Drivers of flexibility in a renewable energy system – correlation analysis with a sector-coupled energy system model

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enerday 2024
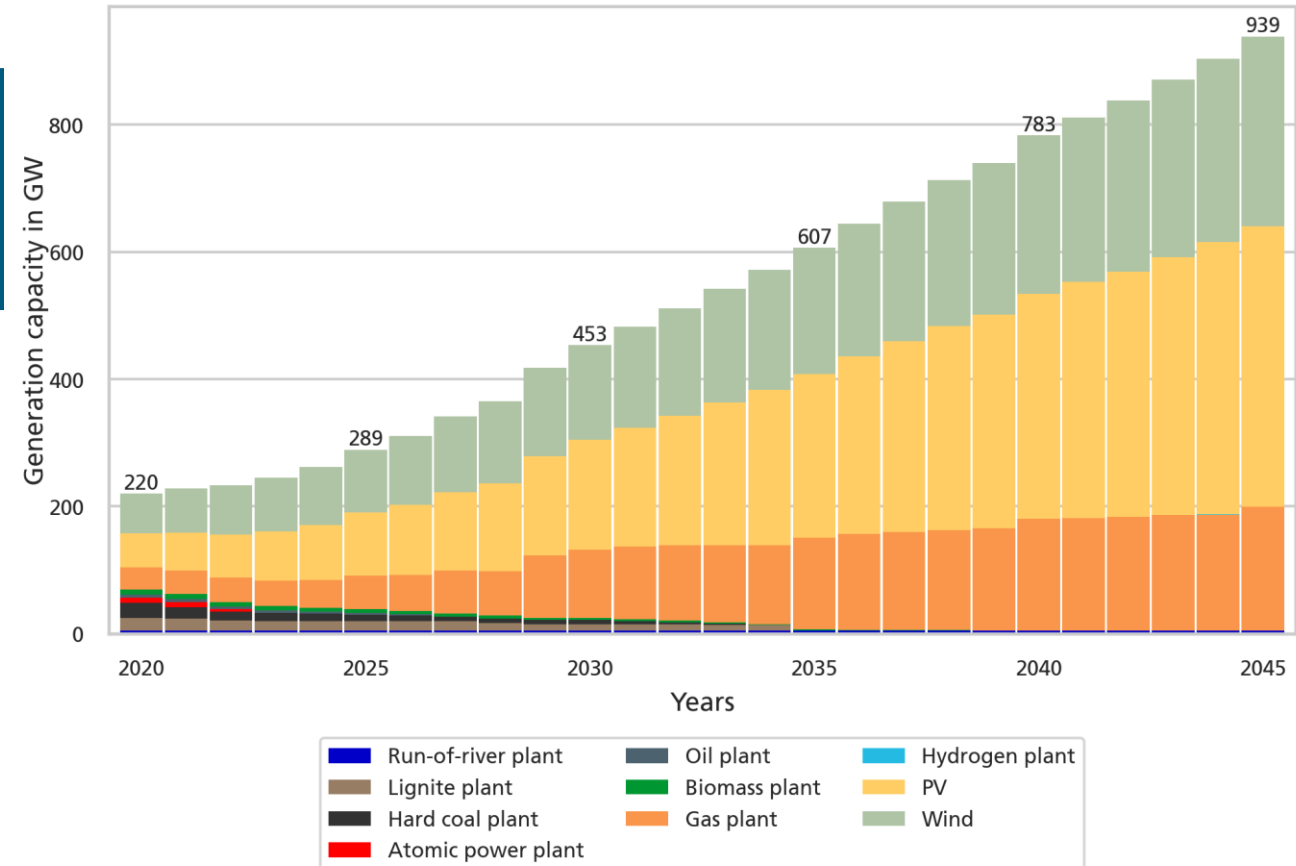**Dresden, April 12, 2024**
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Motivation
Challenges in the energy transition

> **1** **Renewable energy sources**
> Wind and PV fluctuating

Installed generation capacity of electricity

Legend:
- Run-of-river plant
- Lignite plant
- Hard coal plant
- Atomic power plant
- Oil plant
- Biomass plant
- Gas plant
- Hydrogen plant
- PV
- Wind

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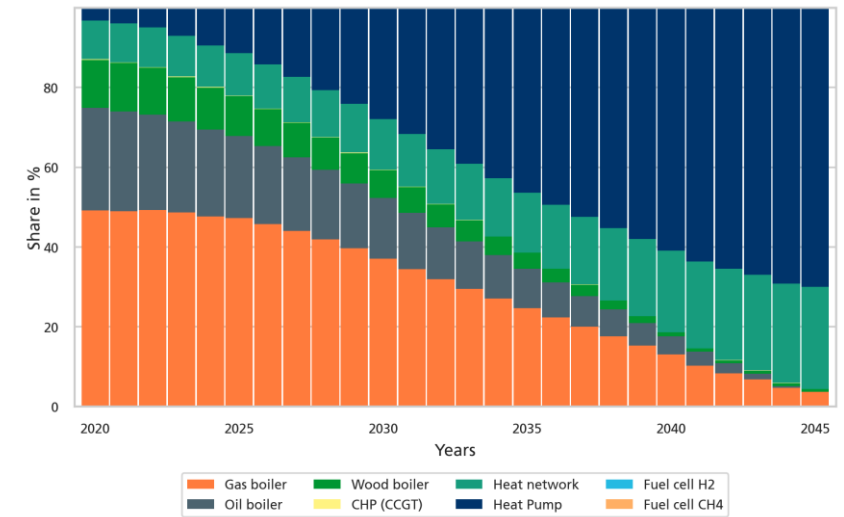# Motivation

Challenges in the energy transition

1 **Renewable energy sources**
Wind and PV fluctuating

2 **End Use Sectors**
Electrification increases sector coupling

Buildings sector
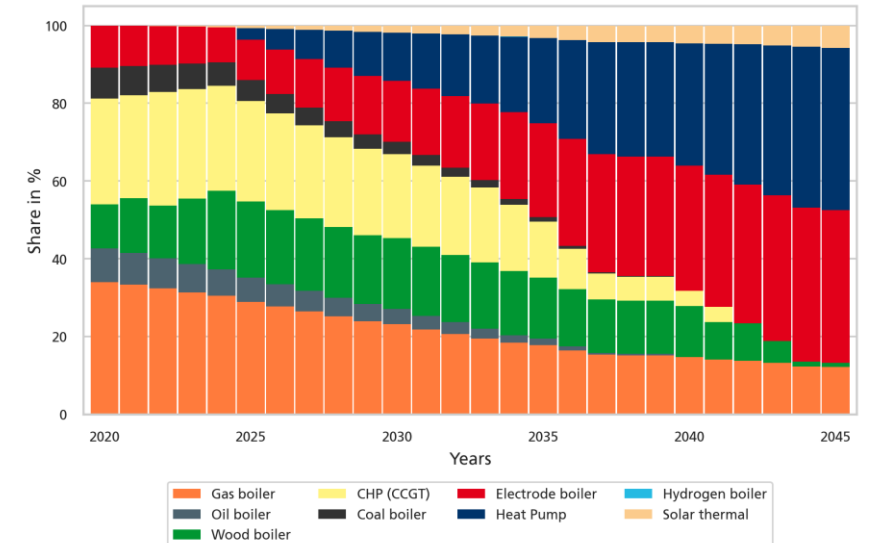
Legend: Gas boiler, Oil boiler, Wood boiler, CHP (CCGT), Heat network, Heat Pump, Fuel cell H2, Fuel cell CH4

Industrial sector

Legend: Gas boiler, Oil boiler, Wood boiler, CHP (CCGT), Coal boiler, Electrode boiler, Heat Pump, Hydrogen boiler, Solar thermal

Motivation
Challenges in the energy transition

1 **Renewable energy sources**
Wind and PV fluctuating

2 **End Use Sectors**
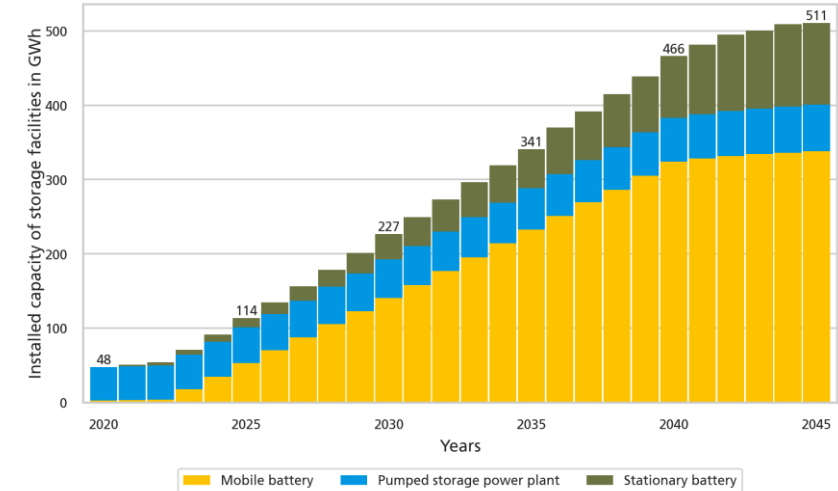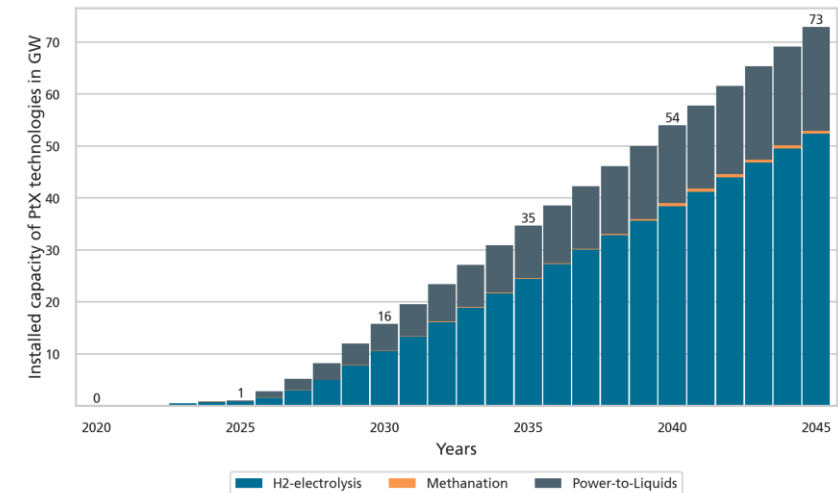Electrification increases sector coupling

3 **Flexibility**
Demand and Supply need to be balanced

Storages

Installed capacity of storage facilities in GWh — Mobile battery, Pumped storage power plant, Stationary battery

Power-to-X

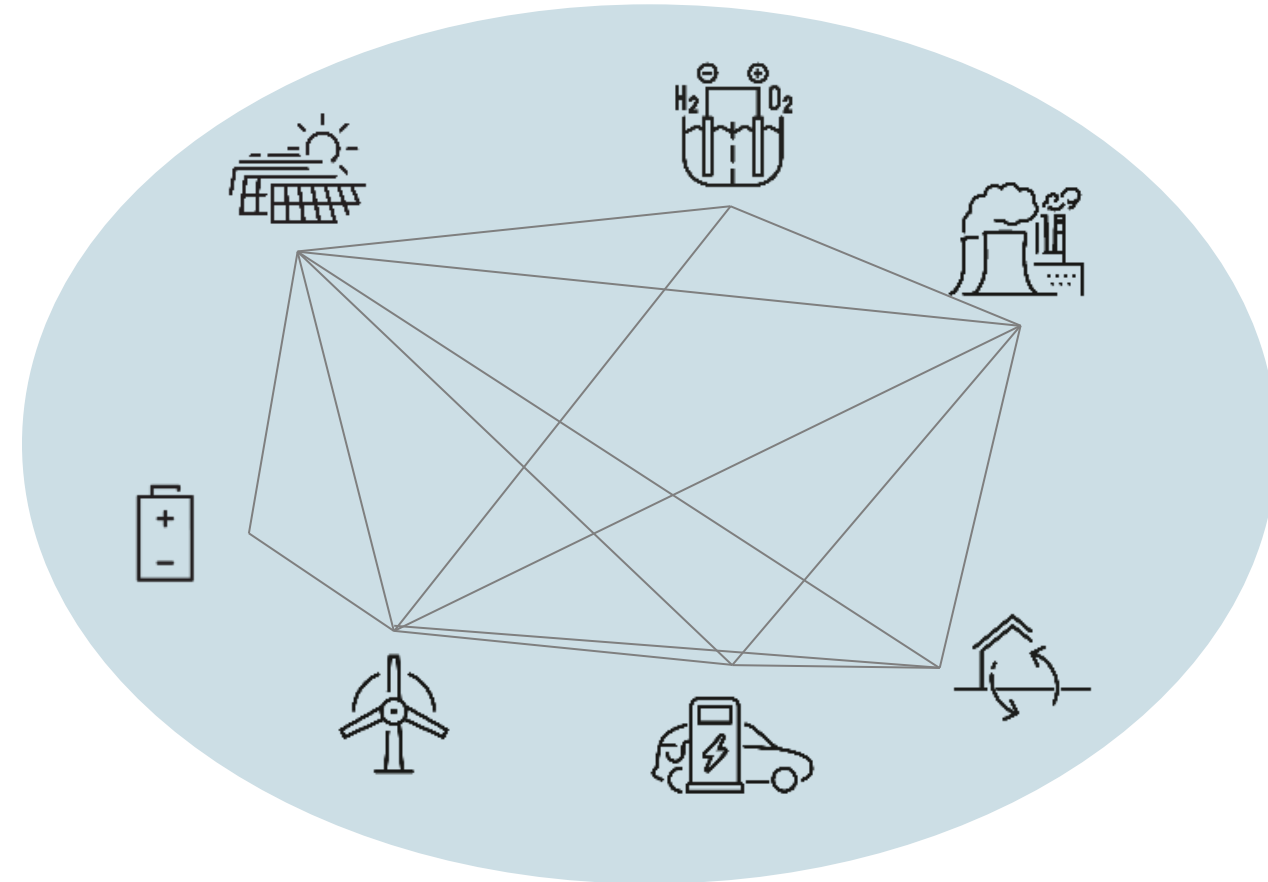Installed capacity of PtX technologies in GW — H2-electrolysis, Methanation, Power-to-Liquids

Research Questions

> **1**   **Which flexibility options can provide the needed flexibility in a renewable energy system?**

Research Questions

1 ▶ **Which flexibility options can provide the needed flexibility in a renewable energy system?**

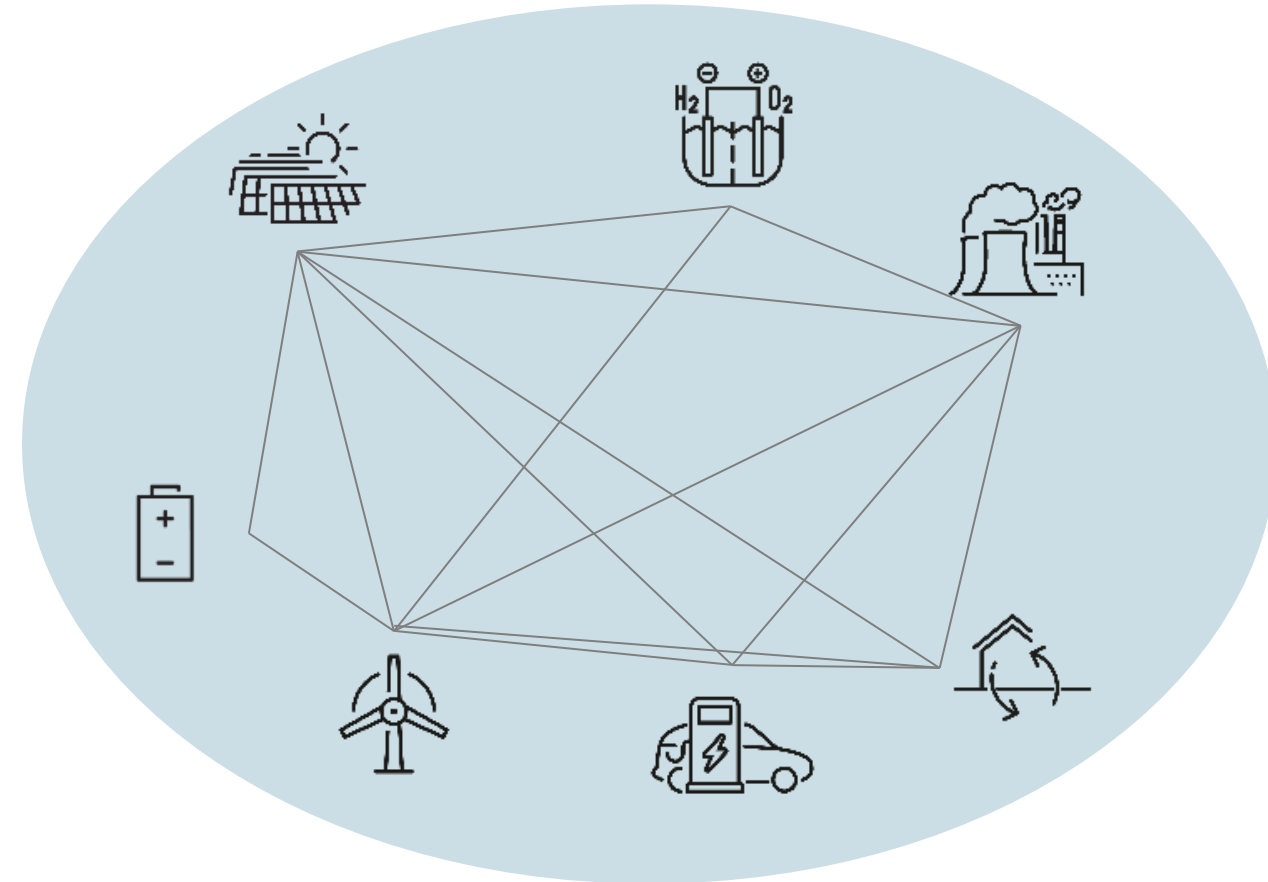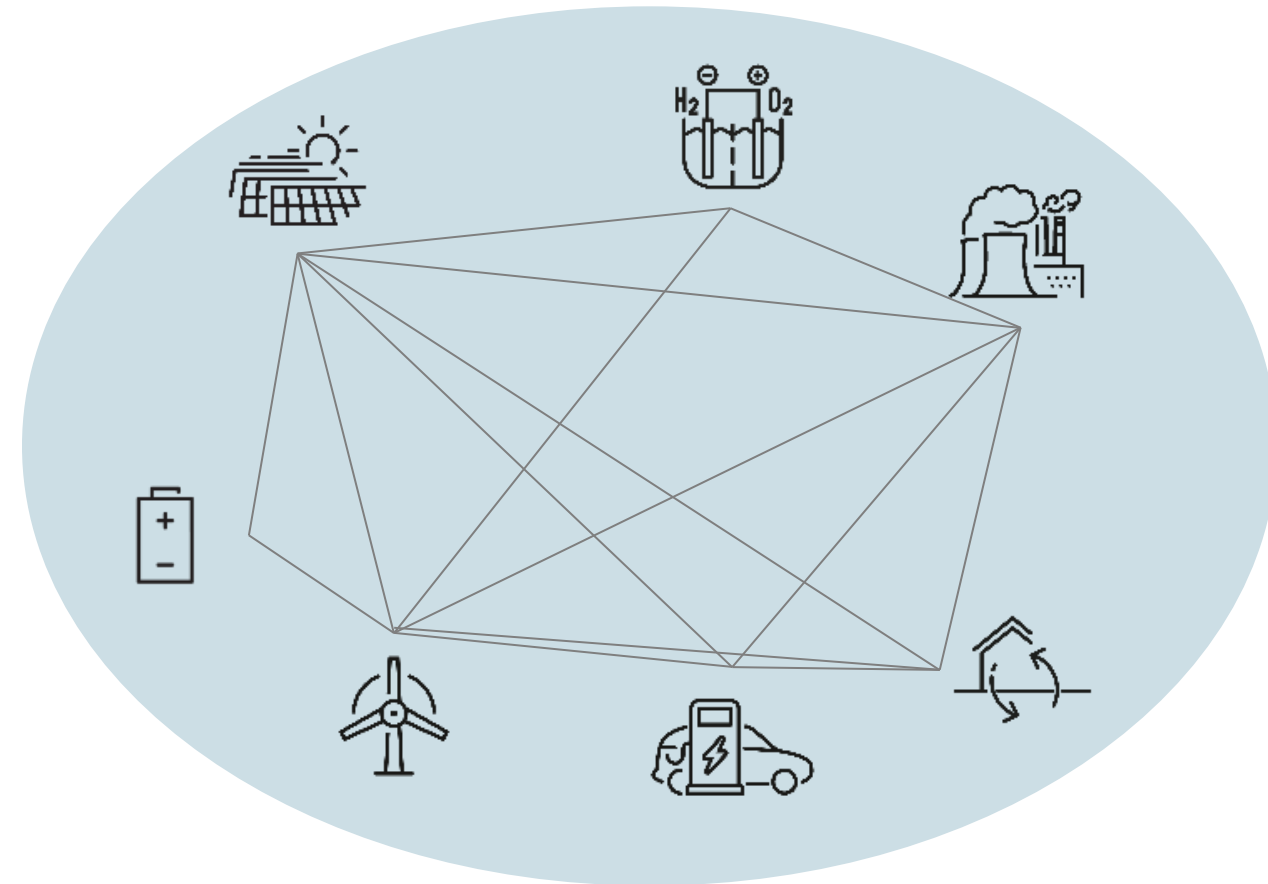**2** ▶ **When and how much are they operated?**

Research Questions

1 ▶ **Which flexibility options can provide the needed flexibility in a renewable energy system?**

2 ▶ **When and how much are they operated?**

3 ▶ **What drives their operation?**

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The energy system model REMod
Modeling approach and scope

Geographical scope
- Germany as one node

Conversion and consumption sectors
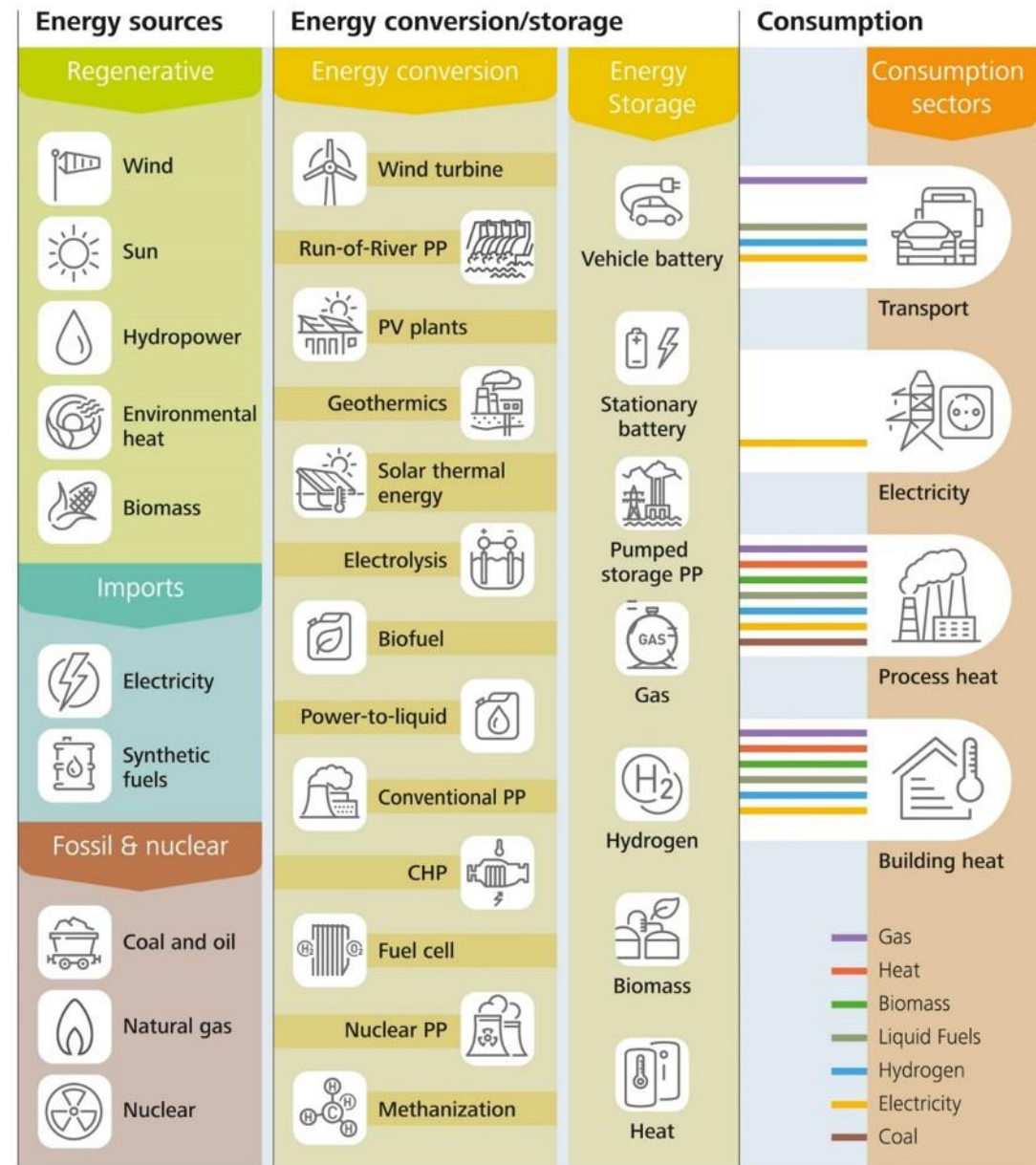- Inclusion of all consumption sectors
- Multiple technologies are optimized separately
- Detailed integration of sector coupling effects

Optimization
- Minimization of transformation costs
- Non-linear „Black box" optimization of transformation path on yearly basis

Simulation
- Simulation of operation on hourly basis
- Including historic timeseries (demand, weather) of five years

The energy system model REMod
Simulation and Optimization

Energy Model REMod
- Simulation of Operation
- Total system costs (CAPEX + OPEX + penalty terms) calculated

Transformation path given

System costs returned

Evolutionary Optimizer (CMA-ES)
- Sampling of different transformation paths
- Algorithm leads to lowest system costs

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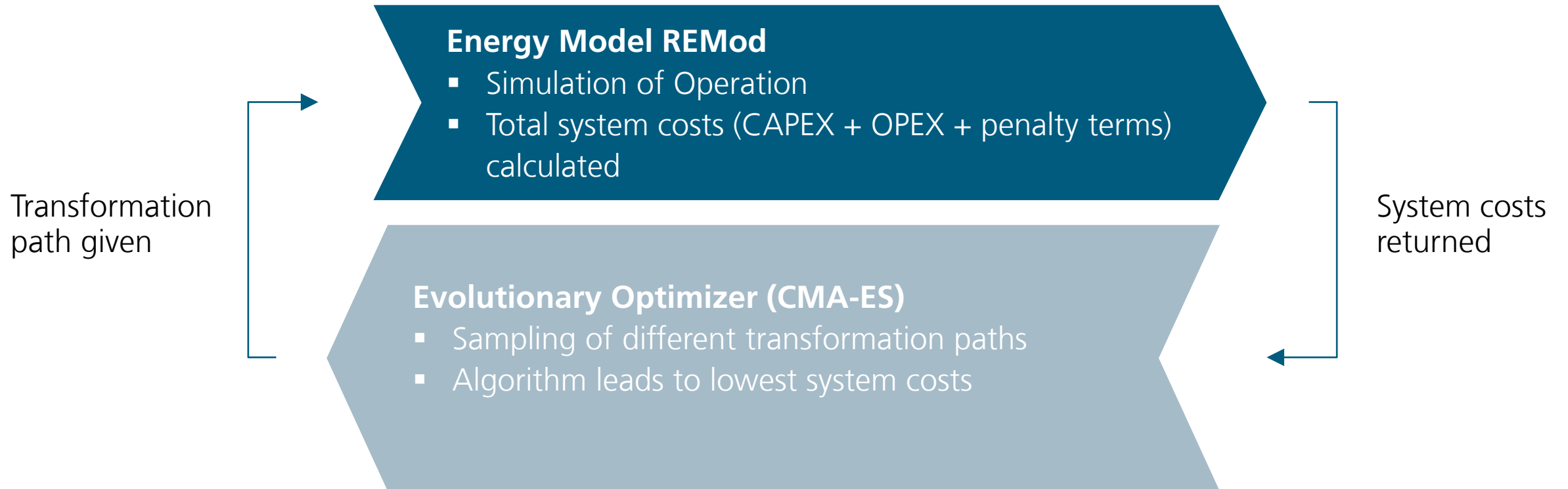
Simulation
Based on a merit order

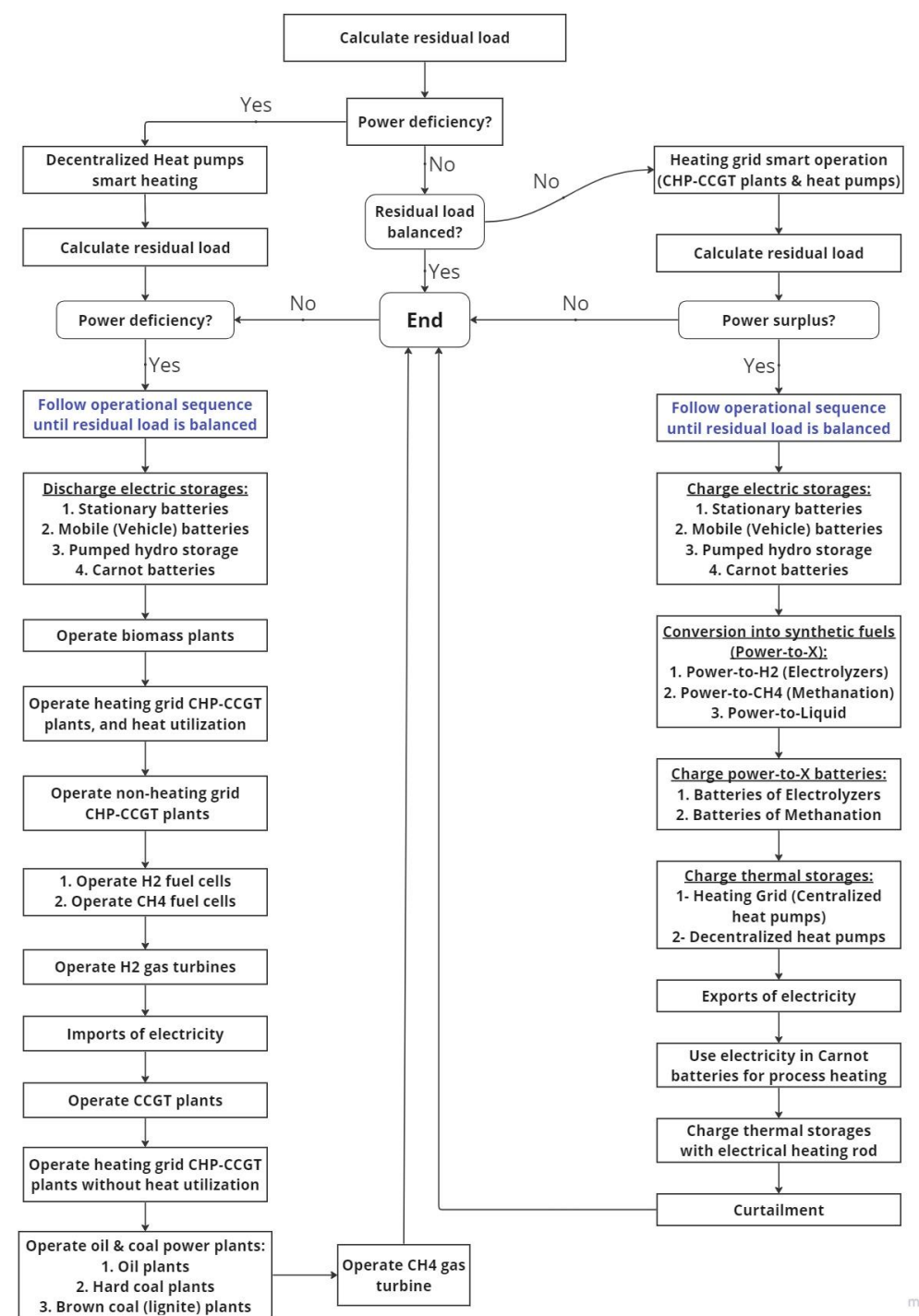**Operational sequence**

Similar to merit order

Minimises costs and emissions, maximises efficiency

→ Not optimized, but fixed during optimization!

Residual load

Difference between inflexible demand and supply

Times of electricity surplus increase

→ Surplus dominates in 2045

Extrema (both positive and negative) increase

Residual Load Yearly Duration Curve - Ariadne-Balanced Scenario
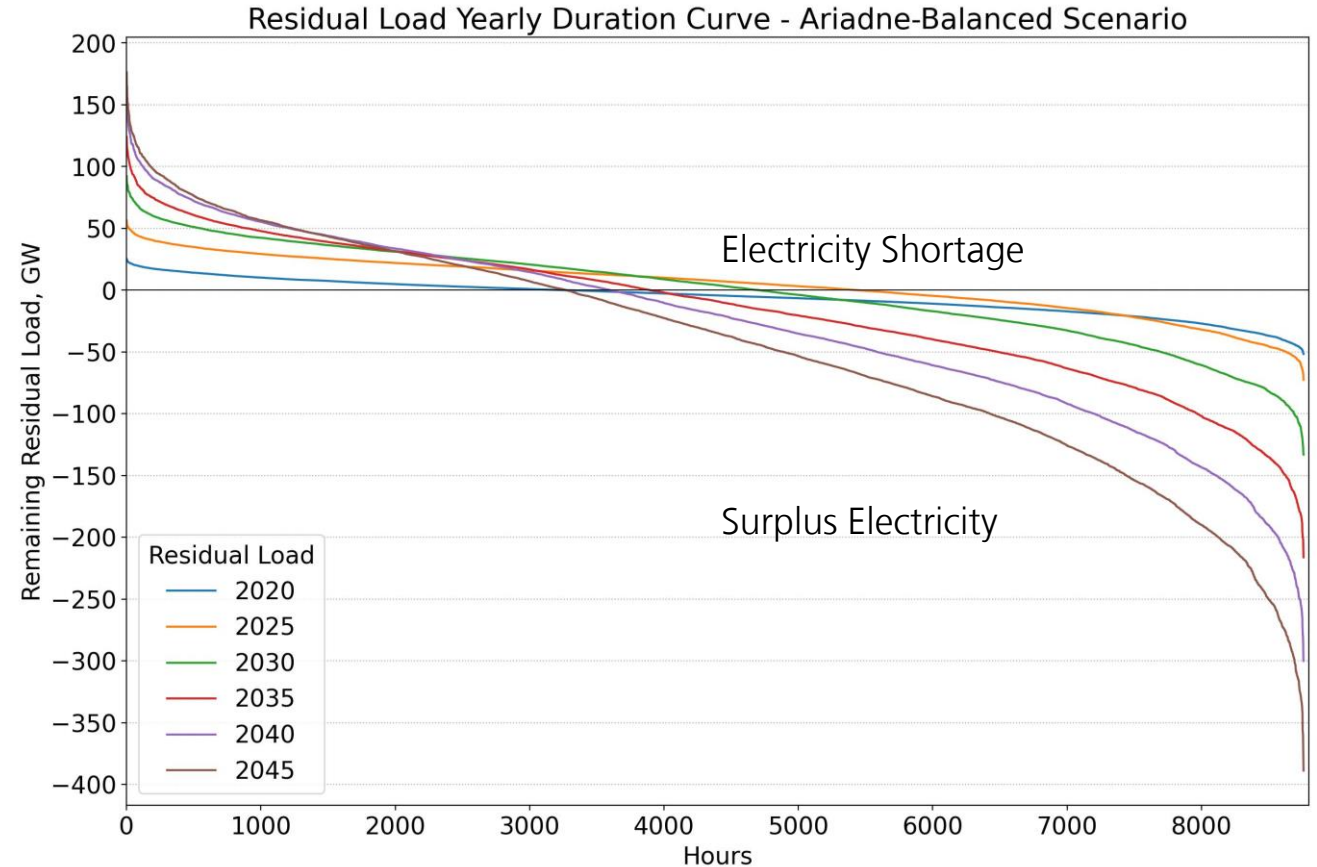
Flexibility provision
In times of excess electricity

Power-to-X (hydrogen, methane, liquids) dominant

Power-to-Heat stronger in winter

Storages, Exports & Curtailment stronger in summer
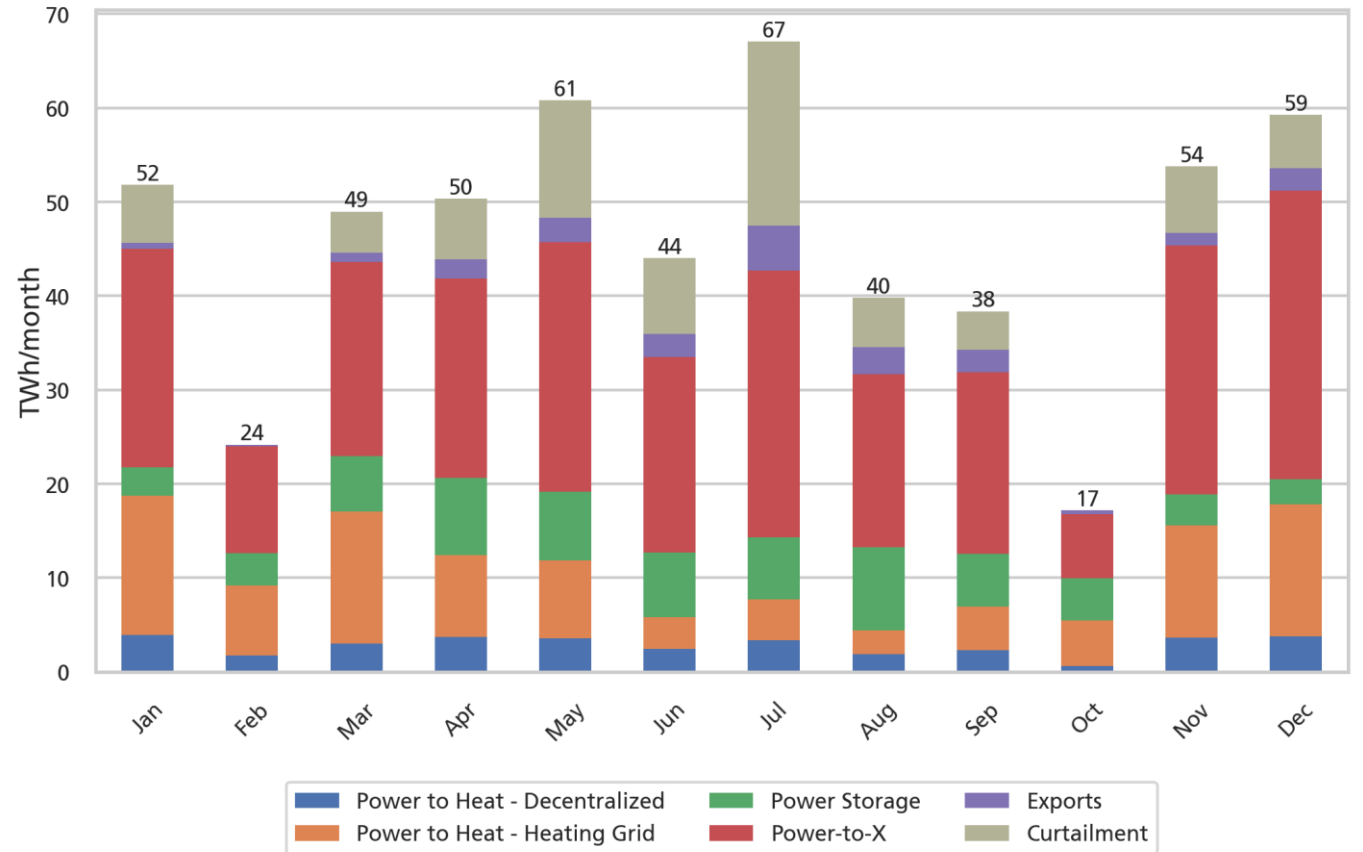
Flexibility provision
In times of electricity shortage

Storages in summer

Flexible power plants & imports in winter
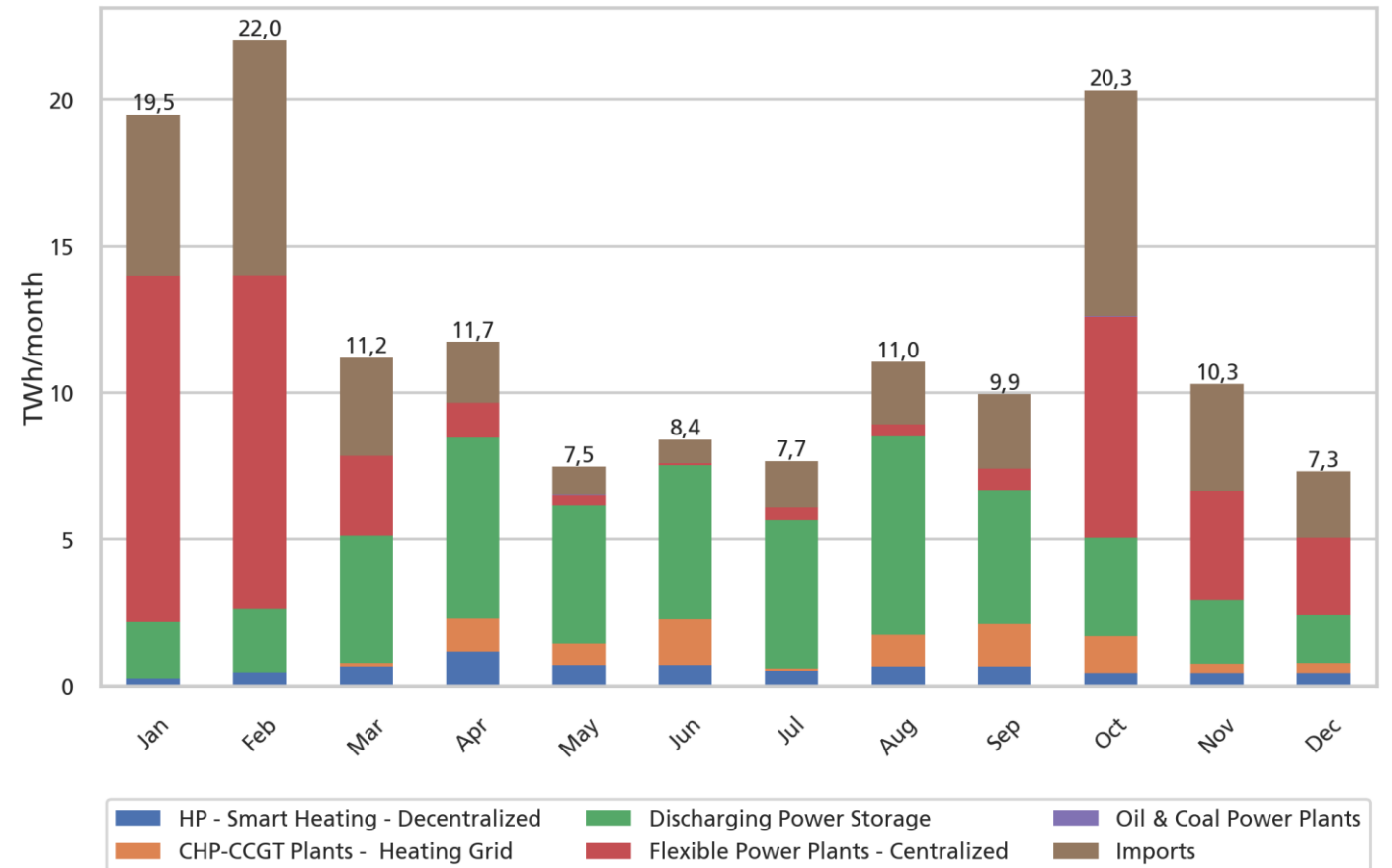
Hourly profiles of selected inflexible and flexible system components

inflexible
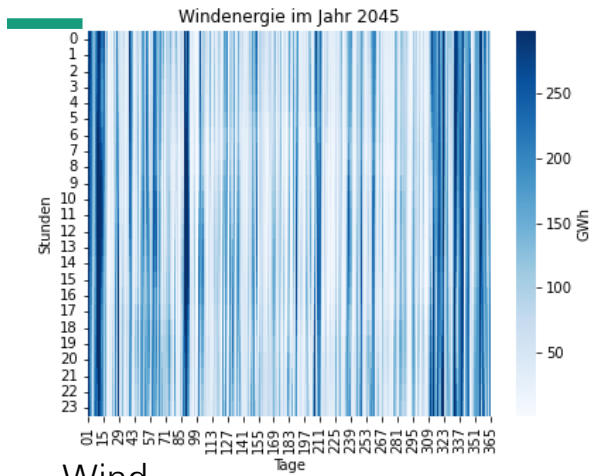
Wind
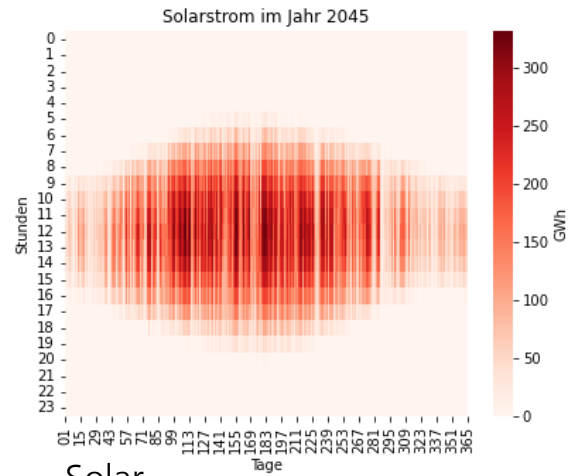
Solar
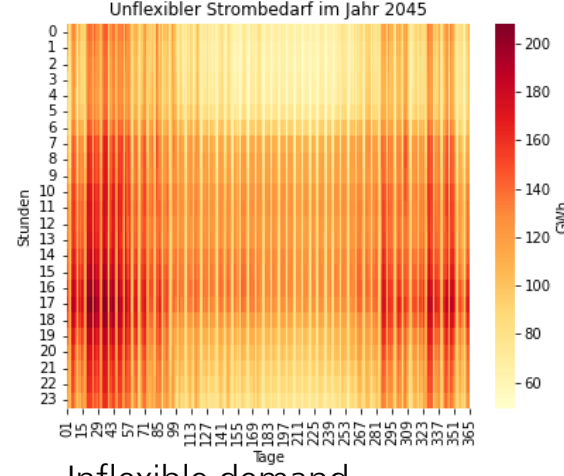
Inflexible demand
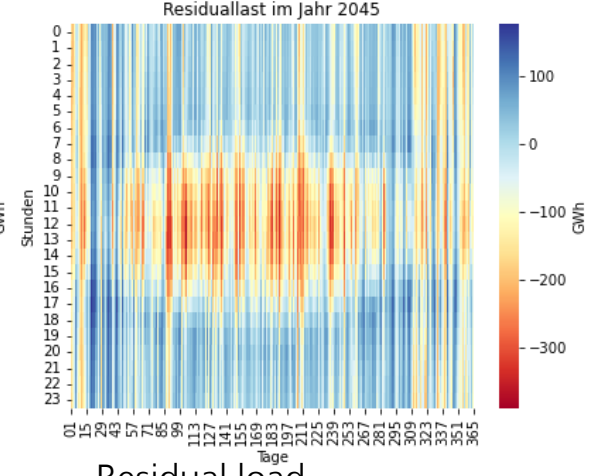
Residual load

flexible

Vehicles (V2G & G2V)

Electrolysers

Im-/Exports

Gas turbines (backup)

Drivers of Flexibility
Correlation analysis

What are the drivers for specific flexibility options?

Interplay between
- Solar production
- Wind production
- Inflexible demand

Stationary Batteries

Electrolyzers

Gas turbines

Drivers: flexible supply

Linear correlation (Pearson)

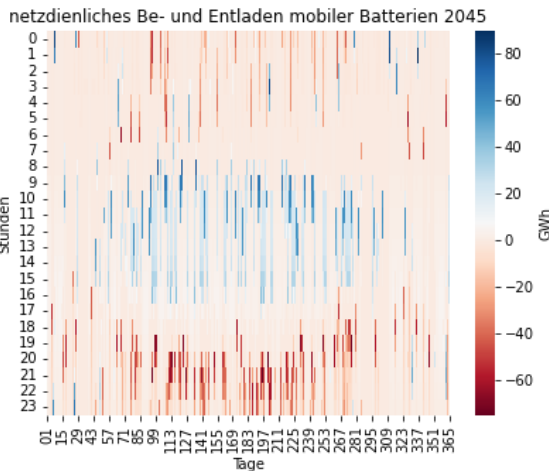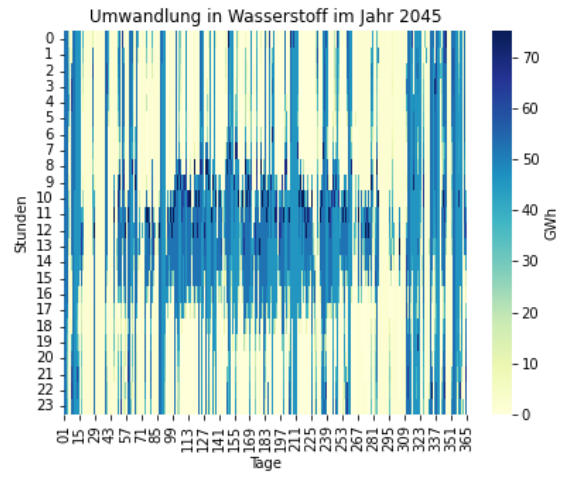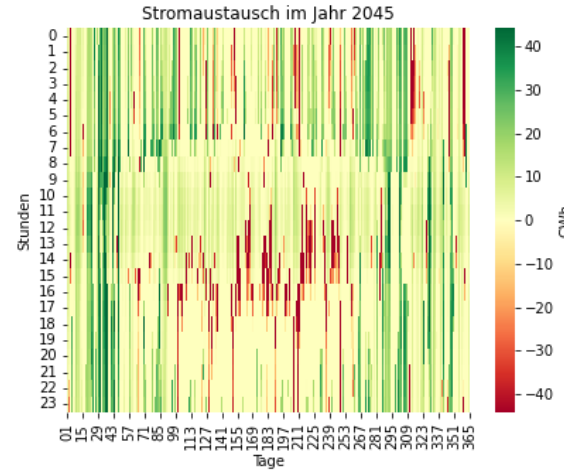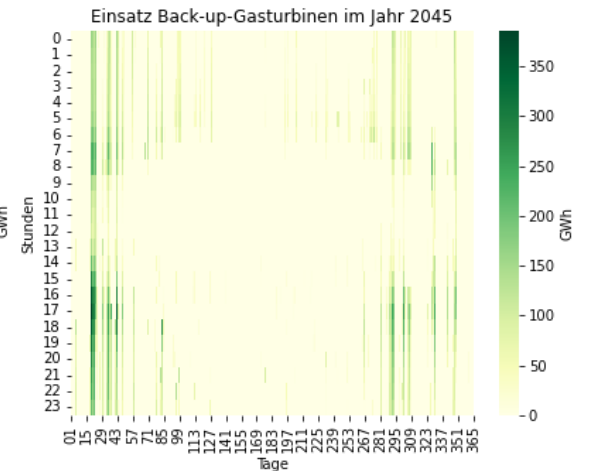|	PV	Wind	Non-Flexible Demand	HP - Smart Heating - Decentralized	CHP-CCGT Plants - Heating Grid	Discharging Power Storage	Flexible Power Plants - Non Heating Grid	Imports
PV	1							
Wind	-0.15	1						
Non-Flexible Demand	0.16	0.055	1					
HP - Smart Heating - Decentralized	-0.15	-0.14	-0.065	1				
CHP-CCGT Plants - Heating Grid	-0.12	-0.23	-0.12	0.029	1			
Discharging Power Storage	-0.21	-0.28	-0.047	0.28	0.055	1		
Flexible Power Plants - Non Heating Grid	-0.2	-0.31	0.34	-0.057	0.07	-0.079	1	
Imports	-0.25	-0.38	0.29	-0.048	0.24	-0.037	0.58	1

Rank correlation (Spearman)

	PV	Wind	Non-Flexible Demand	HP - Smart Heating - Decentralized	CHP-CCGT Plants - Heating Grid	Discharging Power Storage	Flexible Power Plants - Non Heating Grid	Imports
PV	1							
Wind	-0.15	1						
Non-Flexible Demand	0.27	0.051	1					
HP - Smart Heating - Decentralized	-0.36	-0.53	0.00025	1				
CHP-CCGT Plants - Heating Grid	-0.11	-0.28	-0.13	0.27	1			
Discharging Power Storage	-0.29	-0.38	-0.14	0.75	0.21	1		
Flexible Power Plants - Non Heating Grid	-0.27	-0.49	0.14	0.51	0.37	0.17	1	
Imports	-0.27	-0.46	0.19	0.54	0.34	0.18	0.91	1

Legend:
- 1.00 Perfect positive Correlation
- 0.75
- 0.5
- 0.25
- 0.00 No monotonic correlation
- -0.25
- -0.5
- -0.75
- -1.00 Perfect negative correlation

PV and Wind main drivers
demand only drives backup-turbines and imports
rank-based intercorrelation, not linear

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Drivers: flexible demand

Linear correlation (Pearson)

	PV	Wind	Non-Flexible Demand	Power to Heat - Decentralized	Power to Heat - Heating Grid	Power Storage	Power-to-X	Exports	Curtailment
PV	1								
Wind	-0.15	1							
Non-Flexible Demand	0.16	0.055	1						
Power to Heat - Decentralized	0.35	0.31	0.0015	1					
Power to Heat - Heating Grid	0.26	0.46	0.025	0.37	1				
Power Storage	0.48	-0.11	0.046	0.014	-0.017	1			
Power-to-X	0.44	0.62	-0.083	0.49	0.42	0.037	1		
Exports	0.23	0.14	-0.11	0.1	-0.003	-0.015	0.37	1	
Curtailment	0.3	0.3	-0.0084	0.089	0.015	-0.058	0.27	0.025	1

Rank correlation (Spearman)

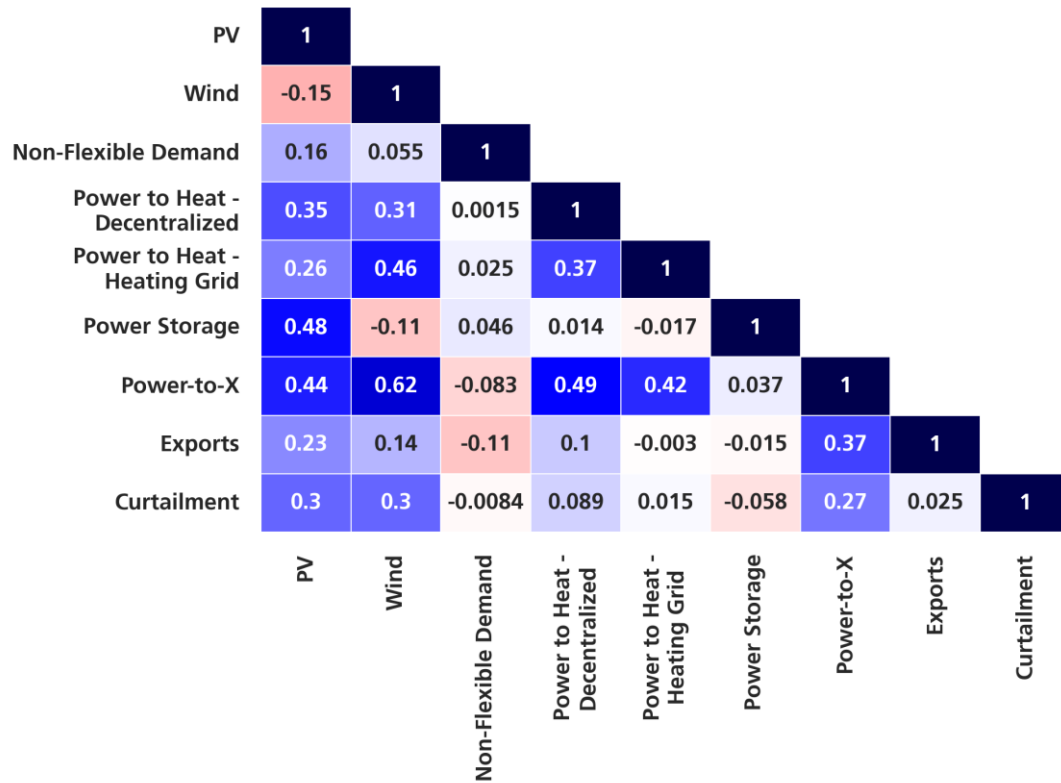|	PV	Wind	Non-Flexible Demand	Power to Heat - Decentralized	Power to Heat - Heating Grid	Power Storage	Power-to-X	Exports	Curtailment
PV	1								
Wind	-0.15	1							
Non-Flexible Demand	0.27	0.051	1						
Power to Heat - Decentralized	0.33	0.46	0.0091	1					
Power to Heat - Heating Grid	0.22	0.56	0.087	0.69	1				
Power Storage	0.49	0.33	0.048	0.31	0.35	1			
Power-to-X	0.36	0.58	-0.054	0.69	0.54	0.54	1		
Exports	0.14	0.15	-0.13	0.18	0.052	0.17	0.4	1	
Curtailment	0.27	0.46	0.0017	0.77	0.62	0.24	0.53	0.1	1

Legend:
- 1.00 Perfect positive Correlation
- 0.75
- 0.5
- 0.25
- 0.00 No monotonic correlation
- -0.25
- -0.5
- -0.75
- -1.00 Perfect negative correlation

**PV and Wind main drivers – Wind and Power Storages not linear correlated
demand not significant driver
rank-based intercorrelations**

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Conclusion

Flexibilities in a sector coupled, net-zero energy system

1 Interaction between different flexibility options

2 Electrolyzers central for flexibility and sector coupling

3 **Different options for different use-cases**
Short-term / summer: storages, smart heating
Long-term / winter: Power-to-X, back-up turbines

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Thank You for Your Attention!

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Submitted to Environmental Research: Energy

System flexibility in the context of transition towards a net-zero sector-coupled renewable energy system - case study of Germany