



dena | DIW Berlin

# Coping with the Dunkelflaute

## Power sector implications of variable renewable energy droughts in Europe

Martin Kittel, Wolf-Peter Schill  
Berlin, 22 September 2025

# Content

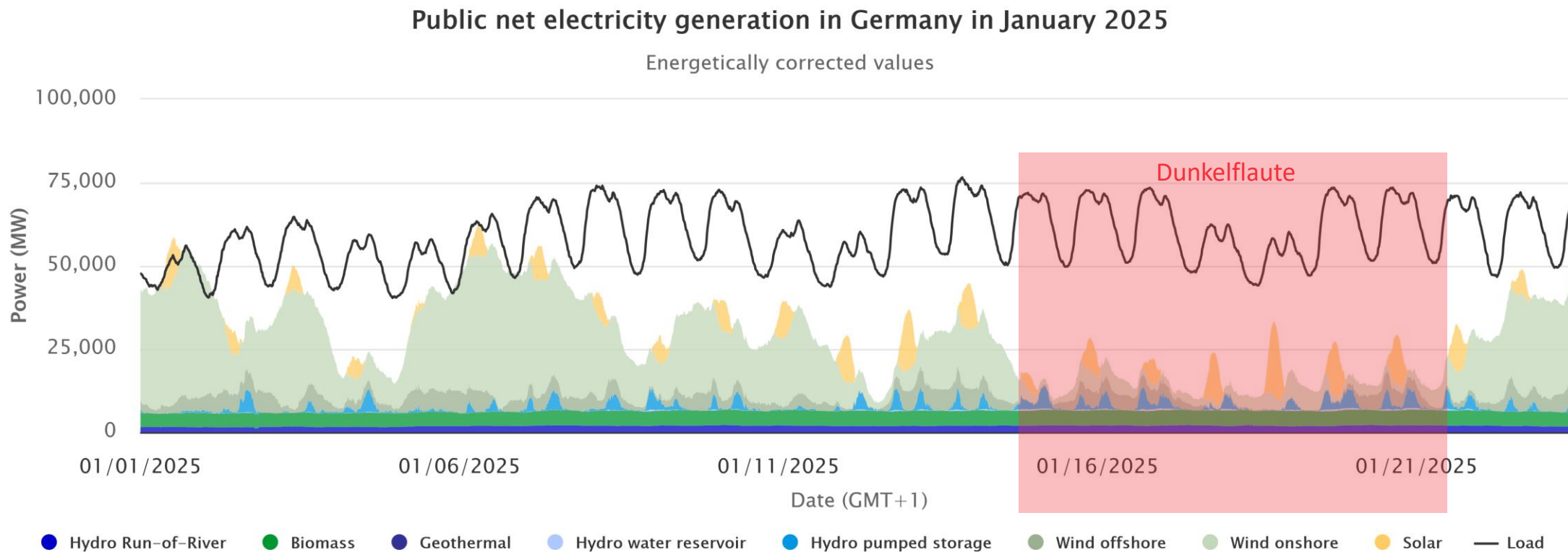
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1. Motivation
2. Methods
3. Results: long-duration electricity storage
4. Results: interaction with electrified space heating
5. Conclusion

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# 1. Motivation

# Recent 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 (VRE) drought or German term “Dunkelflaute”

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


## Dunkelflaute events in public, policy, and academic discourse

**Süddeutsche Zeitung**

Home » Wissen » Energie » Energie: Wie relevant sind Dunkelflauten von Wind- und Solarerzeugung?

**Ökostrom**  
**Sicher durch die Dunkelflaute**

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



Deutschlands Windräder schickten in den vergangenen Wochen...

**Frankfurter Allgemeine Zeitung**

6. Februar 2023, 10:00 Uhr | Lesedauer: 3 min

Die Energiewende ist ein Prozess, der sich über Jahrzehnte erstreckt...

**Dirk Middendorf** • Following

Experte für Energiewirtschaft | Stadtwerke-Geschäftsführer | Energiewende-...

1mo • 1

Gibt es die Dunkelflaute noch? ...

Als Reaktion auf die Dunkelflaute ...

Botschaft: ...

sogenannte ...

- frei erfunden ...

**Met Office**

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

**Abteilung Hydrometeorologie**

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

**DWD**

**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

**Wissenschaftliche Dienste**

**Deutscher Bundestag**

**Dokumentation**

**Sicherstellung der Stromversorgung bei Dunkelflauten**

Dunkelflaute hat es jetzt jedes Jahr. Die Stromversorgung scheitert. Ohne Hilfe aus dem Ausland geht es nicht. Deutsche Energiepolitik.



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

Quelle: dpa



## Characterization of European Dunkelflaute events

- |  |                         |
|--|-------------------------|
| 1. How to identify Dunkelflaute events?  | Kittel & Schill (2024a) |
| 2. How to characterize Dunkelflaute events (duration, frequency, correlation, etc.)? | Kittel & Schill (2024b) |
| 3. What are most extreme Dunkelflaute events?  |                         |

## European power sector implications of extreme Dunkelflaute events

- |  |                                  |
|--|----------------------------------|
| 1. What is the impact on long-duration storage operation and investment?                 | Kittel, Roth, and Schill (2024)  |
| 2. What is the value of cross-country electricity and hydrogen exchange?                 |                                  |
| 3. How do flexibility options interact?  |                                  |
| 4. Are there critical historical weather years?  | Schmidt, Roth, and Schill (2025) |
| 5. Impact of electrified space heating and interactions with long-duration heat storage? |                                  |

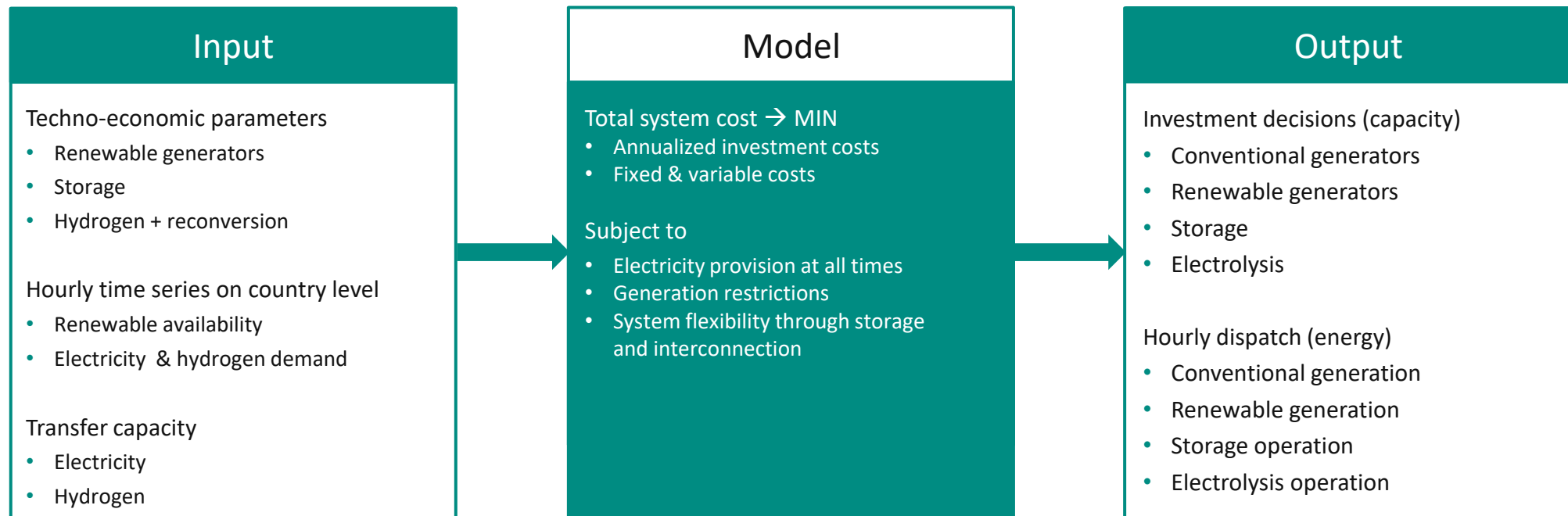
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## 2. Methods

# 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)



# Research design

## 100% renewable European power sector

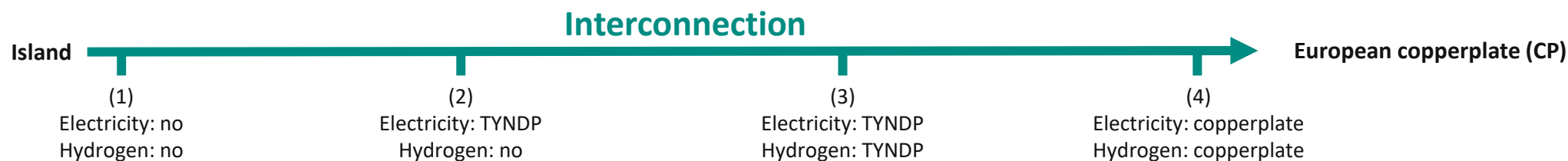
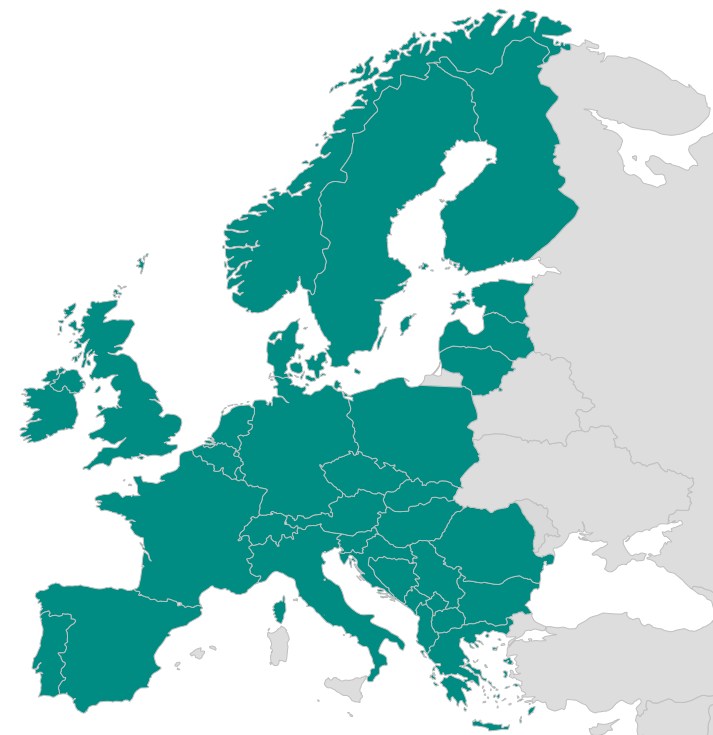
- No fossil fuels, CCS, or nuclear power (relaxed in sensitivity)
- Import of green hydrogen possible
- Largely parameterized to TYNDP 2022 - Distributed Energy
- Sector-coupling “light”: simplified industry, heat, transport

## 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



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## 3. Key insights

# 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

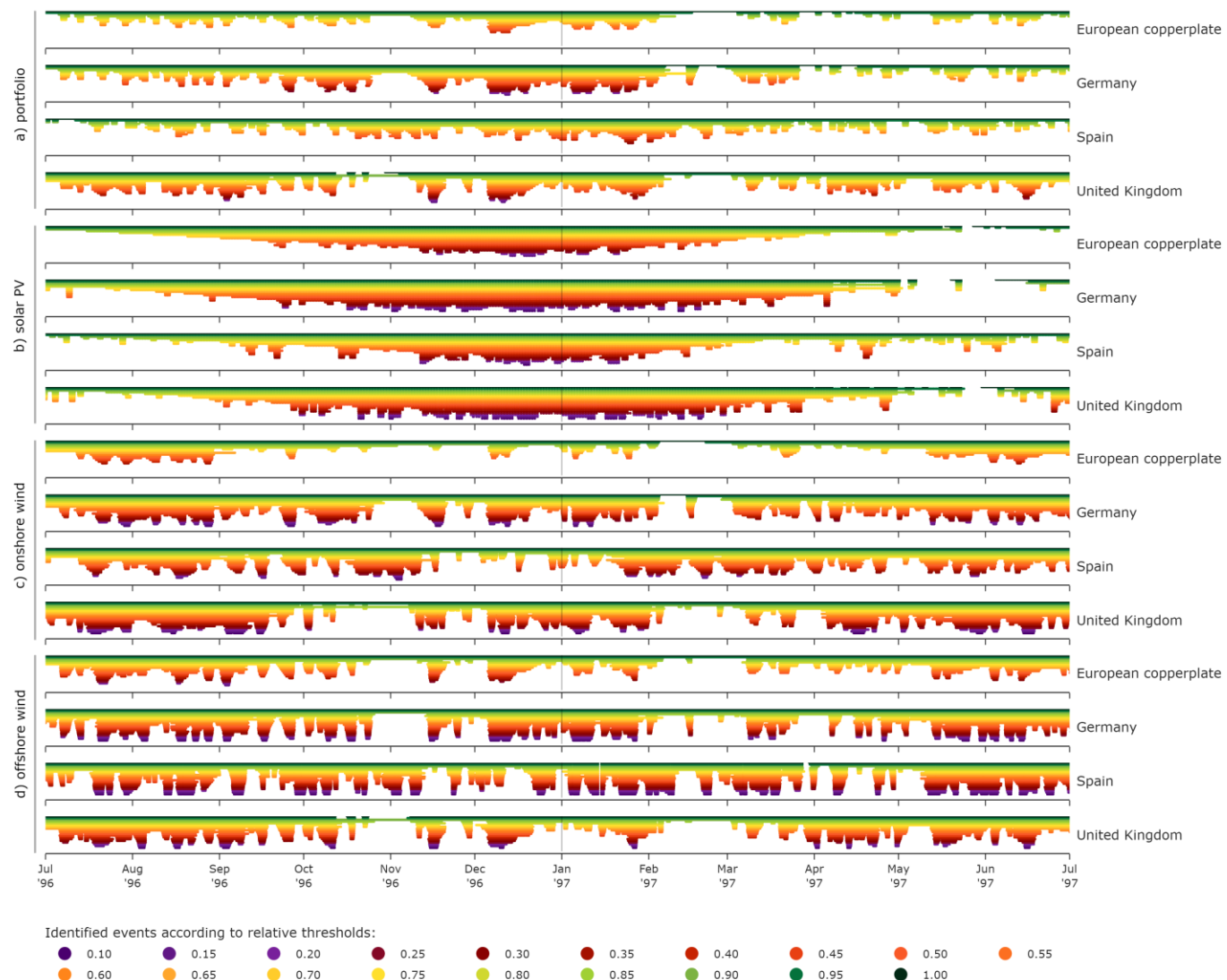
- product of solar seasonality and significant wind droughts

### Portfolio effect

- complementary wind and solar availability profiles reduce drought severity of VRE portfolio

### Balancing effect

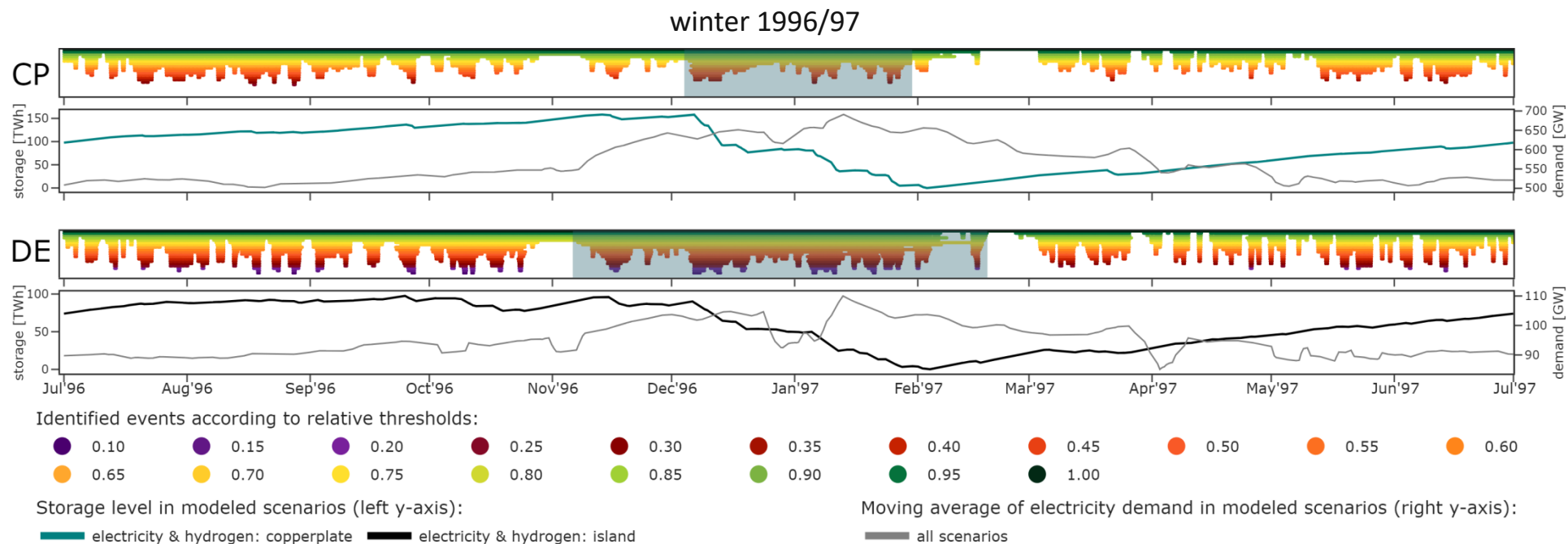
- spatial smoothing of single technologies/VRE portfolio droughts



# Identification of extreme Dunkelflaute events

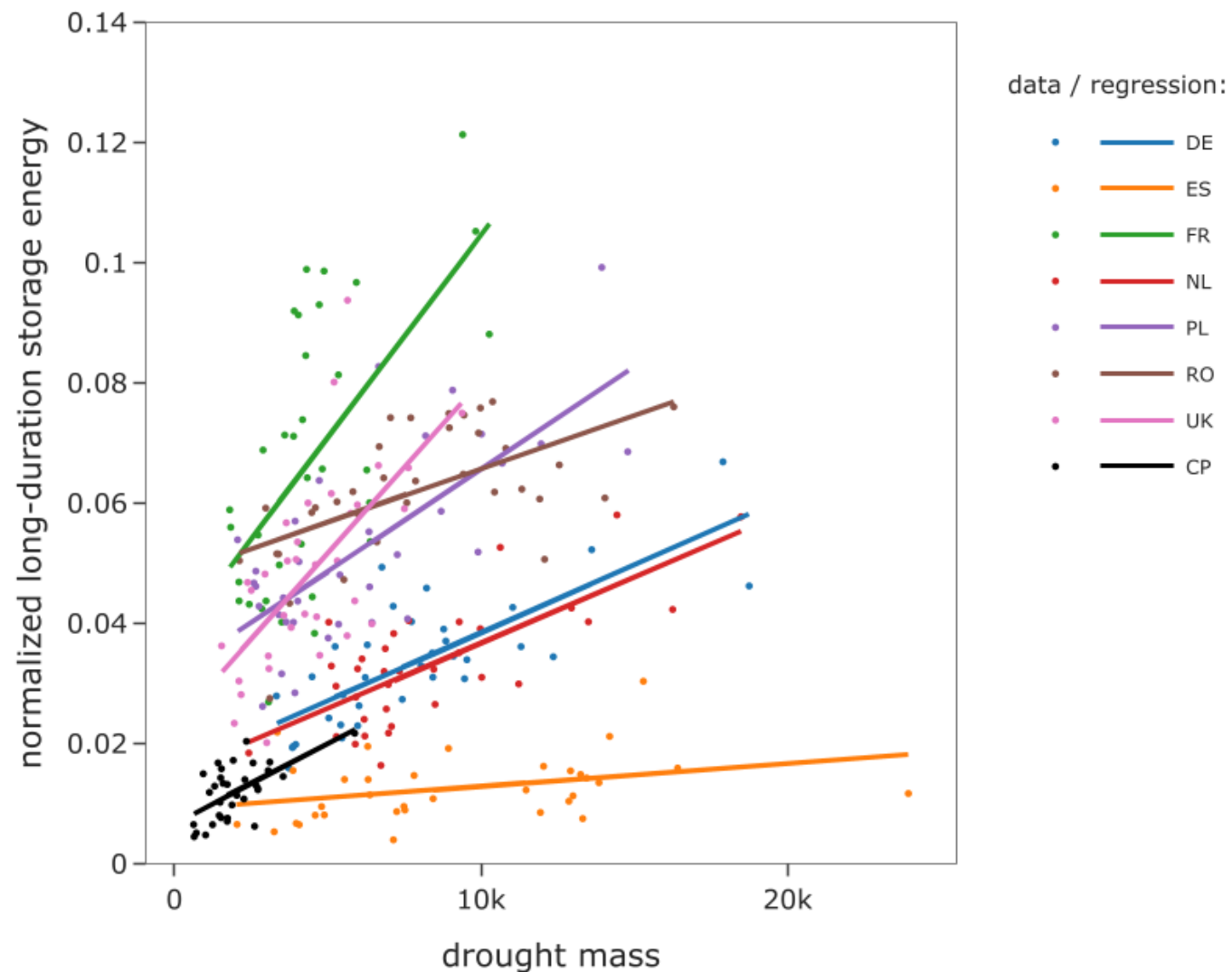
## Identification based on wind and solar availability time series (VREDA)

- 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

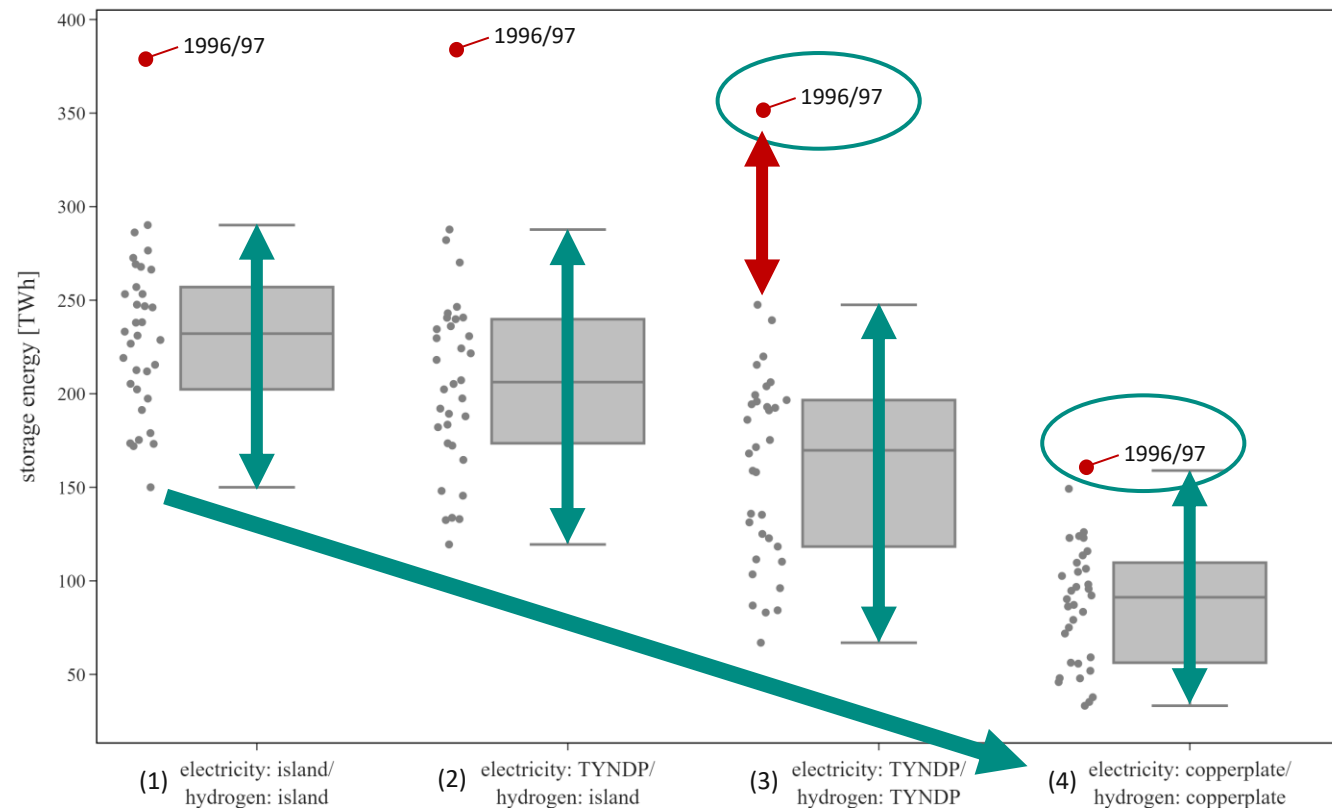


# Long-duration electricity storage investment

- Most extreme Dunkelflaute events drive long-duration storage energy capacity
- Further drivers
  - Other flexibility options
  - Demand seasonality



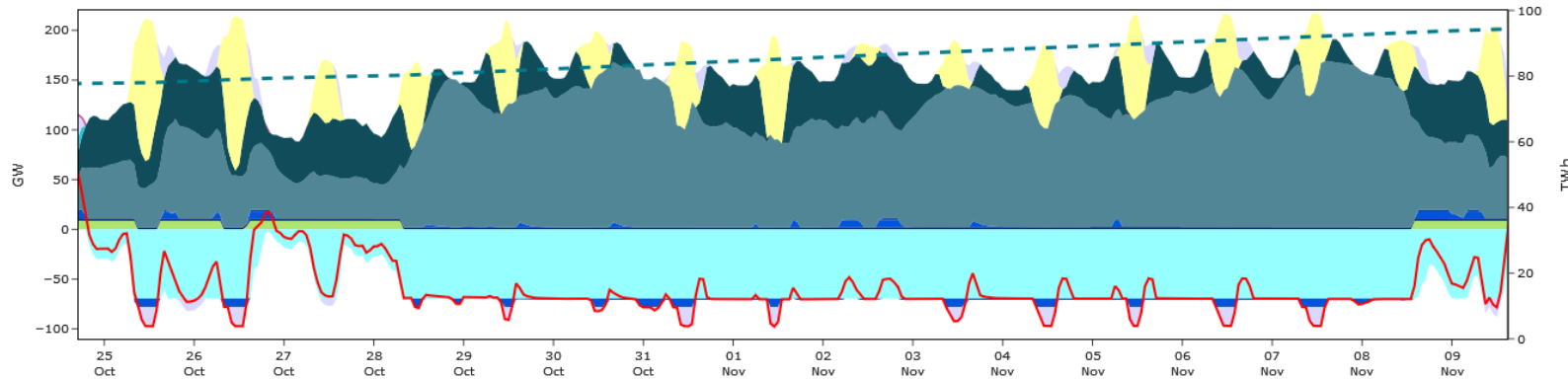
# Long-duration electricity storage (LDS) needs



- Geographical balancing decreases LDS need, but significant levels remain
- Inter-annual variation across weather years → input data matters
- 1996/97 highest LDS need due to European scale of Dunkelflaute → weather-resilient energy system modeling
- Copperplate scenario (4): 159 TWh → minimum need, “no regret” investment
- TYNDP scenario (3): 351 TWh → policy-relevant investment, exceeding next highest storage need in 1984/85 by 42%

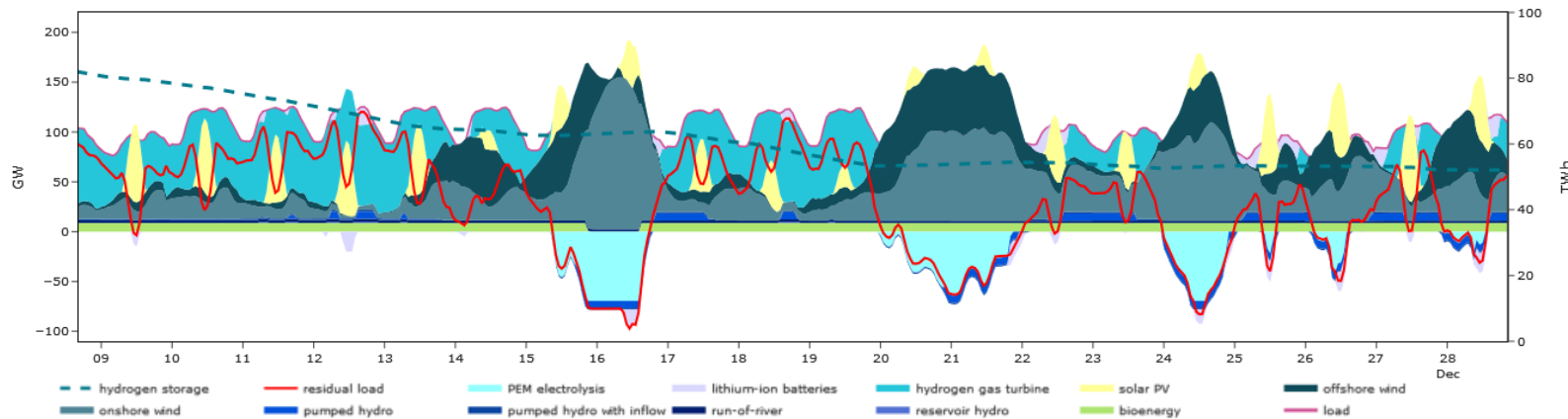
# Interaction of flexibility options

## 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)
- Effect: reduce costly electrolysis capacity

## Power sector operation in Germany inside extreme droughts



- Battery cycling powered by long-duration storage discharge
- Effect: reduce hydrogen turbine capacity entry
- Storage merit order for brief periods of positive residual load
- Effect: higher efficiency

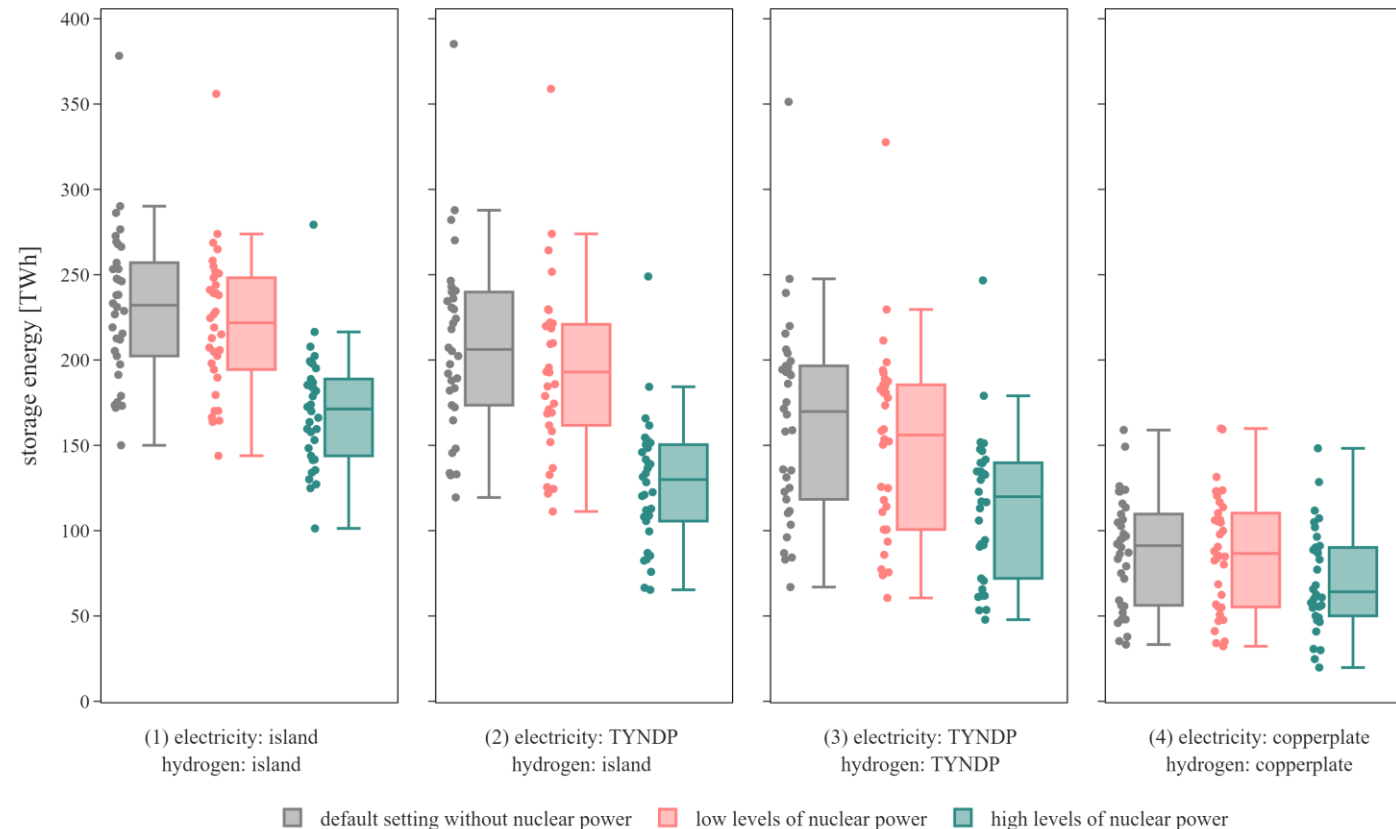
# Sensitivity analysis: Impact of nuclear power

## Exogenous nuclear capacity

- Low (24 GW) and high (102 GW) levels of nuclear power acc. to TYNDP 2022
- Nuclear provides firm generation during extreme Dunkelflaute events
- Nuclear displaces optimal investment in wind and solar, decreasing the system's flexibility need

## Long-duration storage energy capacity under policy-relevant interconnection (3)

- Low levels reduce mean/maximum storage capacity by 8/7%
- High levels reduce mean/maximum storage capacity by 29/30%

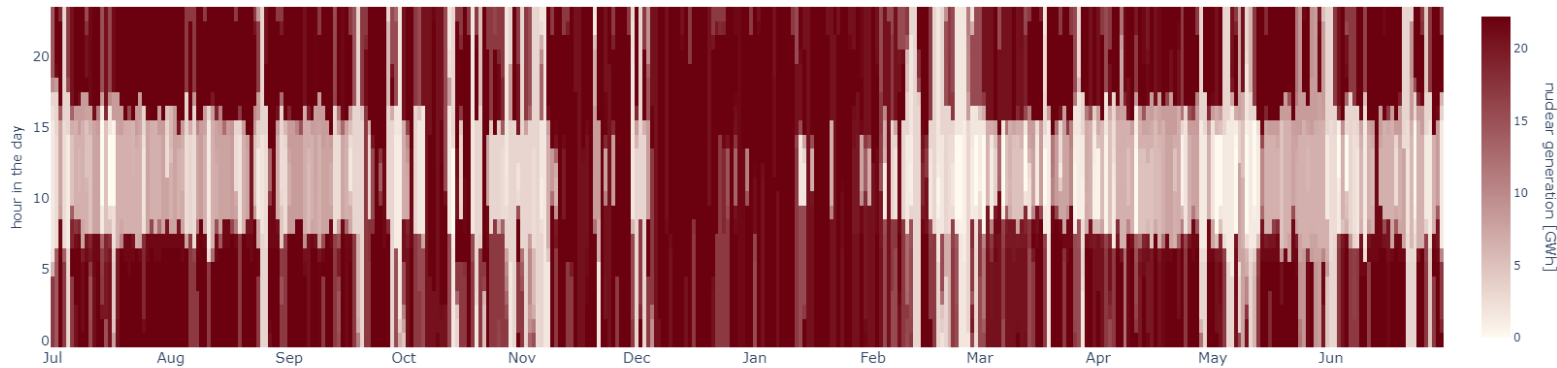


# Sensitivity analysis: Impact of nuclear power

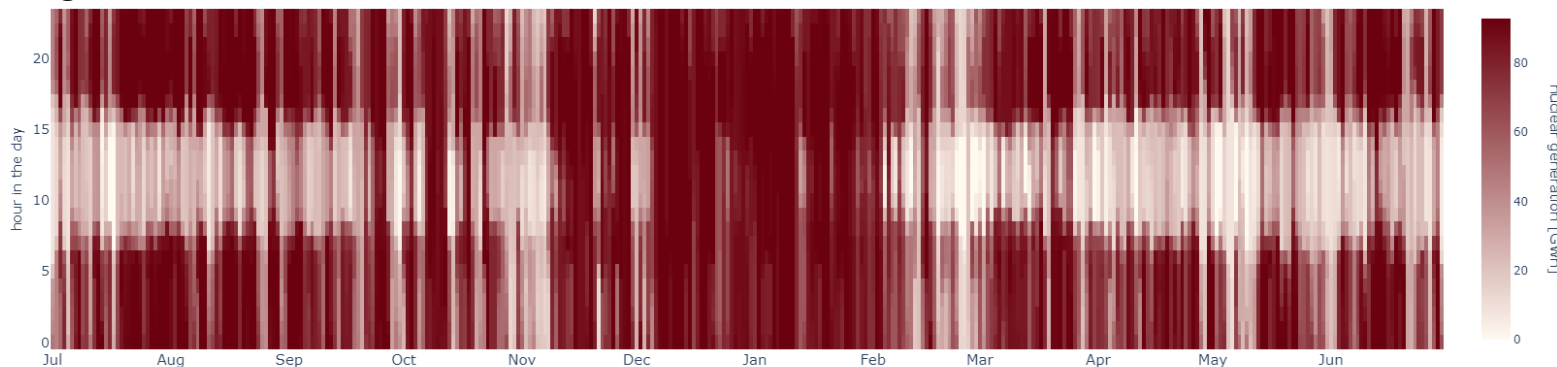
## Operational patterns of nuclear power in winter 1996/97 under policy-relevant interconnection (3)

- 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



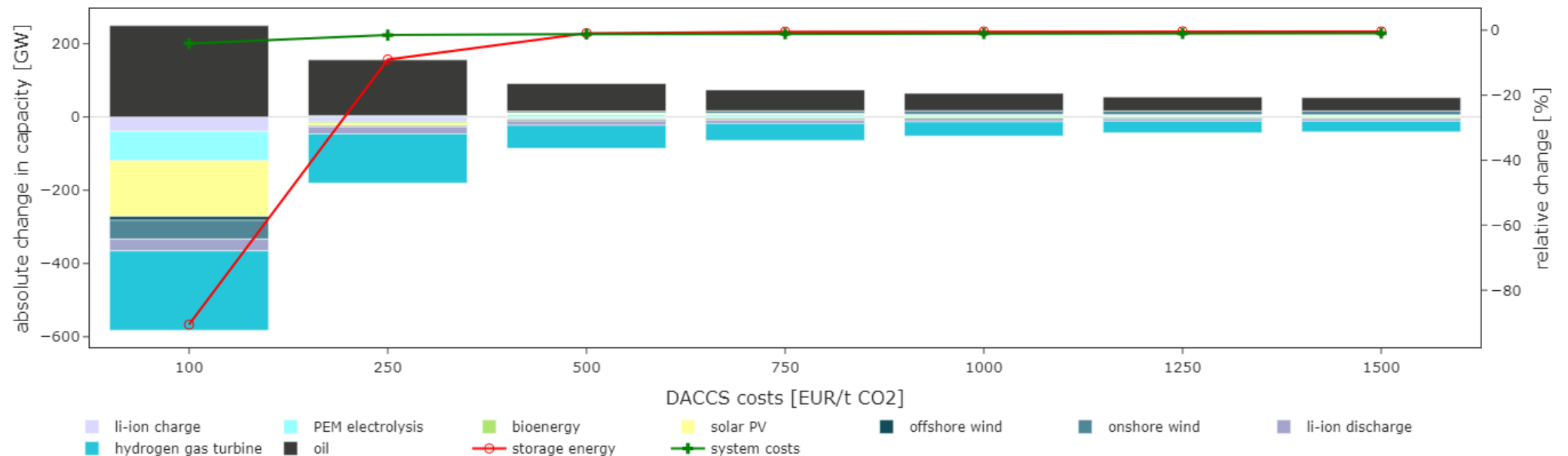
# Sensitivity analysis: oil-fired backup capacity with CCS

## 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 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



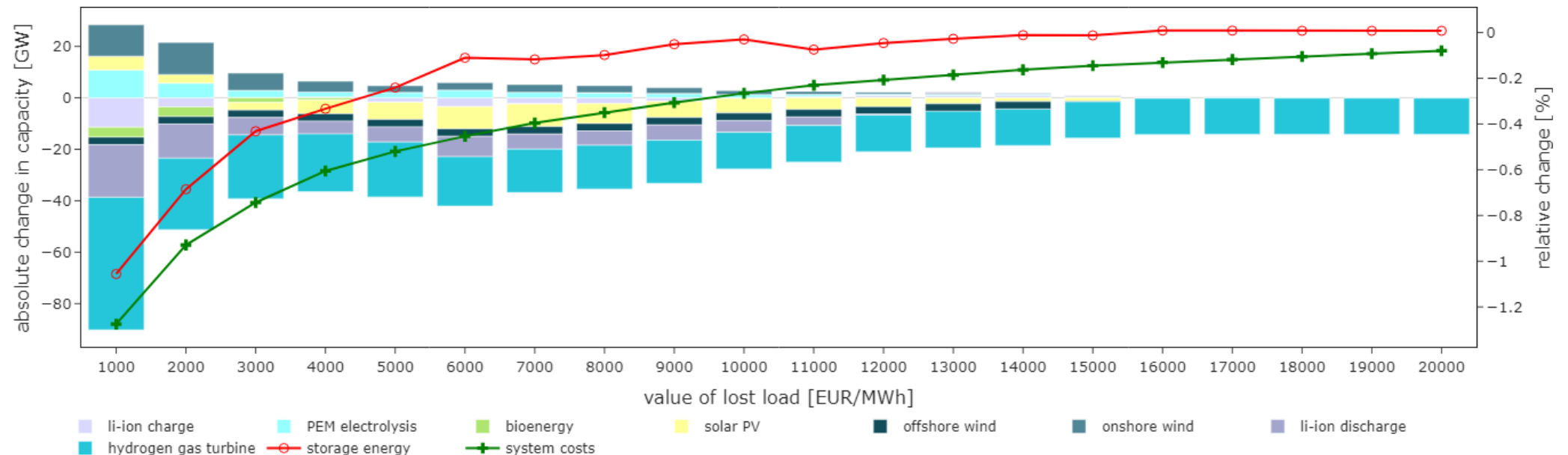
# Sensitivity analysis: load shedding

## 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)

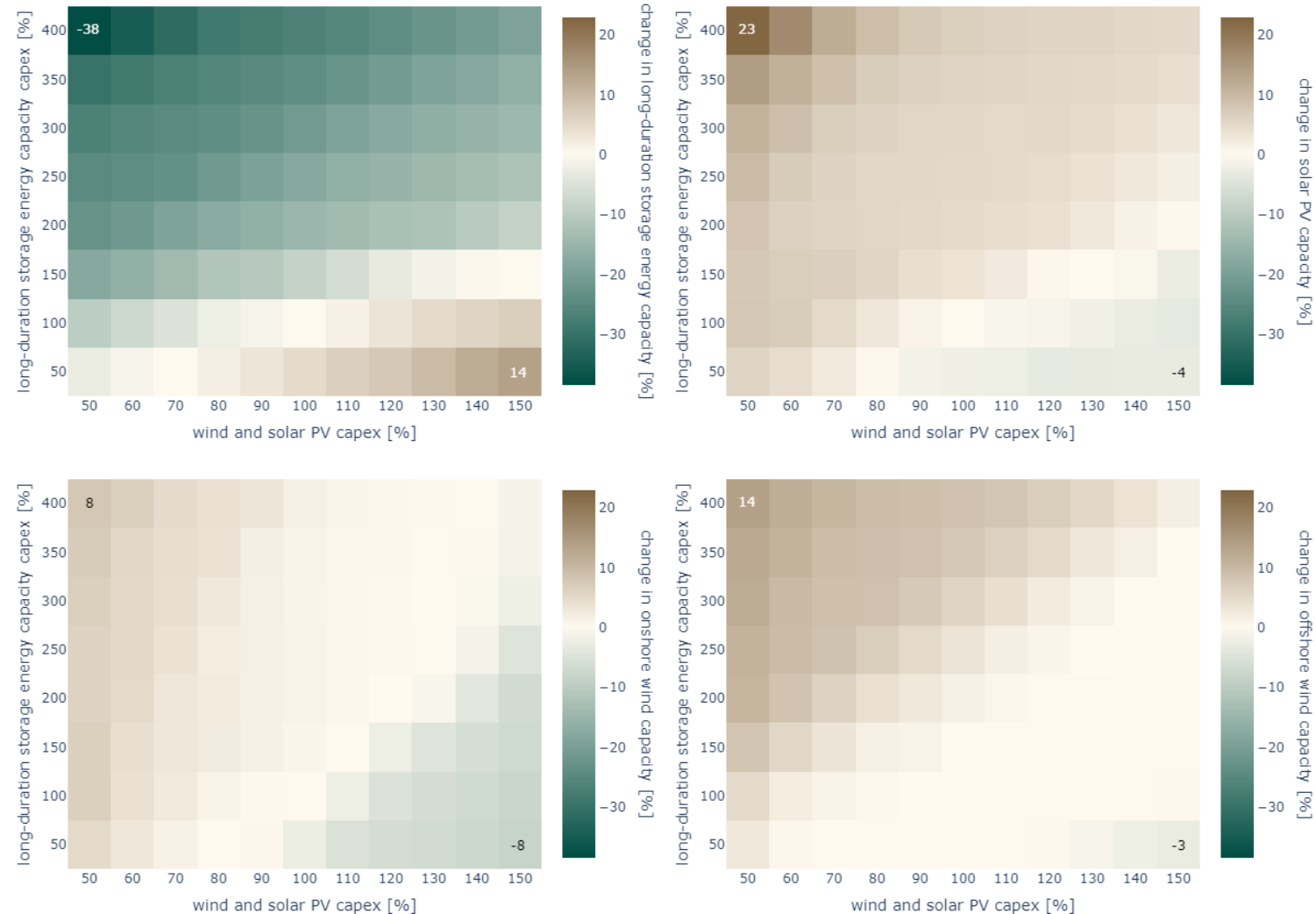
- Lower VOLL displaces long-duration discharging capacity and shorter-duration flexibility such as bioenergy or batteries
- Higher VOLL: effect diminishes
- Long-duration storage energy and system costs hardly affected



# 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



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## 4. Add-on: Interaction with electrified heating

## Three complementary elements

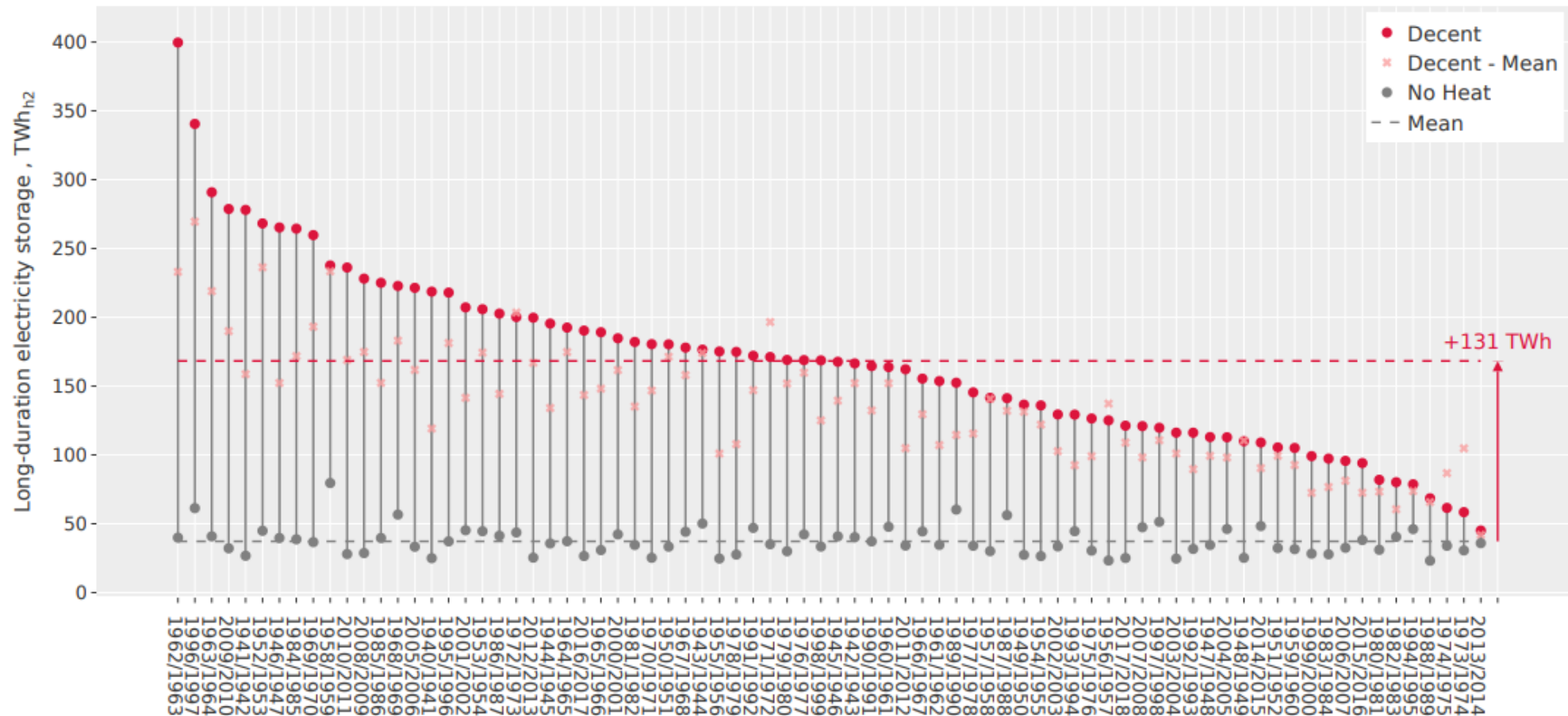
- Effects of additional load for electrified heating
- Effects of long-duration heat storage
- Larger weather year data set (78 years)

## Notes on methods and parameterization

- Slight differences in model setup and parameterization (TYNDP 2022 NTCs)
- 80% of all residential and commercial heat demand electrified with heat pumps
- 32% of heating can be supplied by district heating in combination with LDTS

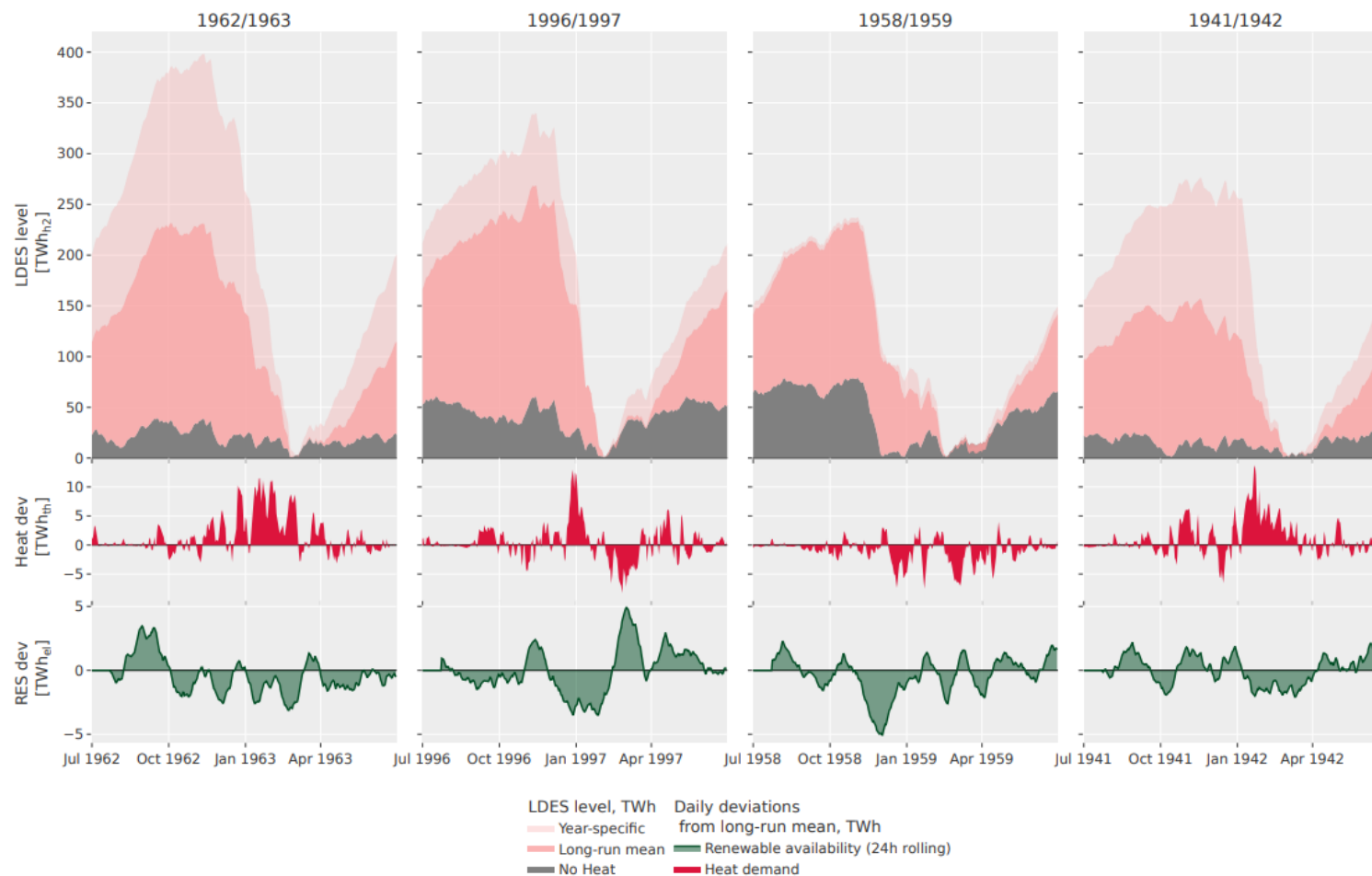
→ More details: Schmidt et al. (2025), <https://arxiv.org/pdf/2505.21516v1>

# Long-duration electricity storage results for all weather years



- ➔ Electric heating substantially increases LDES needs
- ➔ Large variation between weather years – demand-side variability matters

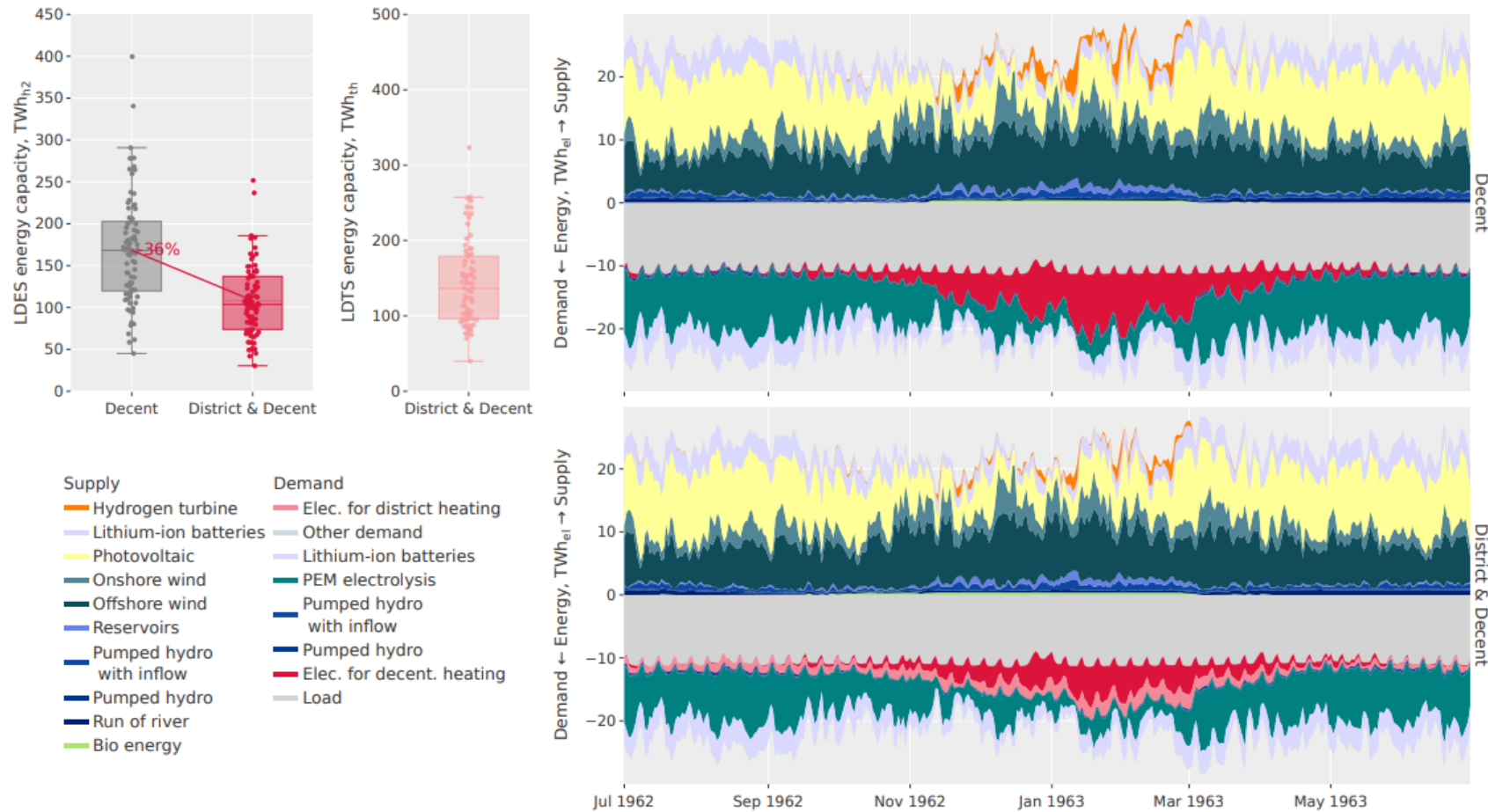
# Illustration of effects in four complementary years



→ *Leverage and compound effects*

→ Leverage effect accounts for ~75% on average

# Storage results and illustration of daily dispatch



→ Sensitivities: LDES need decreases when LDTS gets cheaper and more efficient

→ LDES need decreases further by ~50% if LDHS is available for the total heat demand

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# 5. Conclusion

## Policy implications

- Dunkelflaute events drive long-duration storage operation and investment
- European cooperation beneficial for coping with Dunkelflaute events
- Nuclear power mitigates storage needs from Dunkelflaute events
- Long-duration storage indispensable for renewable energy system
- Electrified heating demand increases electricity storage needs, long-duration heat storage can mitigate this
- Long-duration storage has long lead times (5-15 years) → early adoption for rapid scaling including deployment incentives required

## Modeling implications

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

	Dunkelflaute	Cold Spell	Hydro drought	Sources
1958/59	pronounced			Schmidt et al., 2025
1962/63	pronounced	extreme		Schmidt et al., 2025
1966/67	pronounced	pronounced		Gotske et al., 2024
1968/69	pronounced: wind	pronounced	pronounced	Gotske et al., 2024
1972/73	pronounced		extreme	Gotske et al., 2024
1996/97	extreme	brief		Kittel et al., 2024; Gotske et al., 2024, Schmidt et al., 2025

# Conclusion

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## Known unknowns

- Impact of conventional backup with CCS, load shedding for lower renewable shares (i.e. with nuclear power) → intuition: lower storage need
- Climate sensitivity from climate change: heat demand, wind and solar generation
- Interactions of different hydrogen derivative storage options with long-duration electricity and heat storage
- Perfect foresight assumption impacts long-duration storage operation
- Issue of market power exertion of storage operators as critical elements

## Unknown Unknowns

- High impact, low probability events: green, black, gray swan events

# Literature

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- Kittel & Schill (2024a): “Measuring the Dunkelflaute: How (not) to analyze variable renewable energy shortage.” Environmental Research: Energy 1.3 (2024): 035007.
- Kittel & Schill (2024b): “Quantifying the Dunkelflaute: An analysis of variable renewable energy droughts in Europe.” arXiv preprint arXiv:2410.00244.
- Kittel, Roth, and Schill (2024): “Coping with the Dunkelflaute: Power system implications of variable renewable energy droughts in Europe.” arXiv preprint arXiv: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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