

Sustainable Energy Research Group

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# Coping with the Dunkelflaute

Power sector implications of variable renewable energy droughts in Europe

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Christchurch, 20 February 2026

# Content

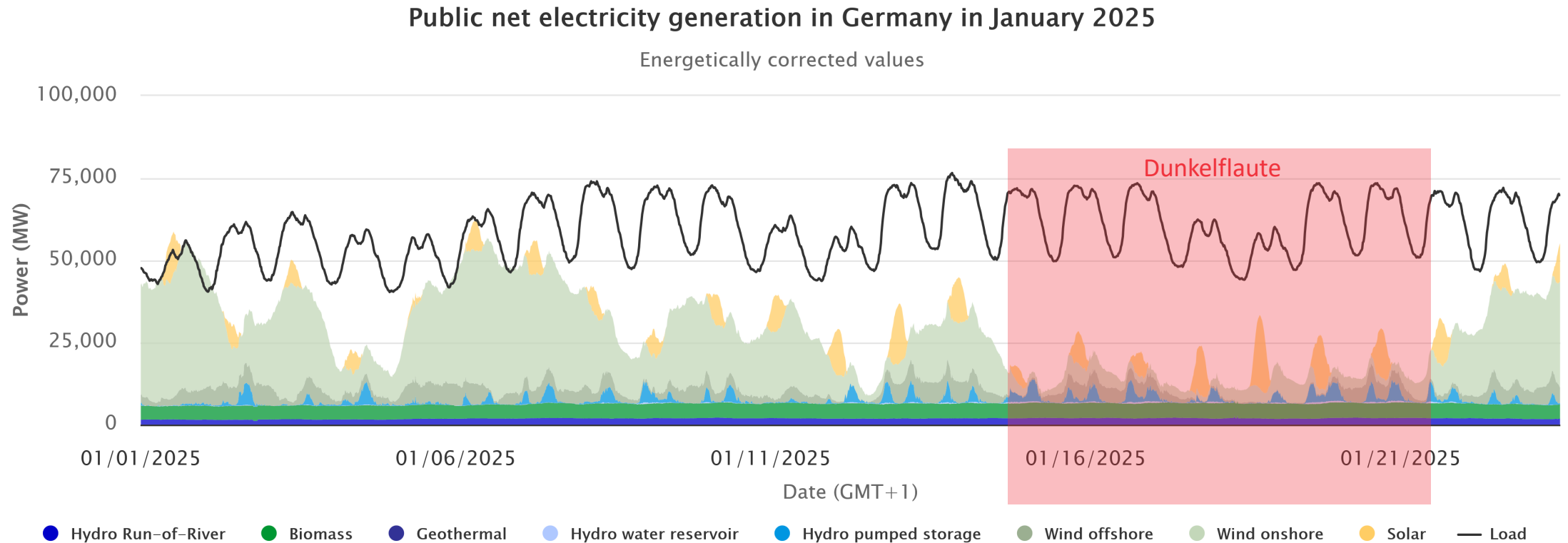
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1. Motivation
2. Research design
3. Results
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# 1. Motivation

# 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

Ökostrom  
**Sicher durch die Dunkelflaute**  
2. Februar 2021, 5:46 Uhr | Lesedauer: 3 min

Deutschlands Windräder schwächelten in den vergangenen Wochen...

Our German live-data fully-renewable electricity simulation deals with another wind lull (Dunkelflaute)! Because of repeated Dunkelflauten, the hydrogen storage now down to 60% full. Will be exciting to see how much further it runs down this winter. The storage was dimensioned by passing through the worst winter 2011 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](https://lnkd.in/gVP_VDeE)

Obviously electrolytic hydrogen isn't the only solution, see my previous post:  
<https://lnkd.in/eiv95f8t>

The graph shows a fluctuating line representing hydrogen storage levels, with a significant dip in the winter months, reaching a low point around 60% full.

**Abteilung Hydrometeorologie**

**Deutscher Wetterdienst**  
Wetter und Klima aus einer Hand

**Klimatologische Einordnung der „Dunkelflaute“ im November 2024**

Autoren: Frank Kaspar<sup>1</sup>, Franziska Bär<sup>2</sup>, Jaqueline Drücke<sup>3</sup>, Paul James<sup>4</sup>, Jennifer Ostermüller<sup>5</sup>, Magdalena Zepperitz<sup>1</sup>  
Stand: 17.12.2024

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

Gibt es die... schlimmer? ... sich im A...  
Als Reakt... ihrer Eign... Botschaft... sogenann...  
- frei erf...  
... viel geht...

**Wissenschaftliche Dienste**

**Deutscher Bundestag**

**Dokumentation**

**Sicherstellung der Stromversorgung bei Dunkelflauten**

**Met Office**

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

Dunkelflaute hat es jetzt jedes Jahr... scheitert. 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 Schmidt, Roth, and Schill (2025), *pre-print*
- Interactions of long-duration electricity and heat storage

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## 2. Research design

# Research design

## 100% renewable European power sector

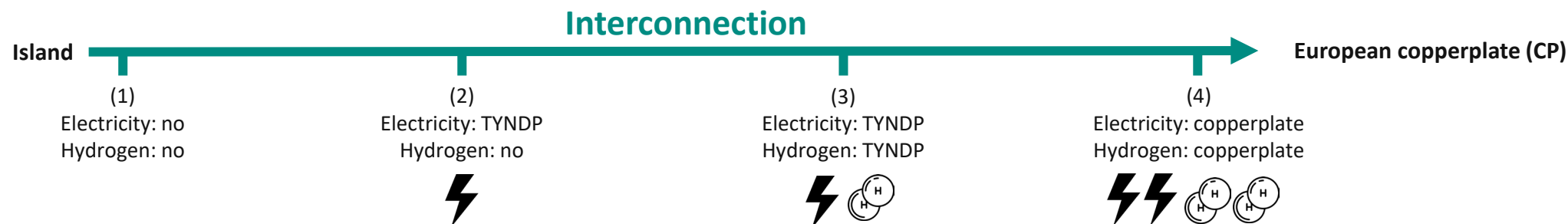
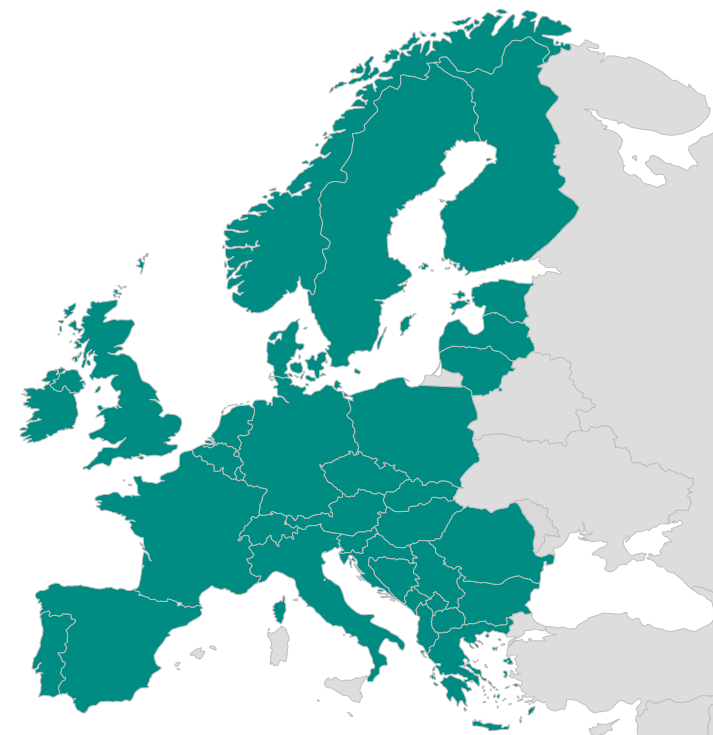
- No fossil fuels, CCS, or nuclear power (relaxed in sensitivity)
- Import of green hydrogen possible
- Largely parameterized to TYNDP 2022 - Distributed Energy
- Sector-coupling “light”: simplified industry, heat, transport

## 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

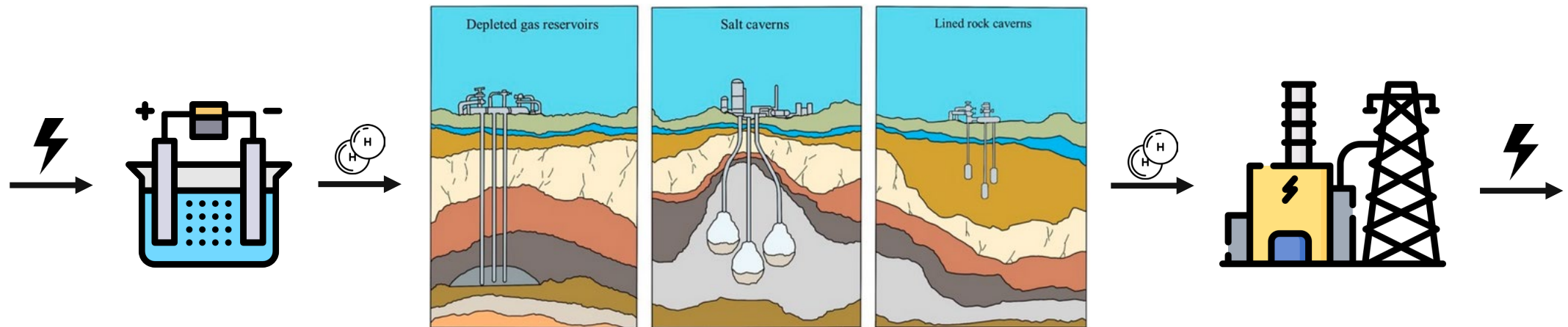
- Different interconnection levels



# 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

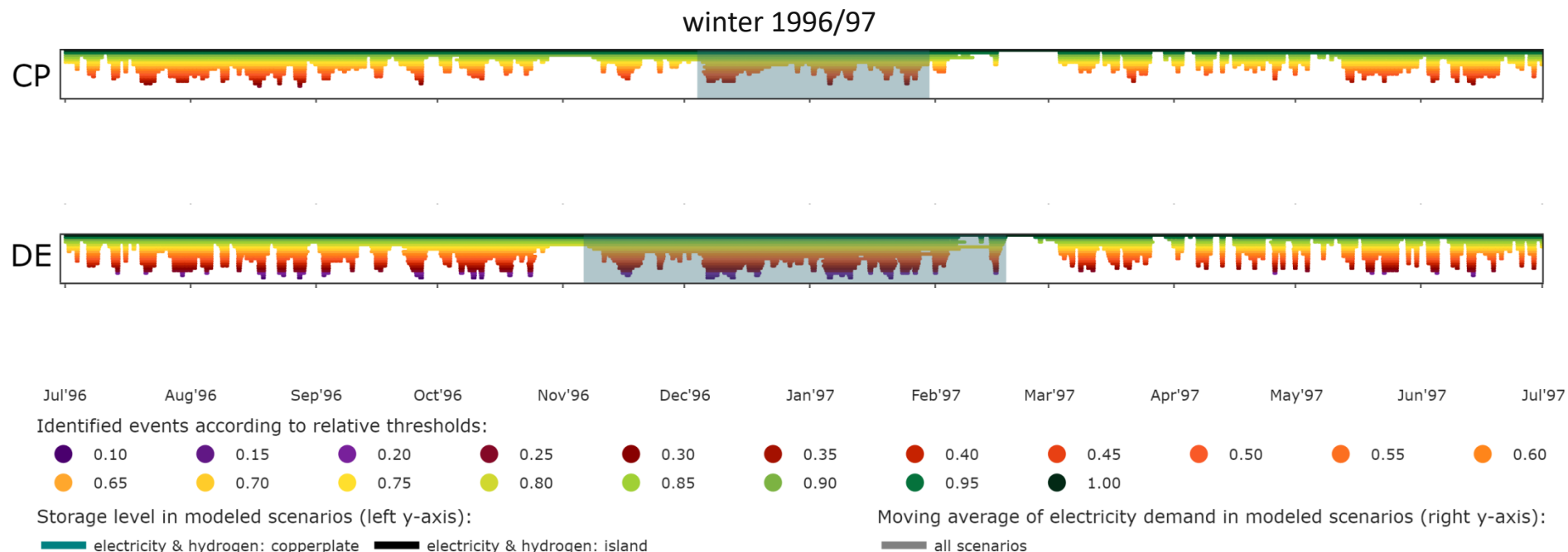
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## 3. Key insights

# Identification of extreme Dunkelflaute events

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

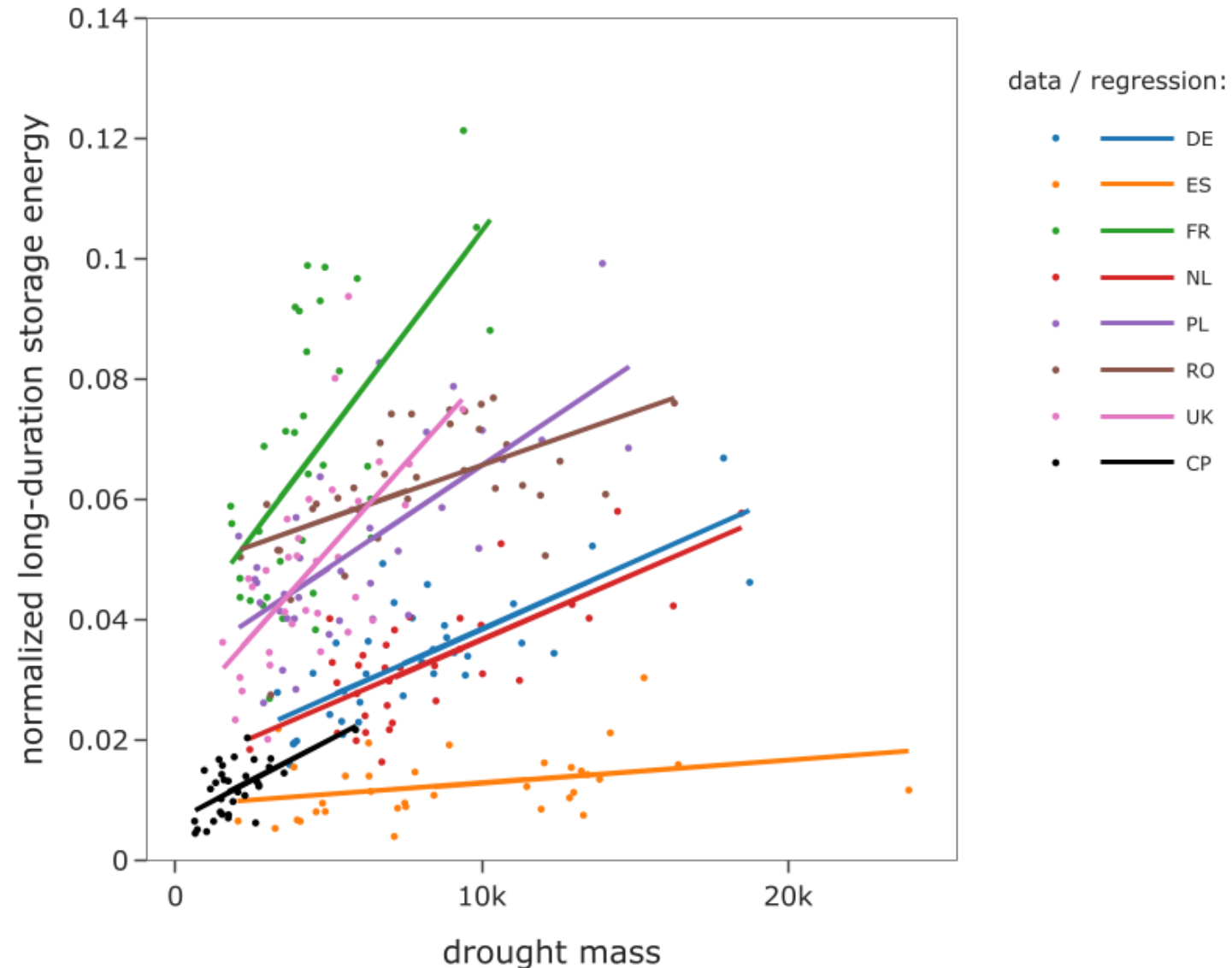
- No meaningful definition for extreme Dunkelflaute events
- Drought mass metric to find events that drive long-duration storage discharge
- Sequence of severe shortage events within a long-lasting, contiguous low-availability period
- Span across turn of year
- Most extreme European event in the data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



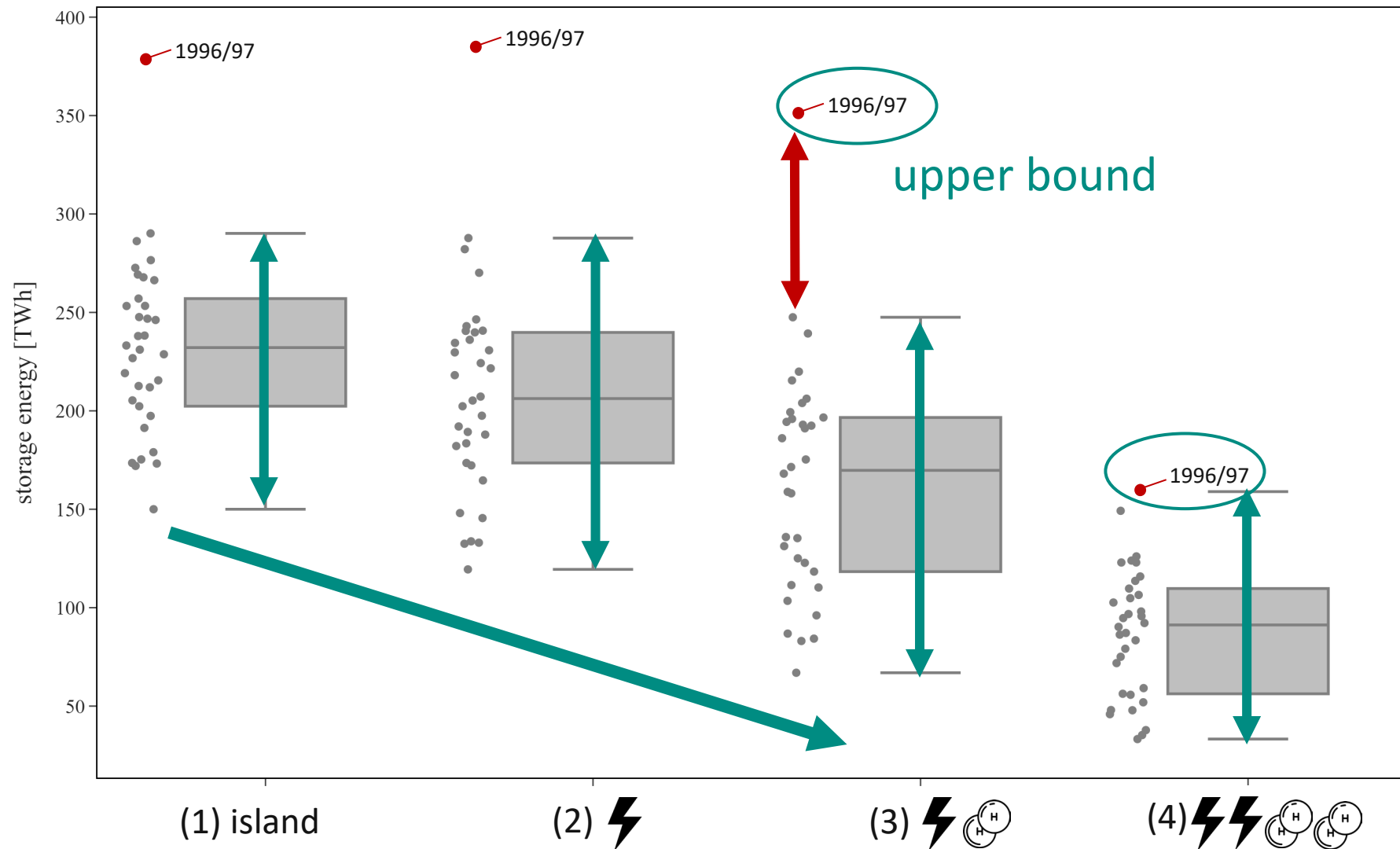
# Extreme Dunkelflaute events and long-duration electricity storage energy

## 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)

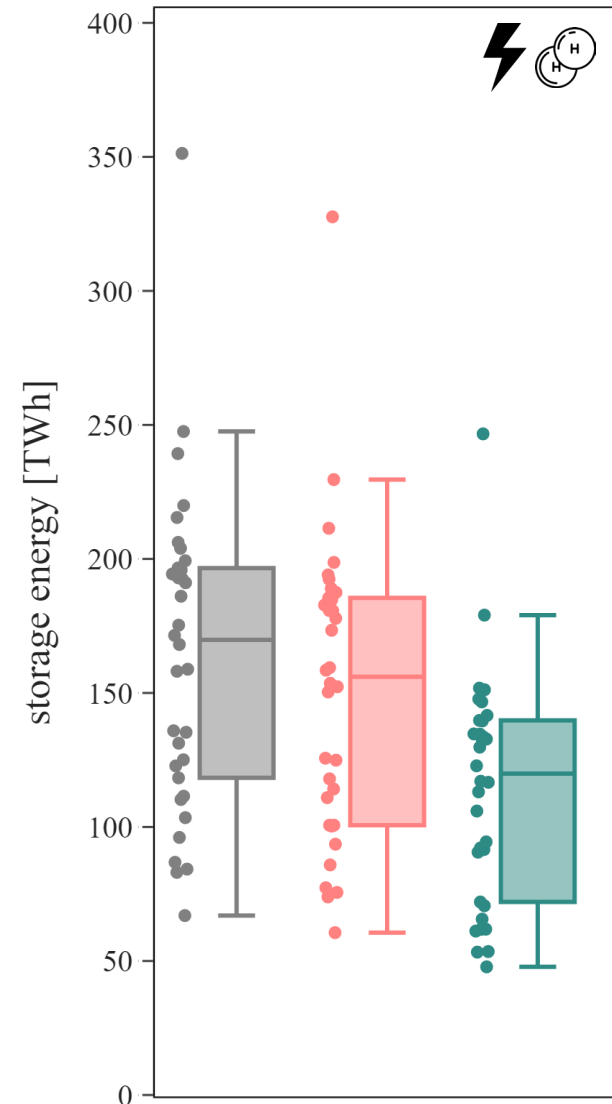
- Default: 0 GW
- Low levels: 24 GW
- High levels: 102 GW
- Policy-relevant exchange of electricity and hydrogen, scenario (3)

## 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



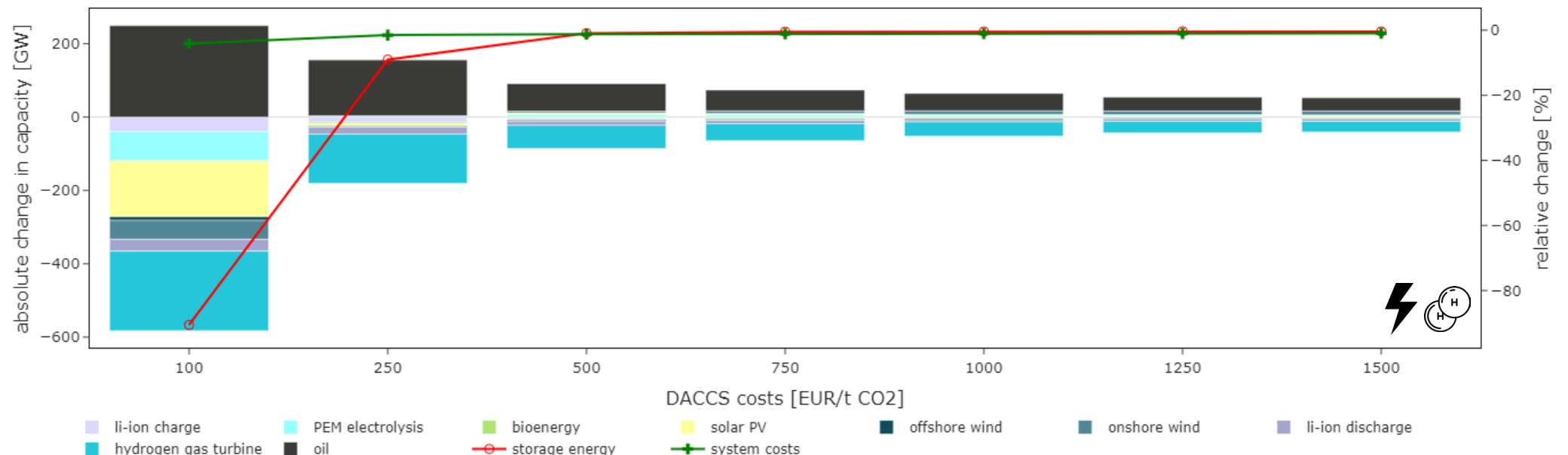
# Sensitivity analysis: oil-fired backup capacity with CCS

## 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 CO<sub>2</sub>: 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



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# 5. Conclusion

## Key insights

- Dunkelflaute events drive long-duration electricity storage operation and investment
- Extreme weather years with Dunkelflaute events create very high storage needs
- Options for mitigating storage needs
  - Interconnection: possible to a limited extent
  - Nuclear power: possible but controversial
  - Fossil backup incl. DACCS: unlikely

# Conclusion

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## Key insights

- Dunkelflaute events drive long-duration electricity storage operation and investment
- Extreme years with substantially higher storage needs
- Mitigation of storage needs
  - Interconnection or nuclear power: possible
  - Fossil backup incl. DACCS or load shedding: 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 / NZ: 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

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- 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 & Schill (2026): Multi-threshold time series analysis enables characterization of variable renewable energy droughts in Europe. *Communications Earth & Environment*. <https://doi.org/10.1038/s43247-026-03251-2> (in press)
- Kittel, Roth, Schill (2026): Long-duration electricity storage needs for coping with Dunkelflaute events in Europe. *Nature Communications (accepted)*. arXiv preprint <https://arxiv.org/abs/2411.17683>.
- 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: arXiv:2505.21516



Thank you for your attention.



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