

Coping with the Dunkelflaute

Power sector implications of variable renewable
energy droughts in Europe

Martin Kittel

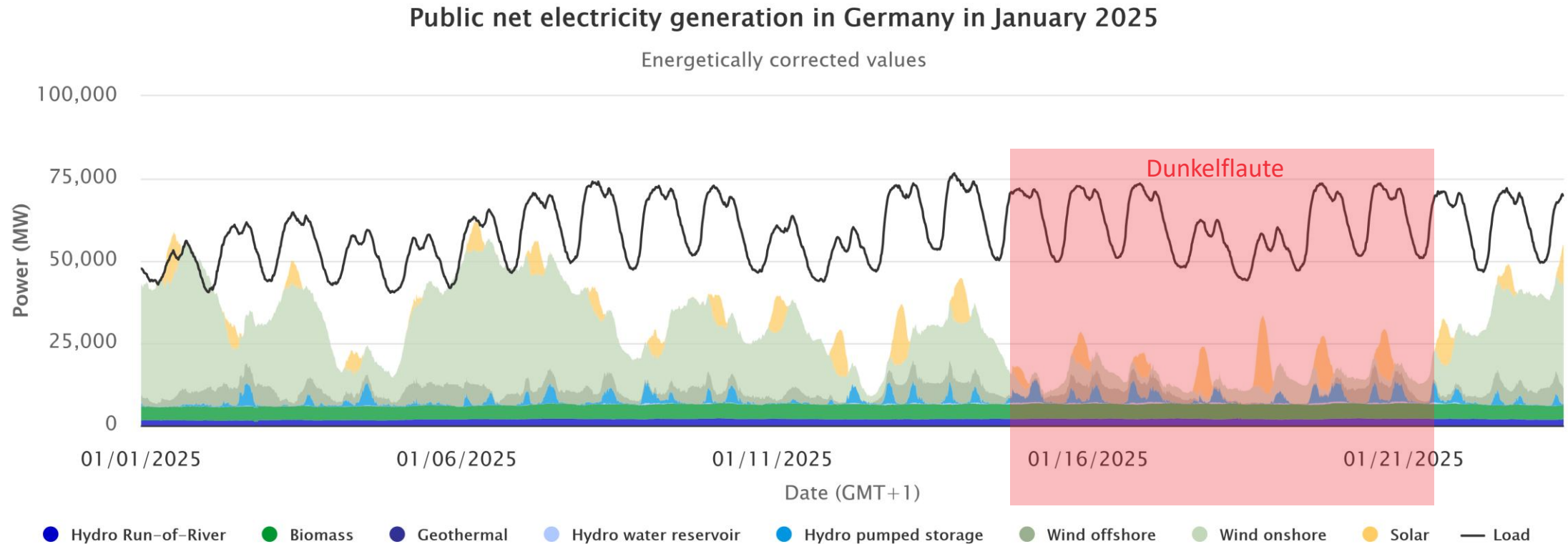
Berlin / Sevilla, 18 June 2026

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1. Motivation

Example of a Dunkelflaute event in Germany



Energy-Charts.info; Data Source: ENTSO-E, AGEE-Stat, Destatis, Fraunhofer ISE, AG Energiebilanzen; Last Update: 01/24/2025, 12:51 PM GMT+1

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

Dunkelflaute events in public, policy, and academic discourse

Süddeutsche Zeitung

Meine SZ | SZ Plus | Ukraine | Israel | Polen | Politik | Wirtschaft | Meinung

Home » Wissen » Energie » Energie, Wind und Dunkelflaute von Wind- und Solarenergie

Übersicht

Sicher durch die Dunkelflaute

2. Februar 2023, 5:46 Uhr | Lesedauer: 3 min

Deutschlands Windräder schwächelten in den vergangenen Wochen...

Tom Brown • 1st
Professor of "Digital Transformation in Energy Systems" at Technical Universit...
1d •

Our German live-data fully-renewable electricity simulation deals with another wind lull (Dunkelflaute)! Because of repeated Dunkelflaute, the hydrogen stor now down to 60% full. Will be exciting to see how much further it runs down th winter. The storage was dimensioned by passing through the worst winter 201 which you can see in the right graphic of the hydrogen storage filling level.

Link to full simulation results (click on each scenario):
https://lnkd.in/gVP_VDeE

Obviously electrolytic hydrogen isn't the only solution, see my previous post:
<https://lnkd.in/eirv5f8t>

Abteilung Hydrometeorologie

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

DWD

Klimatologische Einordnung der „Dunkelflaute“ im November 2024

Autoren: Frank Kaspar¹, Franziska Bär², Jaqueline Drücke³, Paul James⁴, Jennifer Ostermöller⁵, Magdalena Zepperitz¹
Stand: 17.12.2024

Frankfurt

Dirk Middendorf • Following
Experte für Energiewirtschaft | Stadtwerke-Geschäftsführer | Energiewende-...
1mo •

Gibt es di...
schlimm? ...
sich im A...

Als Reakt...
ihrer Eign...
Botschaft...
sogenann...

- frei erf...
viel calt...

Met Office

Characterising Adverse Weather for the UK Electricity System, including addendum for surplus generation events

Wissenschaftliche Dienste

Deutscher Bundestag

Dokumentation

Sicherstellung der Stromversorgung bei Dunkelflauten

Dunkelflaute hat es jetzt jed...
escheitert. Ohne Hilfe aus d...
n Kohle geht es nicht. Deuts...
rgiepolitik.

Schornsteine eines Blockheizkraftwerkes in Berlin - warum produzierten nicht alle verfügbaren Kraftwerke während der Dunkelflaute Strom?

Quelle: dpa



VREDA

Characterization of European Dunkelflaute events

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

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 *Kittel, Roth, and Schill (2026), Nature Communications*
- Role of zero-emission fossil-fueled backup with CCS
- 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

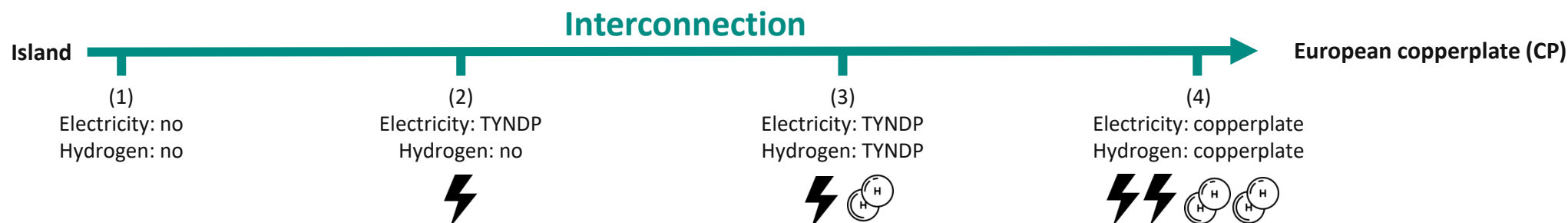
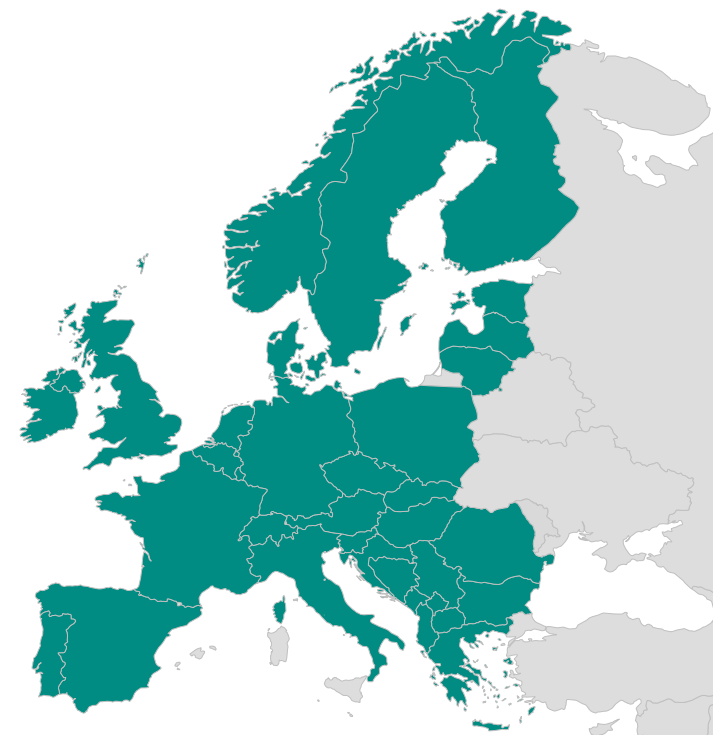
- No fossil fuels, CCS, or nuclear power (relaxed in sensitivity)
- Import of green hydrogen possible
- Largely parameterized to TYNDP 2022 - Distributed Energy
- Sector-coupling “light”

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

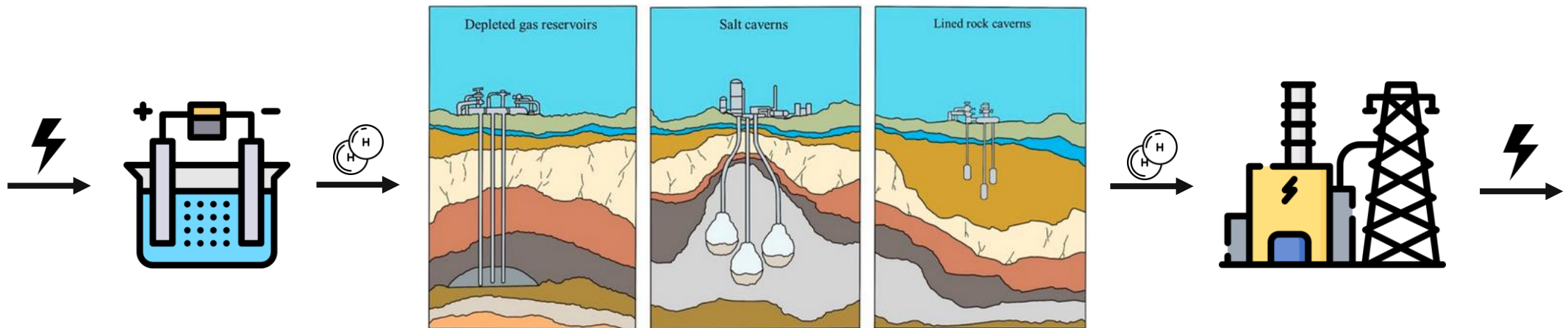
- Different interconnection levels



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

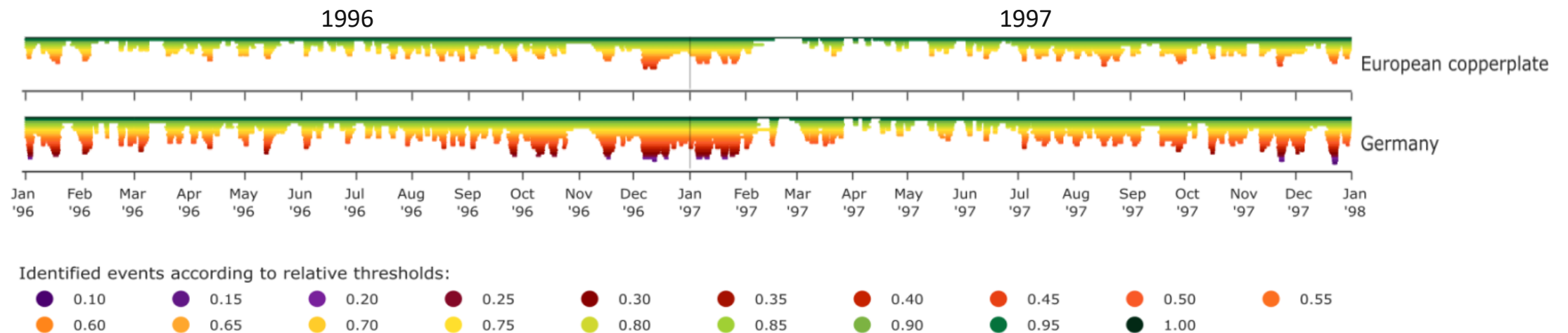


[Chen et al. \(2025\)](#), [flaticon.com](#)

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

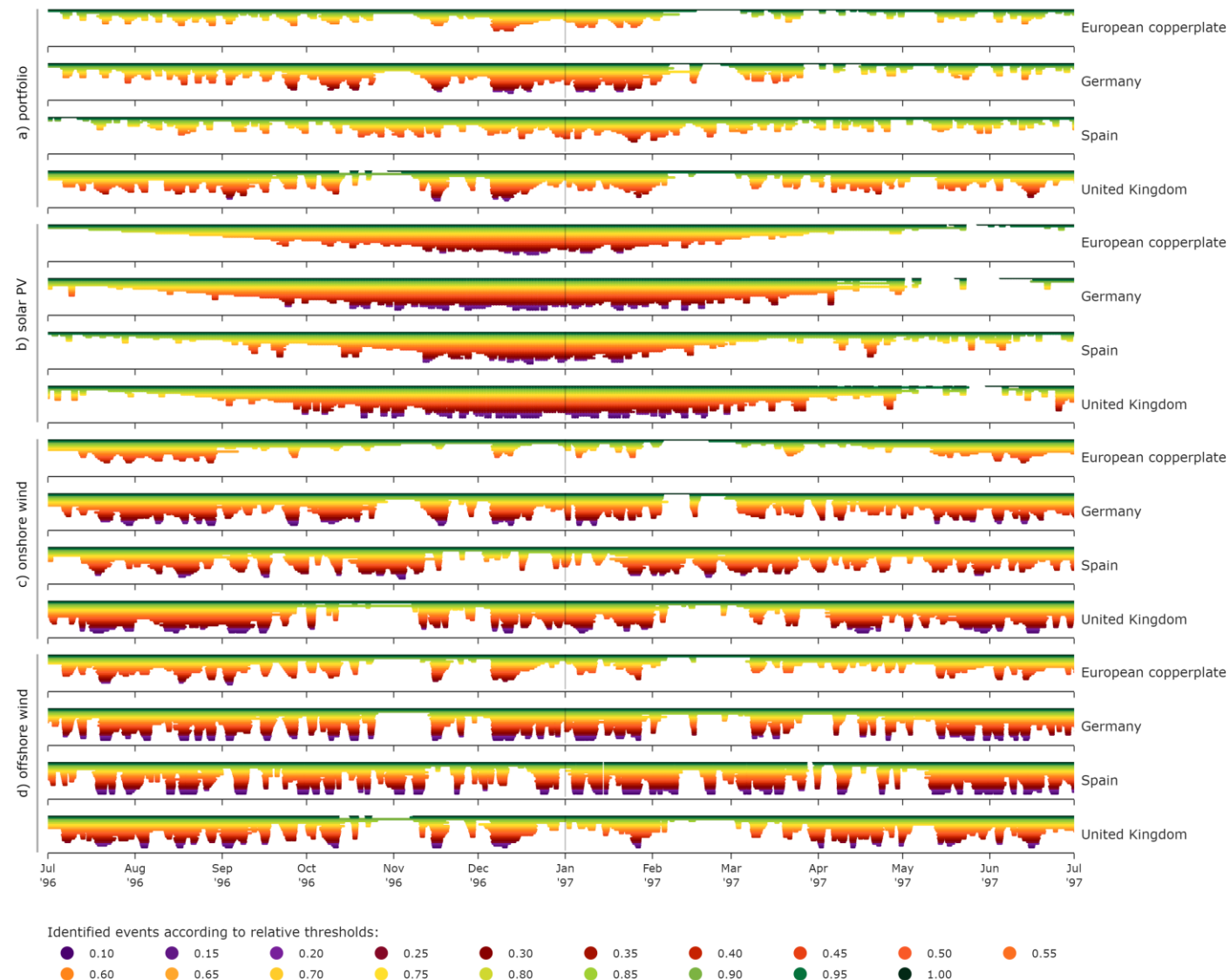
- droughts primarily in summer, some also in winter

VRE portfolio

- product of solar seasonality and significant wind droughts

Complementary wind and solar profiles

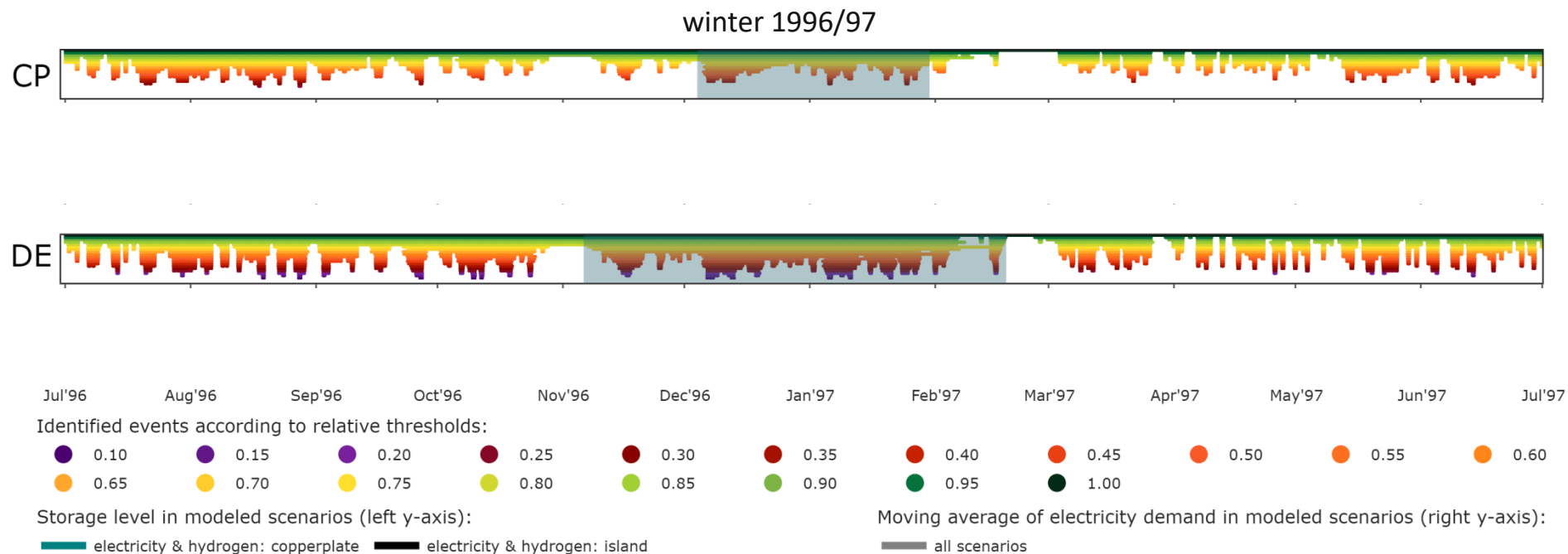
- Portfolio effect within regions
- Balancing effect across regions



Identification of extreme Dunkelflaute events

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

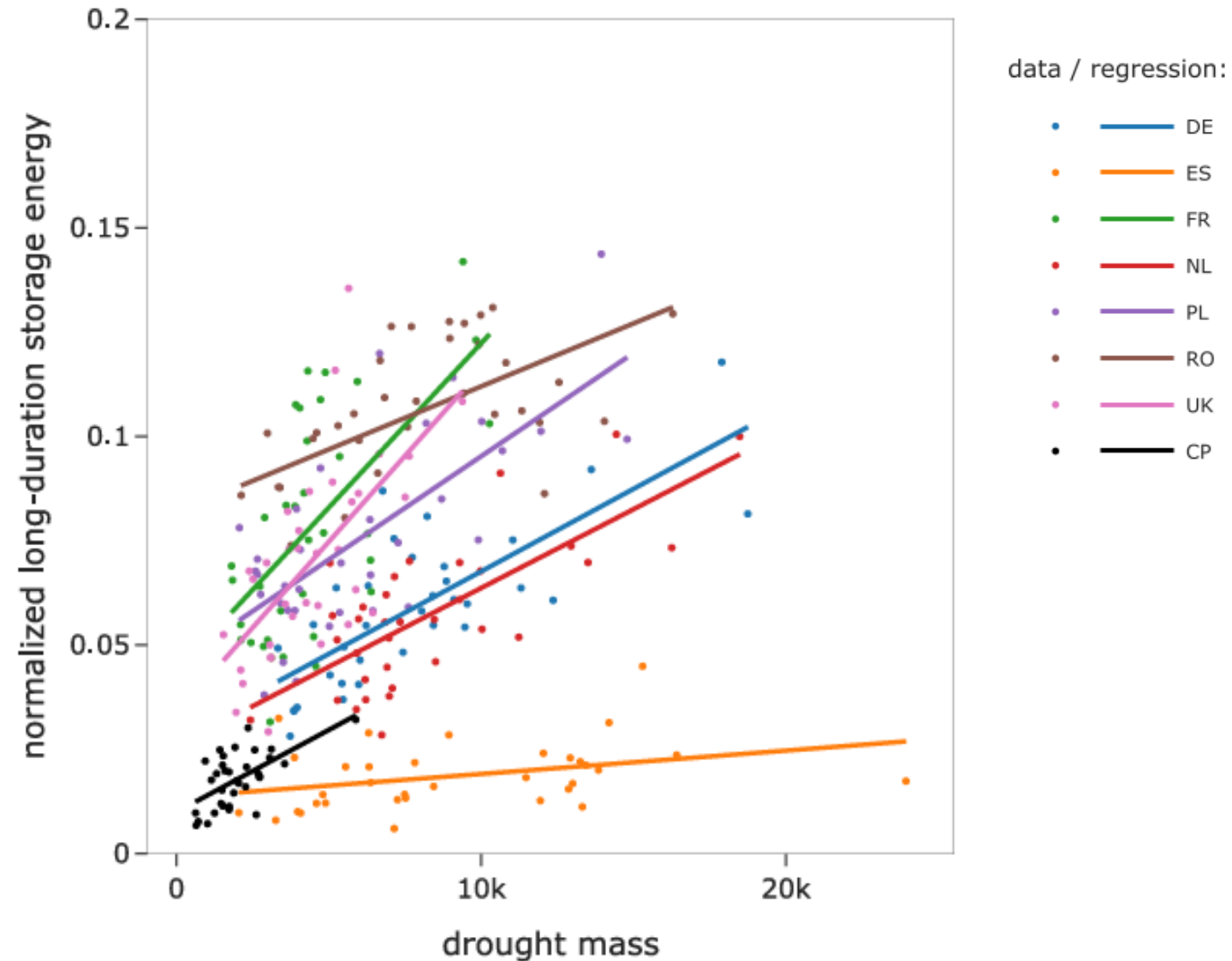
- No meaningful definition for extreme Dunkelflaute events
- Drought mass metric to find events that drive long-duration storage discharge
- Sequence of severe shortage events within a long-lasting, contiguous low-availability period
- Span across turn of year
- Most extreme European event in the data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



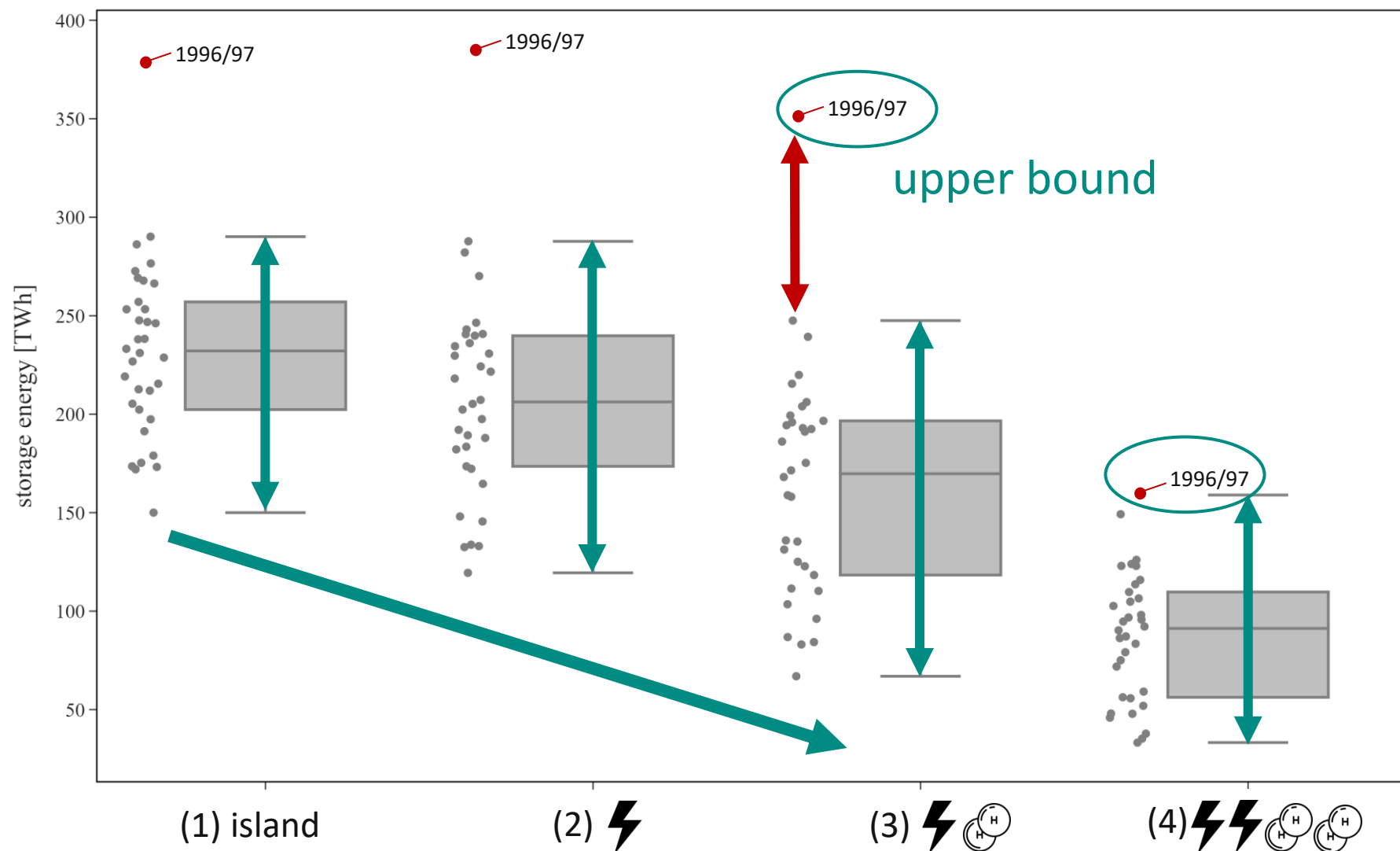
Extreme Dunkelflaute events and long-duration electricity storage energy

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



Sensitivity analysis: Impact of nuclear power

Exogenous nuclear capacity (TYNDP 2022)

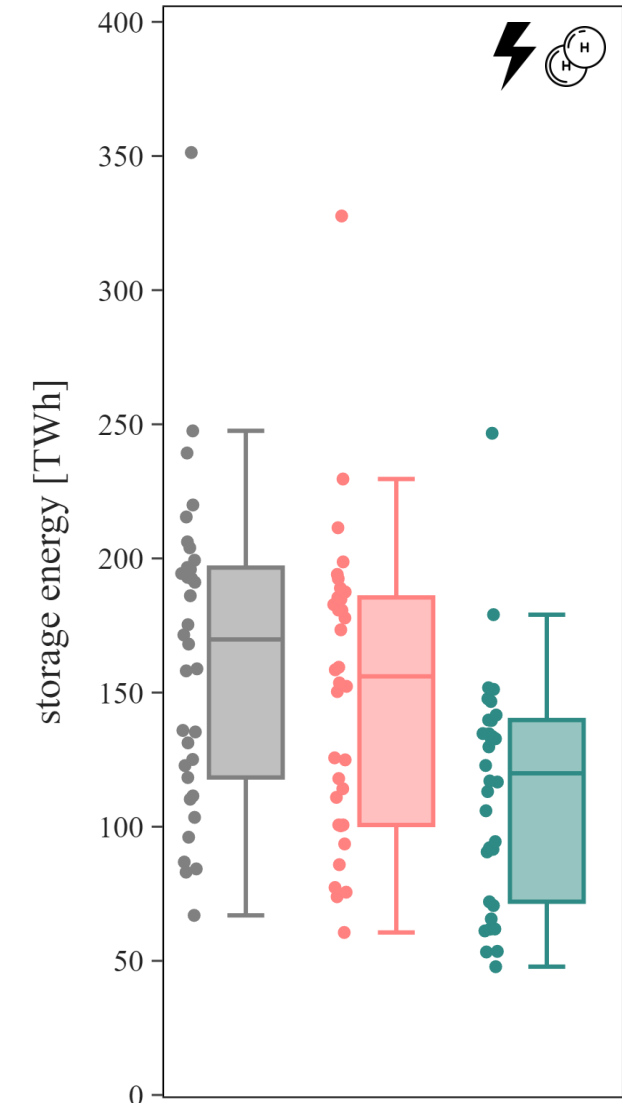
- Default: 0 GW 
- Low levels: 24 GW 
- High levels: 102 GW 
- Policy-relevant exchange of electricity and hydrogen, scenario (3)

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



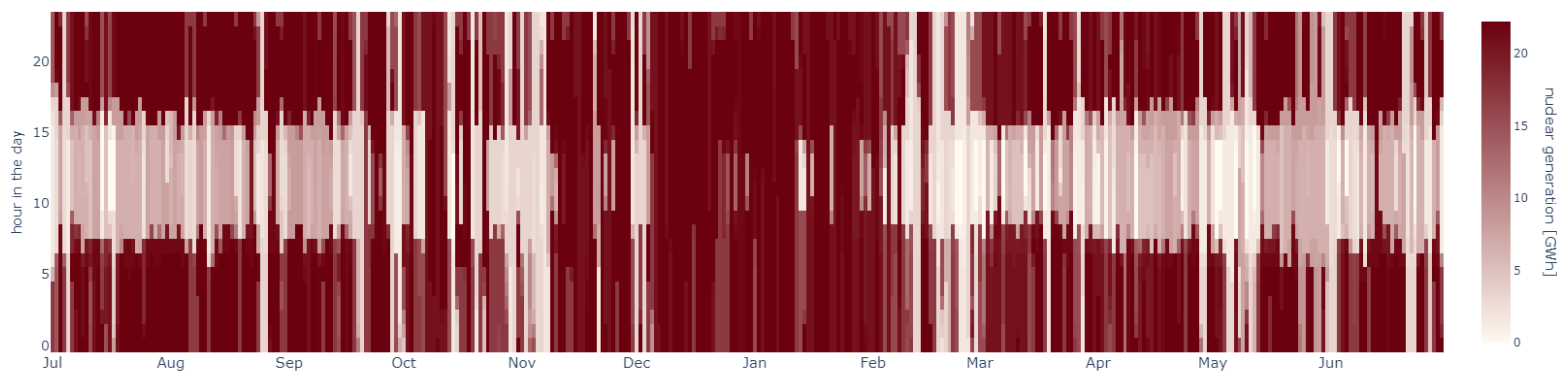
Sensitivity analysis: Impact of nuclear power

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

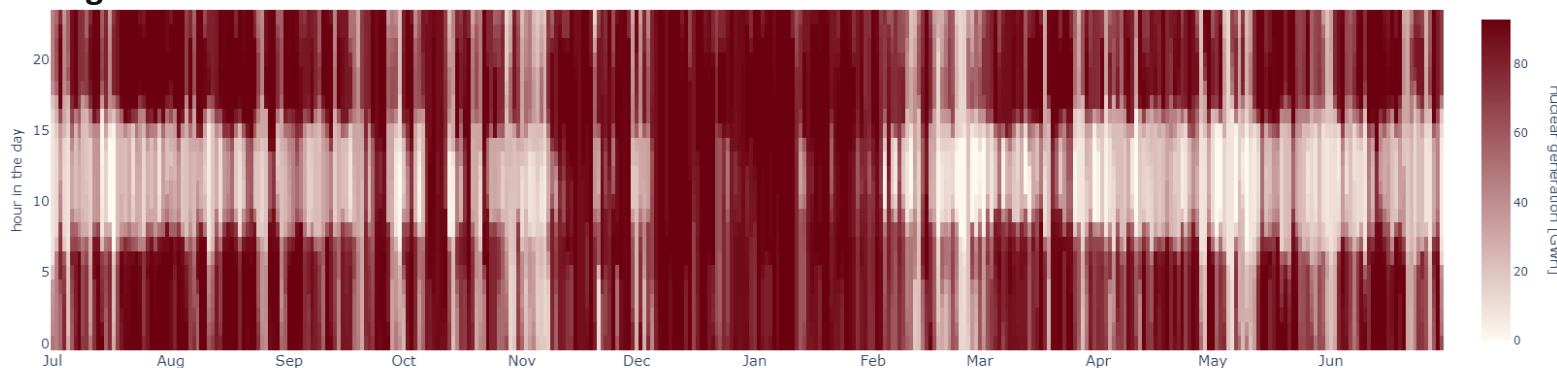


- Flexible operation to complement diurnal solar PV fluctuations
- Continuous dispatch during extreme Dunkelflaute events → reduces optimal long-duration storage discharging and energy capacity

Low levels of nuclear



High levels of nuclear



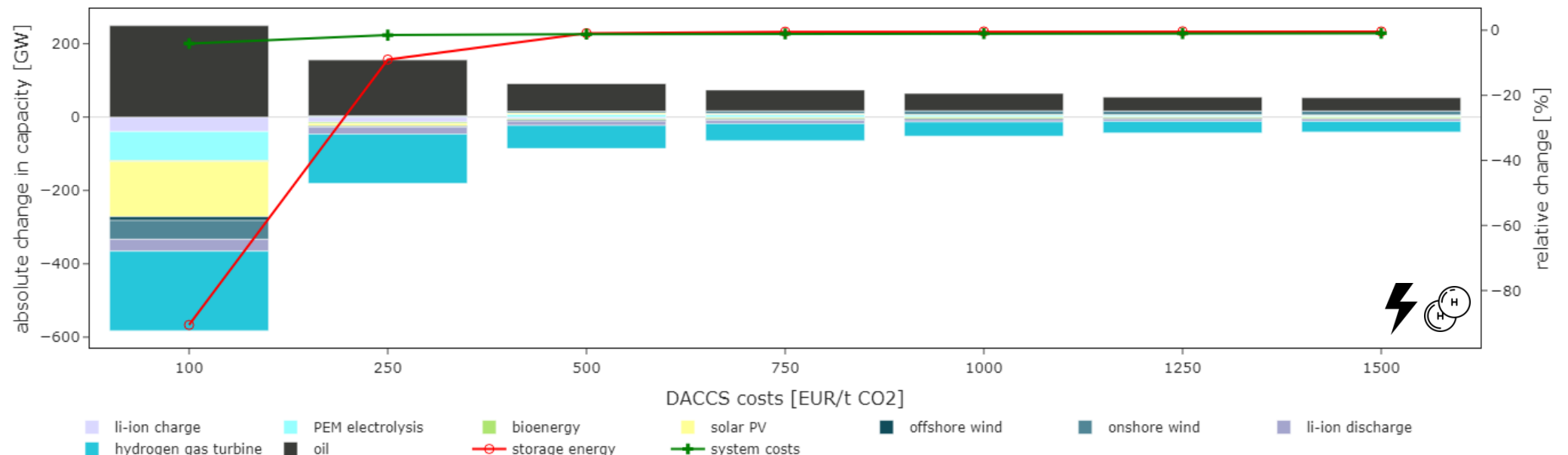
Sensitivity analysis: oil-fired backup capacity with CCS

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

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

Policy implications

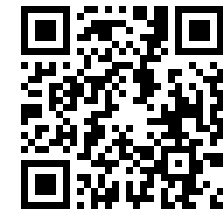
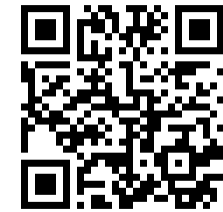
- Long-duration storage indispensable for renewable energy systems
- Lead times 5-15 years → early adoption for rapid scaling required
- Deployment incentives for sufficient capacity likely required

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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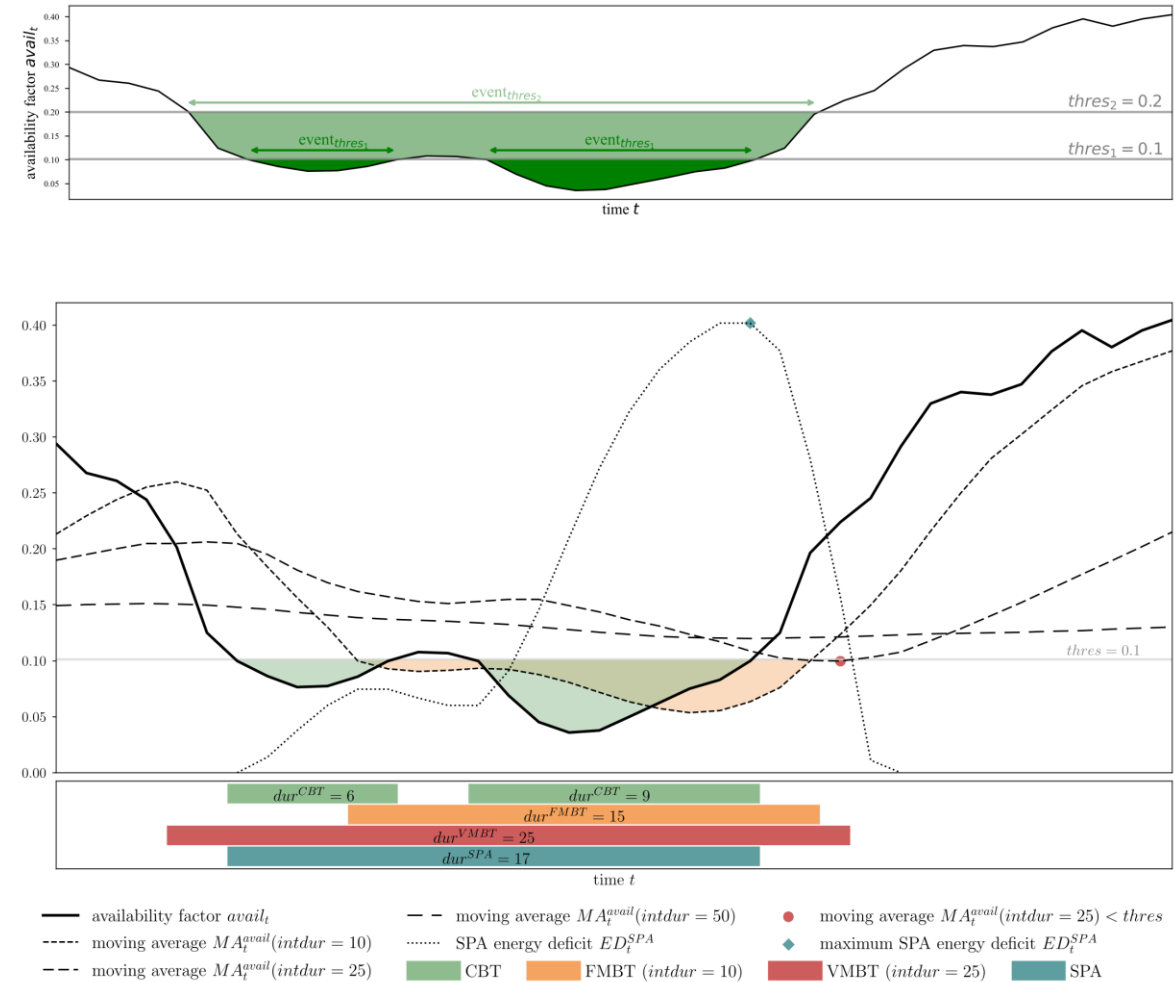


Backup

Methods: renewable drought definition and identification

VREDA – Variable Renewable Energy Drought Analyzer

- Open-source time series analysis tool
- Drought definition: event notion → consecutive period below drought threshold with variable duration to capture complete temporal extend of droughts
- Drought thresholds: ranging from 10 to 100% of multi-annual mean → inter-regional & technological comparability
- Drought identification method: VMBT → finds unique set of events with longest duration possible, pools mutually dependent periods, avoids double counting and overlap



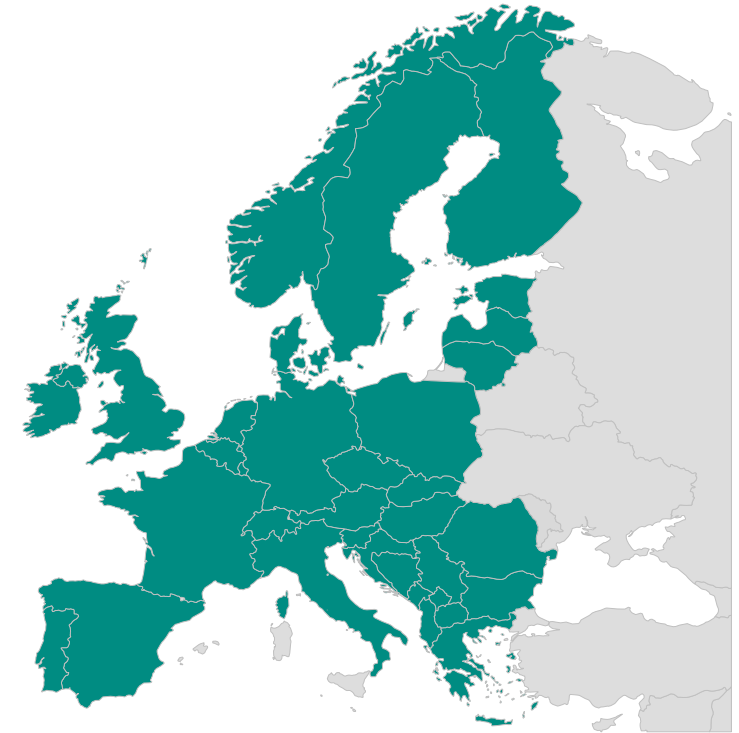
Research design: Dunkelflaute characterization

Variable renewable energy sources in a European power sector

- 34 European countries
- Individual technologies: solar PV, onshore wind, offshore wind
- Policy-oriented renewable technology portfolios (capacity mix acc. to TYNDP 2022 - Distributed Energy)
- 38 historical weather years (1982 – 2019) → Source: Pan-European Climate Database 2021.3

Interconnection scenarios

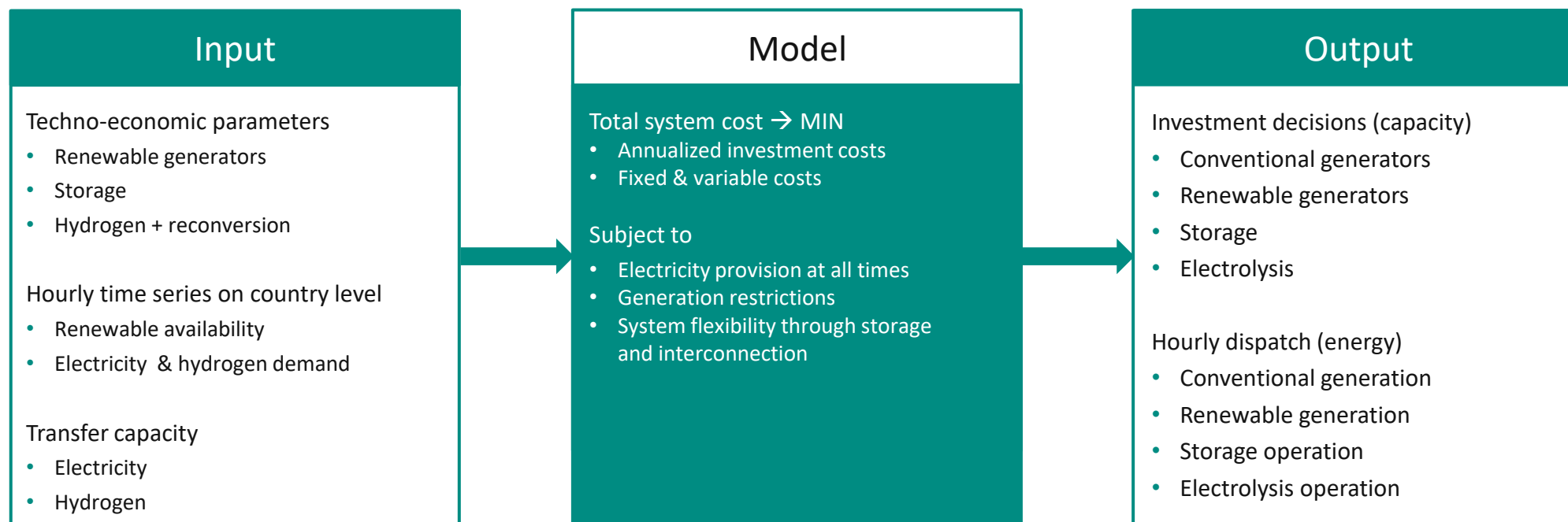
- Island scenario: no electricity exchange
- Pan-European copperplate: unconstrained electricity exchange



Methods: Power sector modeling

DIETER – Dispatch and Investment Evaluation Tool with Endogenous Renewables

- Open-source power sector model
- Linear partial equilibrium model → minimizes total system costs
- European setting with simplified grid representation (one node per country)



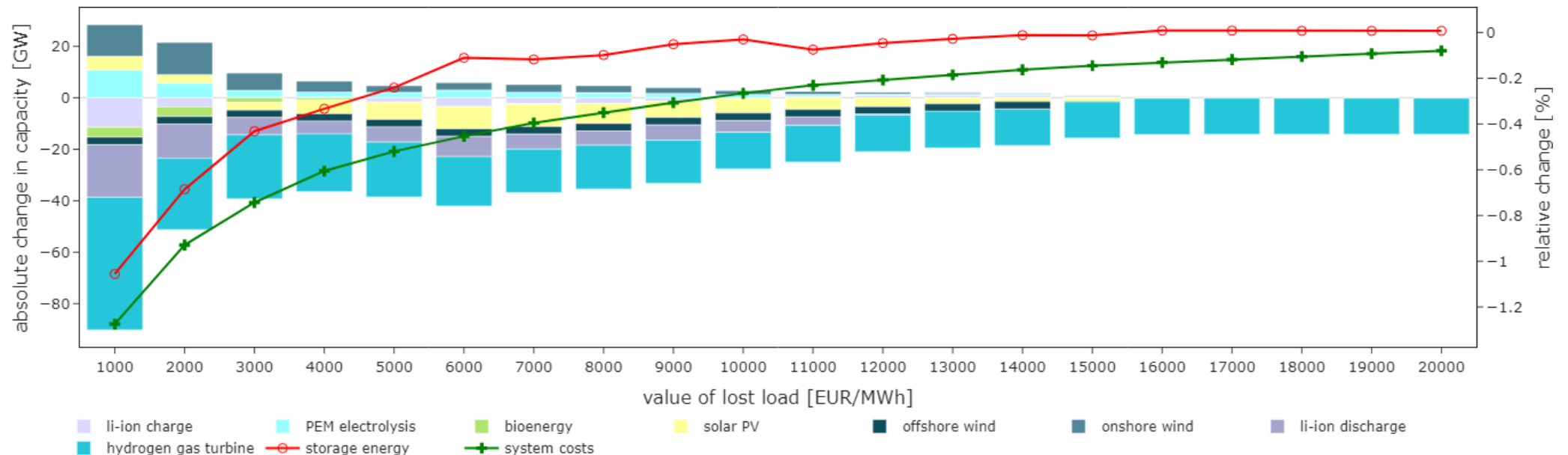
Sensitivity analysis: load shedding

Endogenous load shedding

- Value of lost load (VOLL) as approximation of socio-economic costs: e.g., varies between 7.000 and 17.000 EUR/MWh in Germany
- Note: Not a single cost, but large range for various end energy users

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

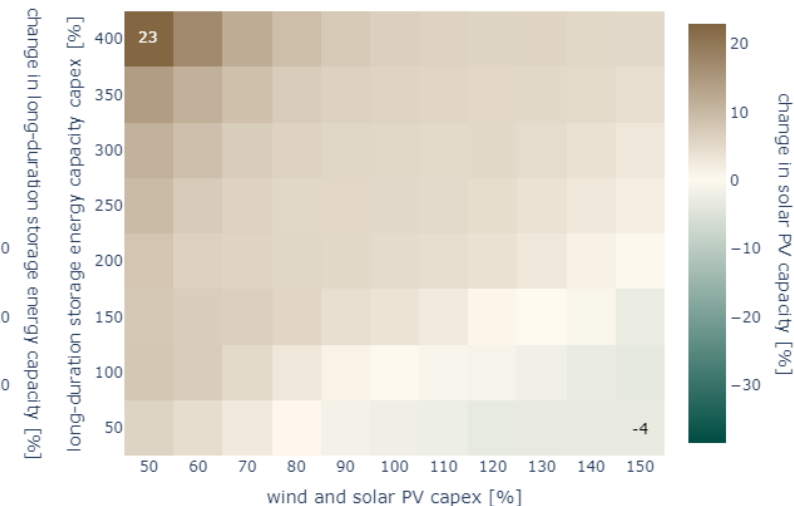
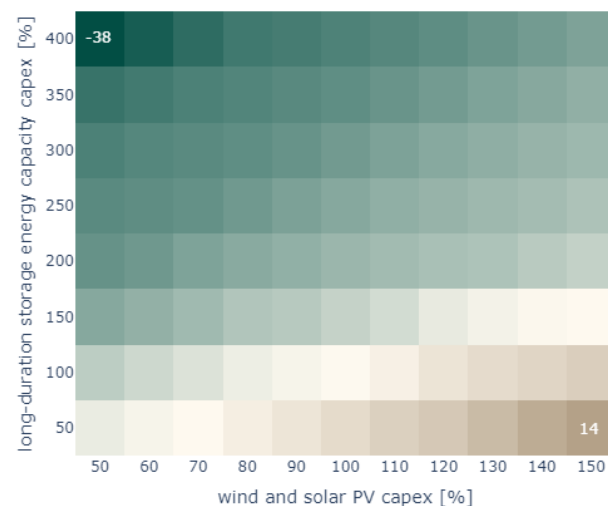
- Lower VOLL displaces long-duration discharging capacity and shorter-duration flexibility such as bioenergy or batteries
- Higher VOLL: effect diminishes
- Long-duration storage energy and system costs hardly affected



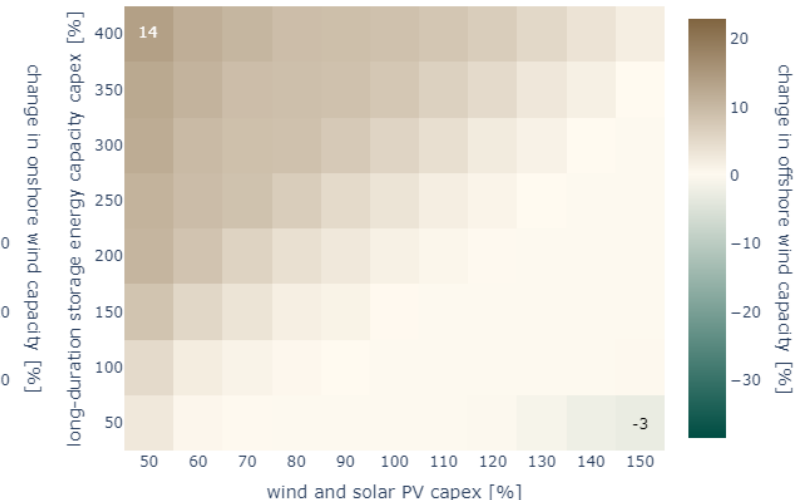
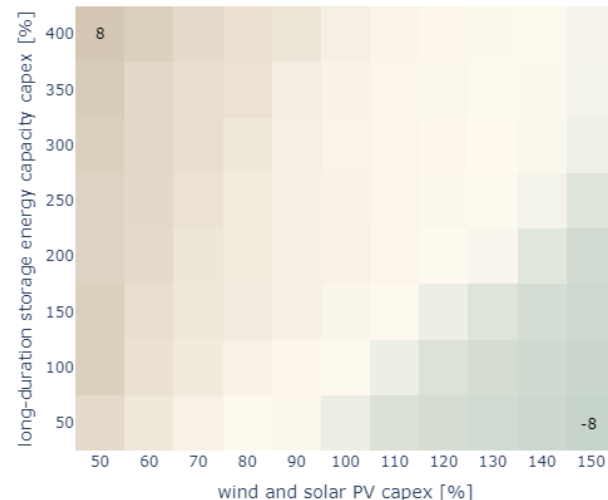
Sensitivity analysis: capex variation for wind, solar PV, and storage energy

Sensitivity for 1996/97 under policy-relevant interconnection (3)

- Massive cost reductions of wind and solar PV → likely to continue with economies of scale
- Hydrogen-based underground storage hardly deployed → larger uncertainty range

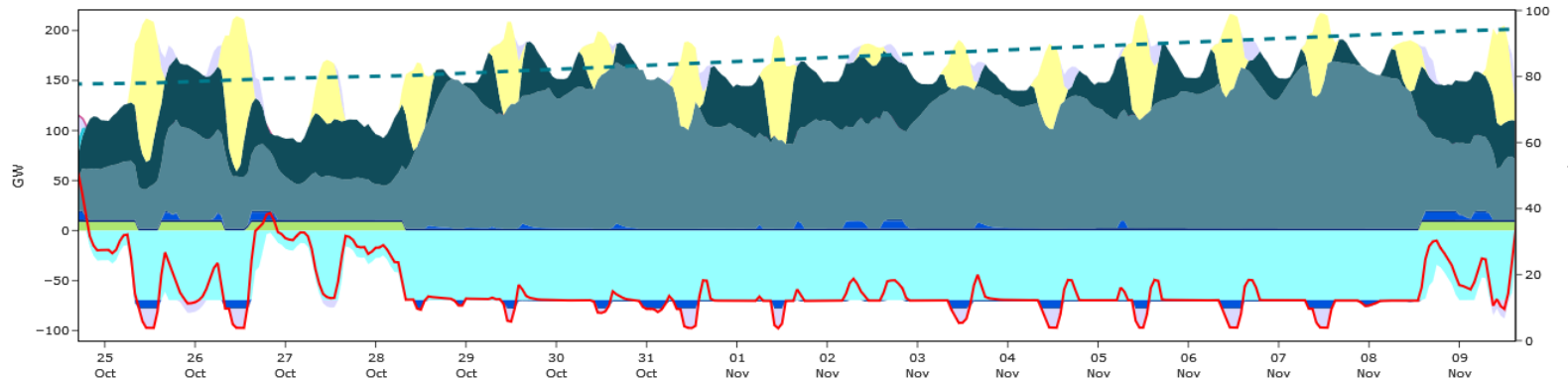


- Lower renewable capex favors overbuilding over long-duration storage due to lower residual demand
- Lower storage costs vice versa
- Moderate renewable capex reductions most plausible → storage hardly affected



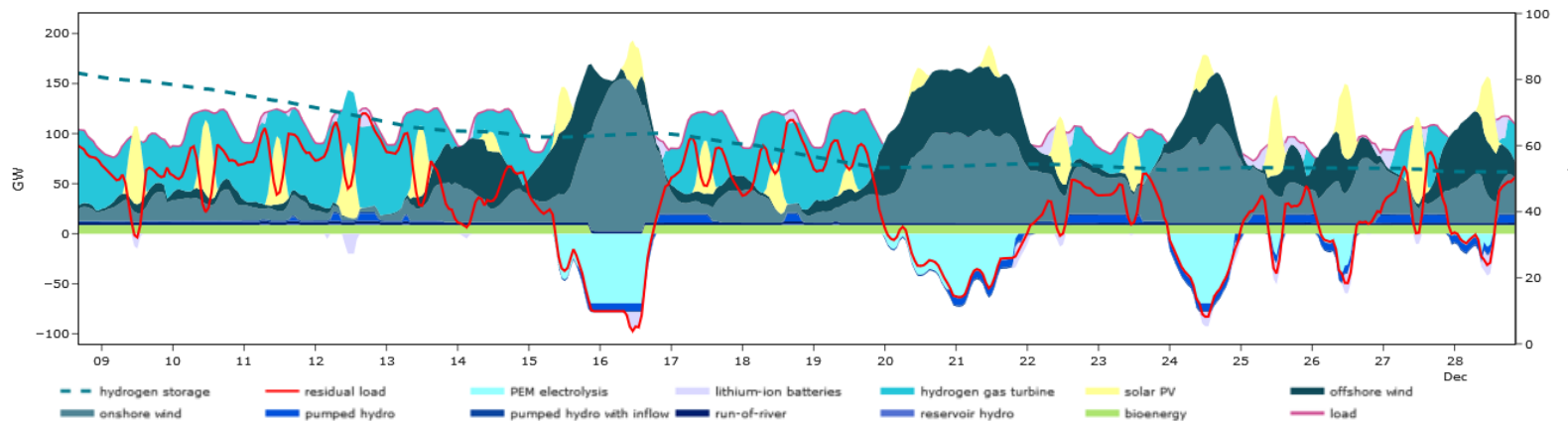
Interaction of flexibility options (island systems)

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

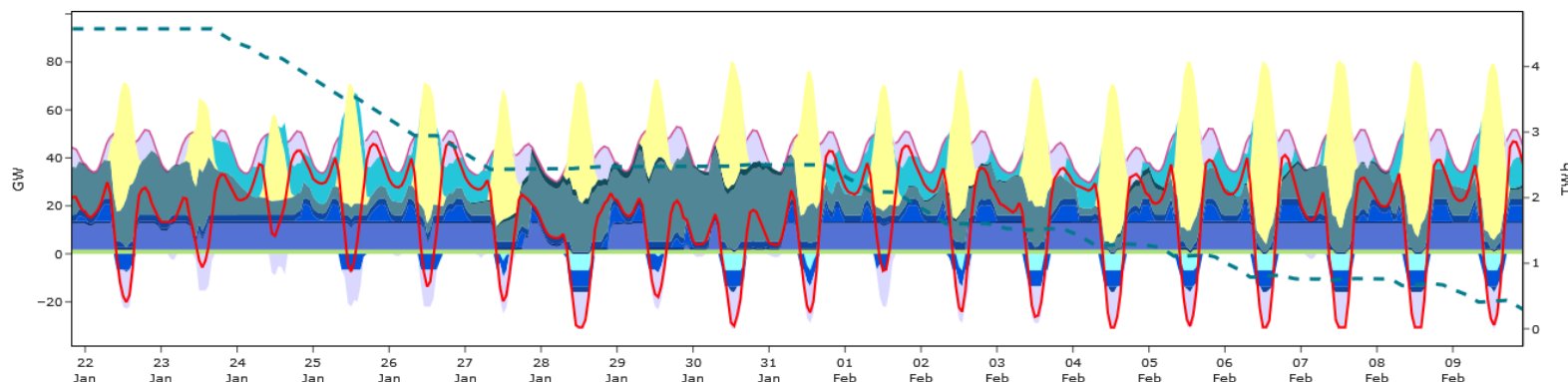
Power sector operation in Germany during extreme droughts



- 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

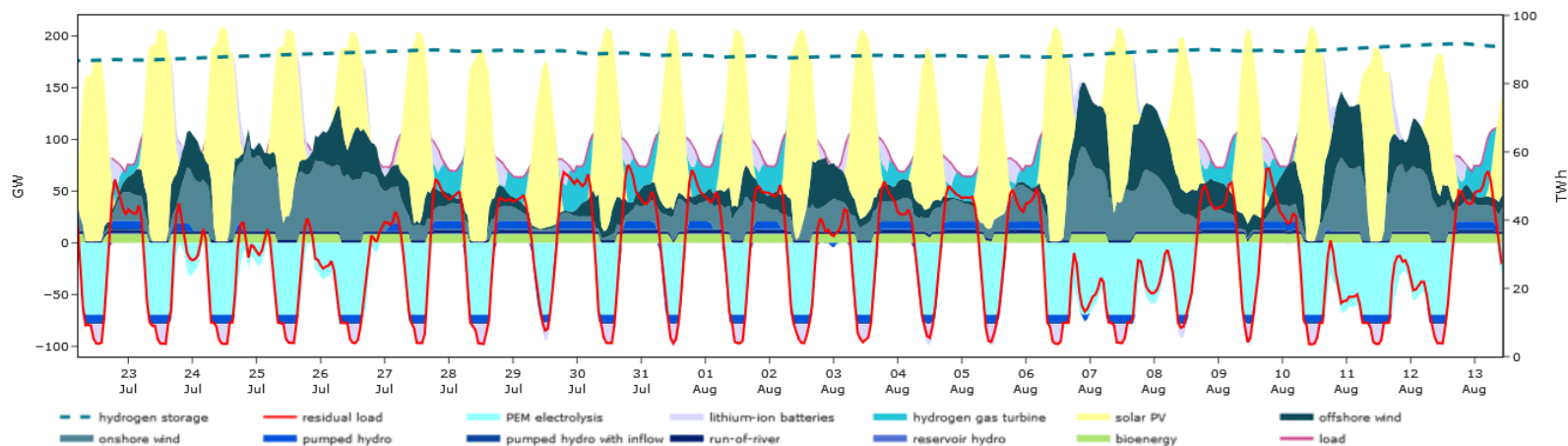
Interaction of flexibility options (island systems)

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