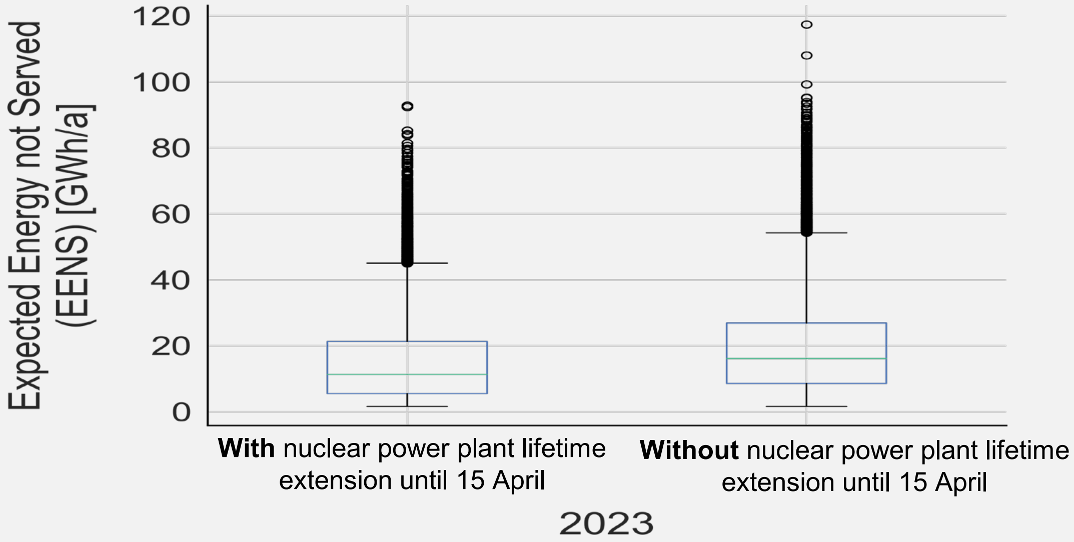
Distribution of the security of supply indicators: LoLE and EEnS

Results: influence of the extension of the operating lives of nuclear power plants on LoLE and EEnS in the period 1 January 2023 to 15 April 2023

Loss of Load Expectation (LoLE)



Expected Energy not Served (EEnS)



- **With nuclear power plant runtime extension,** undersupply time (**LoLE**) **decreases** by **1.3 hours on average** and energy shortfall (**EEnS**) by **4.3 GWh on average.**
- **Depending on the scenario,** the **decrease for** the **LoLE** due to the lifetime extension is **between 0.0 and 3.2 hours and** for the **decrease** in **EEnS between 0.0 and 12.1 GWh** in the 5 % and 95 % confidence interval.

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Key findings and outlook

Meta-modeling

- **Metamodels** show that the classic probabilistic convolution model can be approximated with **high accuracy**
- **New scenarios with 30 weather years** can be approximated **within seconds** instead of several hours

Case study - Nuclear Power Plants in Germany (2023)

- **Continued operation of** the nuclear power plants remaining in Germany until 15 April 2023 means that, according to our calculations, a **statistically positive contribution** to security of supply can be expected in the period under review
- Analysis cannot make **any statement on other aspects** such as the impact on the security of supply with natural gas and other energy sources, electricity prices, CO_2 emissions, risks of reactor accidents, final storage problems with radioactive waste and acceptance by the population.

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Outlook

- **Transfer of the developed methods** to further probabilistic models for the evaluation of supply security (time-coupled optimisation methods) → *forecast of* ***storage dispatch and (non-)availabilities***
- Extension of the **methodology for the selection of support points (Design of Experiment)**
- The approximation introduces **additional fuzziness** into the analysis ("black box models“) → **Explainable AI**

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Contact
RWTH Aachen University
E.ON Energy Research Center
Mathieustraße 10
52074 Aachen
Germany

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philipp.daun@eonerc.rwth-aachen.de

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Backup

KIVi research project

Artificial intelligence to study the security of electricity supply

Project duration: 01 June 2020 – 30 November 2023

Projektträger Jülich
Forschungszentrum Jülich

Network partner

Hochschule Düsseldorf
University of Applied Sciences

Chair of Energy System Economics (FCN-ESE) | RWTH Aachen University

Centre for Innovative Energy Systems (ZIES) | Düsseldorf University

Practice Advisory Board

Amprion, Bundesnetzagentur, 50hertz | Elia Group, TransnetBW, TenneT

Philipp Daun, Marius Tillmanns, Jan Priesmann, Aaron Praktiknjo; Chair for Energy System Economics (FCN-ESE)
[philipp.daun; marius.tillmanns; apraktiknjo]@eonerc.rwth-aachen.de

The security of electricity supply: background

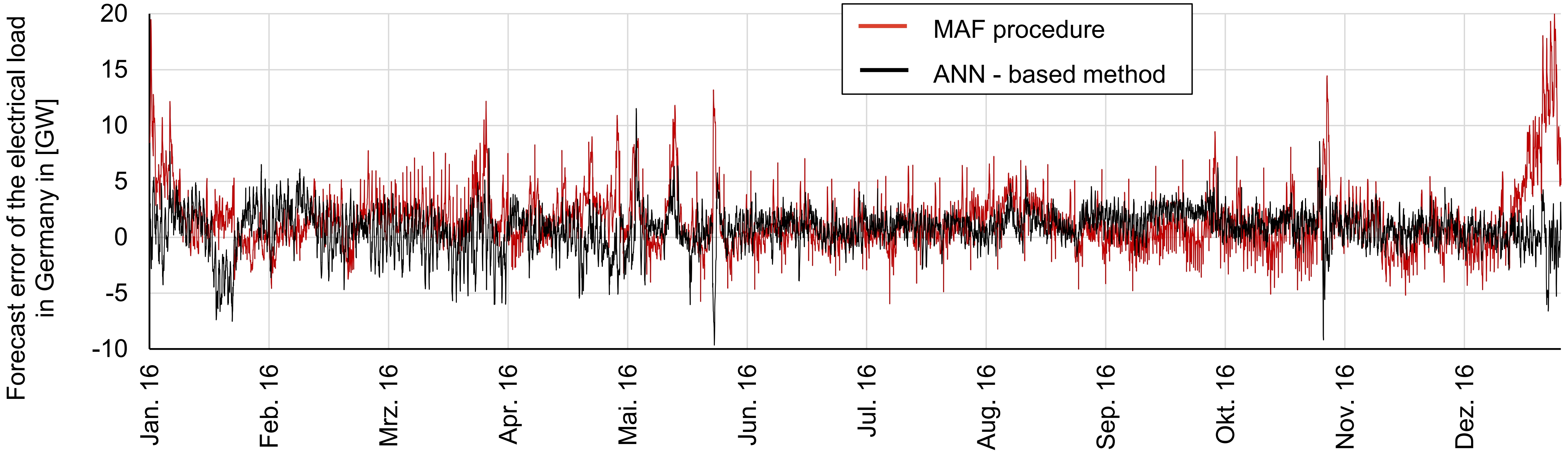
Eight Challenges

1. Forecasting loads and renewable feed-in: residual loads
2. Forecasting the unavailability of generation plants
3. Boundary-coupling services, mapping of international load flows
4. Complexity of the models: computing times and memory requirements
5. Mapping of uncertainties: increasing number of scenarios necessary
6. Water levels and temperatures: cooling water, supply chains, Run-of-river, storage water and pumped storage power plants
7. Integration of balancing power and balancing power markets
8. Mapping of market mechanisms and market behaviour

Philipp Daun, Marius Tillmanns, Jan Priesmann, Aaron Praktiknjo; Chair for Energy System Economics (FCN-ESE)
[philipp.daun; marius.tillmanns; apraktiknjo]@eonerc.rwth-aachen.de

Time series forecast example: Weather dependence of the electrical load

Load forecast: Status quo (Midterm Adequacy Forecast, MAF) and ANN-based method (Artificial Neural Network) in Germany (Year 2016)



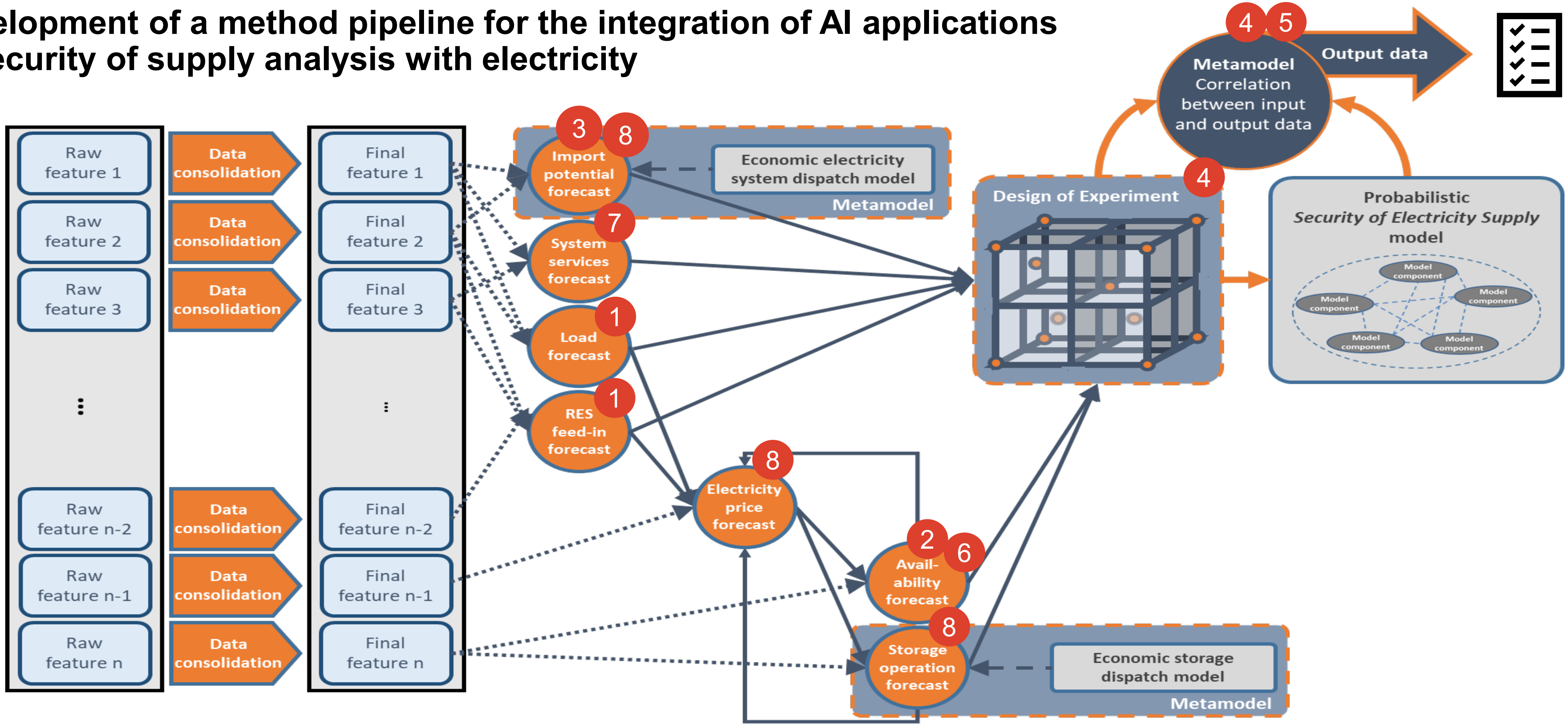
Source: Behm, C., Nolting, L., Praktiknjo, A. (2020). How to Model European Electricity Load Profiles using Artificial Neural Networks, Applied Energy, 277, 115564.

- Artificial neural networks can be used to **improve** the mapping of **weather effects** on **electrical load**
- Similar **improvements** are also feasible for the **weather-dependent feed-in power of** renewable energies

Philipp Daun, Marius Tillmanns, Jan Priesmann, Aaron Praktiknjo; Chair for Energy System Economics (FCN-ESE)
[philipp.daun; marius.tillmanns; apraktiknjo]@eonerc.rwth-aachen.de

Research project: time series prediction and meta-modeling

Development of a method pipeline for the integration of AI applications in security of supply analysis with electricity



Source: Priesmann, J., Münch, J., Ridha, E., Spiegel, T., Reich, M., Adam, M., Nolting, L., Praktiknjo, A.: Artificial Intelligence and Design of Experiments for Assessing Security of Electricity Supply: A Review and Strategic Outlook

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Philipp Daun, Marius Tillmanns, Jan Priesmann, Aaron Praktiknjo; Chair for Energy System Economics (FCN-ESE)
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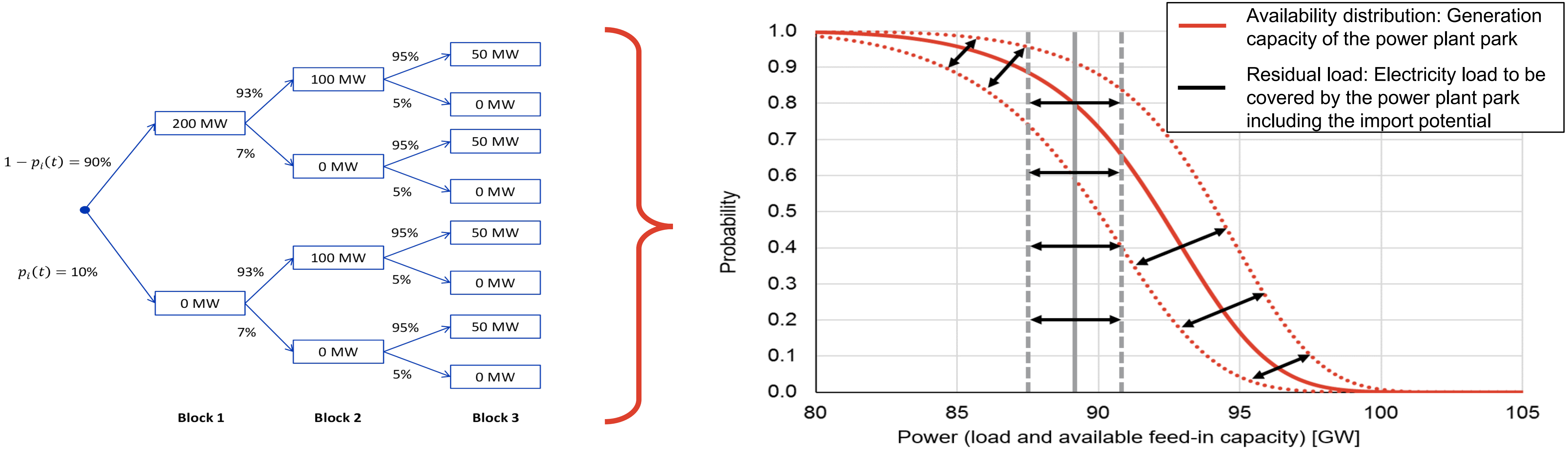
Methods for the analysis of the security of electricity supply

Basics of the probabilistic simulation model



Mapping of the **distribution function of the secured feed-in power** using **recursive convolution:**

$$\underset{i}{Pr}(P_A > P) = \underset{(i-1)}{Pr}(P_A > P) \cdot \big(1 - p_i(t)\big) + \underset{(i-1)}{Pr}\big(P_A > (P - P_i)\big) \cdot p_i(t)$$

Cf. Brückl (2006)

- Mapping of the **electrical load**, the **feed-in capacity of the renewable generation plants** (wind, PV and run-of-river) as well as the **import potentials** based on **30 weather years**
- Scenario-based mapping of the **flexibility potential of sector coupling technologies** such as heat pumps and electric vehicles

Philipp Daun, Marius Tillmanns, Jan Priesmann, Aaron Praktiknjo; Chair for Energy System Economics (FCN-ESE)
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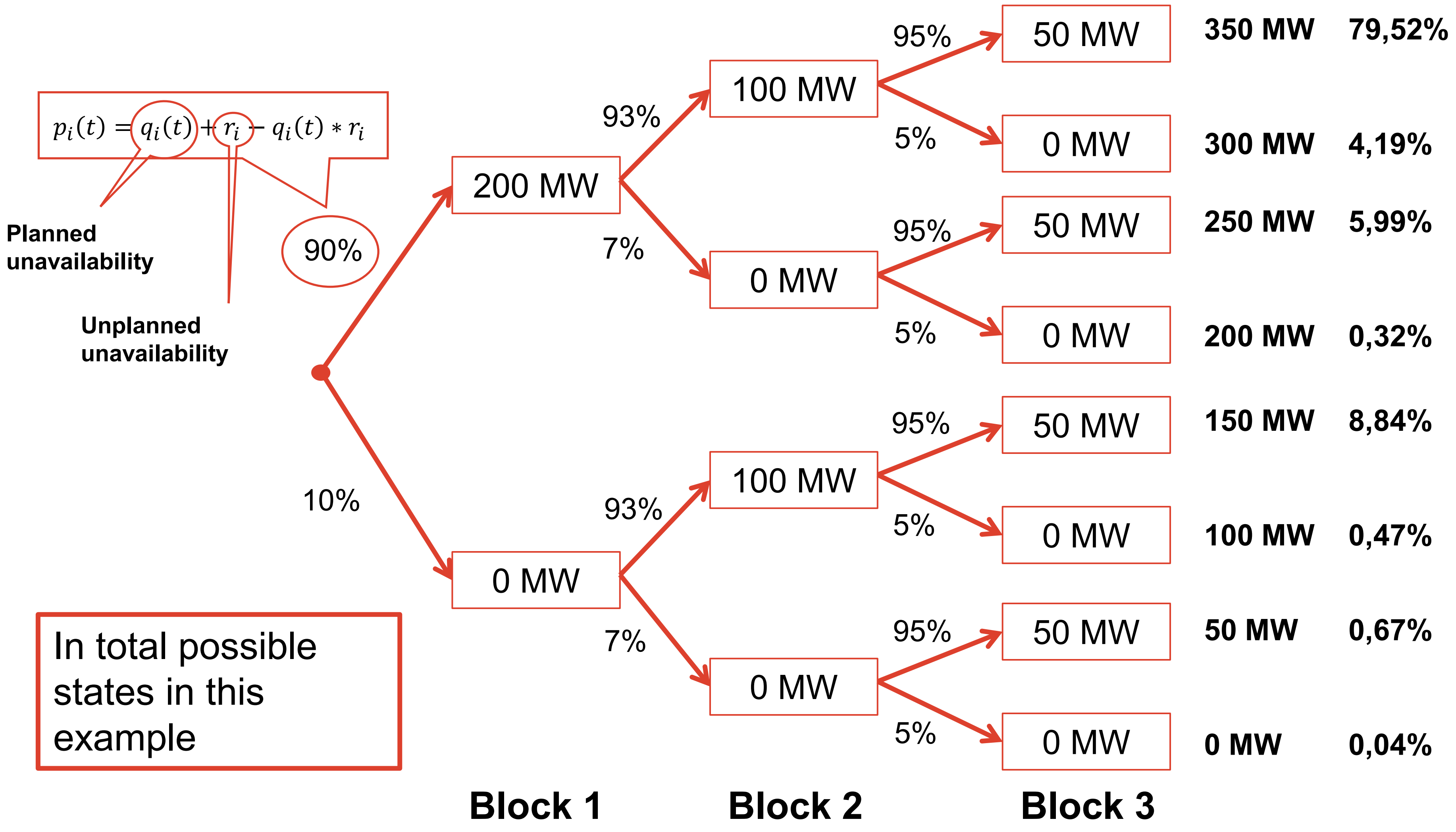
Example with 3 power plant units



In total possible states in this example

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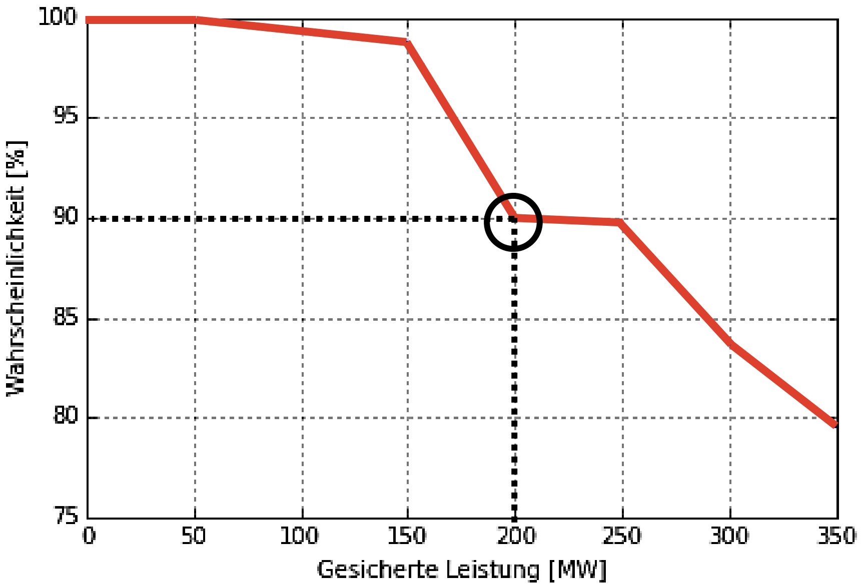
Tabular and graphical evaluation of the convolution

Non-availability [MW]	Assured performance [MW]	p [%]	p, cumulated [%]
0	350	79.52	79.52
50	300	4.19	83.70
100	250	5.99	89.69
150	200	0.32	90.00
200	150	8.84	98.84
250	100	0.47	99.30
300	50	0.67	99.97
350	0	0.04	100.00



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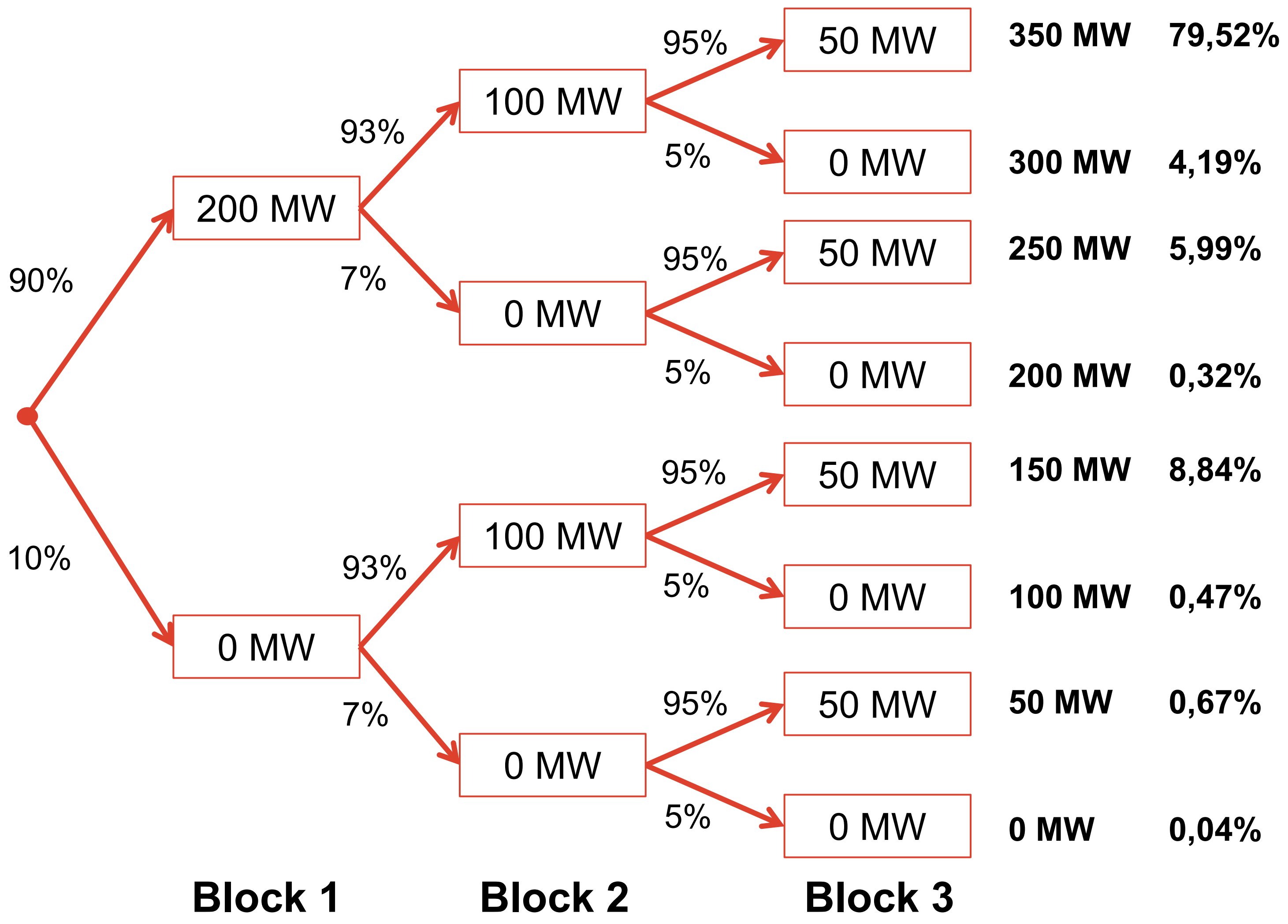
Comparison with Monte Carlo simulation



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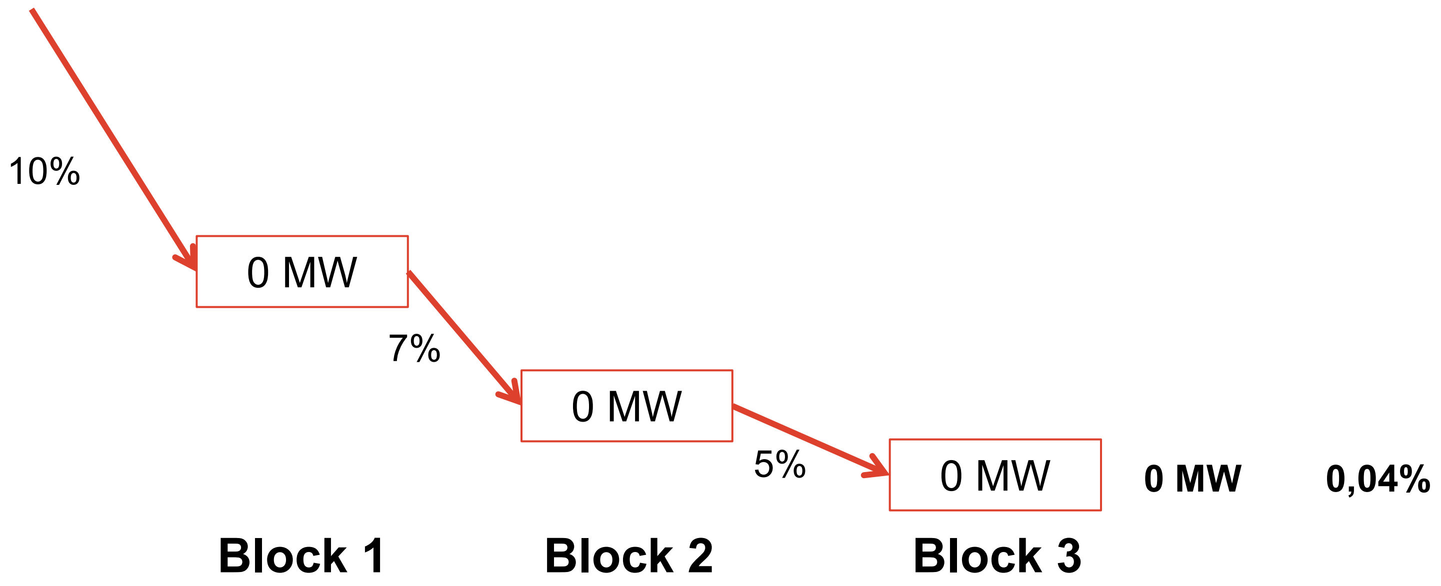

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Procedure for large numbers of power plant units: Recursive convolution

Number of possible states for *n* power plant units

With approx. 800 blocks in Germany Possible conditions

Therefore, use of the recursive formulation according to Brückl (2006) for the probability of a total failure of more than P_A of the installed capacity:

$$\Pr_i(P_A > P) = \Pr_{(i-1)}(P_A > P) * \left(1 - p_i(t)\right) + \Pr_{(i-1)}\left(P_A > (P - P_i)\right) * p_i(t)$$

With:

Pr := Probability := Probability of default
P := Power of block i
P_i := Power of power plant unit i
P_A := Power failure

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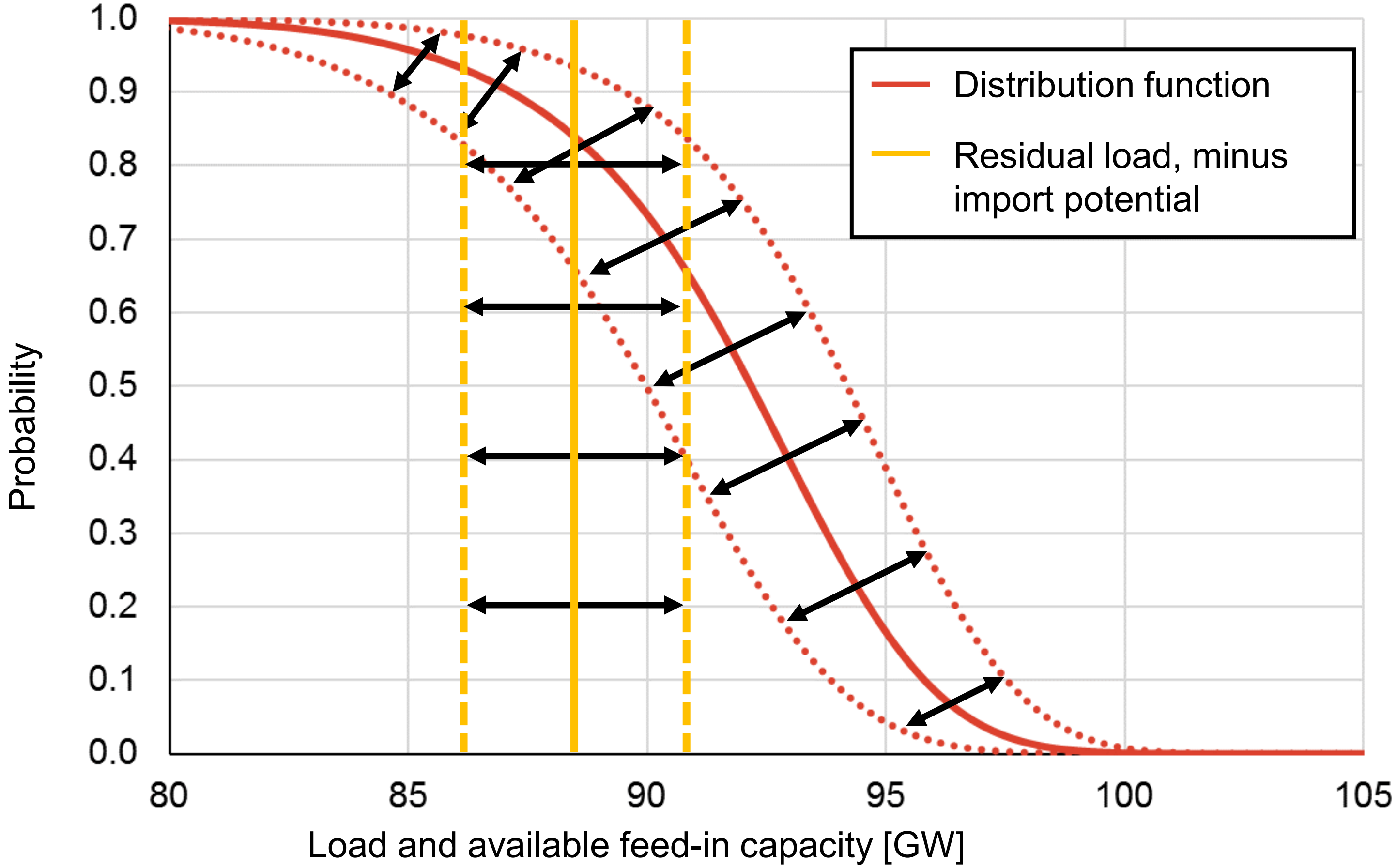
Models and input data: Security of supply model

Load-side consideration of the import potential



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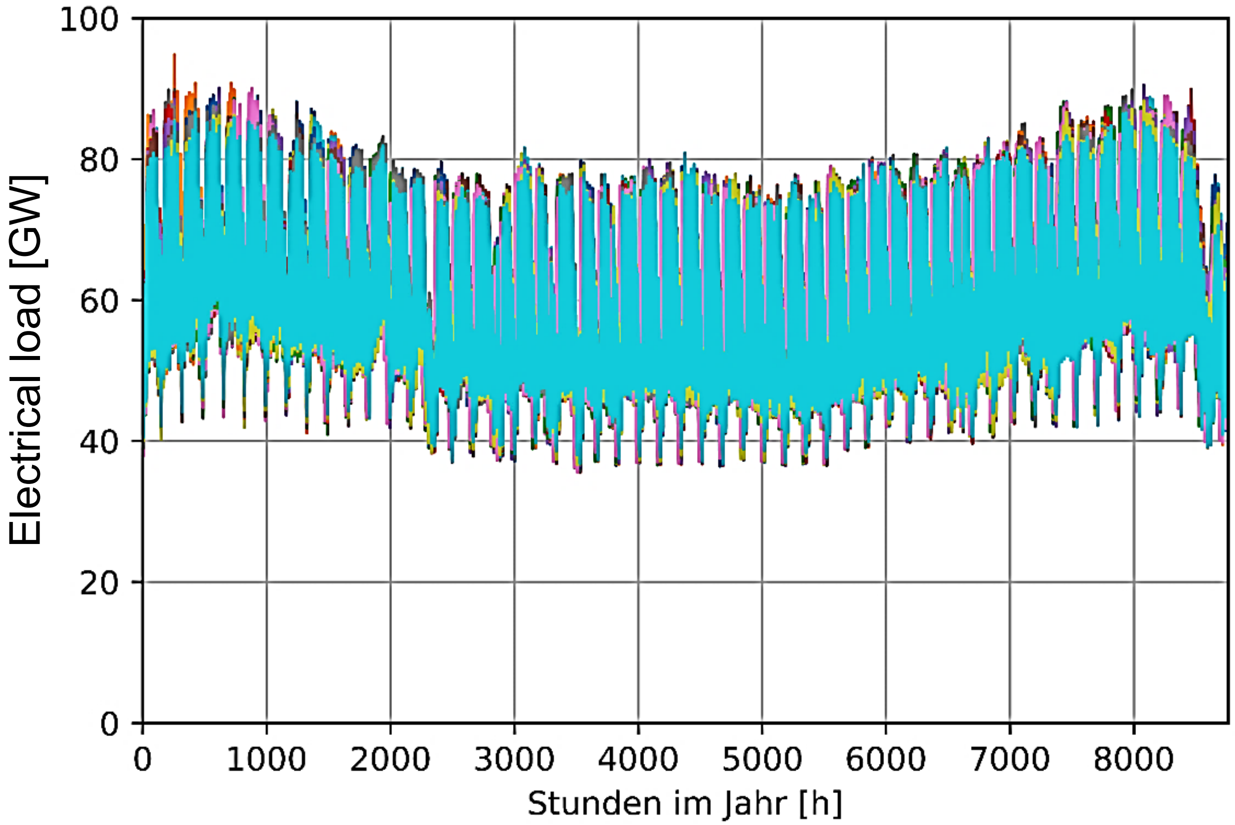
Scenario framework for the calendar year 2023: Weather influences

- Illustration of 30 weather years
- Influence of weather years on electrical load, RES-E generation, as well as import potentials



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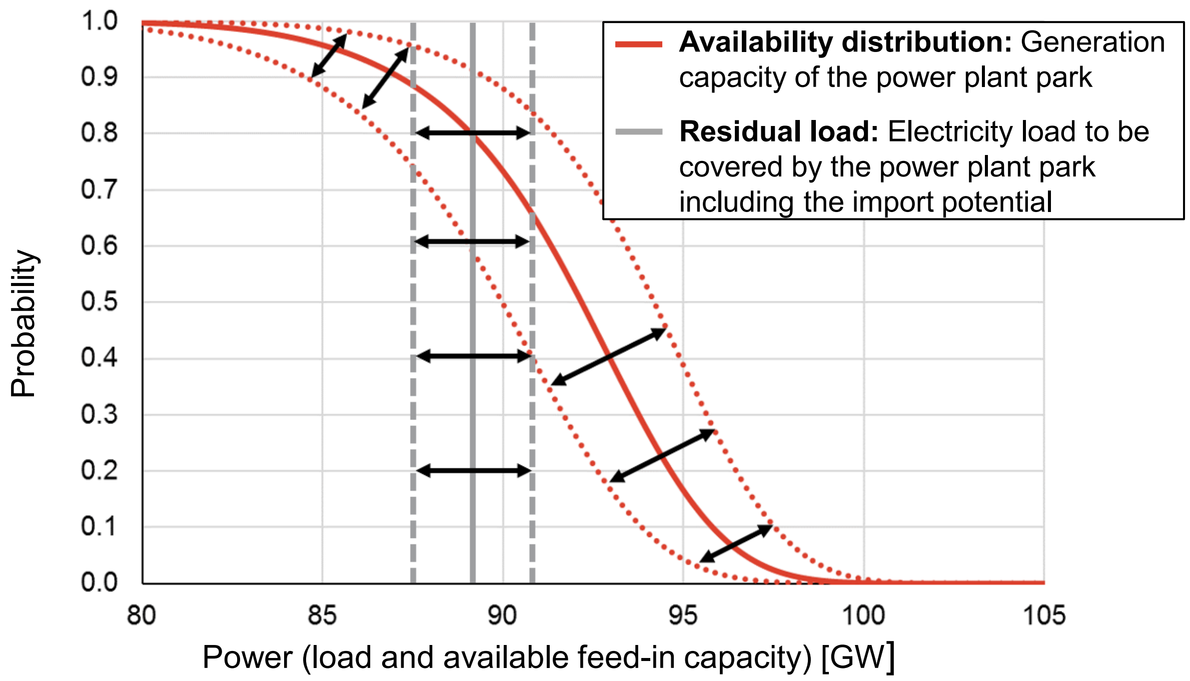
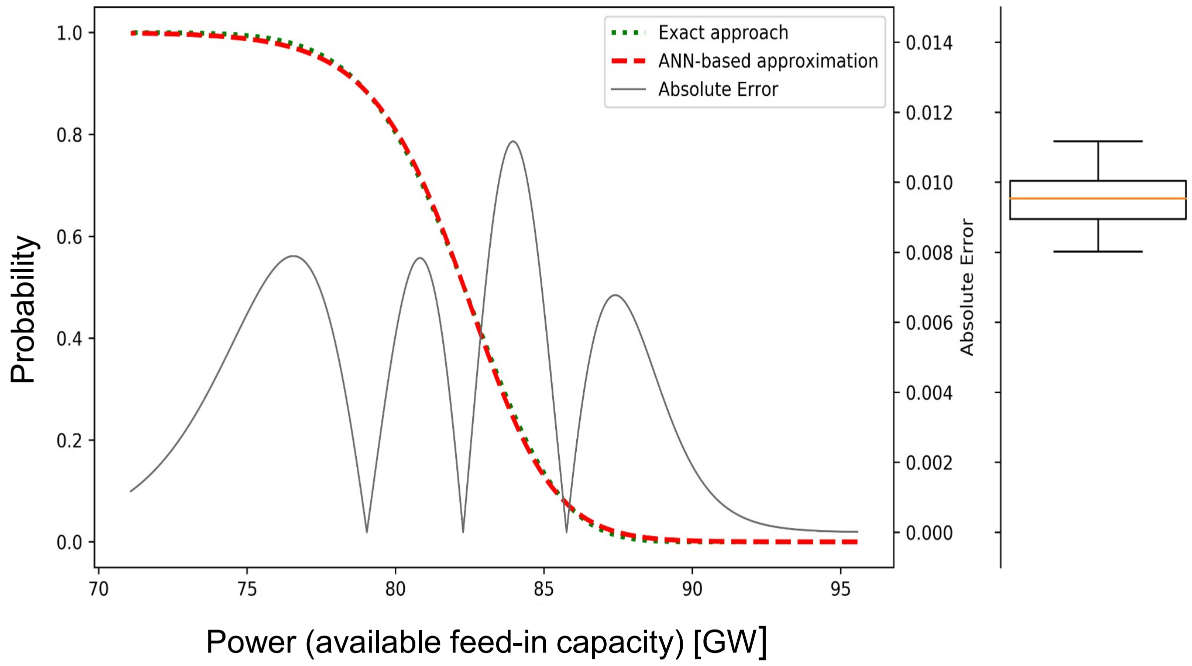
First approach of meta-modeling

Approximation of the convolution curve of the probabilistic simulation model via sigmoid function





- **Metamodel based on artificial neuronal network (ANN) shows** very good results with **deviations from** the convolution curve of ~**1 %** mean square error
- **ANNs can help to reduce computation time** and avoid model complexity, **per scenario year from originally ~8.5 h to now ~1.5 min (i.e. – 99.7 %)**
- ANNs do not replace adapted (linear) metamodels. "Tailor-made" approach for **convolution models** is needed

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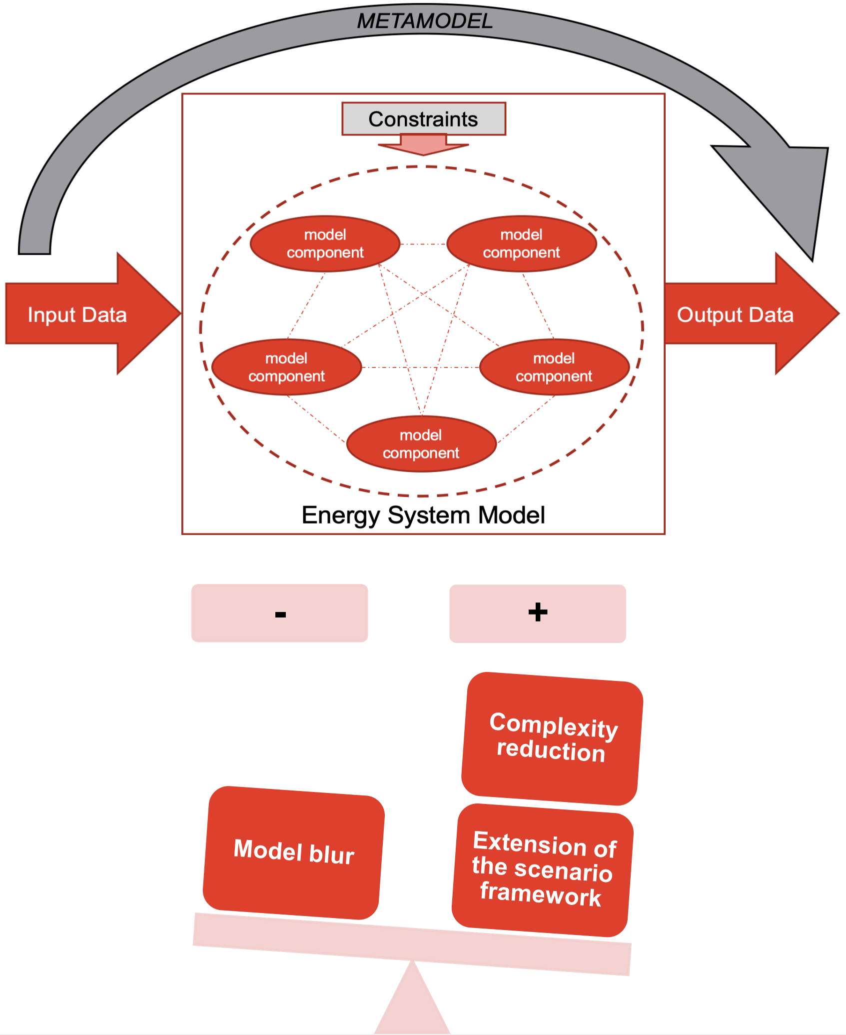
Second approach of meta-modelling

Direct prediction of key figures of security of supply

Input data

- Conventional Power plant park (controllable)
- Renewable Power plant park (conditionally controllable)
- Import potential from neighbouring countries
- Electrical load (*net electricity demand*)
- Sector coupling EV, heat pumps



Output data

Loss of Load Probability (LoLP)
(Probability that the load cannot be met in one hour)

$$\boldsymbol{LoLP(t)} = 1 - Pr_{Load\ coverage}(t)$$

Loss of Load Expected (LoLE)
(expected duration of the load interruption in hours)

$$LOLE = \sum_{t=1}^{t=8.760} LOLP(t) \cdot 1\frac{h}{a}$$

Expected Energy not Served (EEnS)
(Electricity demand in MWh/h or MWh/a that is not expected to be met)

$$\boldsymbol{EEnS(t)} = \int_{P=0\ GW}^{P=P_{res}(t)} (1 - Pr_{available}(t))\, dP$$

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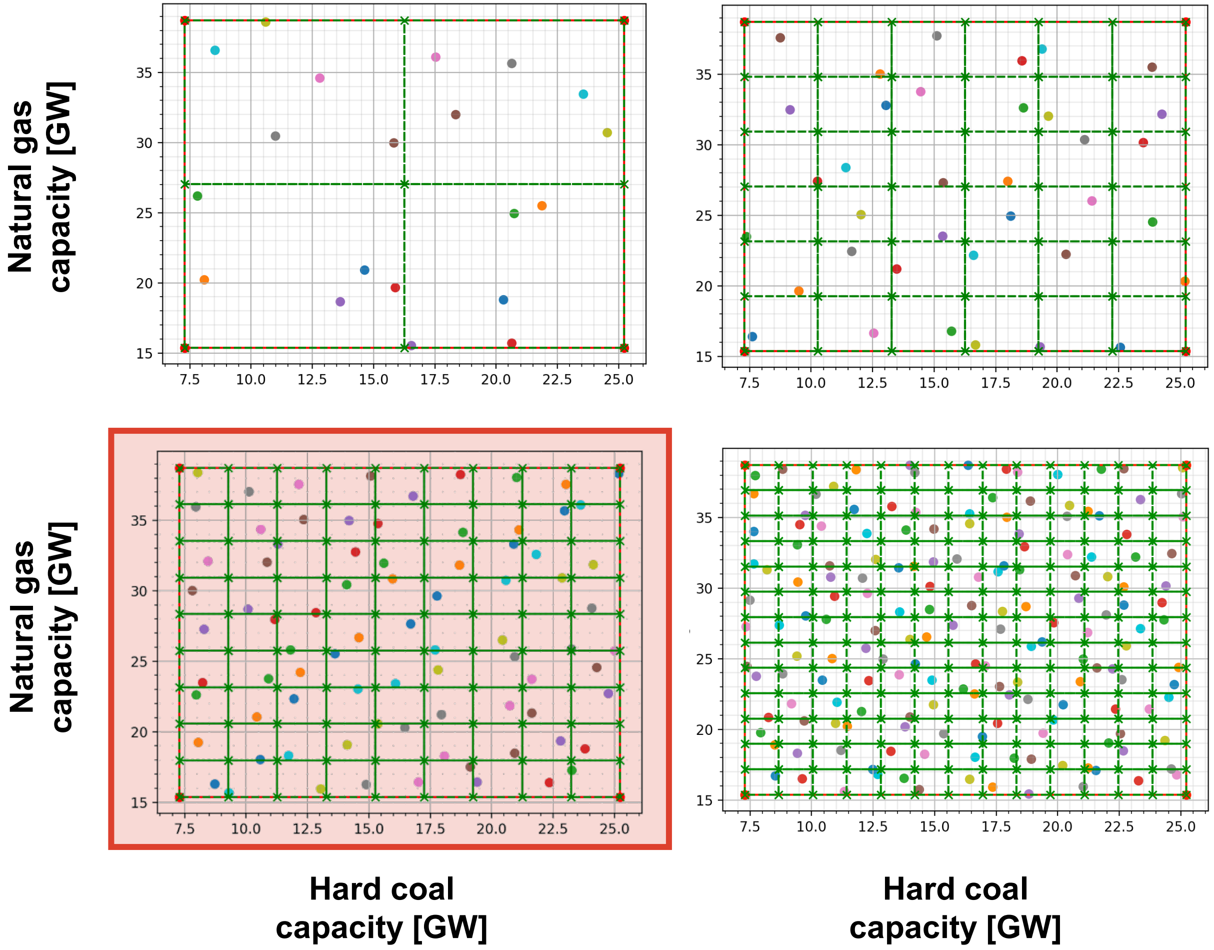
Selection of training data with the help of statistical Design of Experiments

Support points are defined for training the metamodel, that span an experimental space



+ other variations of capacities for:

- Lignite
- Oil
- Other
- ...

+ hourly Resolved weather years for:

- Electrical load
- Import potential
- Renewable feed-in
- Unavailabilities

→ A total of **~600 million** possible **trial points**

- Definition of **~20 variable input variables** for the metamodel
- From these, **~5,000 - 10,000 variants** are sampled for model training

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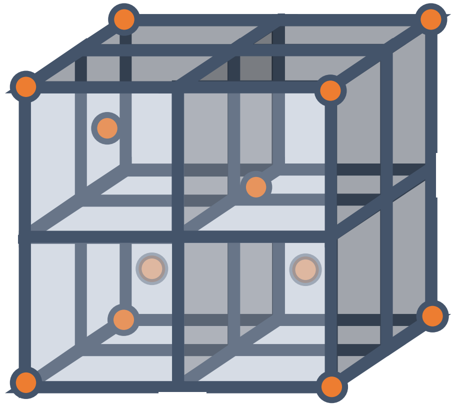
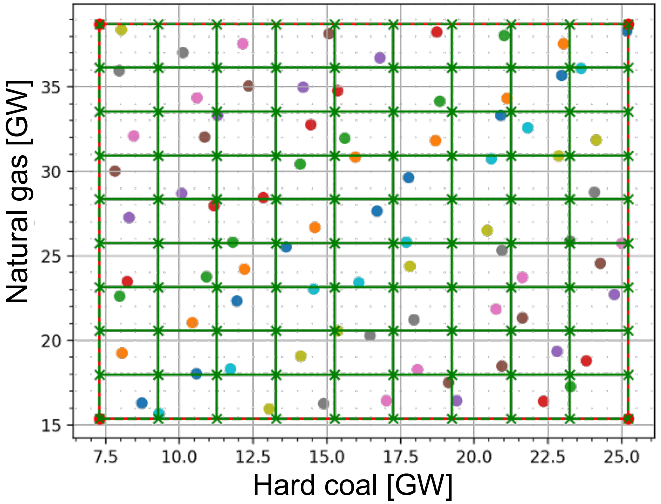
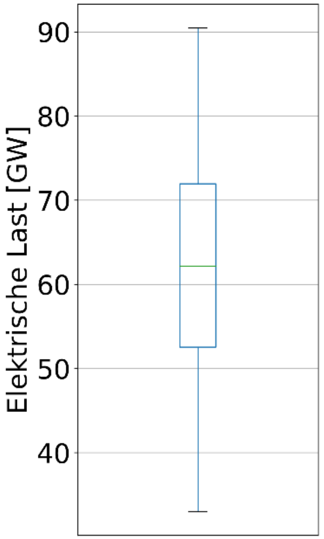
Artificial neuronal network: The experimental room

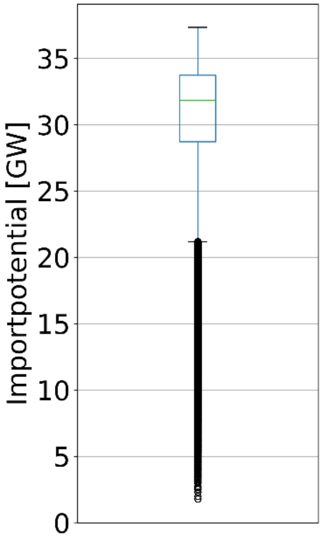


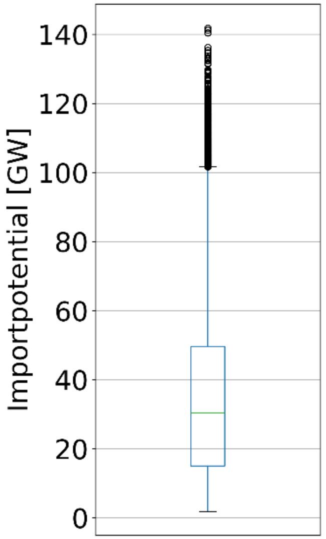


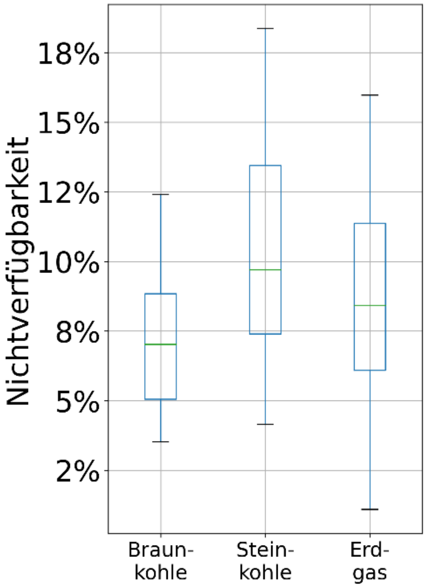
+ other variations of capacities for:

- Lignite
- Oil
- Other









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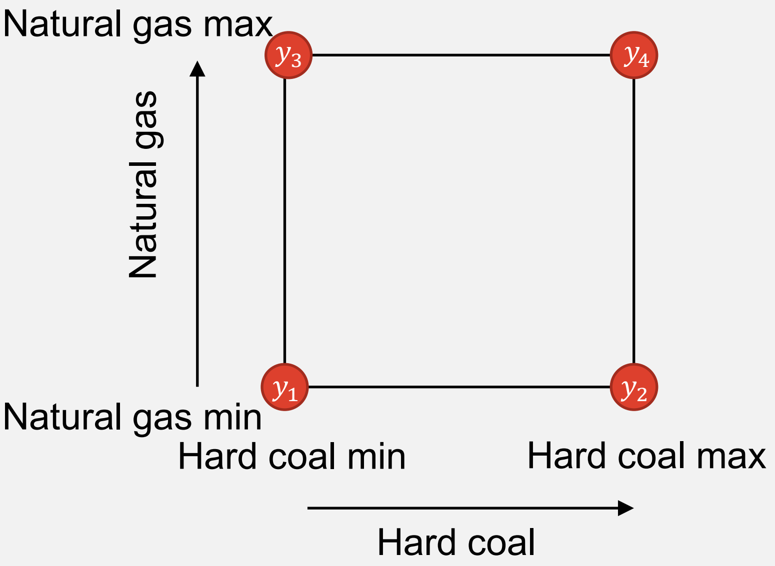
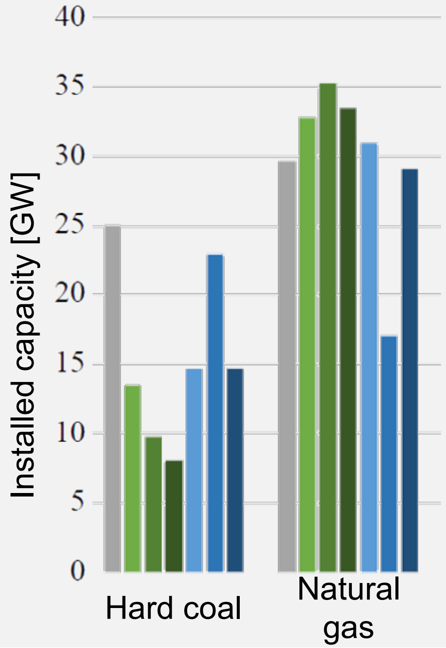
[philipp.daun; marius.tillmanns; apraktiknjo]@eonerc.rwth-aachen.de

To train the metamodel, support points are defined that span an experimental space

Capacities of the conventional power plants



Steinkohle	Erdgas	y
–	–	y_1
+	–	y_2
–	+	y_3
+	+	y_4



- Scenarios based on the **Grid Development Plan 2030** (as of 2019)
- Additional consideration of an **uncertainty band of** +/- 10%.

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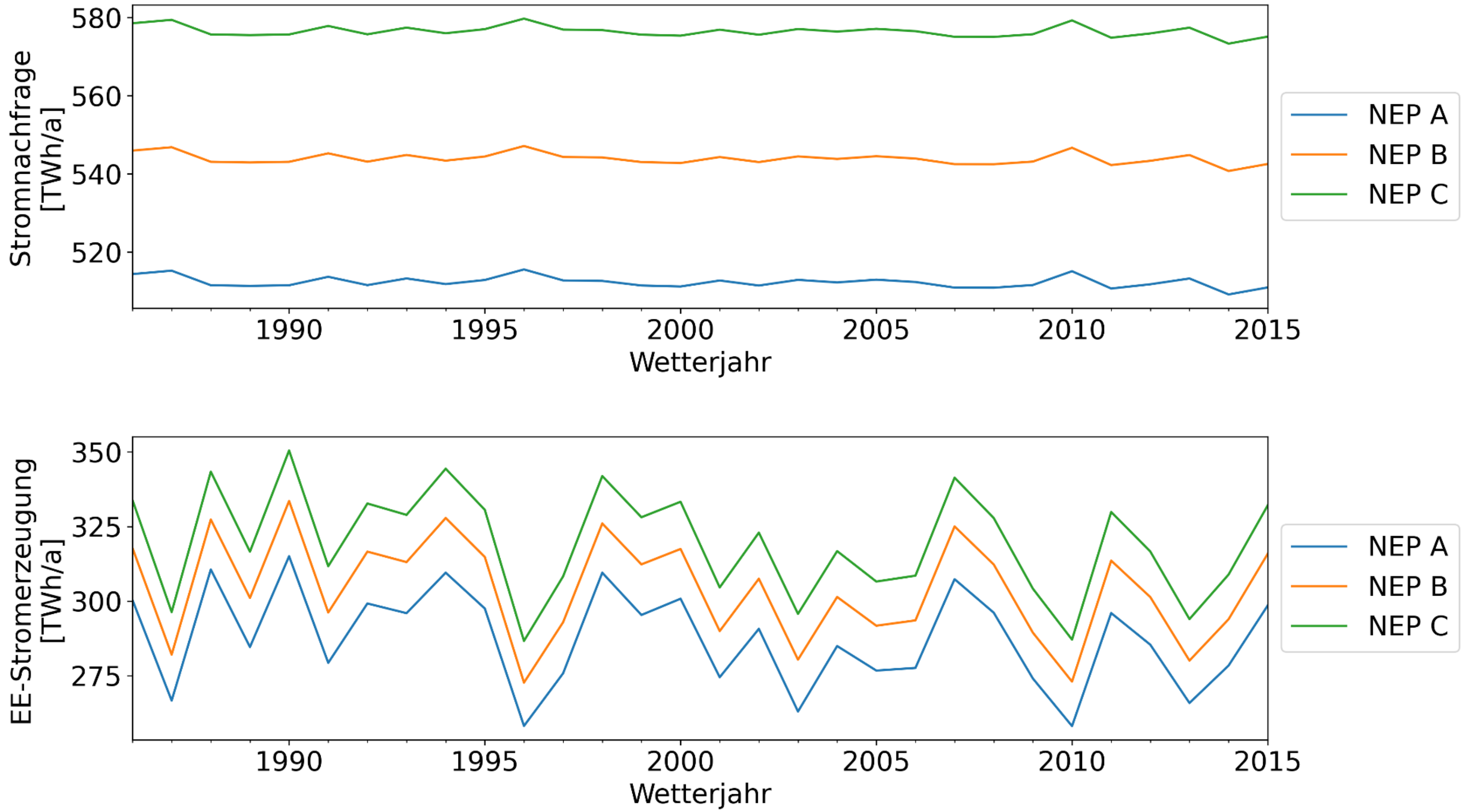
[philipp.daun; marius.tillmanns; apraktiknjo]@eonerc.rwth-aachen.de

Mapping of different scenarios for the development of electricity demand and the expansion of renewable energies



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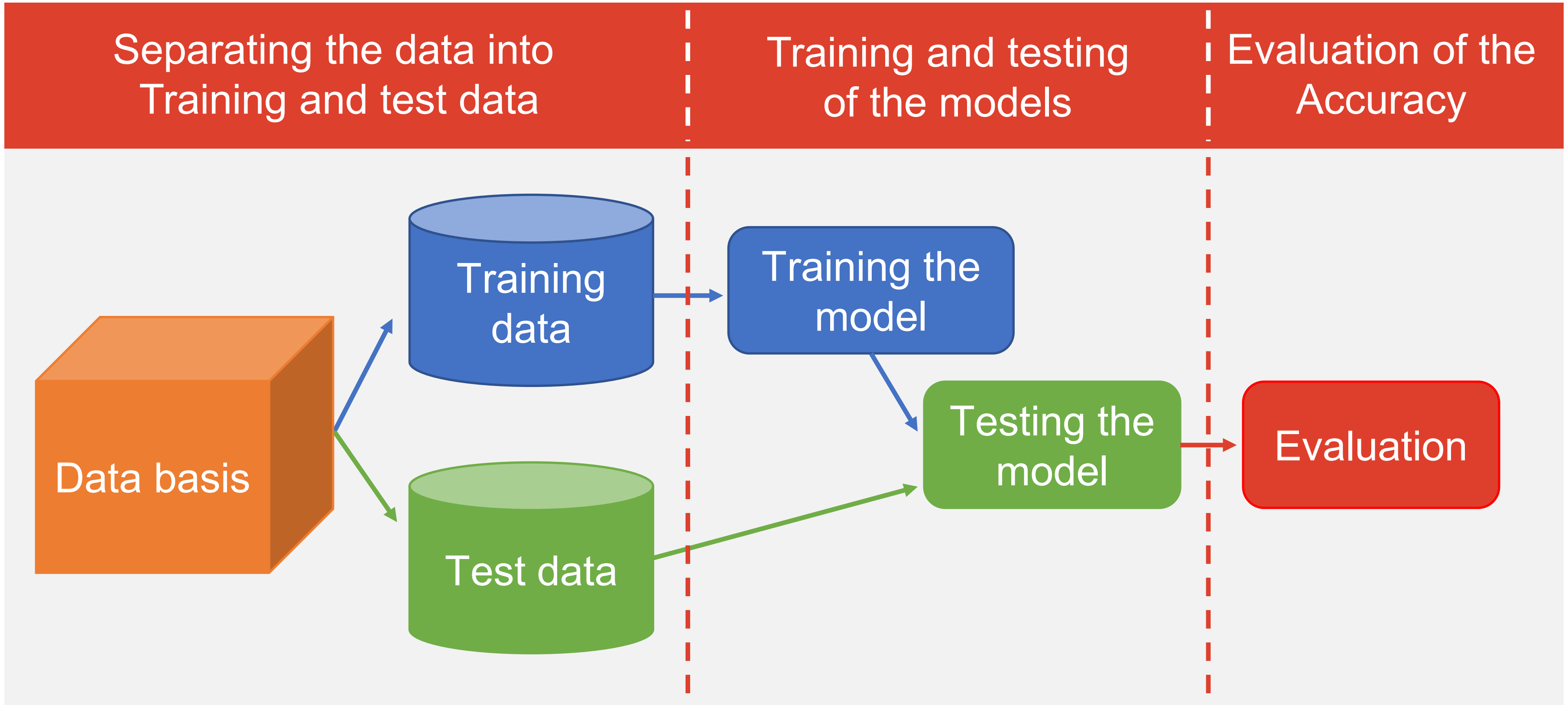
Procedure for training the metamodels



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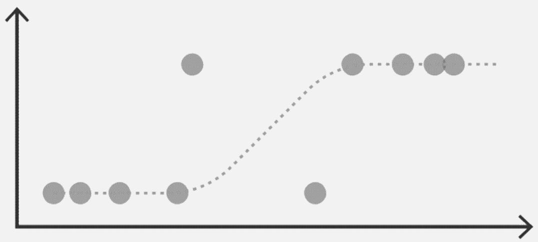
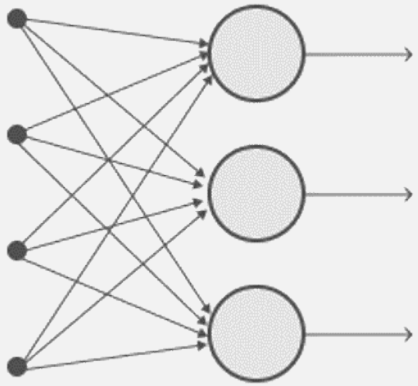
Testing different types of metamodels

Logistic regression (Logit)



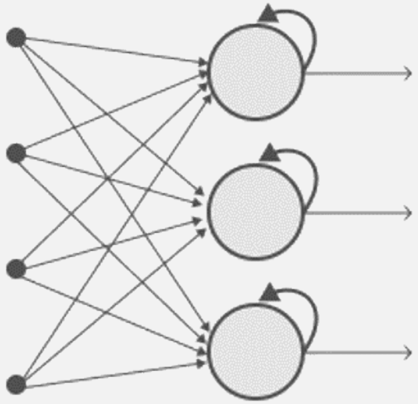
+ Low training duration
– Little possibility for modification

Feed-Forward Neural Network



+ Diverse possibility for modification
– Average training duration
– Black box model

Long Short-Term Memory Neural Network



+ Diverse possibility for modification
– High training duration
– Black box model

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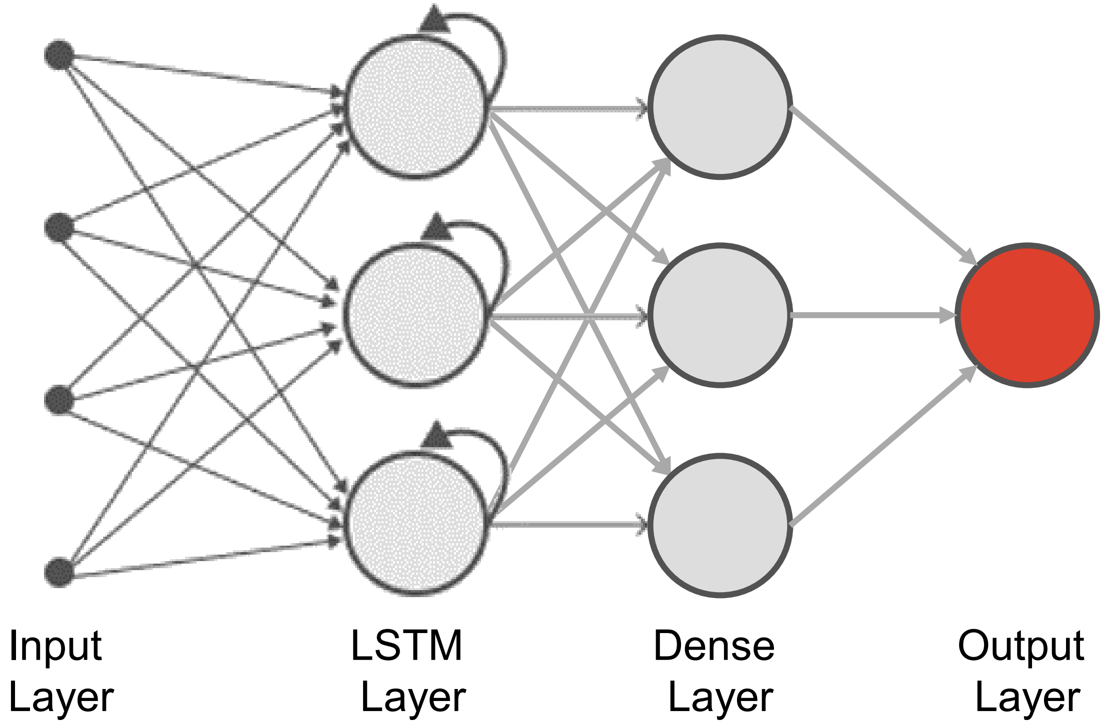
The metamodel: Long Short-Term Memory (LSTM) Neural Network



Key figures:

- 4 layers: Input, LSTM, Dense and Output layers
- 3,081 Training weights
- Trained with 262,800 input-output relations

In **comparison with** other tested meta-models, the **recurrent neural network** (here LSTM) shows the **highest accuracy** in the approximation of the simulations

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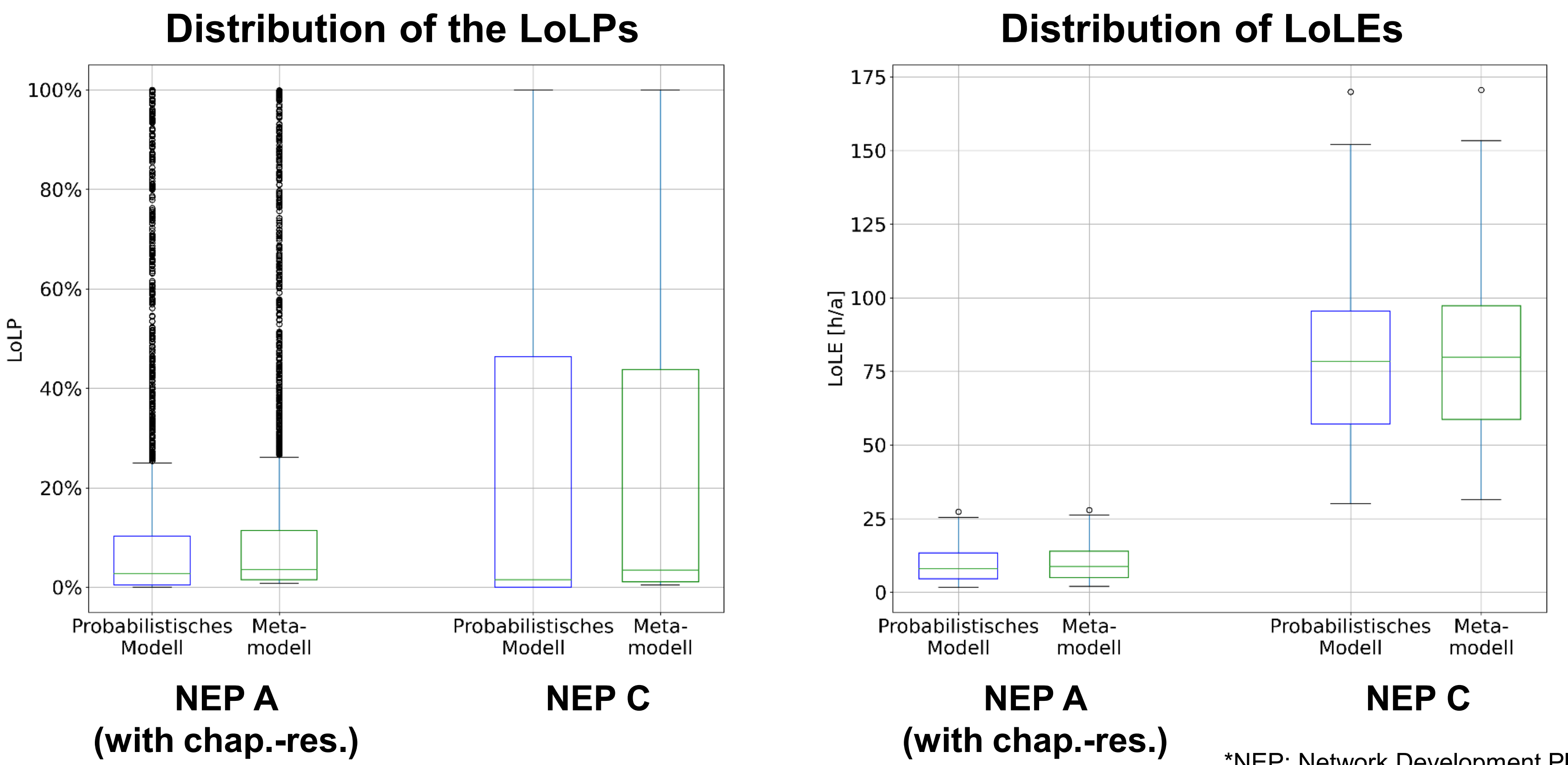
Validation of the metamodel: comparison with scenarios of the NDP*.



*NEP: Network Development Plan

Both hourly (LoLP) and aggregated annual ratios (LoLE) are approximated with **high accuracy** and **low computation time** (seconds)

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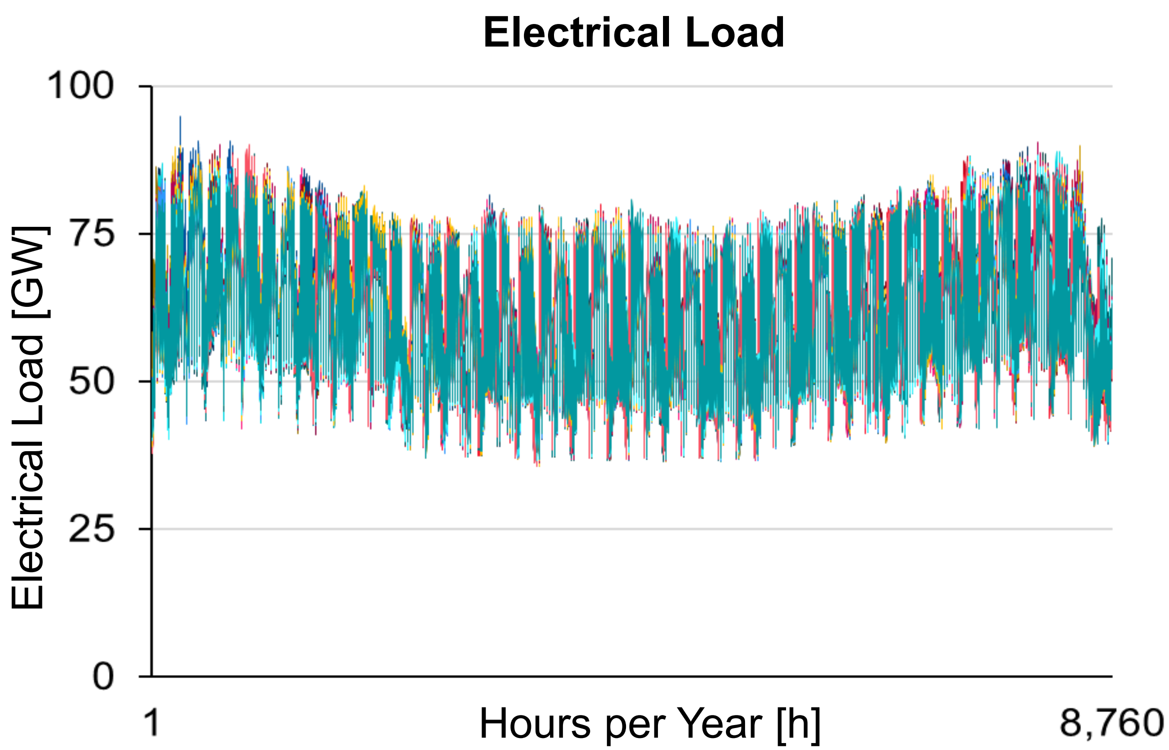
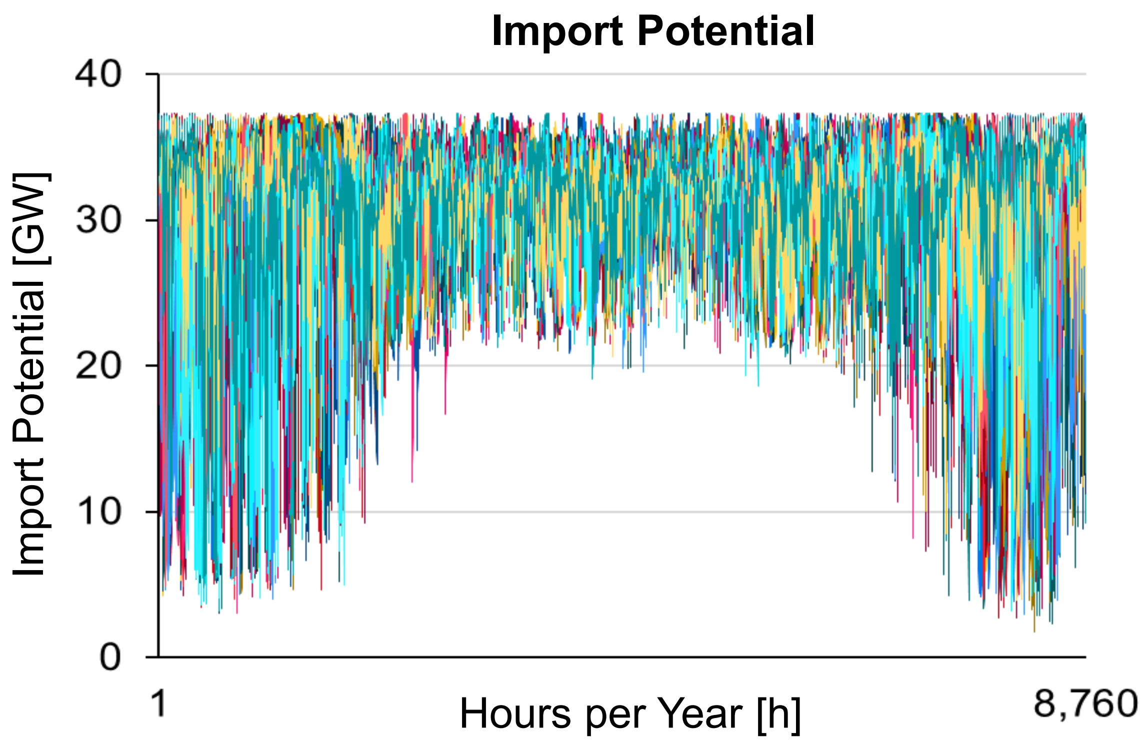
[philipp.daun; marius.tillmanns; apraktiknjo]@eonerc.rwth-aachen.de

Scenario framework for the calendar year 2023

Weather influences

- Illustration of **30 weather years**
- Influence of weather years on electrical load, renewable sources of electricity (RES-E) generation, as well as import potentials





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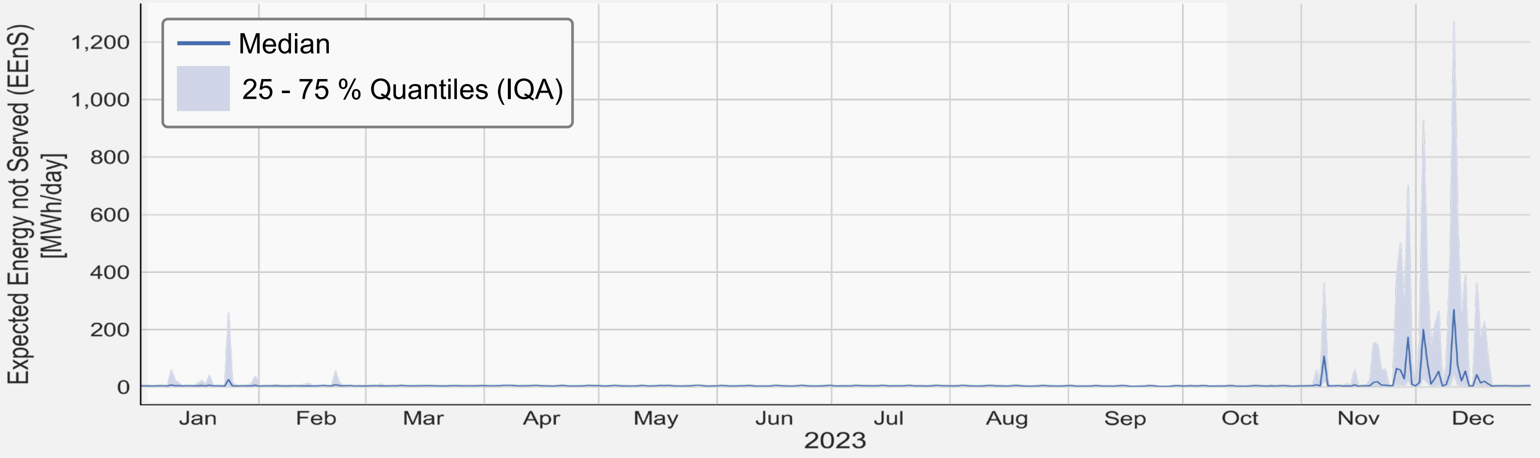
Results: Time course of the expected load shortfall

For each hour, 30.000 simulations were carried out

Variant A:
Nuclear power plant lifetime extension until 15 April 2023

Median: 11.4 GWh/a
IQA: 5.5 - 21.3 GWh/a

IQA: Interquartile range



Variant B:
Without nuclear power extension after 31 December 2022

Median: 16.1 GWh/a
IQA: 8.6 - 26.9 GWh/a

IQA: Interquartile range

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