

Community of Practice

Coping with the Dunkelflaute

Power sector implications of variable renewable
energy droughts in Europe

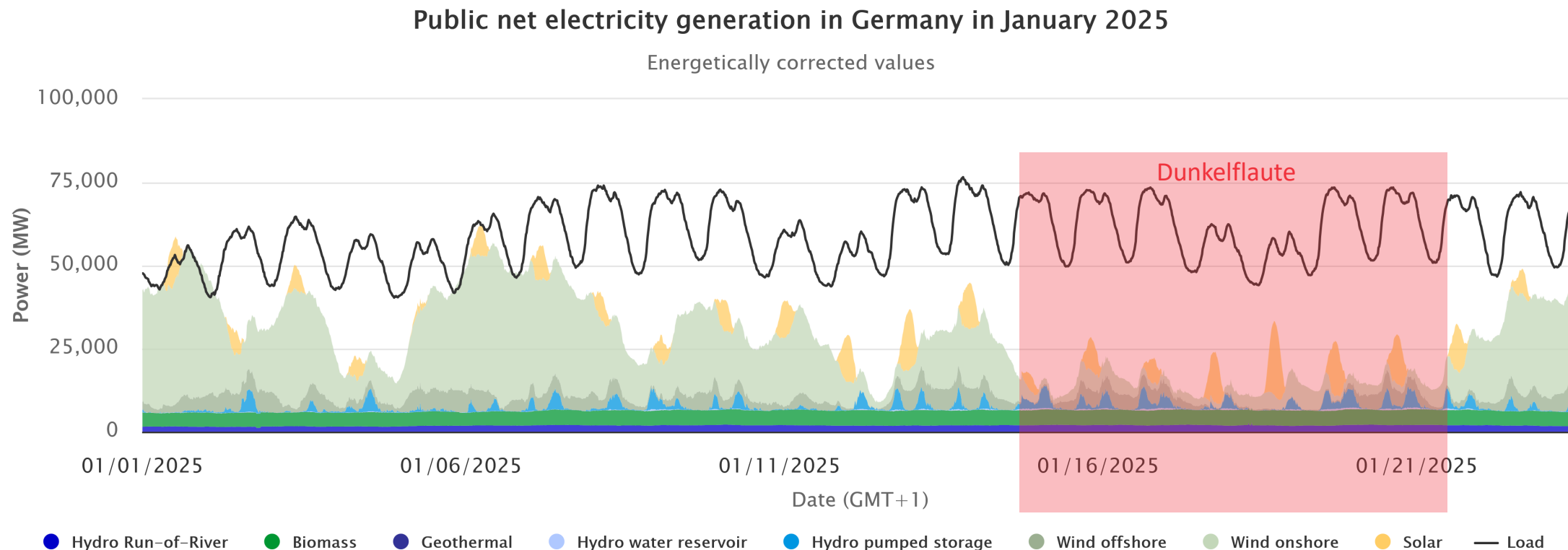
Martin Kittel
Berlin, 28 May 2026

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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

Home > Wissen > Energie > Energie: Wie robust sind Dunkelflauten von Wind- und Solaranlagen?

Ökostrom
Sicher durch die Dunkelheit

2. Februar 2021, 5:46 Uhr | Lesedauer: 3 min



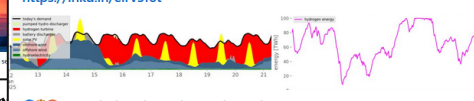
Deutschlands Windräder schwächelten in den vergangenen Wochen...

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

Our German live-data fully-renewable electricity simulation deals with another wind lull (Dunkelflaute)! Because of repeated Dunkelflauten, 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/eiv9f8t>



Abteilung Hydrometeorologie

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Klimatologische Einordnung der „Dunkelflaute“ im November 2024

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

Frankfurter Allgemeine Zeitung

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

Gibt es die Gefahr, dass die Energiewende scheitert?

Als Reaktion auf die Botschaft sogenannter „Energiewende“-Kritiker...

- frei erfunden...

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 jeder weiß. Ohne Hilfe aus dem Ausland geht es nicht. Deutsche Energiepolitik.



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 Schmidt, Roth, and Schill (2025), *pre-print*
- Interactions of long-duration electricity and heat storage

2. Research design

Research design: Power sector implications

100% renewable European power sector

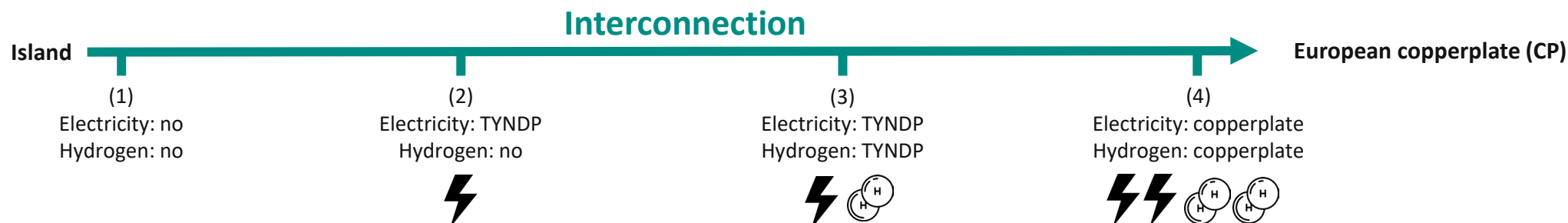
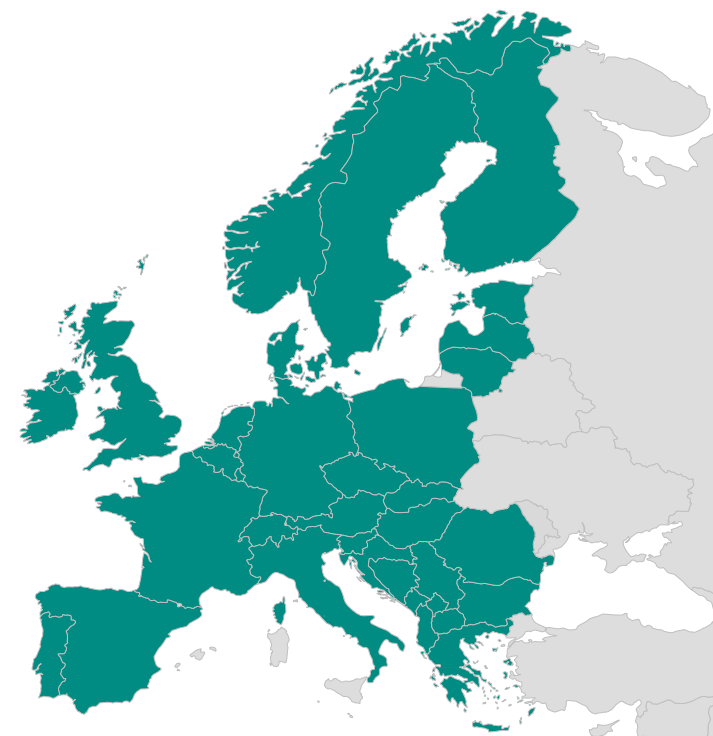
- No fossil fuels, CCS, or nuclear power (relaxed in sensitivity)
- Import of green hydrogen possible
- Largely parameterized to TYNDP 2022 - Distributed Energy
- Sector-coupling “light”: simplified industry, heat, transport

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

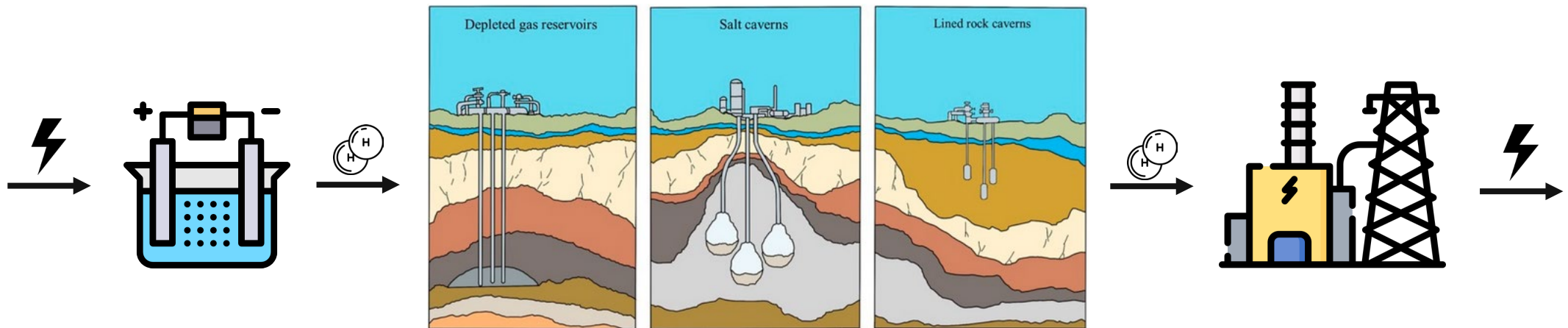
- Different interconnection levels



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

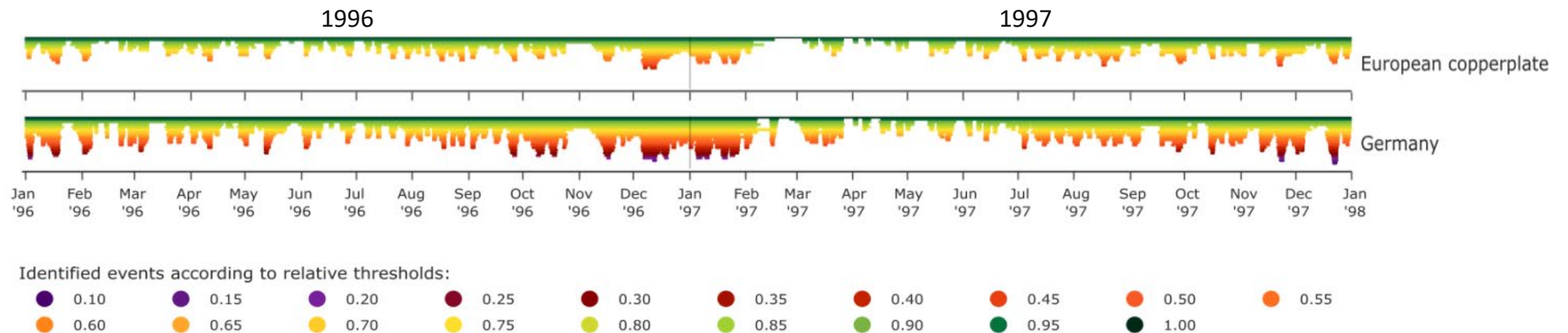


[Chen et al. \(2025\)](#), [flaticon.com](#)

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

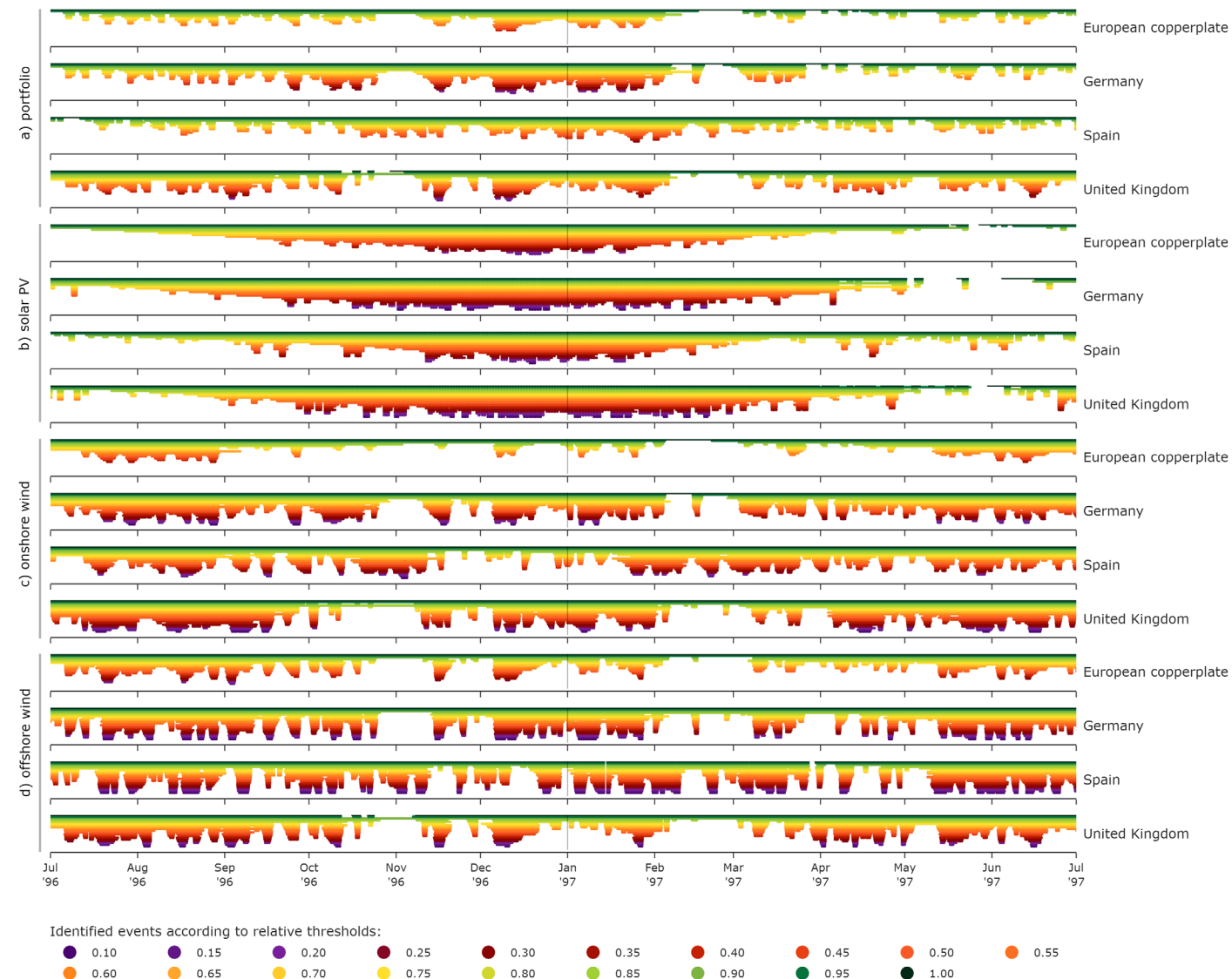
- droughts primarily in summer, some also in winter

VRE portfolio

- product of solar seasonality and significant wind droughts

Complementary wind and solar profiles

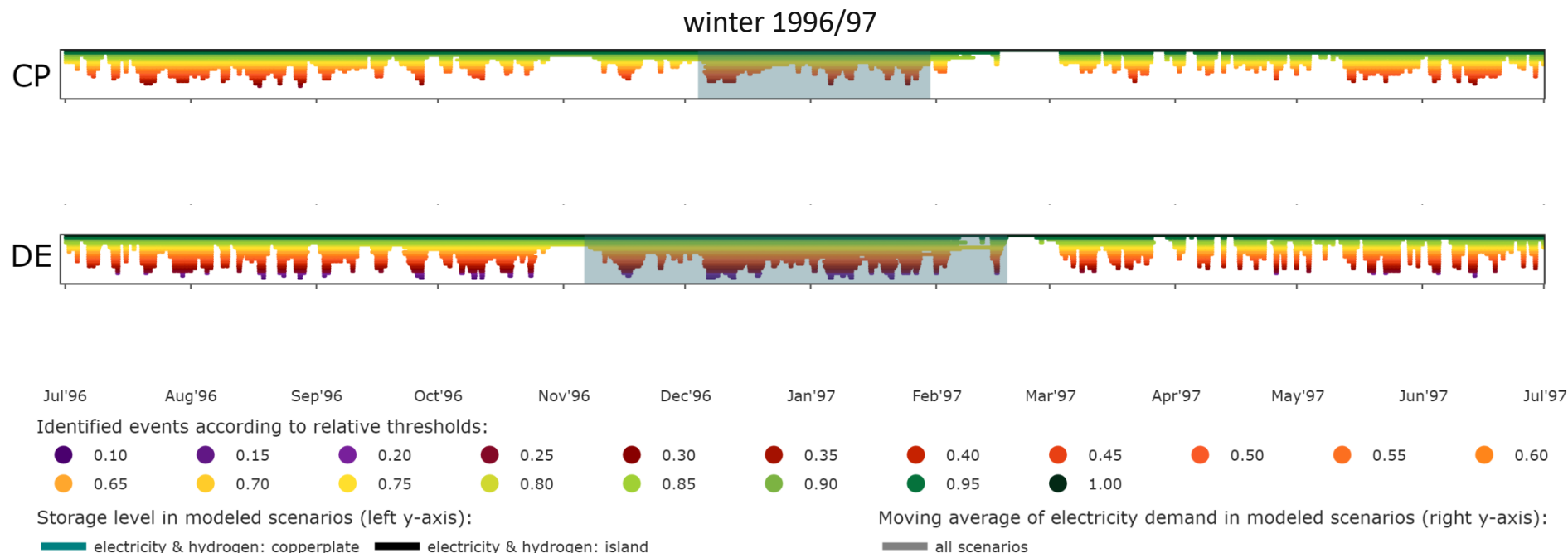
- Portfolio effect within regions
- Balancing effect across regions



Identification of extreme Dunkelflaute events

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

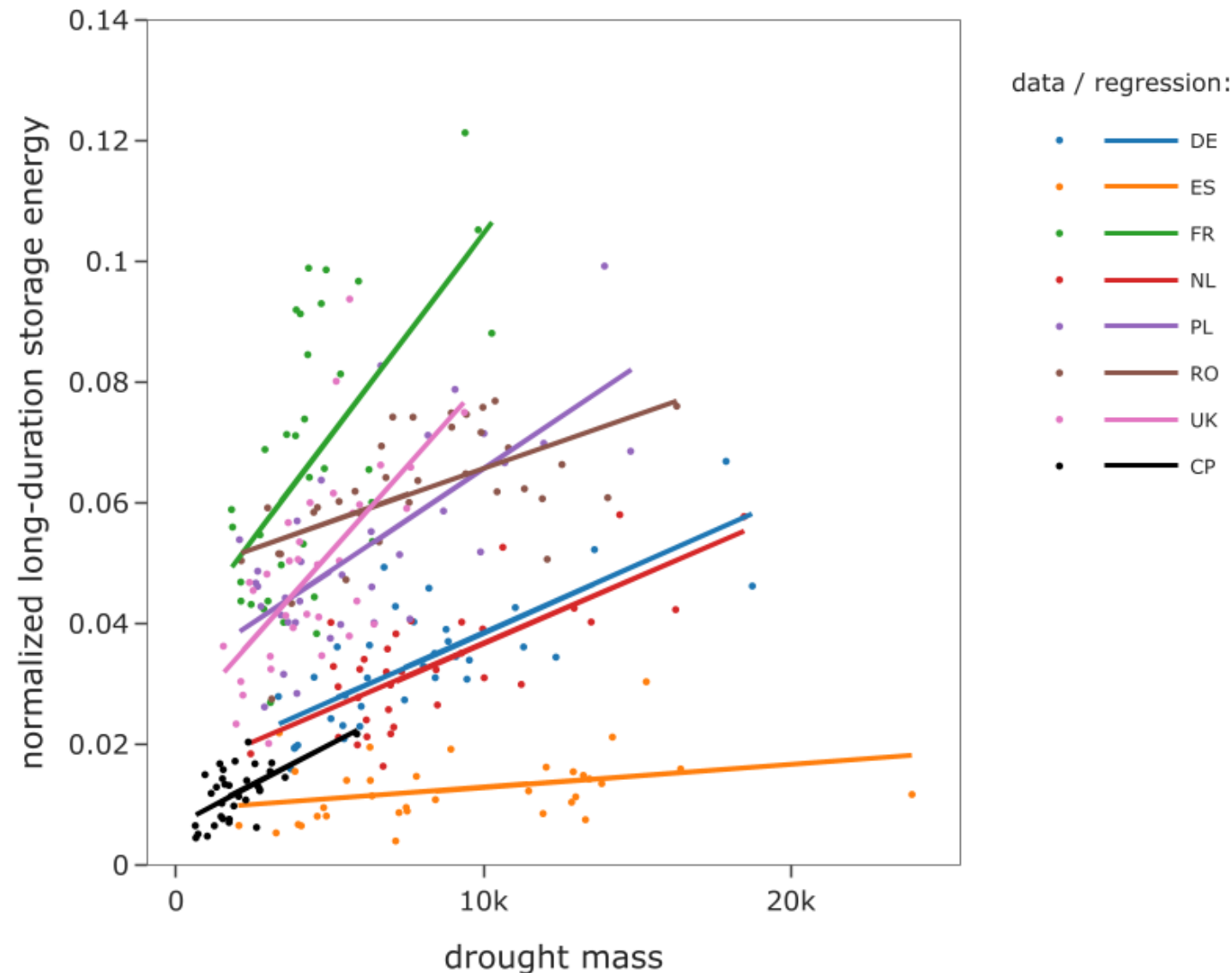
- No meaningful definition for extreme Dunkelflaute events
- Drought mass metric to find events that drive long-duration storage discharge
- Sequence of severe shortage events within a long-lasting, contiguous low-availability period
- Span across turn of year
- Most extreme European event in the data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



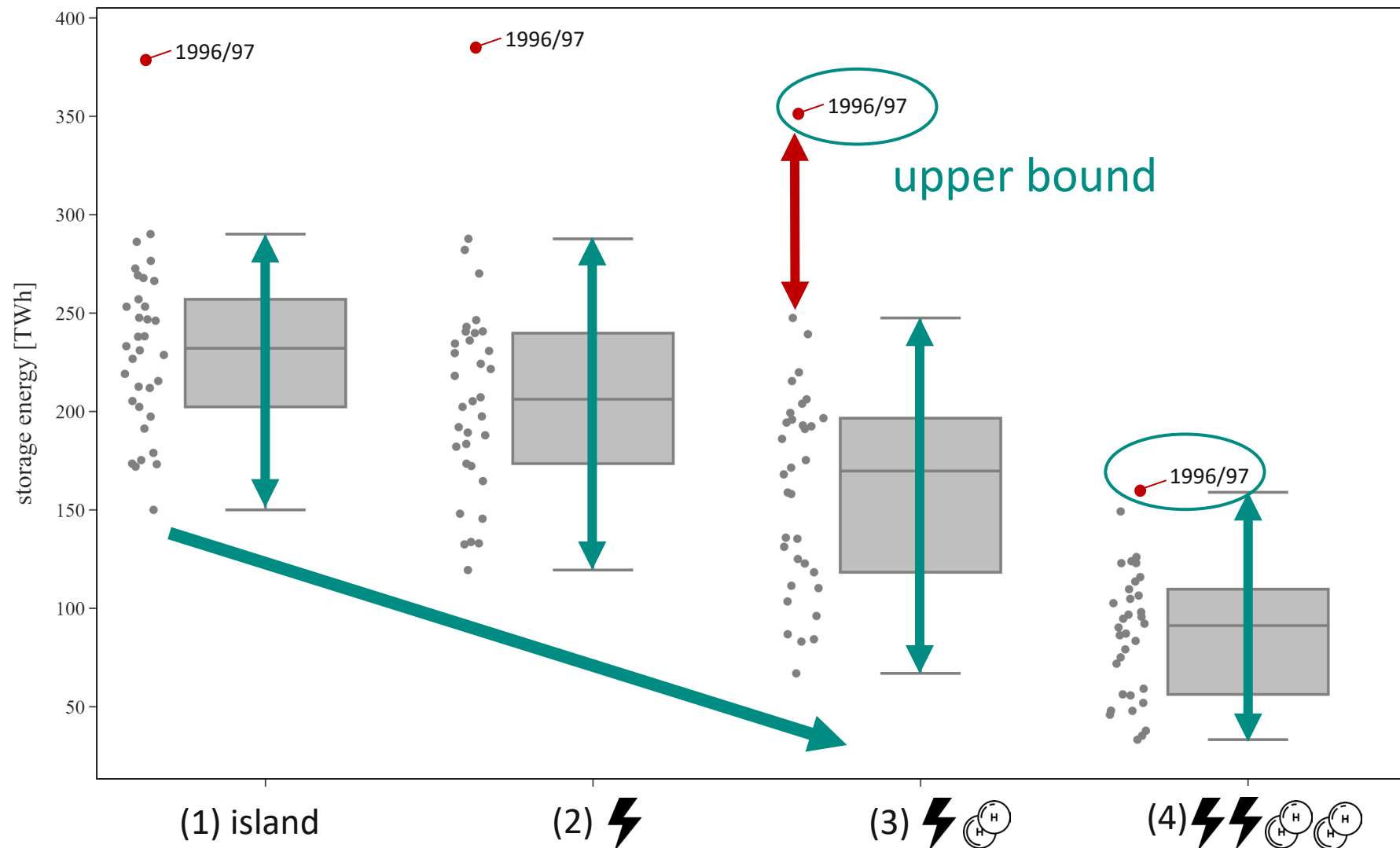
Extreme Dunkelflaute events and long-duration electricity storage energy

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)

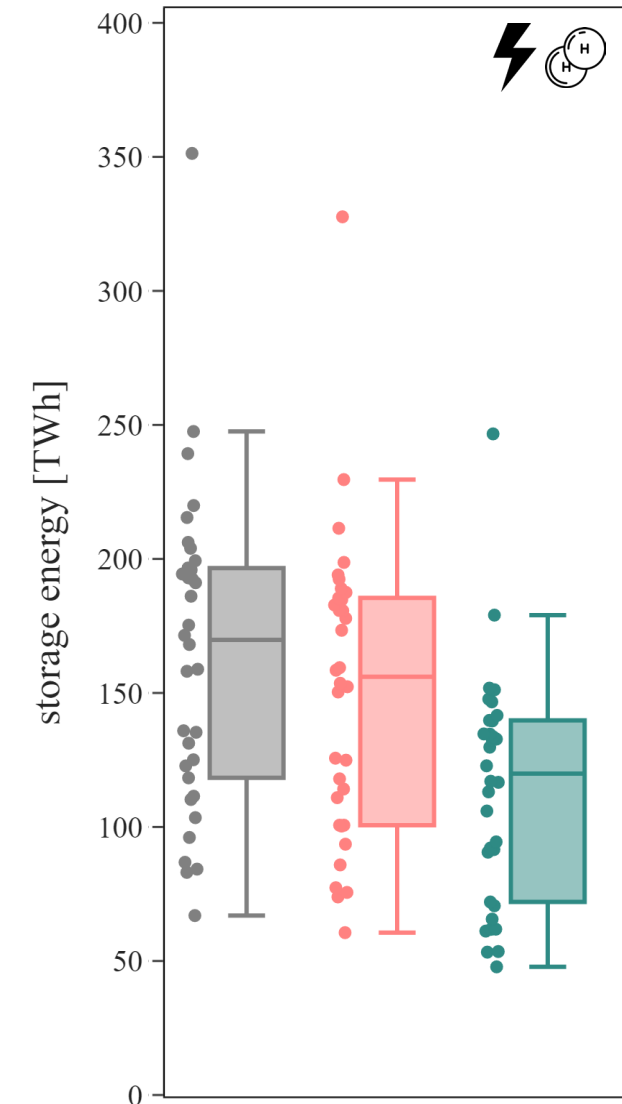
- Default: 0 GW 
- Low levels: 24 GW 
- High levels: 102 GW 
- Policy-relevant exchange of electricity and hydrogen, scenario (3)

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



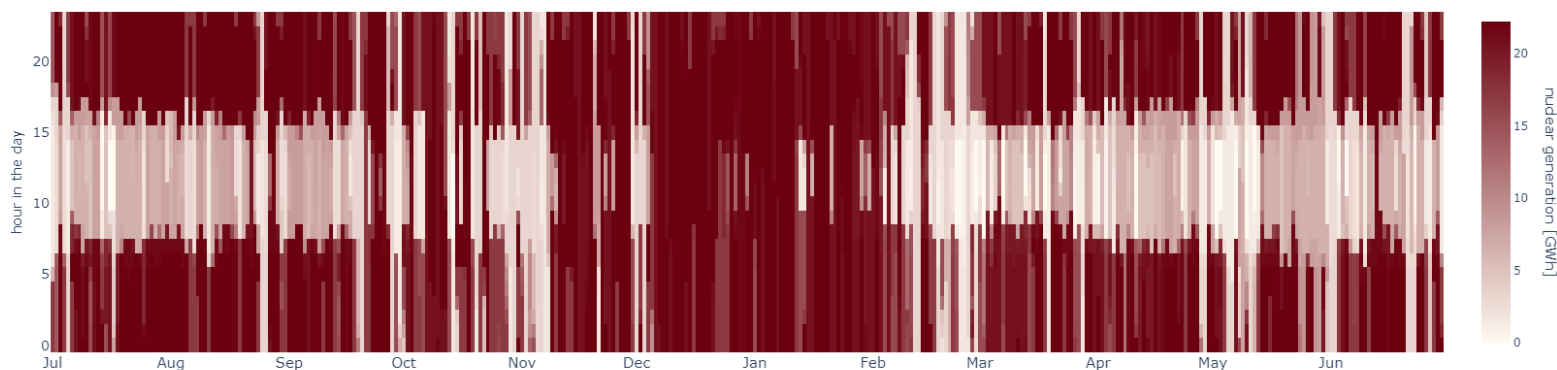
Sensitivity analysis: Impact of nuclear power

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

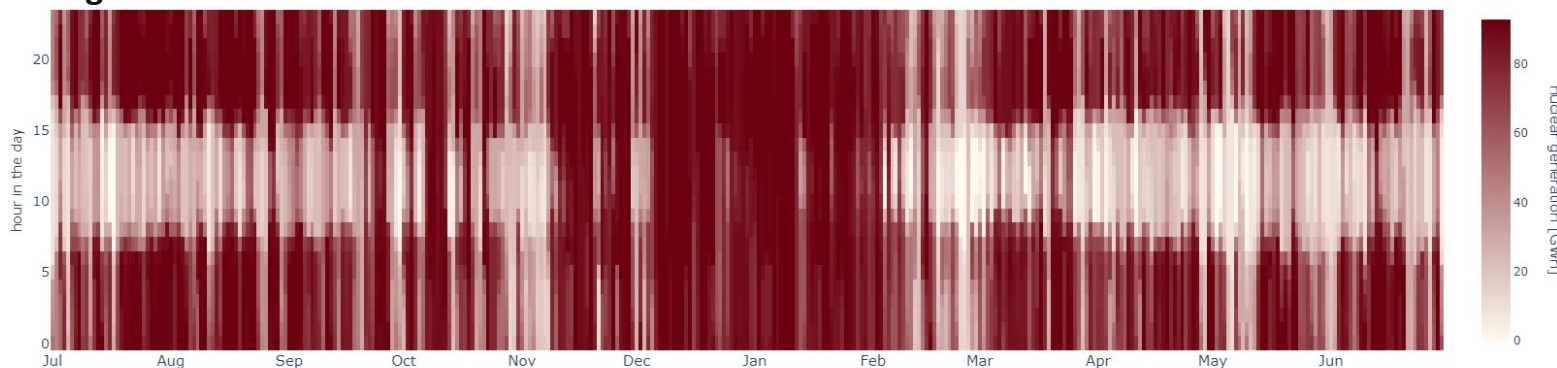


- Flexible operation to complement diurnal solar PV fluctuations
- Continuous dispatch during extreme Dunkelflaute events → reduces optimal long-duration storage discharging and energy capacity

Low levels of nuclear



High levels of nuclear



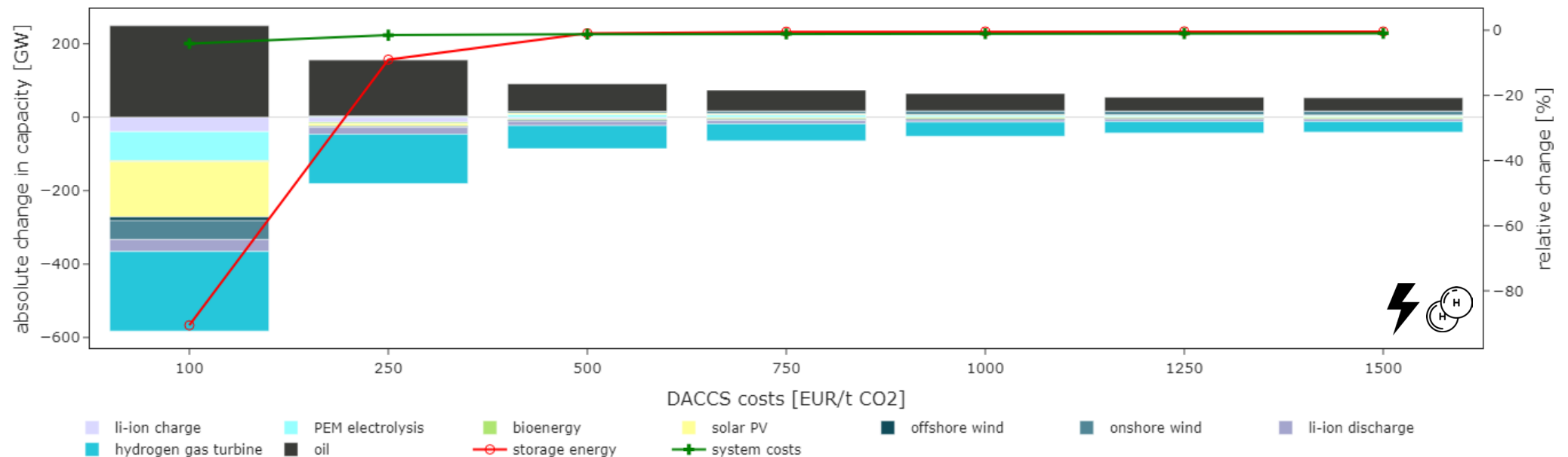
Sensitivity analysis: oil-fired backup capacity with CCS

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

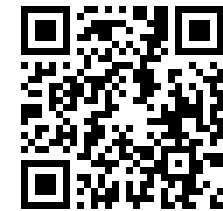
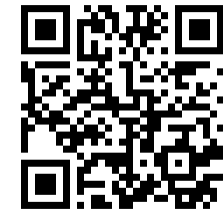
- Long-duration storage indispensable for renewable energy systems
- Lead times 5-15 years → early adoption for rapid scaling required
- Deployment incentives for sufficient capacity likely required
- AUS: Europe in need of green commodities imports

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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