Peaks and Lulls in Sector Integrated Energy Systems – a Risk for Security of Supply?

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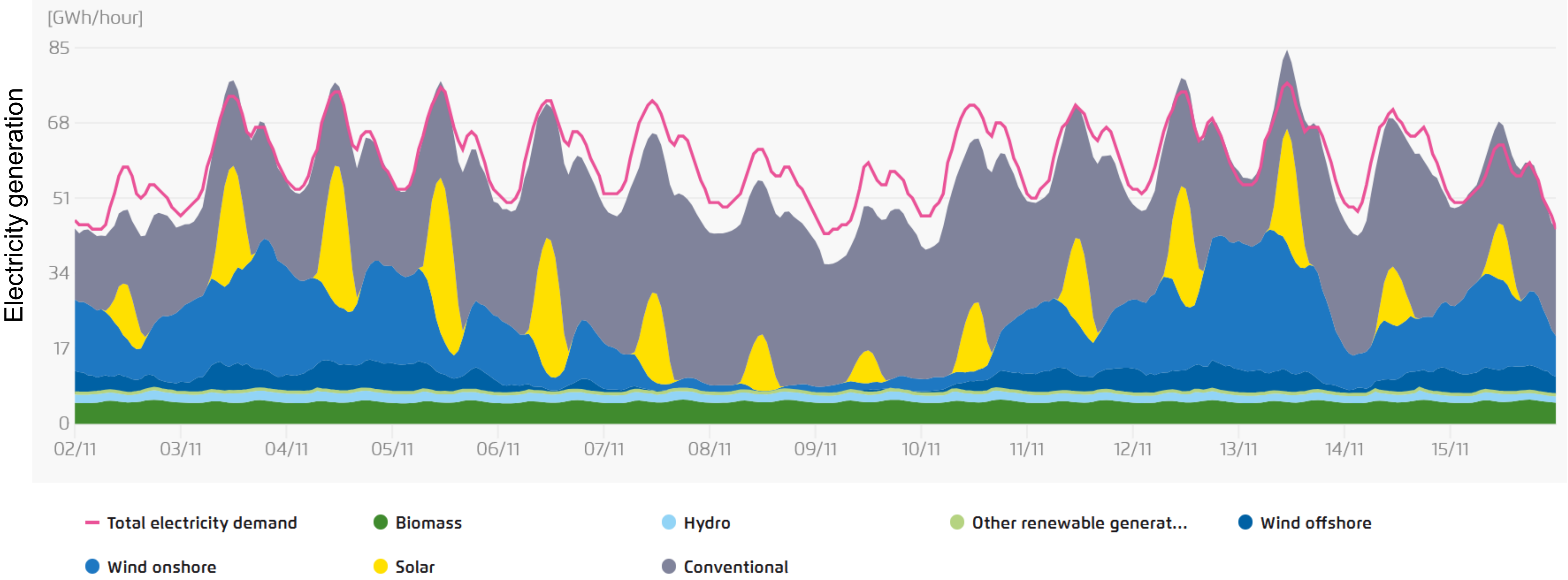
Motivation: Germany‘s Electricity Generation in November 2025



[1]

- 2024: 59.4% renewable share in electricity generation [2]
- ➢ Transformation towards renewable-based system will increase effects of peaks and lulls

[1] Agora Energiewende: Agorameter, available: https://www.agora-energiewende.org/data-tools/agorameter/live/chart/power_generation/02.11.2025/15.11.2025/hourly (accessed 17.11.2025)

[2] Statistisches Bundesamt, 2025, available: https://www.destatis.de/DE/Presse/Pressemitteilungen/2025/03/PD25_091_43312.html (accessed 17.11.2025)

Research Questions

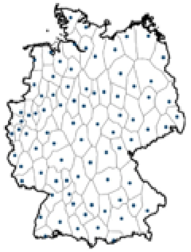
Are peaks and lulls of renewable electricity generation a risk for security of supply in sector integrated energy systems?

What are optimal operational strategies to deal with such situations?

Methods: ETHOS.Infrastructure German Energy System Model [1],[2]

ETHOS.Infrastructure
Multi-region model

Greenhouse gas-neutral Germany 2045



Import
- Hydrogen import via import corridors of the European Hydrogen Backbone
- Electricity import
- Natural gas import
- Liquefied hydrogen import via harbors in northern Germany

Conversion and energy sources
- Wind onshore
- Wind offshore
- Photovoltaics (open field)
- Photovoltaics (rooftop)
- Electrolyzers
- Fuel Cells + H_2 power plants
- Methane power plants
- Purification plants (biogas)
- Methanation plants
- Biogas CHP
- Wood chips CHP
- Heat pumps (air, geothermal)
- Electro vessels
- Run-of-river power plants
- Biogas plants
- Liquefaction plants
- Regasification plants

Transmission
- AC lines
- DC lines
- Offshore DC connections
- Pipelines (Methane) existing and new
- Pipelines (Hydrogen) retrofit and new

Storage
- Li-ion batteries
- PHES (existing, planned)
- Pore storage (Methane) existing
- Salt caverns (Methane) existing, planned
- Pipe systems (Methane)
- Salt caverns (Hydrogen) retrofit, new
- Pipe systems (Hydrogen)
- Cryogenic tanks (Liquefied hydrogen)
- Biogas storage
- Heat storage steel

Demand
- Electricity demand
- Methane demand
- Heat demand
- Hydrogen demand

Export
- Electricity export

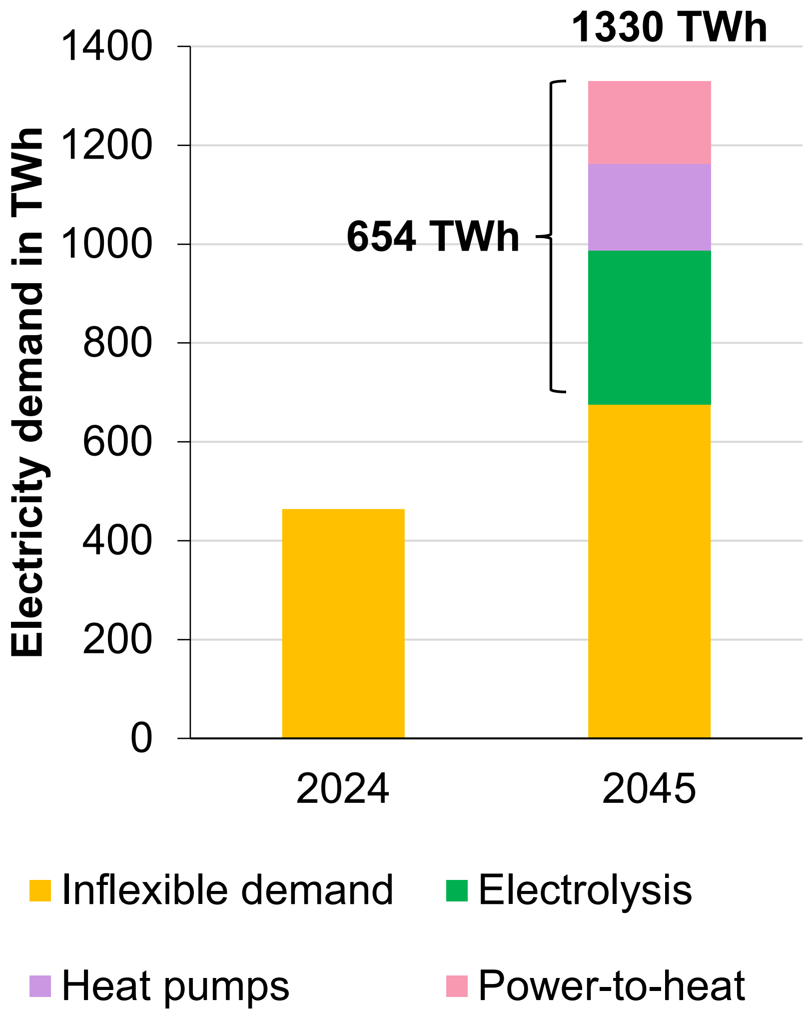
Legend
Energy flow

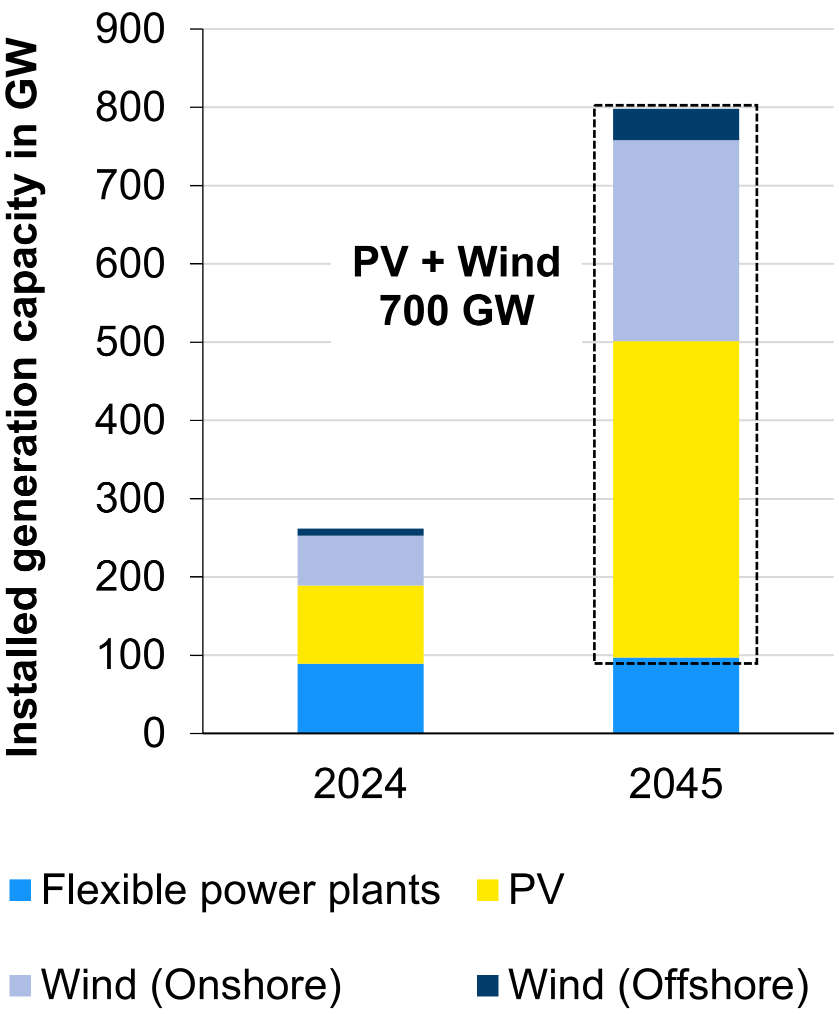
Scenario definition: Net-zero emissions in 2045 & Synthetic cold dark lull of two weeks included in January

[1] T. M. Groß, "Multiregionales Energiesystemmodell mit Fokus auf Infrastrukturen," RWTH Aachen University, 2022. doi: 10.18154/RWTH-2023-01485.

[2] T. Busch et. al., "The role of liquid hydrogen in integrated energy systems–A case study for Germany," International Journal of Hydrogen Energy, 2023, doi: 10.1016/j.ijhydene.2023.05.308.

Optimization Results: German Electricity Sector in the Year 2045





Installed capacities in 2045:

- 97 GW flexible power plants
- 244 GWh battery storage

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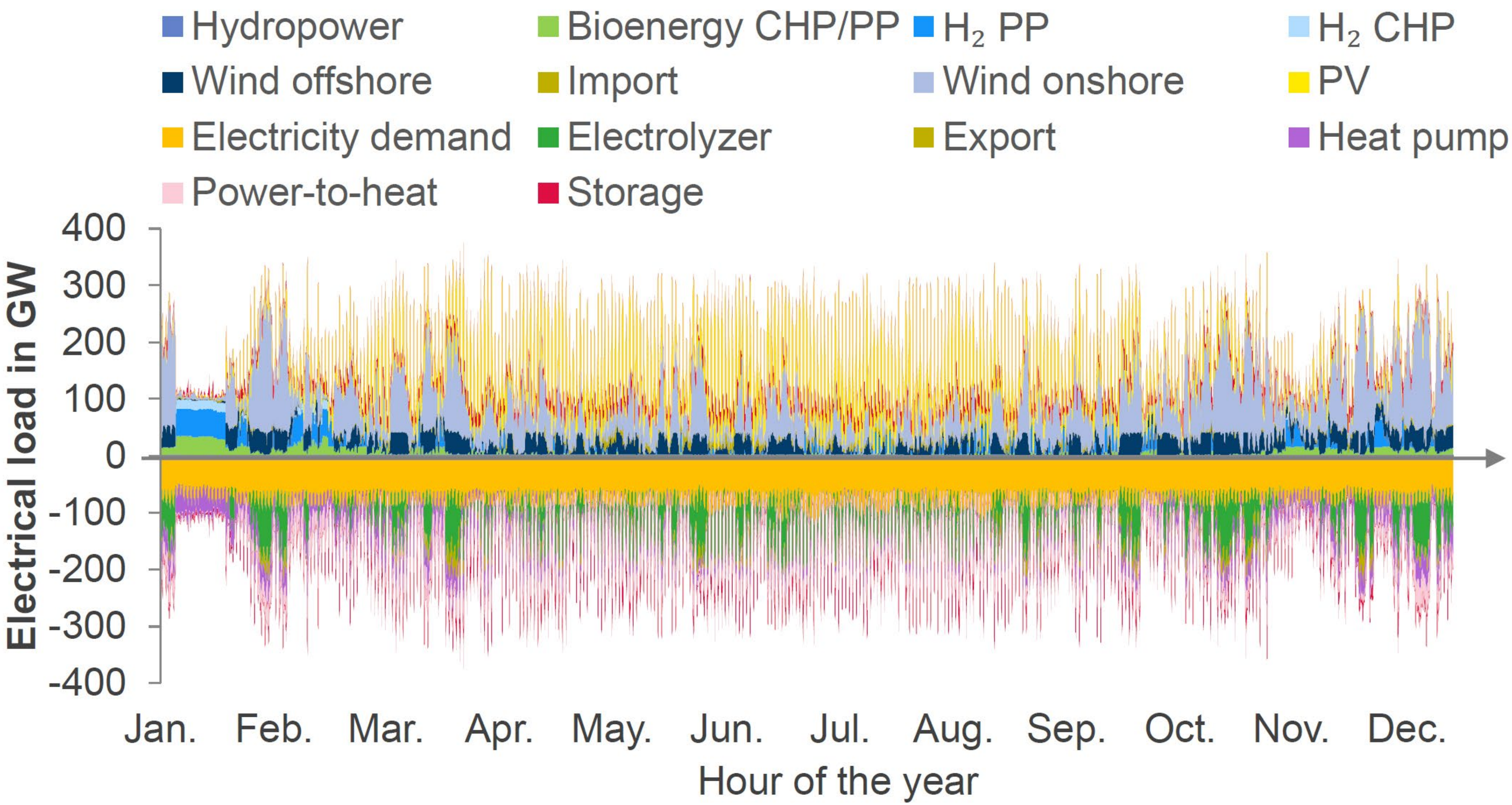
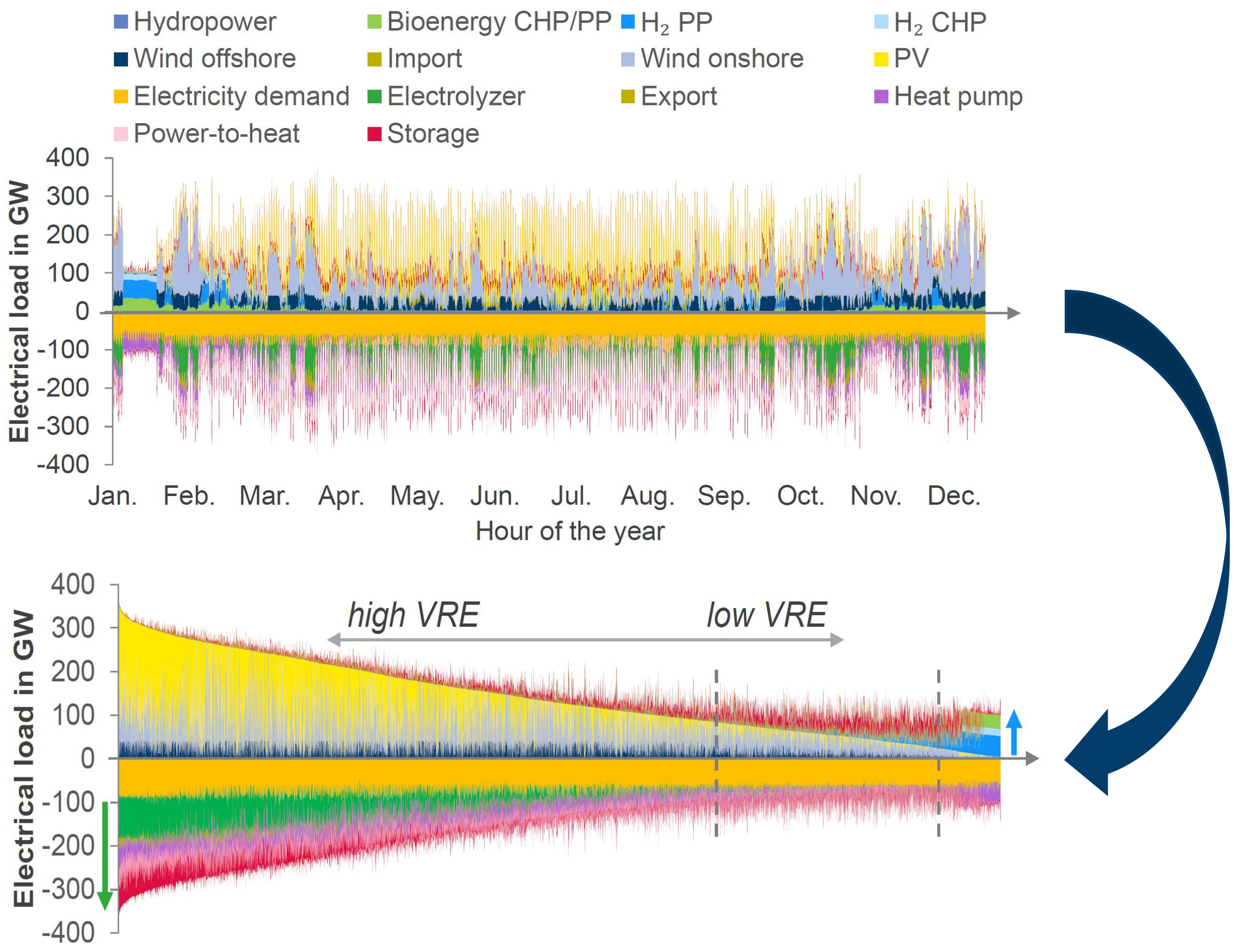
Optimization Results: Electricity Generation & Demand 2045

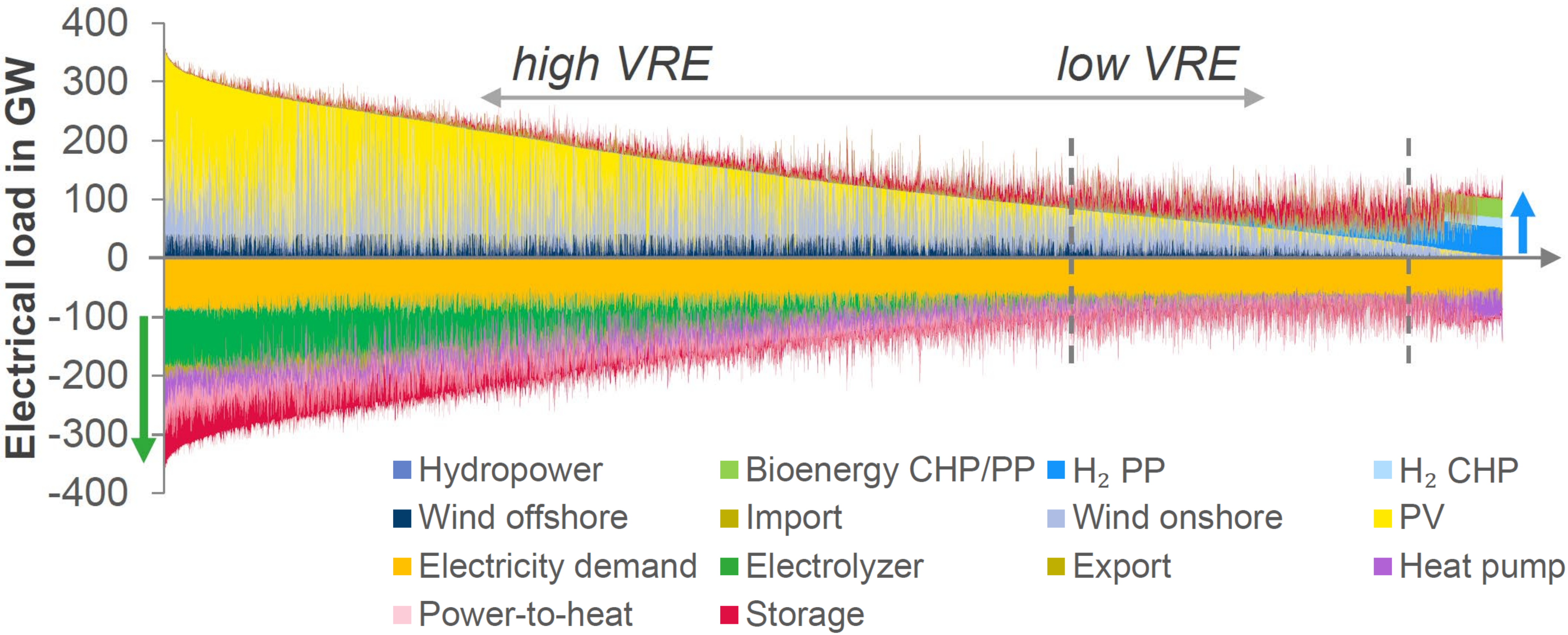


Optimization Results: Electricity Generation & Demand 2045

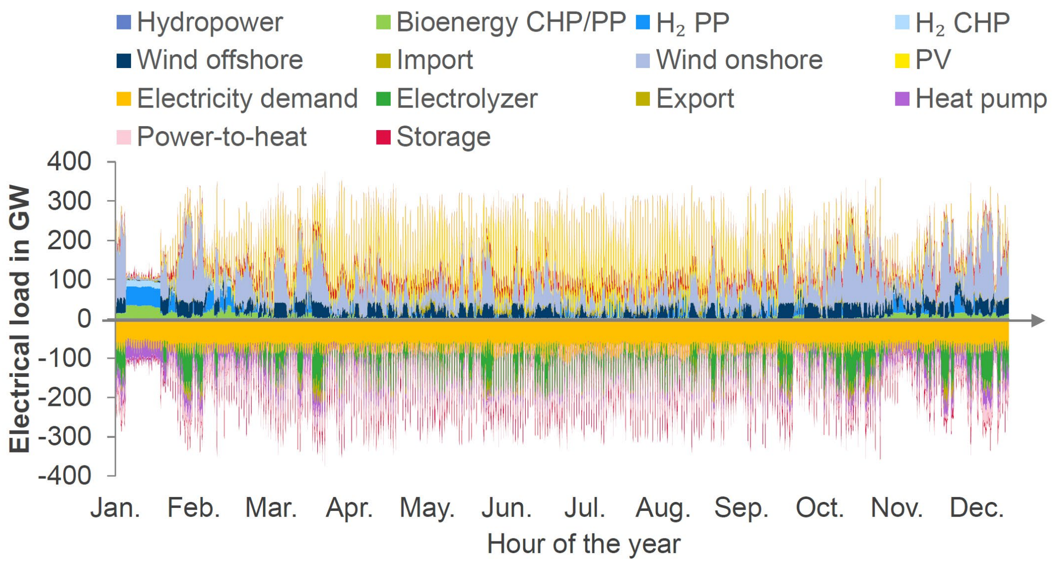


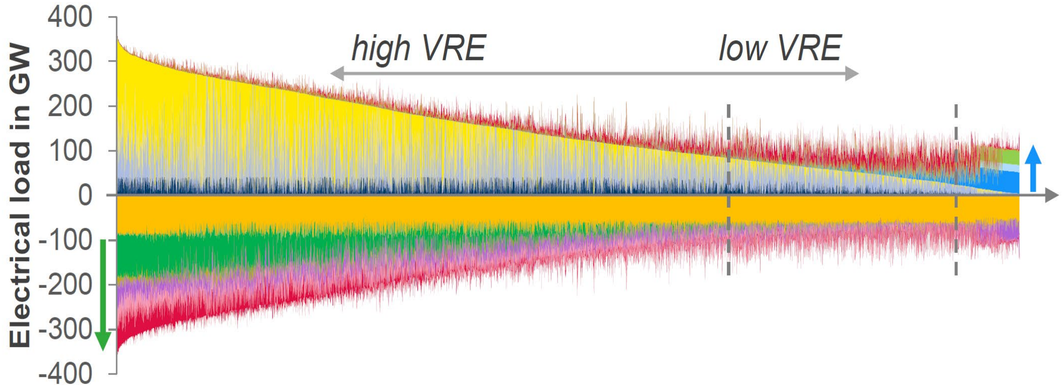
Ordering by variable renewable energy (VRE) supply

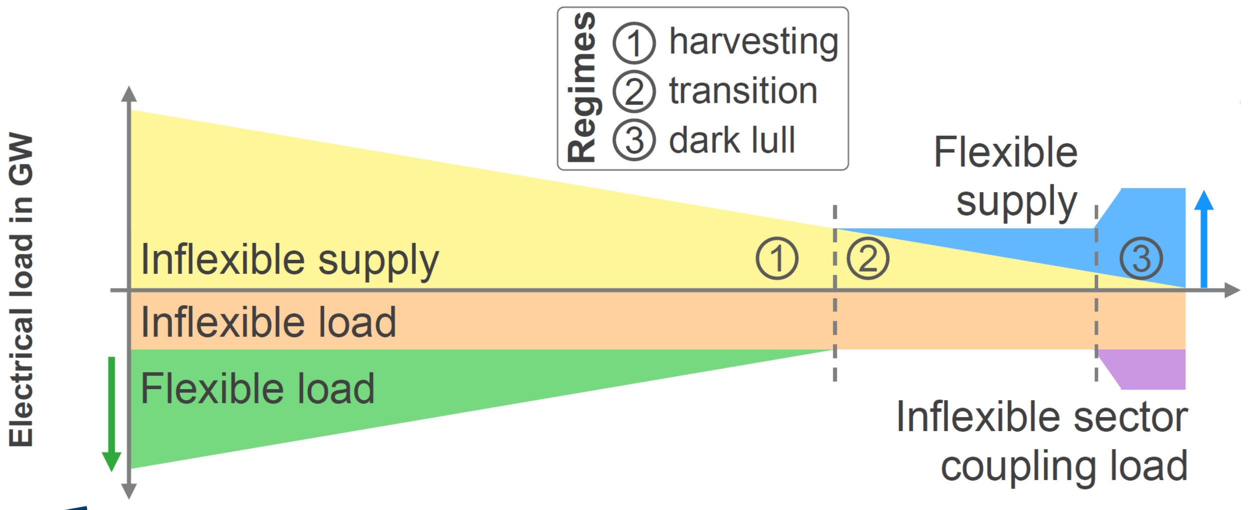
Optimization Results: Ordered Electrical Load 2045



Optimization Results: Electricity Generation & Demand 2045

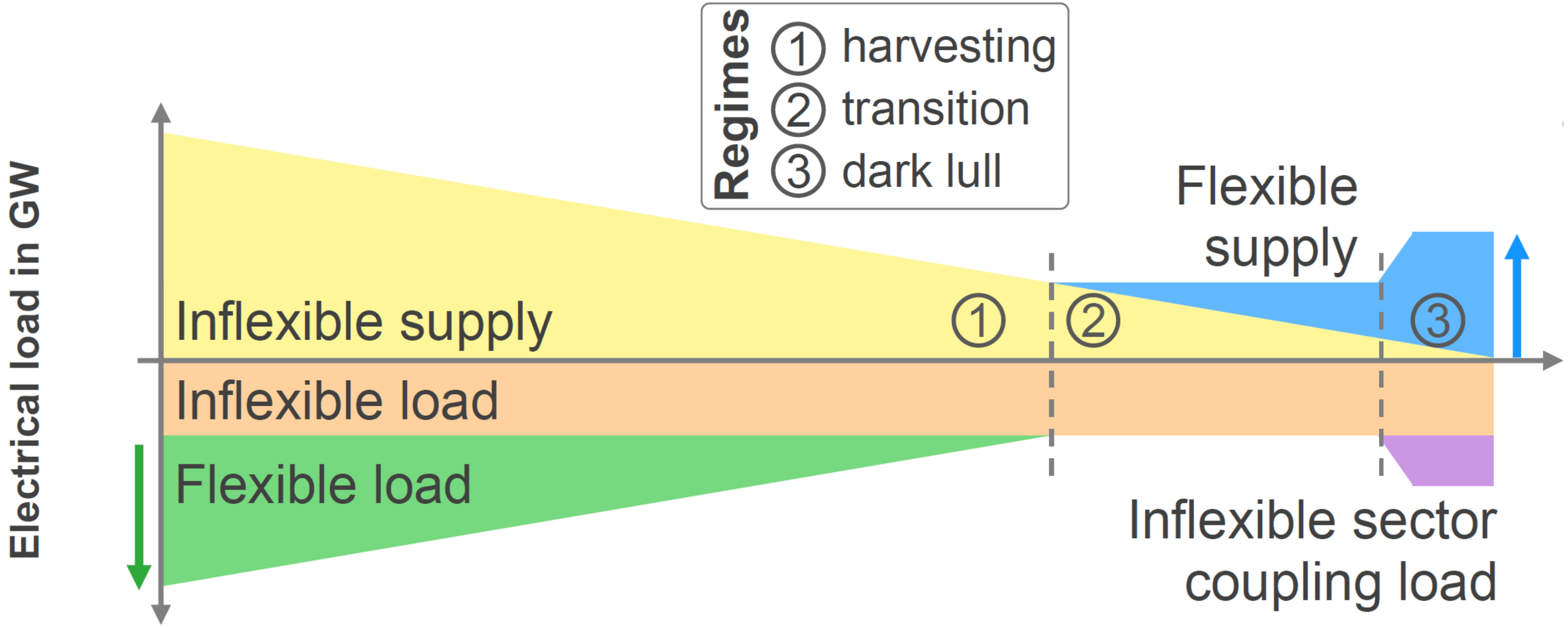






Identifying operation regimes

Operation Regimes

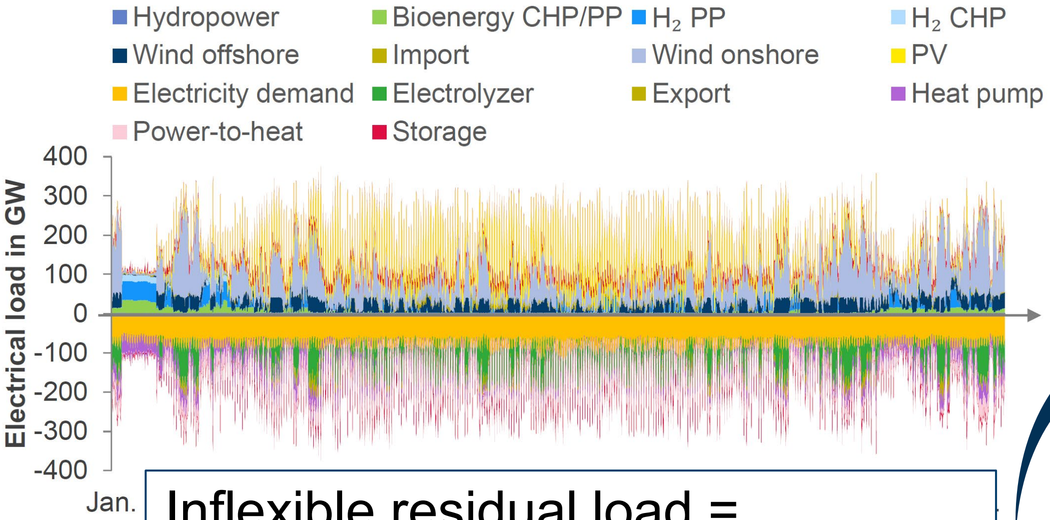


① Harvesting period: Flexible demand utilizes inflexible renewable energy

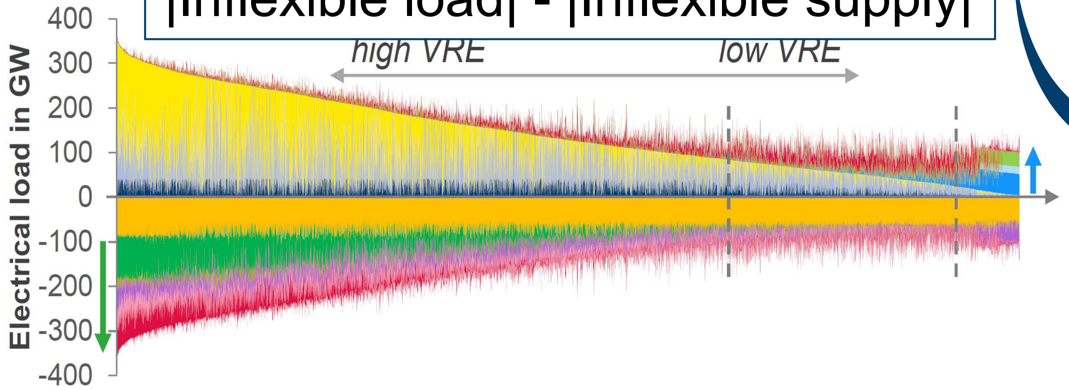
② Transition period: Renewables & flexible supply options cover inflexible demand

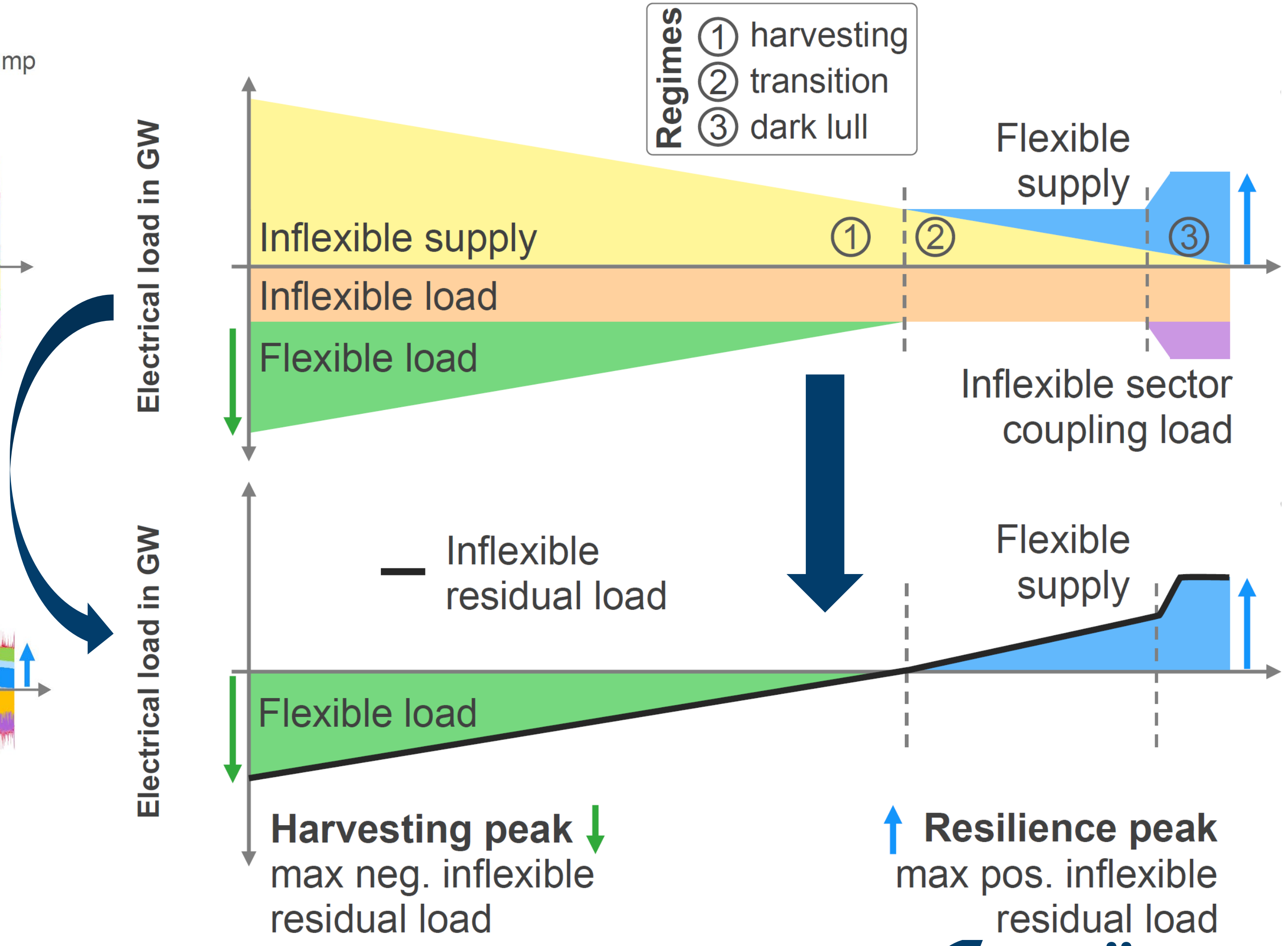
③ Dark lull: Flexible supply options cover inflexible demand

Optimization Results: Electricity Generation & Demand 2045

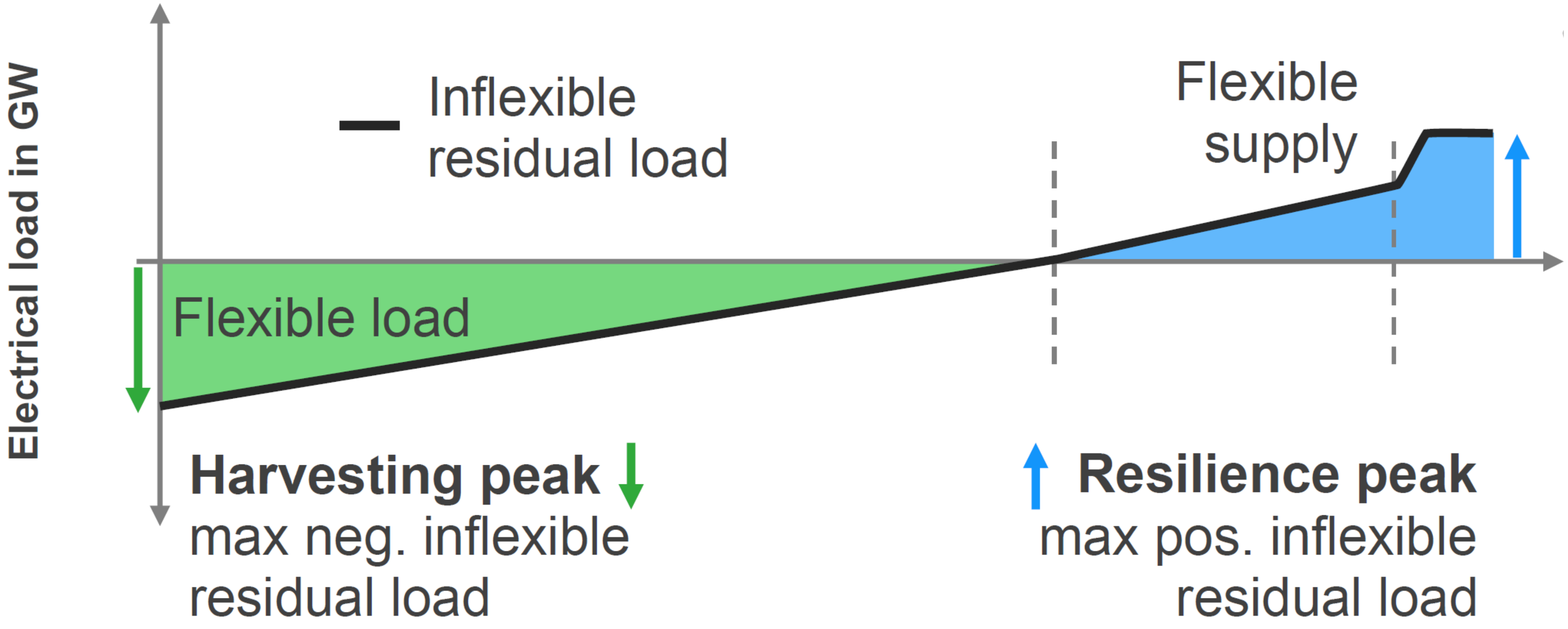


Inflexible residual load =
|Inflexible load| - |Inflexible supply|





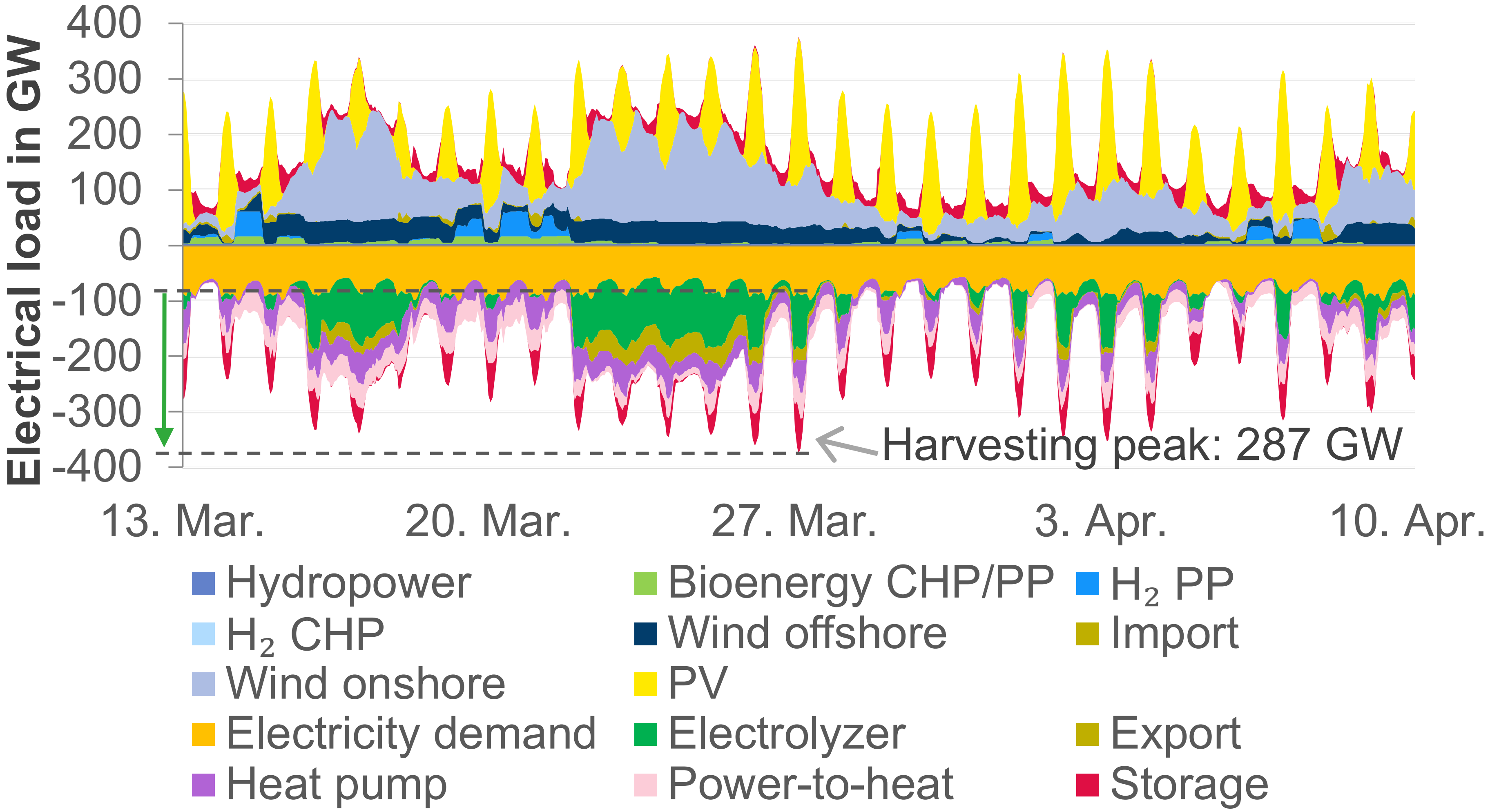
Harvesting and Resilience Peak Load Concepts



- Dual peaks in sector-integrated, renewable energy systems
- ➢ Different operation strategies needed

Harvesting Peak Load

$$\text{Harvesting Peak Load} = \left|\min_t\left(\text{Inflexible Residual Load}_t\right)\right|$$

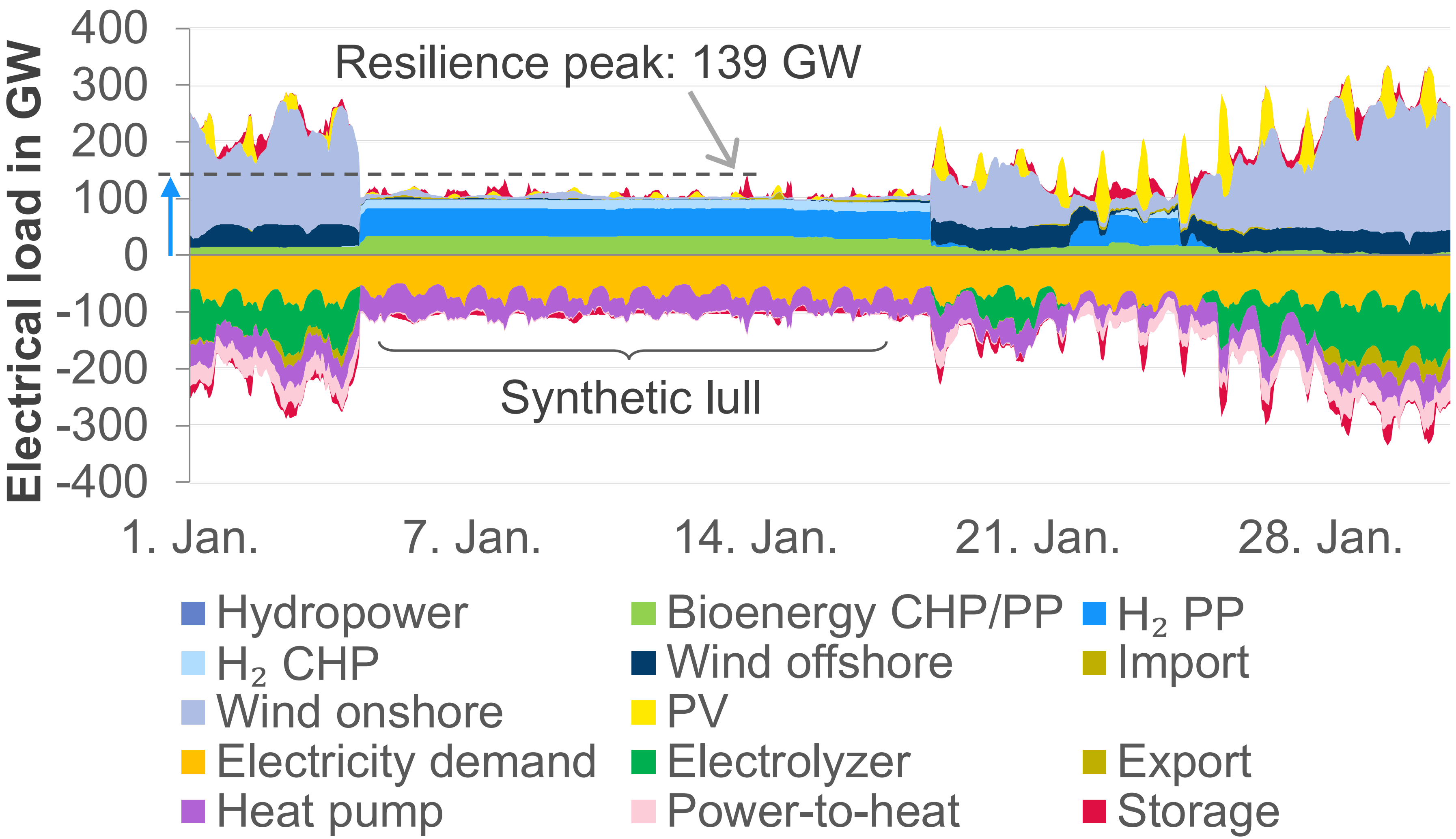


- Flexible sector coupling technologies and storages use electricity to maximum

➢ **Not a critical situation for security of supply**

Resilience Peak Load

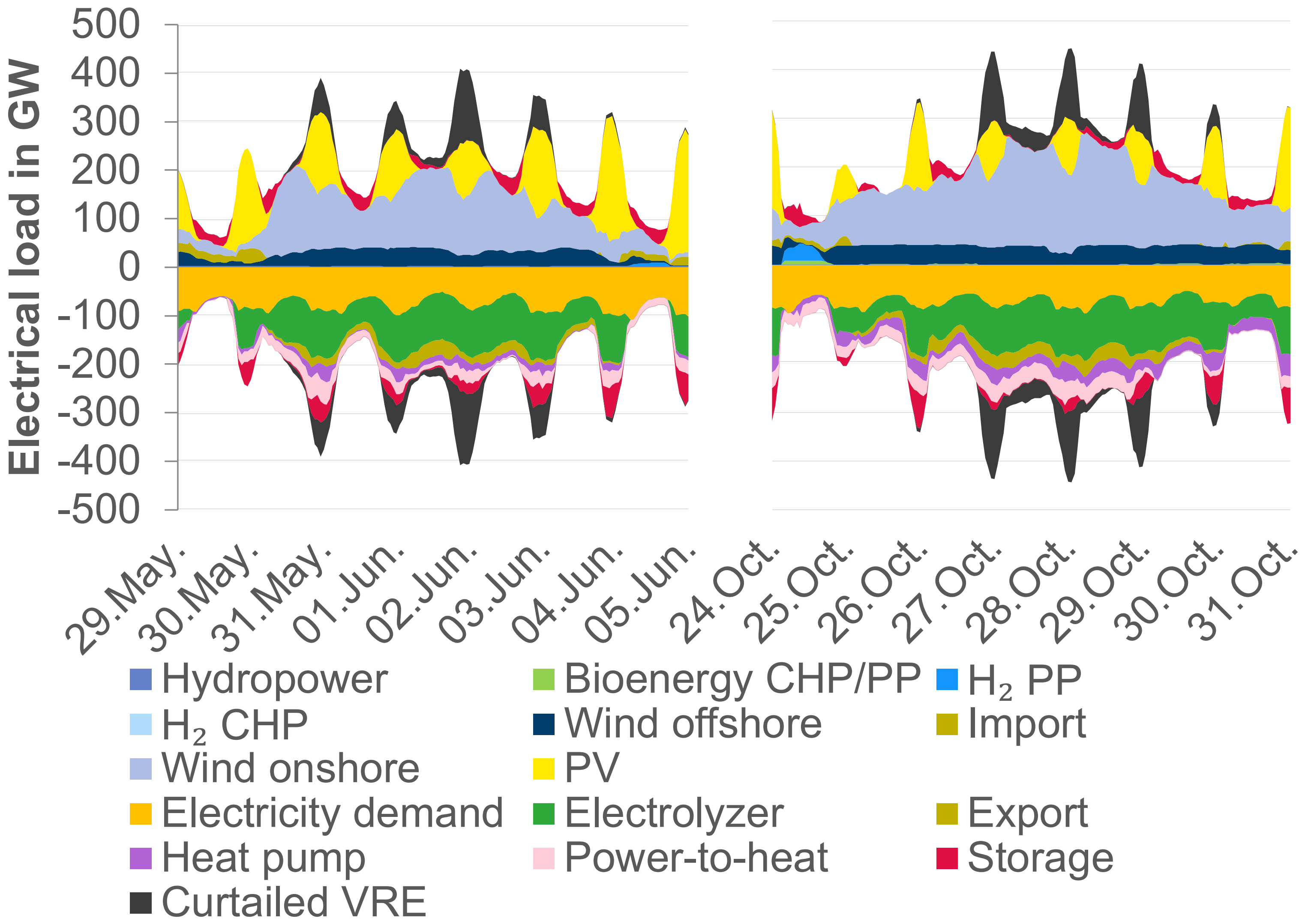
$$\text{Resilience Peak Load} = \left|\max_t\left(\text{Inflexible Residual Load}_t\right)\right|$$



- Flexible power plants supply 96 GW at resilience peak
- Load reduced as much as possible
- 73 TWh long-term H_2 storage needed to bridge dark lull

➢ **Critical situation for security of supply**

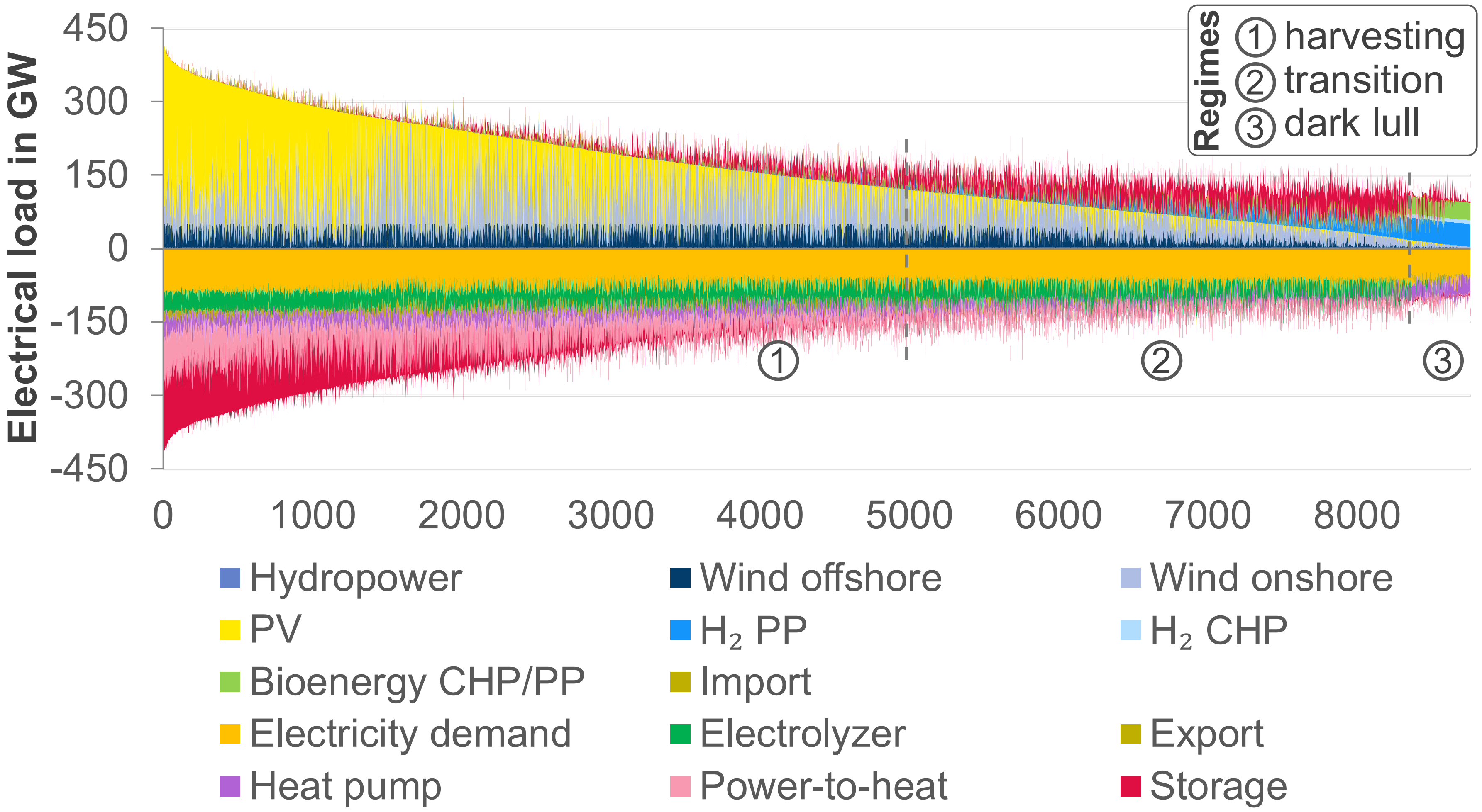
Curtailment of Renewable Energy



- Maximum curtailment of 152 GW on 2nd June
- Only ~ 2% of electricity generation curtailed in 2045

➢ **Curtailment is economically feasible to a certain extent**

Sensitivity Analysis: Minimum of 8000 FLH for Electrolyzers



- +186% battery storage capacity, +25% installed offshore wind & PV capacity
- Curtailment nearly doubled
- +10.5% net energy system costs

➢ **Flexible operation of sector coupling technologies crucial**

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Conclusions

- Harvesting peak load is not critical for security of supply & is utilized by flexible sector coupling technologies as much as possible

- Dark lull is critical for security of supply & defines required capacity of flexible power plants and long-term energy storage
- Energy system planning should consider dark lulls to ensure a resilient energy system design

- Flexibility of electricity demand is key for optimal operation strategies and should be incentivized by policymakers and system planners

- Curtailment of some renewable energy is cost-optimal, even with flexible electricity demand

Thank you for your attention!

For further questions, please contact:

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