DIW BERLIN

Vattenfall

Coping with the Dunkelflaute

Power sector implications of variable renewable energy droughts in Europe

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KOPERNIKUS PROJEKTE
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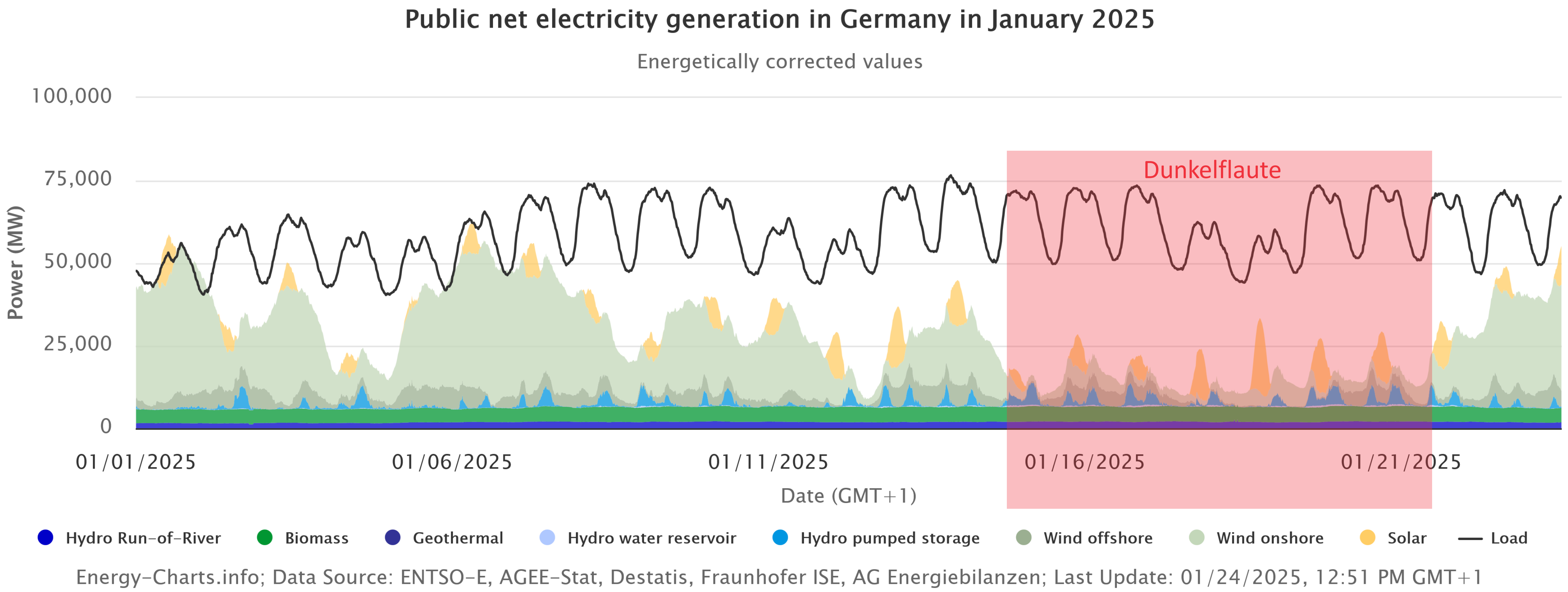
Content

1. Motivation

Example of a Dunkelflaute event in Germany

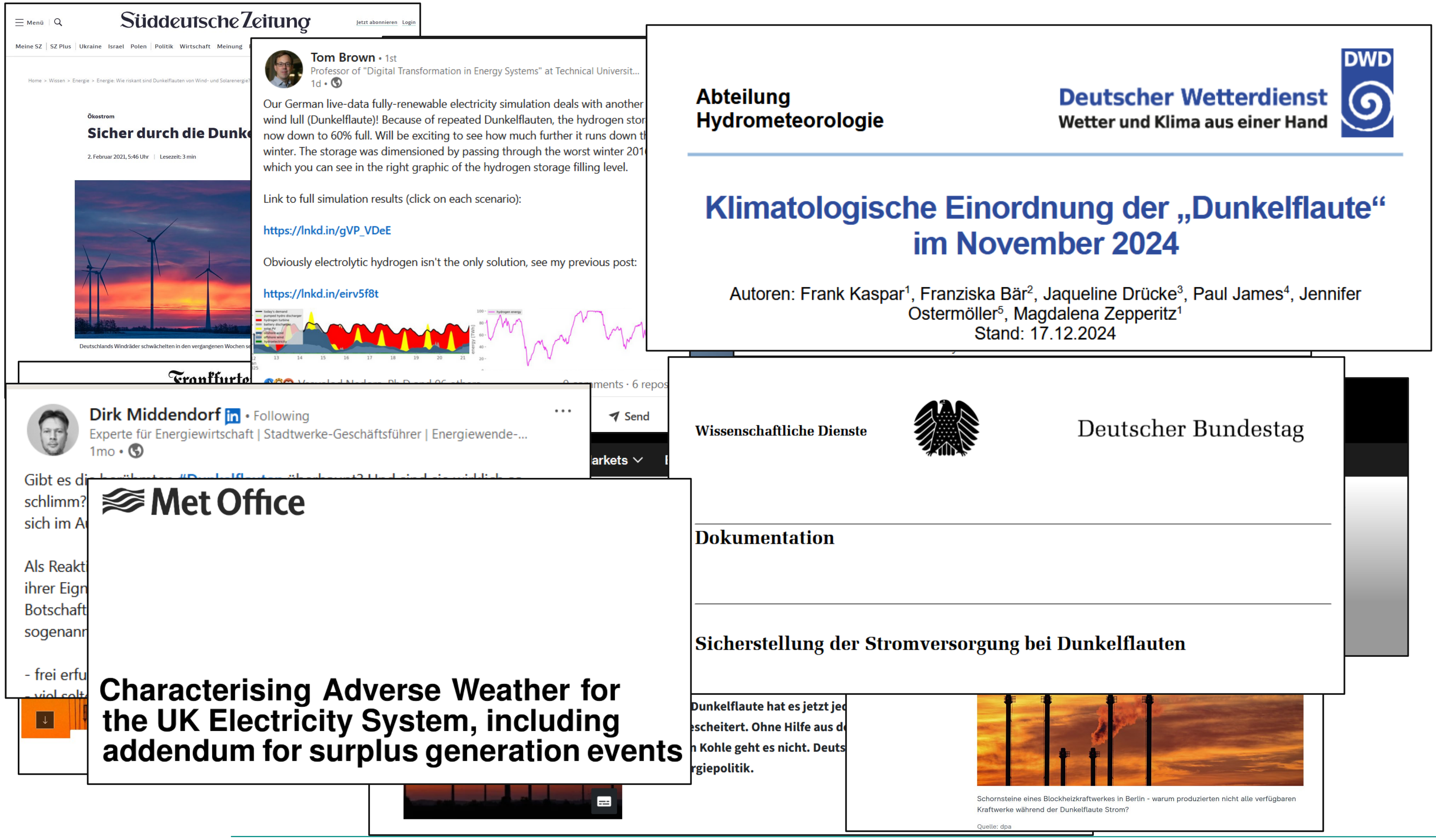


Variable renewable energy droughts, wind and solar lulls, or German term “Dunkelflaute”

- Extended period with low renewable availability
- Increasing reliance on wind and solar energy → Dunkelflaute events become key challenge for realizing energy transition

Relevance

Dunkelflaute events in public, policy, and academic discourse



Research Questions

VREDA

Characterization of European Dunkelflaute events

• Dunkelflaute definition and detection methods	Kittel & Schill (2024), *Environmental Research: Energy*
• Dunkelflaute characteristics (duration, frequency, correlation) and thresholds • Extreme Dunkelflaute events	Kittel & Schill (2026), *Communications Earth & Environment*

DIETER

European power sector implications of extreme Dunkelflaute events

• Impact on long-duration storage operation and investment • Value of cross-country electricity and hydrogen exchange • Role of zero-emission fossil-fueled backup with CCS	Kittel, Roth, and Schill (2026), *Nature Communications*
• Impact of electrified heating • Interactions of long-duration electricity and heat storage	Schmidt, Roth, and Schill (2025), *pre-print*

2. Research design

Research design: Power sector implications

100% renewable European power sector

- No fossil fuels, CCS, or nuclear power (relaxed in sensitivity)
- Import of green hydrogen possible
- Largely parameterized to TYNDP 2022 - Distributed Energy
- Sector-coupling “light”: simplified industry, heat, transport

Scenarios: temporal dimension

- 35 independent runs based on 35 historical weather years (1982 – 2016)
- Source: Pan-European Climate Database 2021.3
- summer2summer planning horizon

Scenarios: spatial dimension

- Different interconnection levels

Interconnection

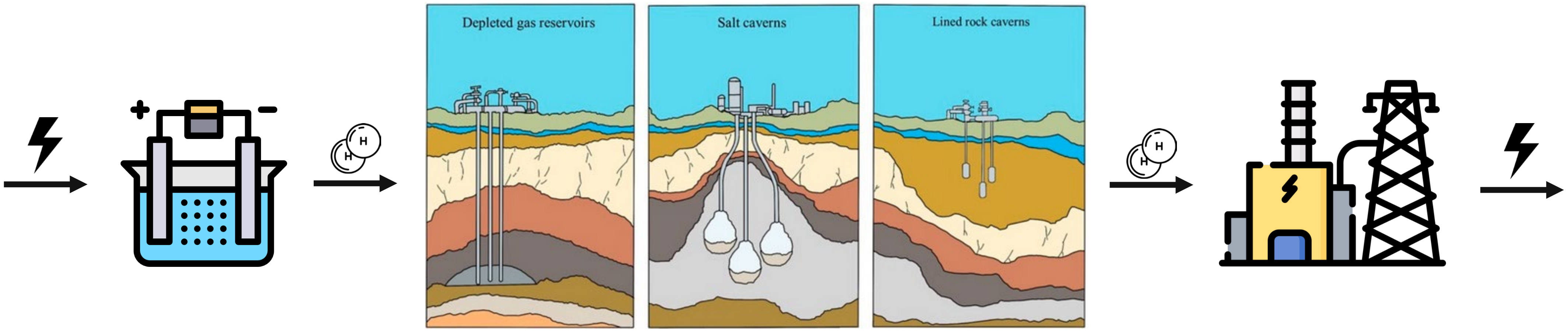
Island → **European copperplate (CP)**

(1)	(2)	(3)	(4)
Electricity: no	Electricity: TYNDP	Electricity: TYNDP	Electricity: copperplate
Hydrogen: no	Hydrogen: no	Hydrogen: TYNDP	Hydrogen: copperplate

Long-duration electricity storage set-up

Components (connected via hydrogen grid)

- Electrolysis for green hydrogen production
- Underground hydrogen-based storage
- Gas turbine for reconversion to electricity



Chen et al. (2025) , flaticon.com

3. Results

Characterization of Dunkelflaute events

- **Renewable droughts patterns in 1996/97**
- Policy-oriented renewable technology portfolios: solar PV, onshore wind, offshore wind
- Pan-European Copperplate: assuming unconstrained geographical balancing across Europe
- Germany: assuming island system

Characterization of Dunkelflaute events

Renewable droughts patterns in 1996/97

Solar PV

- solar seasonality drives droughts

On- and offshore wind

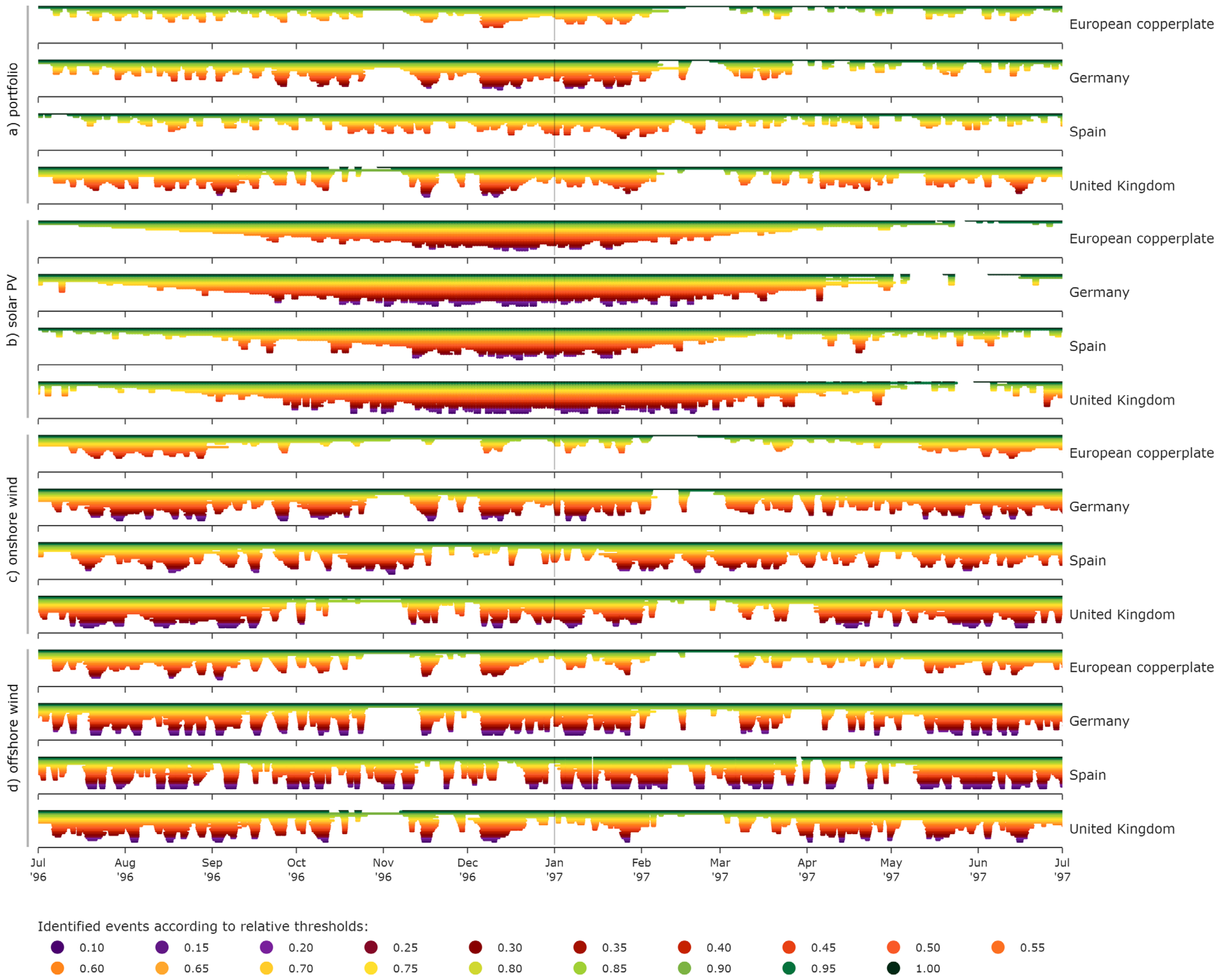
- droughts primarily in summer, some also in winter

VRE portfolio

- product of solar seasonality and significant wind droughts

Complementary wind and solar profiles

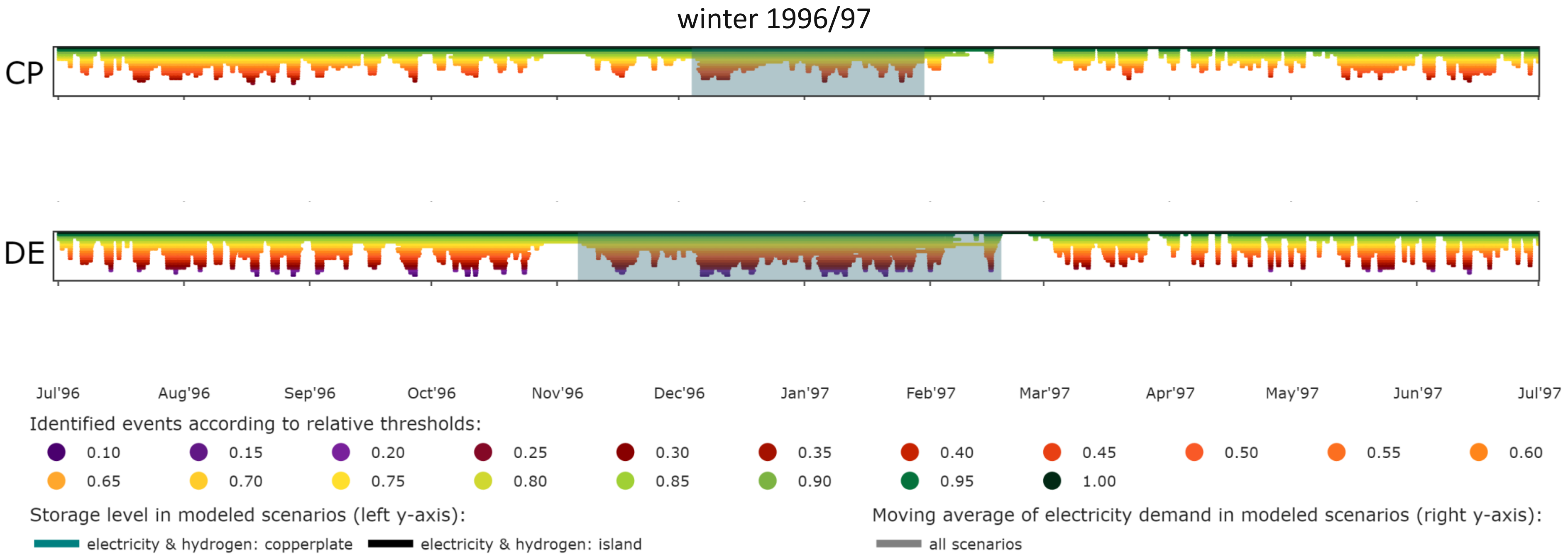
- Portfolio effect within regions
- Balancing effect across regions



Identification of extreme Dunkelflaute events

Dunkelflaute detection based on wind and solar availability time series (VREDA)

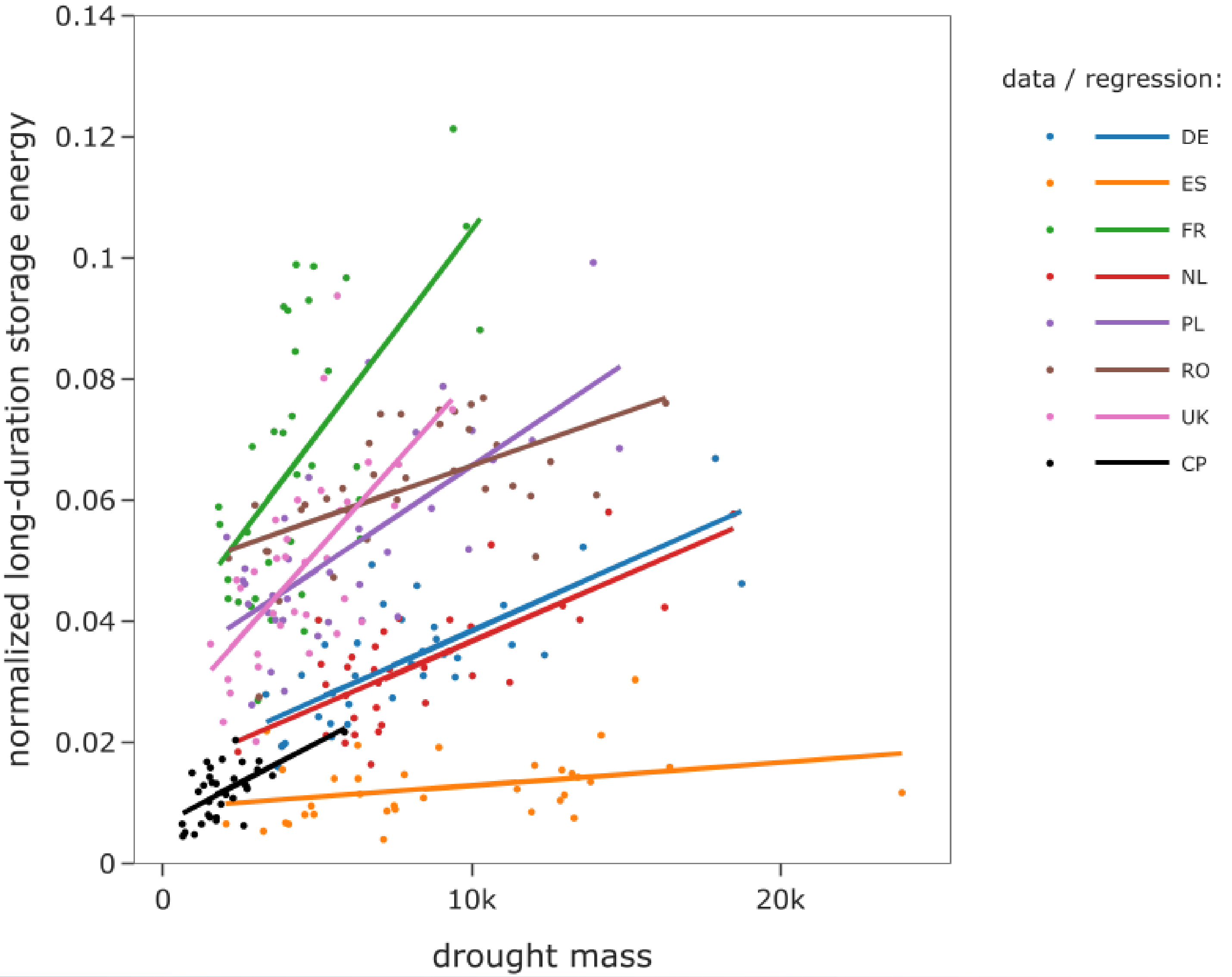
- No meaningful definition for extreme Dunkelflaute events
- Drought mass metric to find events that drive long-duration storage discharge
- Sequence of severe shortage events within a long-lasting, contiguous low-availability period
- Span across turn of year
- Most extreme European event in the data in winter 1996/97



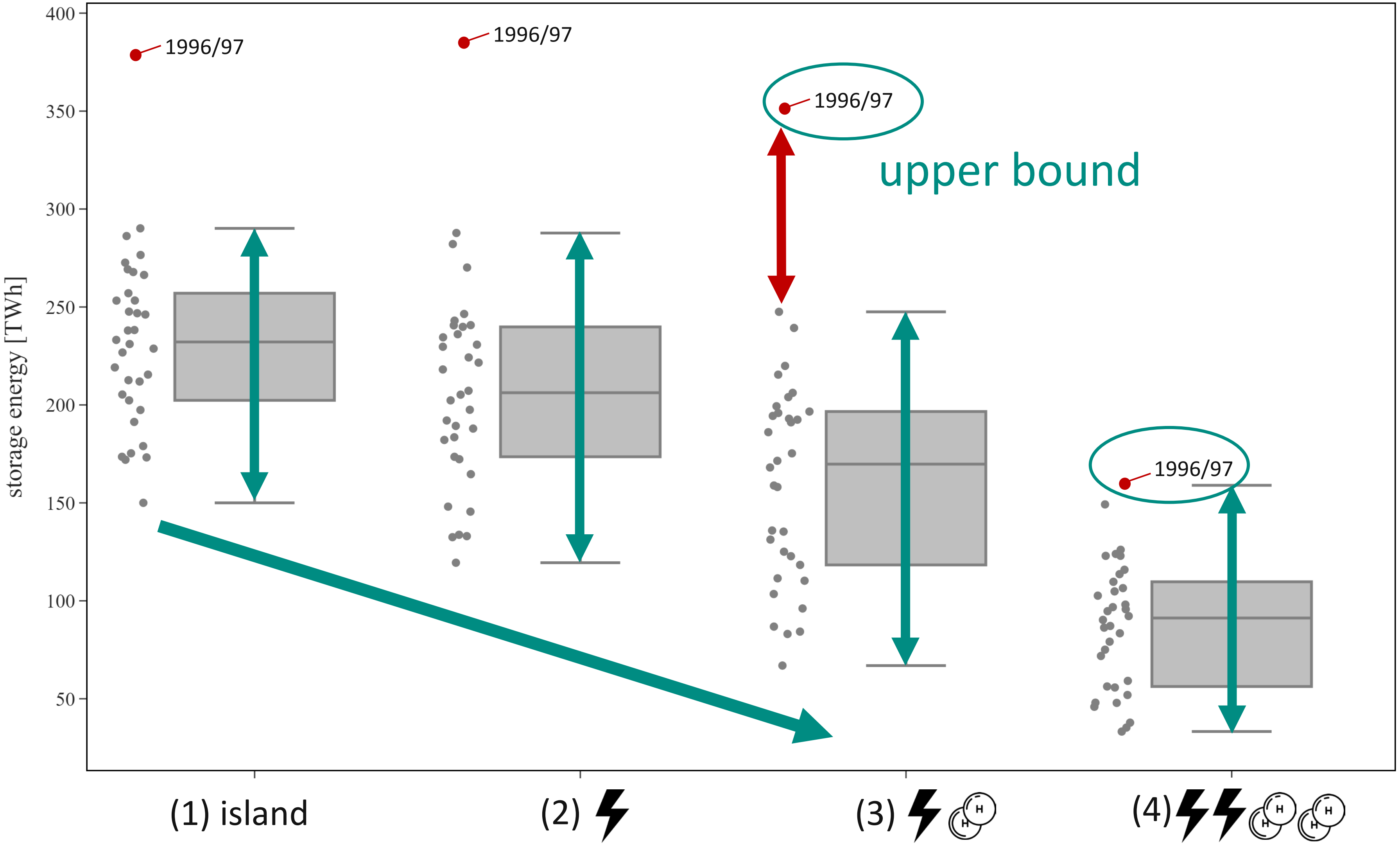
Extreme Dunkelflaute events and long-duration electricity storage energy

Storage energy drivers

- Severity of extreme Dunkelflaute events
- Other flexibility options, e.g., hydro reservoir
- Electricity demand seasonality

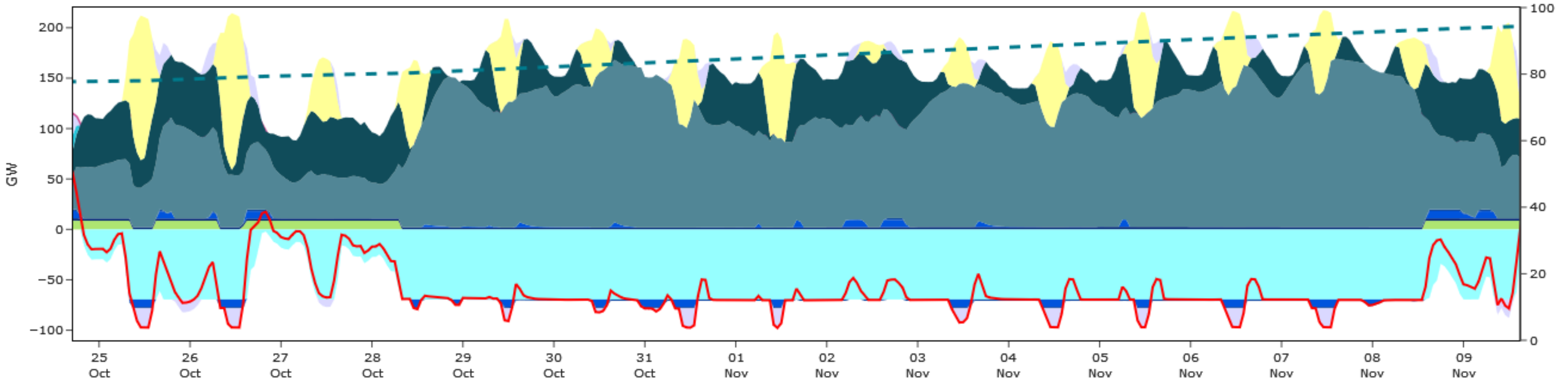


Long-duration electricity storage energy: Impact of interconnection



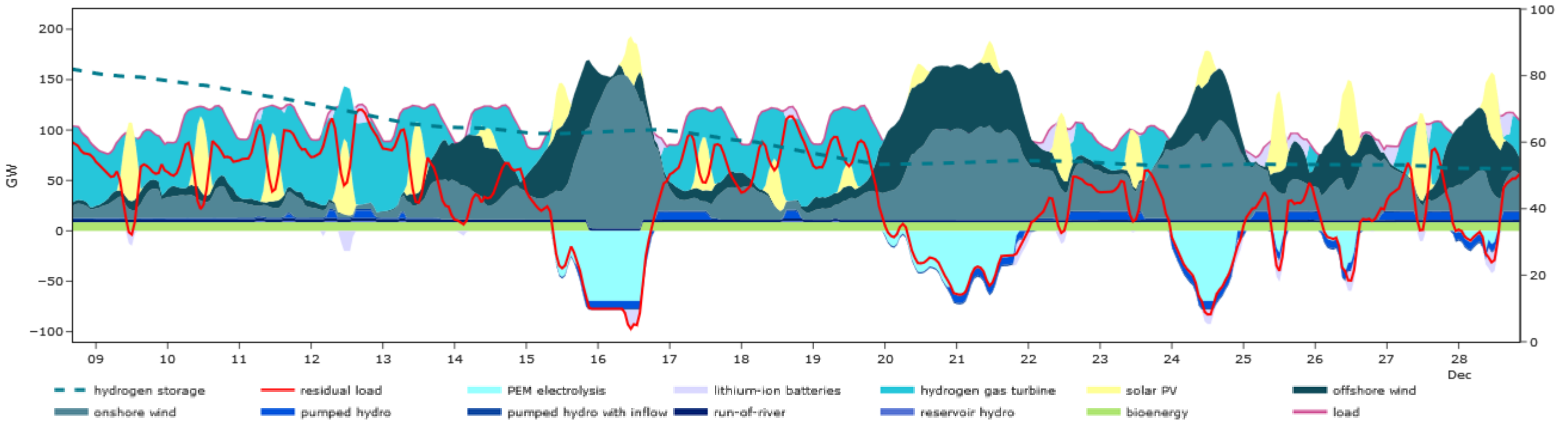
Interaction of flexibility options (island systems)

Power sector operation in Germany before extreme droughts



- Battery cycling, hydro and biomass generation to enable more consistent electrolysis operation (even in positive residual load periods) → reduces electrolysis capacity

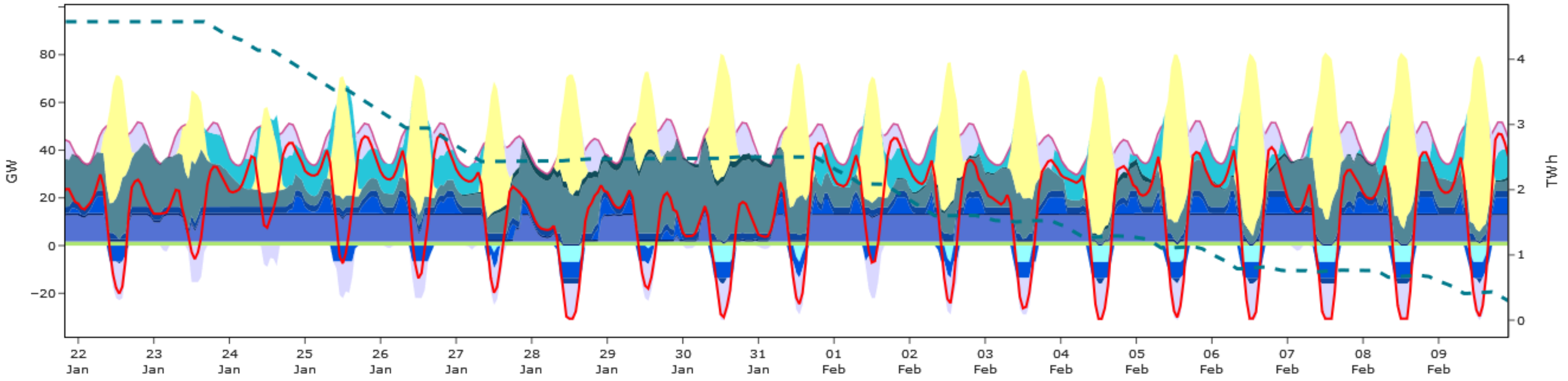
Power sector operation in Germany during extreme droughts



- Battery cycling powered by long-duration storage discharge to enable battery discharge (during solar peak and long-lasting positive residual load periods) → reduces hydrogen turbine capacity

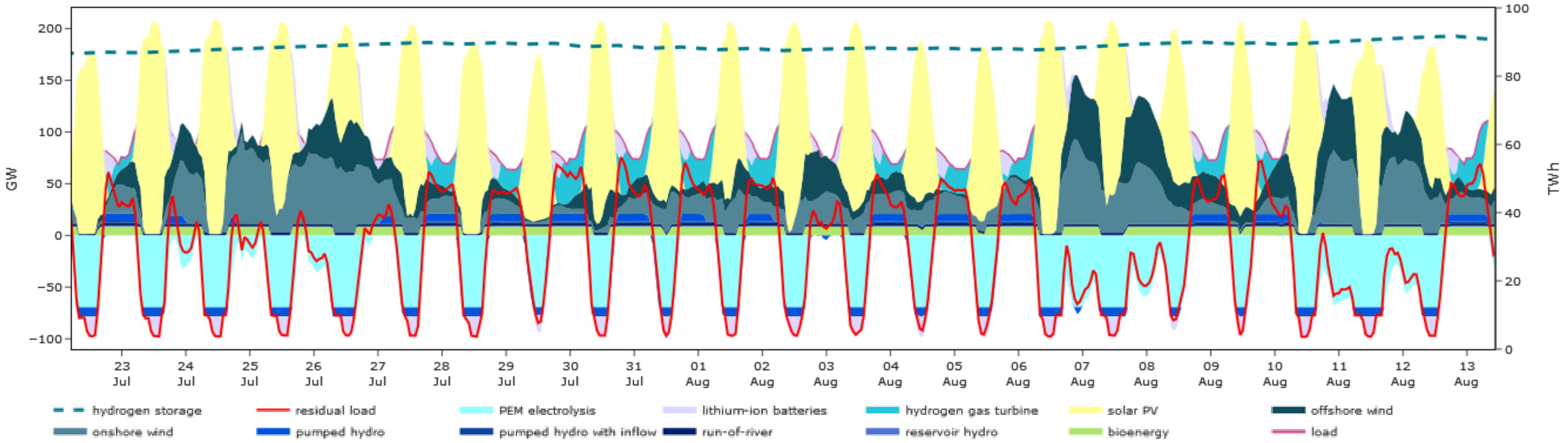
Interaction of flexibility options (island systems)

Power sector operation in Spain during extreme droughts



- Spain: higher (lower) battery (long-duration storage) capacity
- Hydrogen turbine generation enables battery charging even after solar peak → reduces hydrogen turbine capacity

Power sector operation in Germany in summer



- Long-duration storage sized for winter droughts, but used any time when economic
- Diurnal long-duration storage cycling to integrate solar peak → reduces battery storage energy and power capacity

Sensitivity analysis: Impact of nuclear power

Exogenous nuclear capacity (TYNDP 2022)

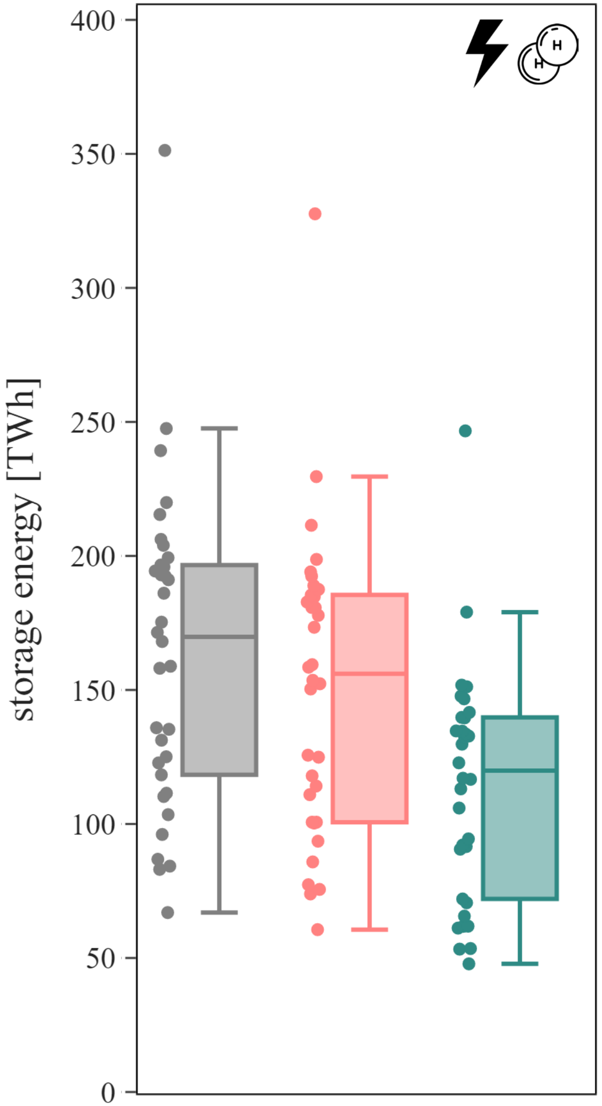
- Default: 0 GW
- Low levels: 24 GW
- High levels: 102 GW
- Policy-relevant exchange of electricity and hydrogen, scenario (3)

General effects

- Nuclear plants provide firm generation during extreme Dunkelflaute events
- Nuclear plants displace wind and solar → lower flexibility need

Storage need mitigation

- Low: 8/7% mean/max
- High: 29/30% mean/max
- Flexible operation of nuclear power plants required

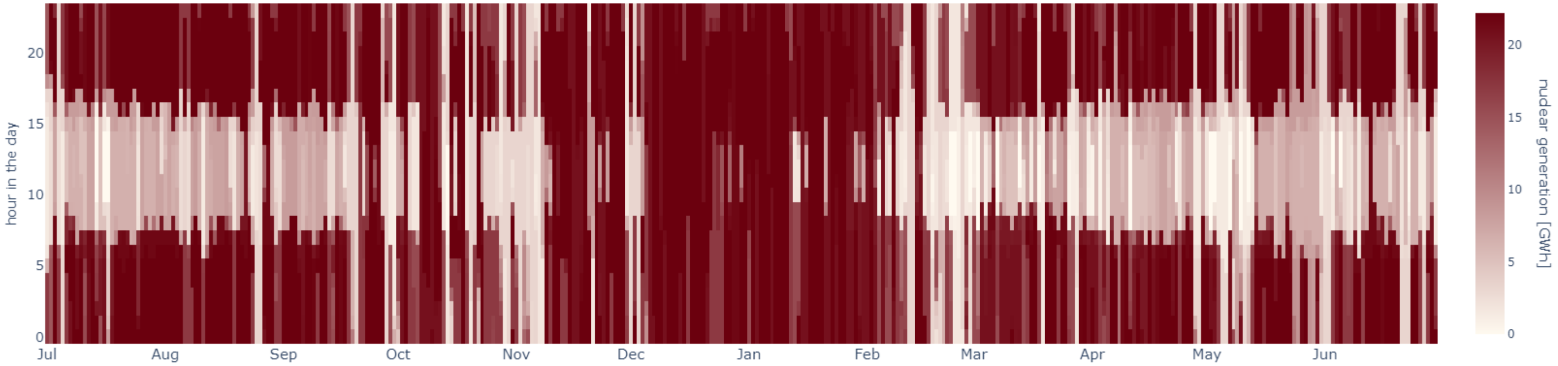


Sensitivity analysis: Impact of nuclear power

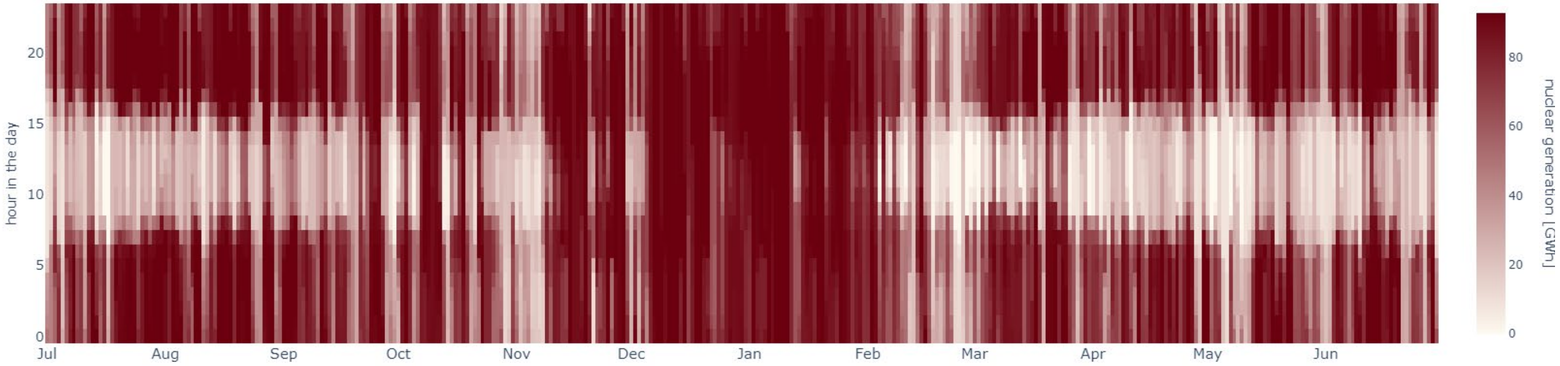
Operational patterns of nuclear power in winter 1996/97 under policy-relevant interconnection (3)

- Flexible operation to complement diurnal solar PV fluctuations
- Continuous dispatch during extreme Dunkelflaute events → reduces optimal long-duration storage discharging and energy capacity

Low levels of nuclear



High levels of nuclear



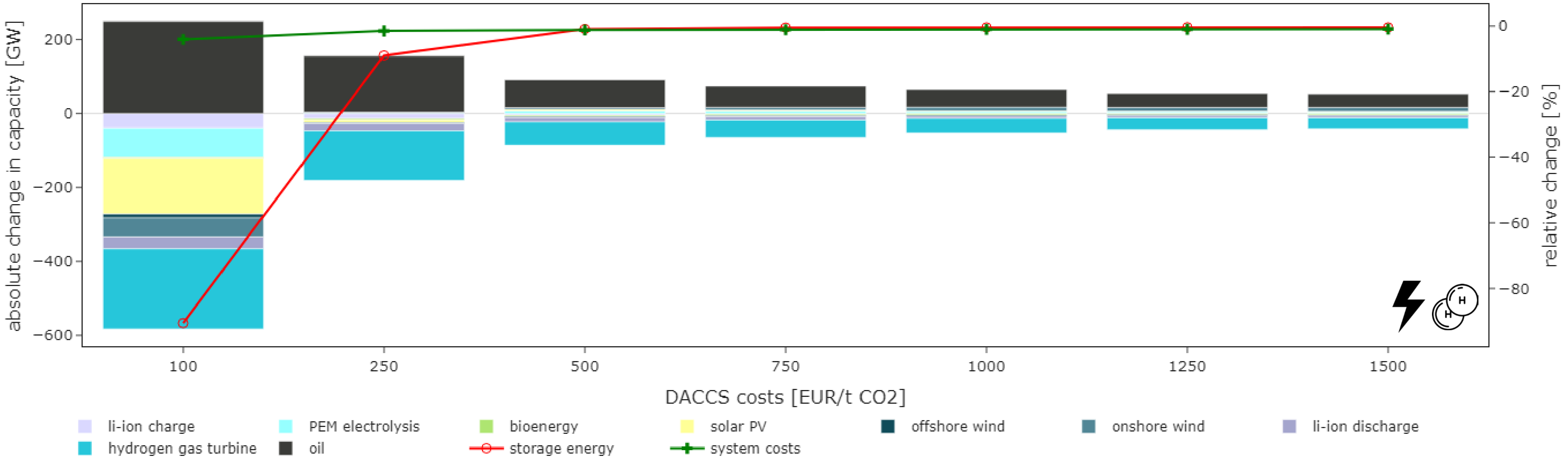
Sensitivity analysis: oil-fired backup capacity with CCS

Endogenous backup capacity

- Oil can be storage above ground and transported via trucks → no capital-intensive infrastructure requirements
- DACCS costs very uncertain → depends on policy support, economies of scale, technological learning curves, and the profile of its electricity demand

Impact in winter 1996/97 under policy-relevant interconnection (3)

- 100€/t CO2: substantial substitution effects and 4% systems costs reduction → long-duration storage remains optimal
- Higher DACCS costs: substitution of storage discharging capacity and 1% system costs reduction → long-duration storage energy hardly affected



4. Conclusion

Conclusion

Key insights

- Dunkelflaute events drive long-duration electricity storage operation and investment
- Extreme years with substantially higher storage needs
- Mitigation of storage needs
  - Interconnection: possible to a limited extend
  - Nuclear power: possible but controversial
  - Fossil backup incl. DACCS: unlikely

Conclusion

Policy implications

- Long-duration storage indispensable for renewable energy systems
- Lead times 5-15 years → early adoption for rapid scaling required
- Deployment incentives for sufficient capacity likely required
- AUS: Europe in need of green commodities imports

Modeling implications

- Choice of weather year matters → 1996/97 relevant (not in TYNDP 2022)
- Model planning horizon maintaining complete winter periods
- Computational restrictions → Dunkelflaute identification based on renewable availability time series supports the selection of critical weather years

Literature

- Kittel & Schill (2024): Measuring the Dunkelflaute: How (not) to analyze variable renewable energy shortage. *Environmental Research: Energy 1.3 (2024): 035007.* https://doi.org/10.1088/2753-3751/ad6dfc

- Kittel, M., Schill, WP. Multi-threshold time series analysis enables characterization of variable renewable energy droughts in Europe. *Commun Earth Environ* **7**, 242 (2026). https://doi.org/10.1038/s43247-026-03251-2

- Kittel, M., Roth, A. & Schill, WP. Long-duration electricity storage needs for coping with Dunkelflaute events in Europe. *Nat Commun* **17**, 4210 (2026). https://doi.org/10.1038/s41467-026-72681-5

- Schmidt, Roth, and Schill (2025): “A mix of long-duration hydrogen and thermal storage enables large-scale electrified heating in a renewable European energy system”. arXiv preprint: https://doi.org/10.48550/arXiv.2505.21516.

Thank you for your attention.

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