Australian Energy Market Operator (AEMO)

Coping with the Dunkelflaute

Power sector implications of variable renewable energy droughts in Europe

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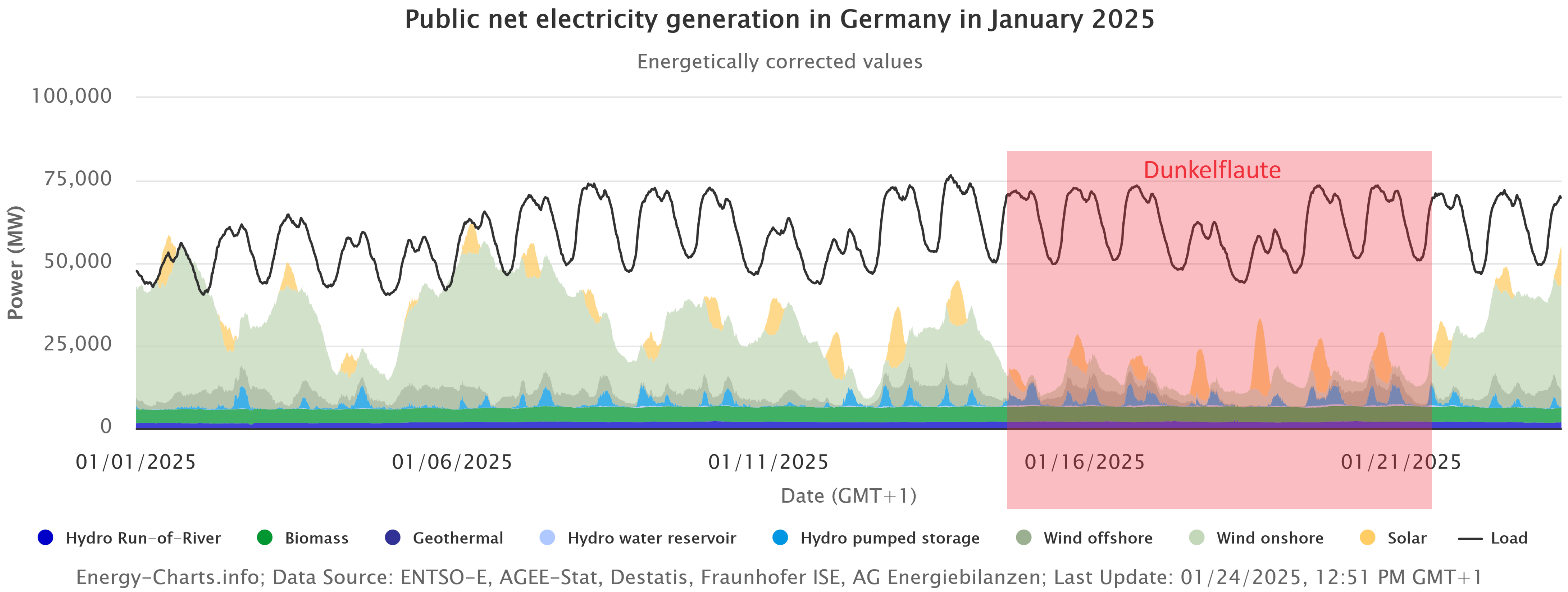
Content

1. Motivation

Recent Dunkelflaute event in Germany

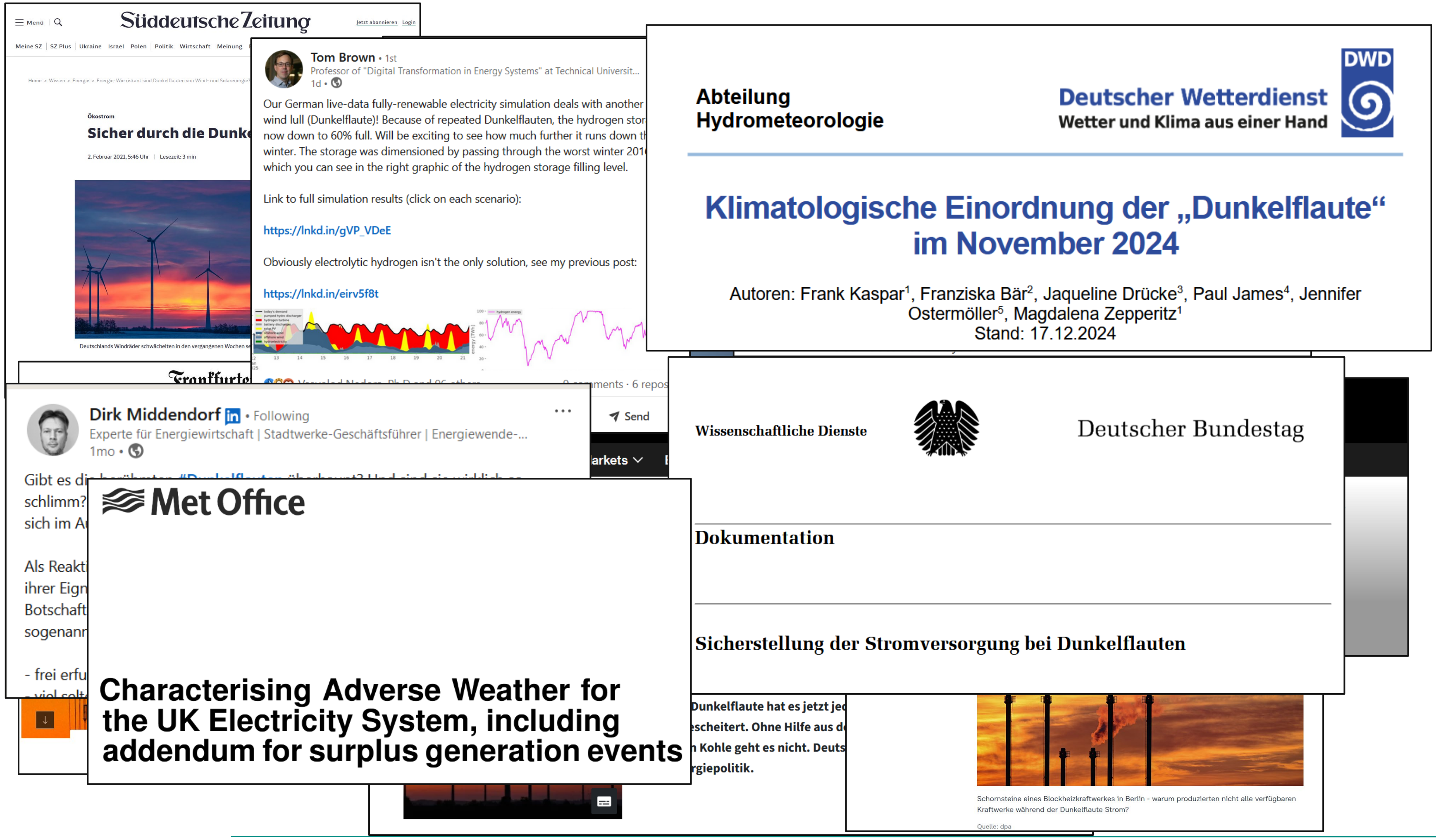


Variable renewable energy (VRE) drought or German term "Dunkelflaute"

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

Relevance

Dunkelflaute events in public, policy, and academic discourse



Research Questions

VREDA

DIETER

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 (2026)
3.	What are most extreme Dunkelflaute events?	

European power sector implications of extreme Dunkelflaute events

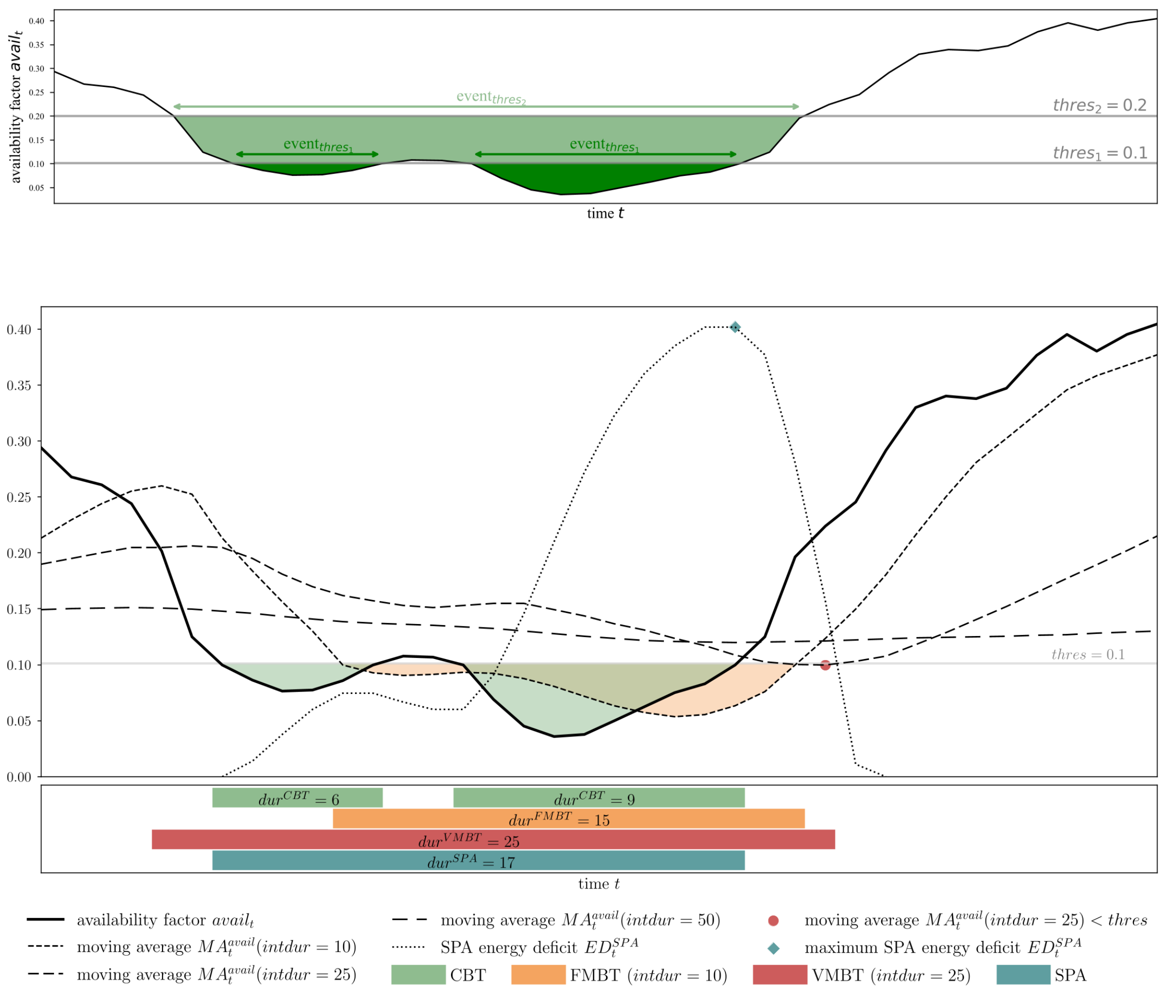
1.	What is the impact on long-duration storage operation and investment?	Kittel, Roth, and Schill (2026)
2.	What is the value of cross-country electricity and hydrogen exchange?	
3.	How do flexibility options interact?	
4.	Are there critical historical weather years?	
5.	Impact of electrified space heating and interactions with long-duration heat storage?	Schmidt, Roth, and Schill (2025)

2. Methods

Renewable drought detection

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



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)

Input

Techno-economic parameters
- Renewable generators
- Storage
- Hydrogen + reconversion

Hourly time series on country level
- Renewable availability
- Electricity & hydrogen demand

Transfer capacity
- Electricity
- Hydrogen

→

Model

Total system cost → MIN
- Annualized investment costs
- Fixed & variable costs

Subject to
- Electricity provision at all times
- Generation restrictions
- System flexibility through storage and interconnection

→

Output

Investment decisions (capacity)
- Conventional generators
- Renewable generators
- Storage
- Electrolysis

Hourly dispatch (energy)
- Conventional generation
- Renewable generation
- Storage operation
- Electrolysis operation

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

Interconnection

Island → **European copperplate (CP)**

(1)
Electricity: no
Hydrogen: no

(2)
Electricity: TYNDP
Hydrogen: no

(3)
Electricity: TYNDP
Hydrogen: TYNDP

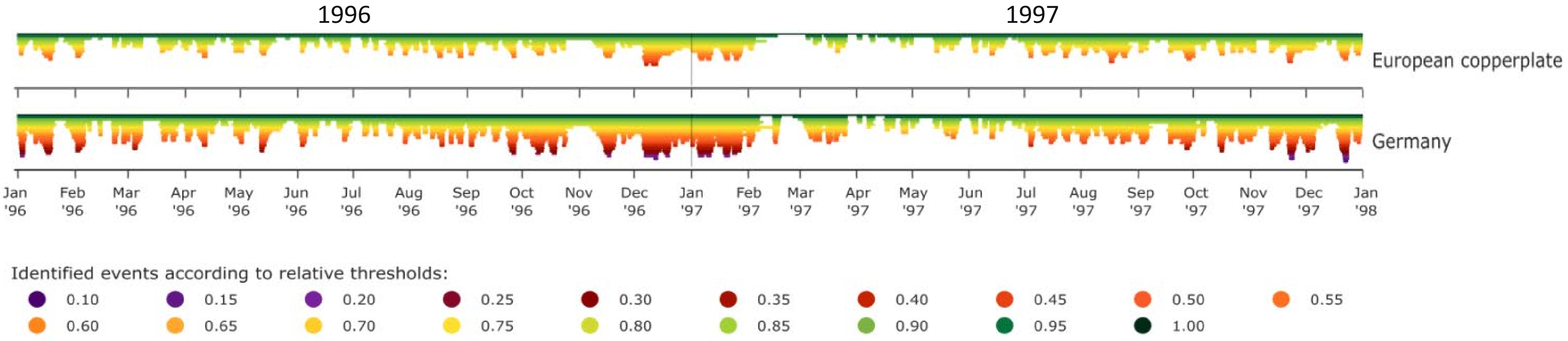
(4)
Electricity: copperplate
Hydrogen: copperplate

3. Dunkelflaute characterization in Europe

Characterization of Dunkelflaute events

Renewable droughts patterns in 1996/97

- Policy-oriented renewable technology portfolios: solar PV, onshore wind, offshore wind
- 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

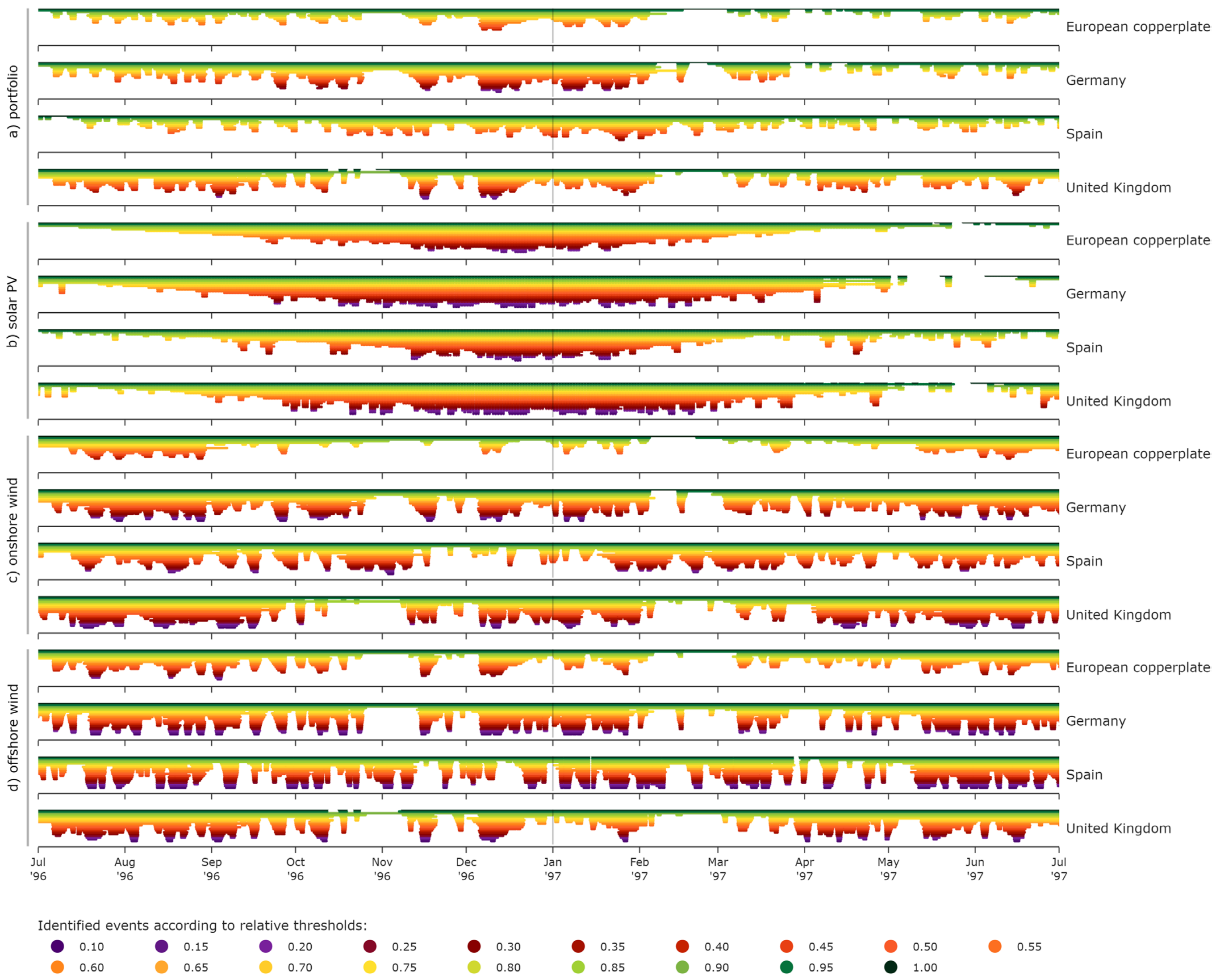
- droughts primarily in summer, some also in winter

VRE portfolio

- product of solar seasonality and significant wind droughts

Complementary wind and solar profiles

- Portfolio effect within regions
- Balancing effect across regions



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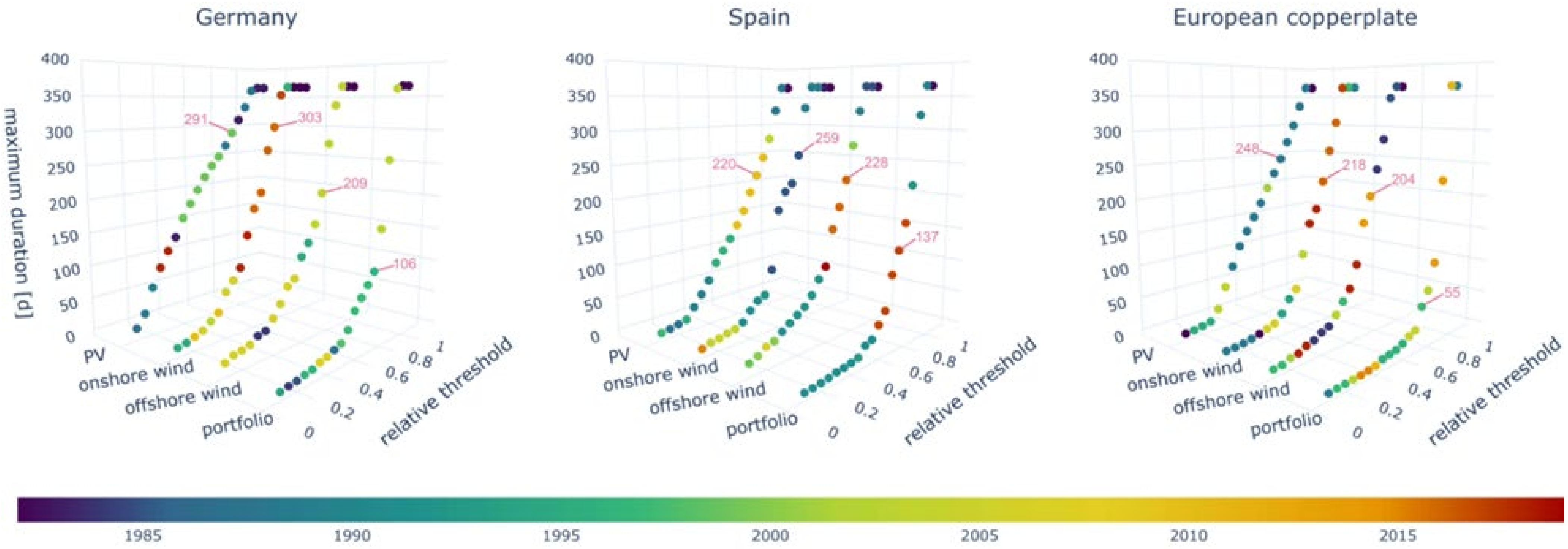
Characterization of Dunkelflaute events

Maximum drought duration per year and threshold

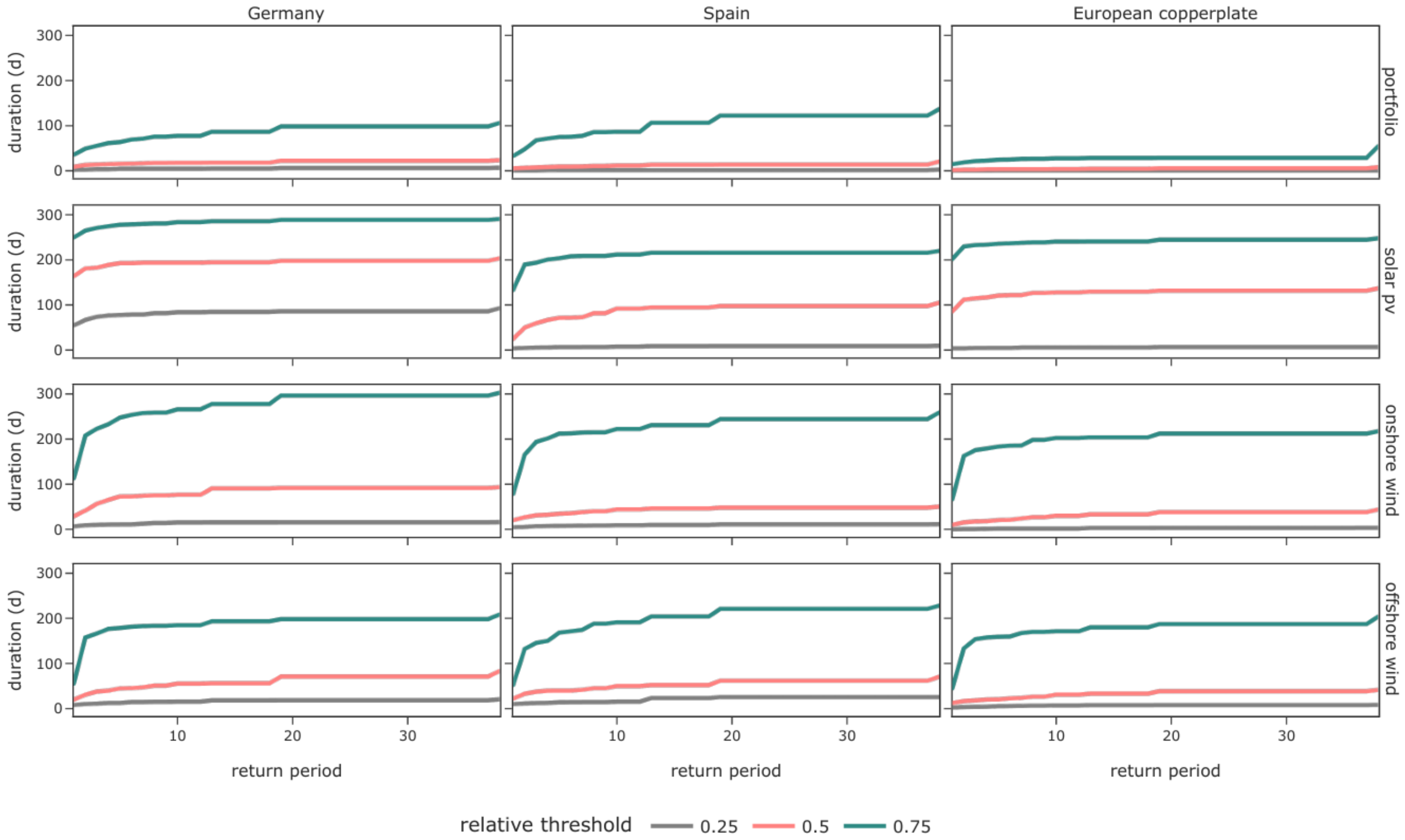
- Maximum duration increases for higher thresholds
- Ranking of years with maximum duration varies

→ single threshold-analysis incomplete



Characterization of Dunkelflaute events

Return periods of extreme droughts across thresholds → single threshold-analysis incomplete



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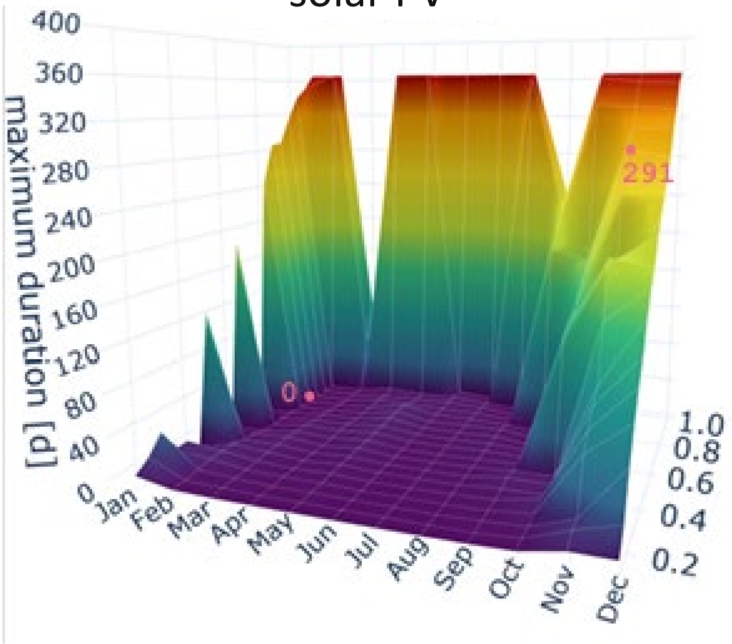
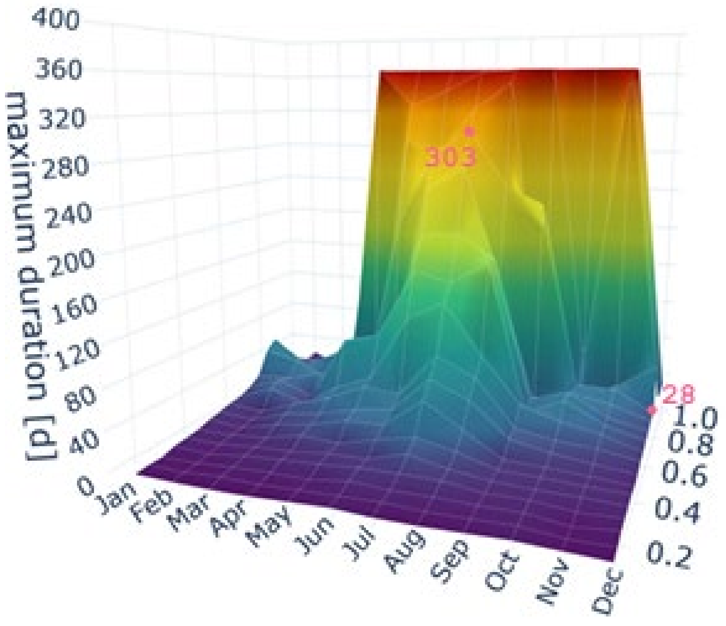
Characterization of Dunkelflaute events

Seasonality of extreme droughts across thresholds in Germany → single threshold-analysis incomplete

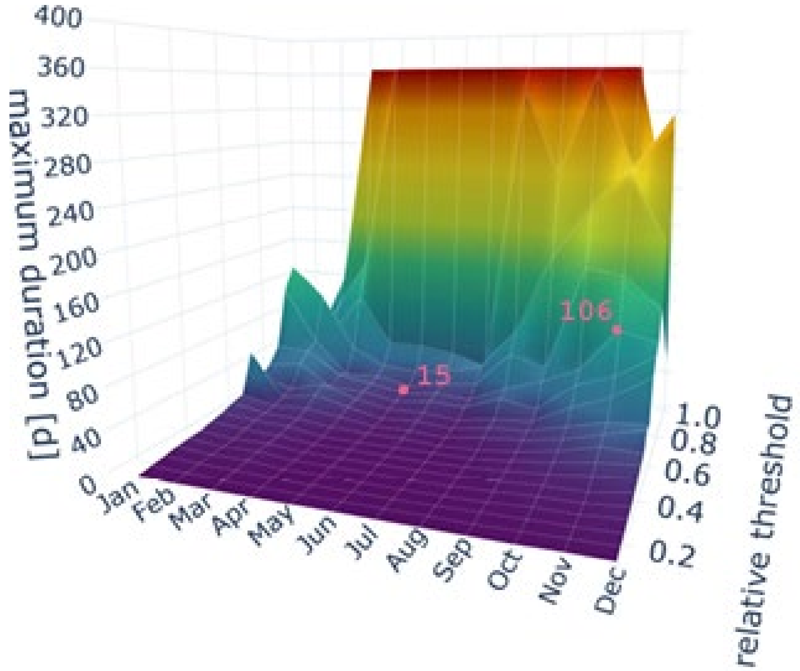
solar PV



onshore wind



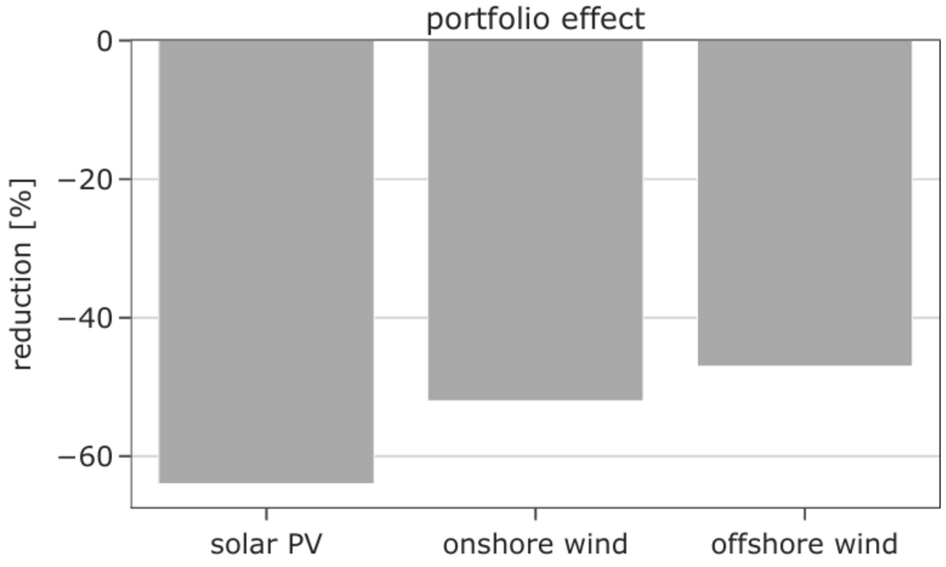
portfolio

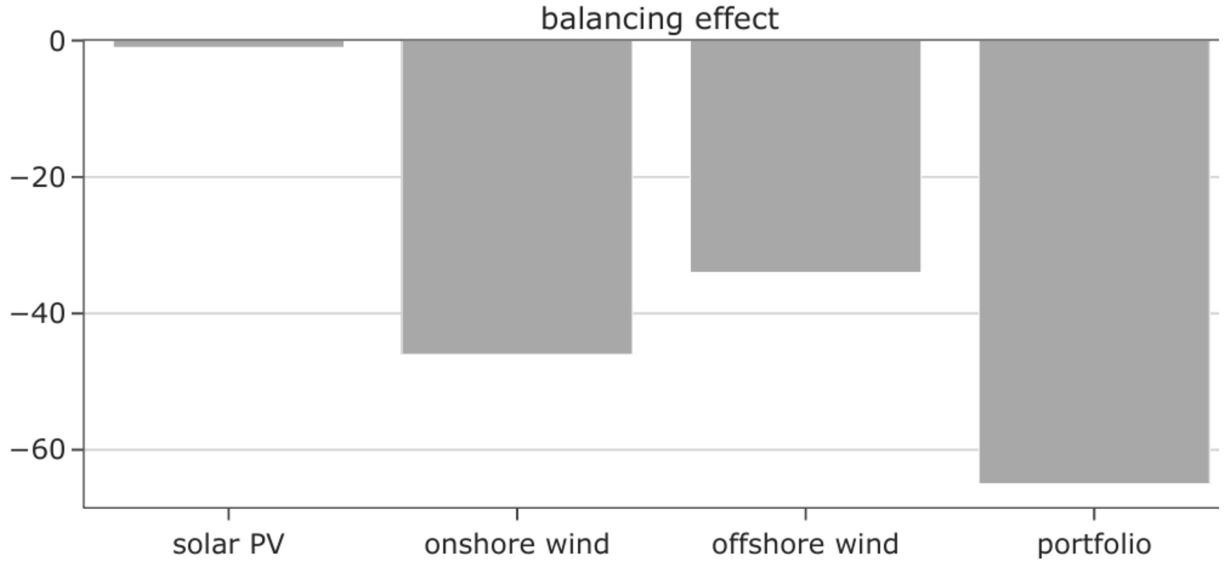


Characterization of Dunkelflaute events

Average portfolio and balancing effects from wind and solar complementary across thresholds and countries

- Decrease maximum drought duration <u>within</u> regions
- Decrease maximum drought <u>across</u> regions → European transmission grid highly meshed



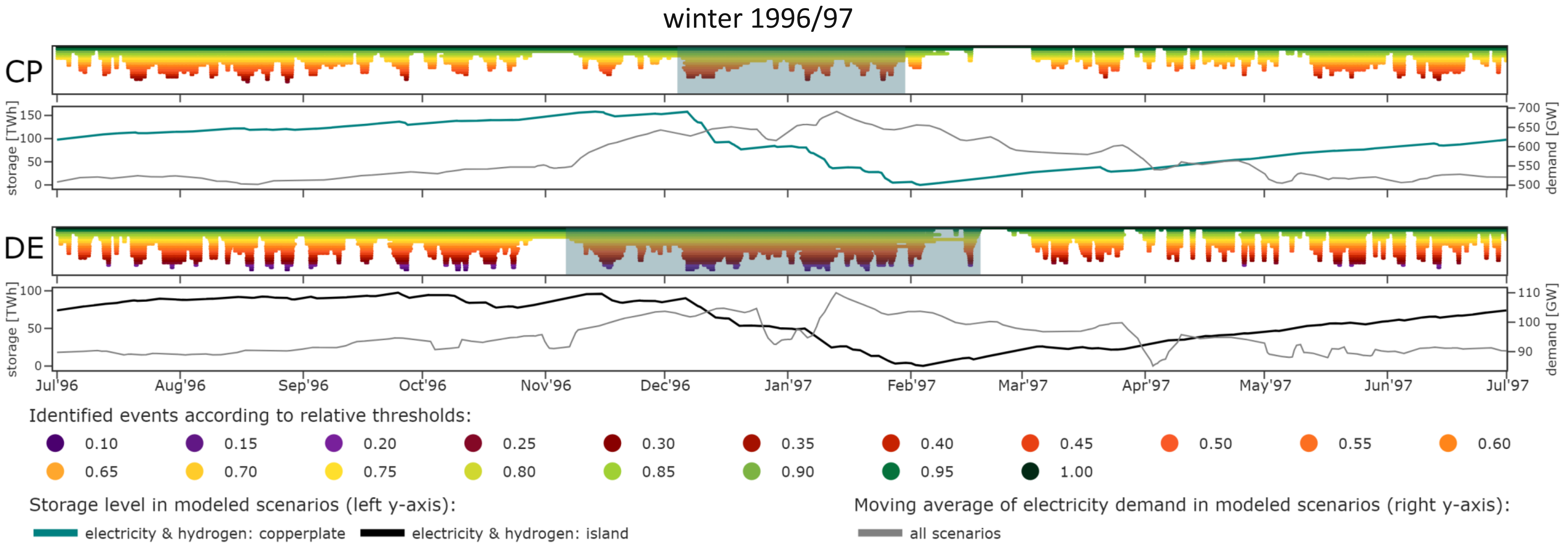


4. Long-duration electricity storage needs

Identification of extreme Dunkelflaute events

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

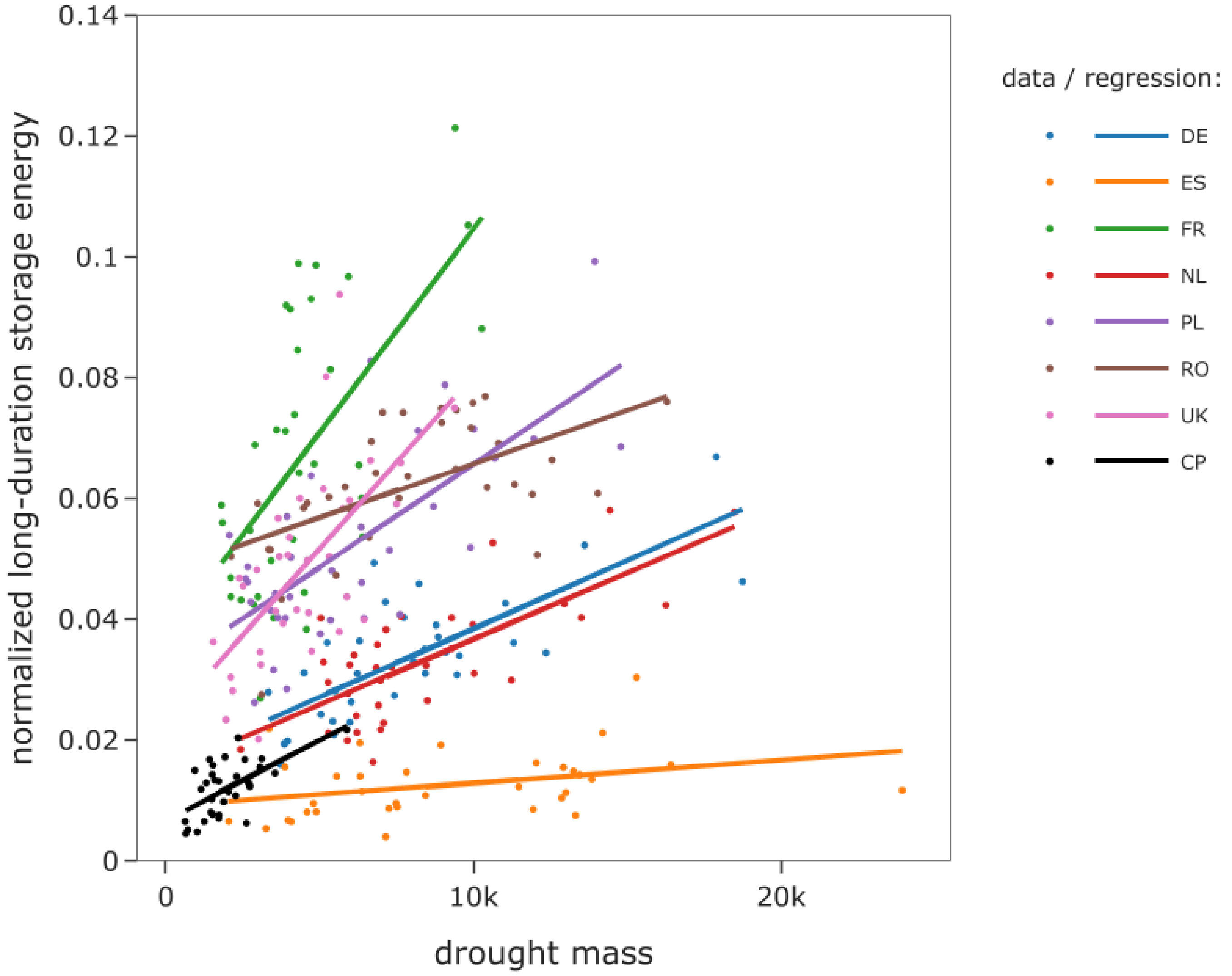
- No meaningful definition for extreme Dunkelflaute events
- Drought mass metric to find events that drive long-duration storage discharge
- Sequence of severe shortage events within a long-lasting, contiguous low-availability period
- Span across turn of year
- Most extreme European event in the data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



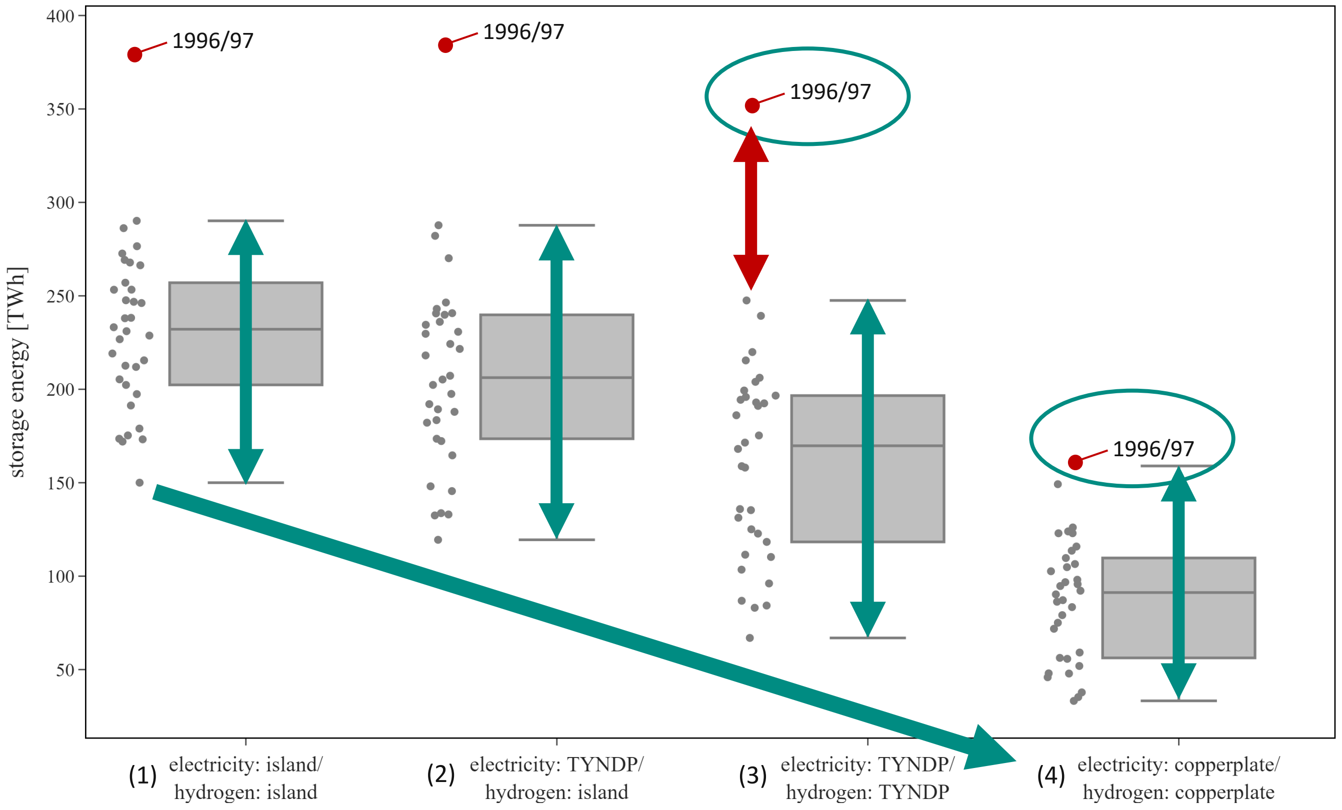
Long-duration electricity storage investment

- Most extreme Dunkelflaute events drive long-duration storage energy capacity

- Further drivers
  - Other flexibility options
  - Demand seasonality



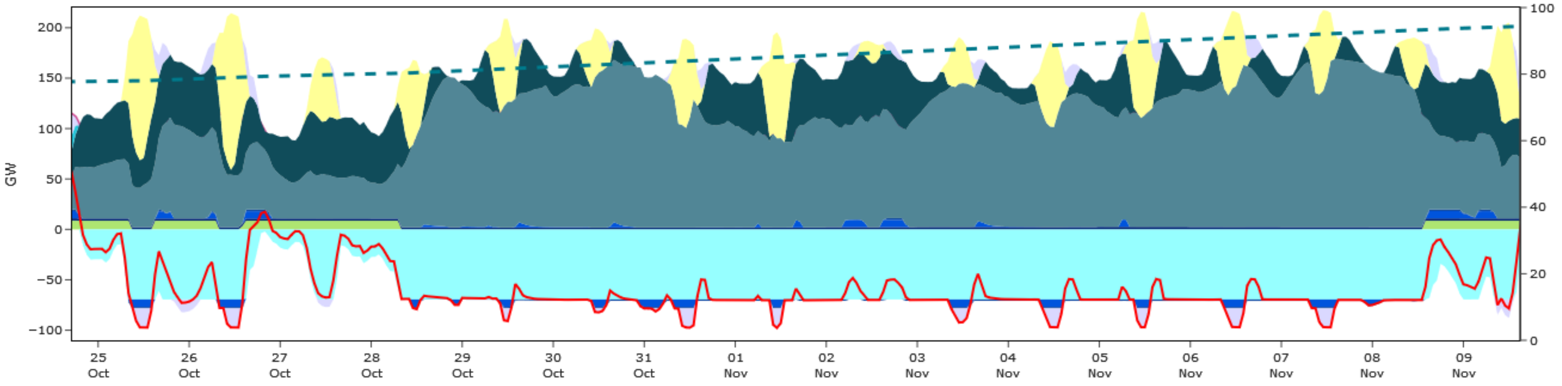
Long-duration electricity storage (LDS) needs



- 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%

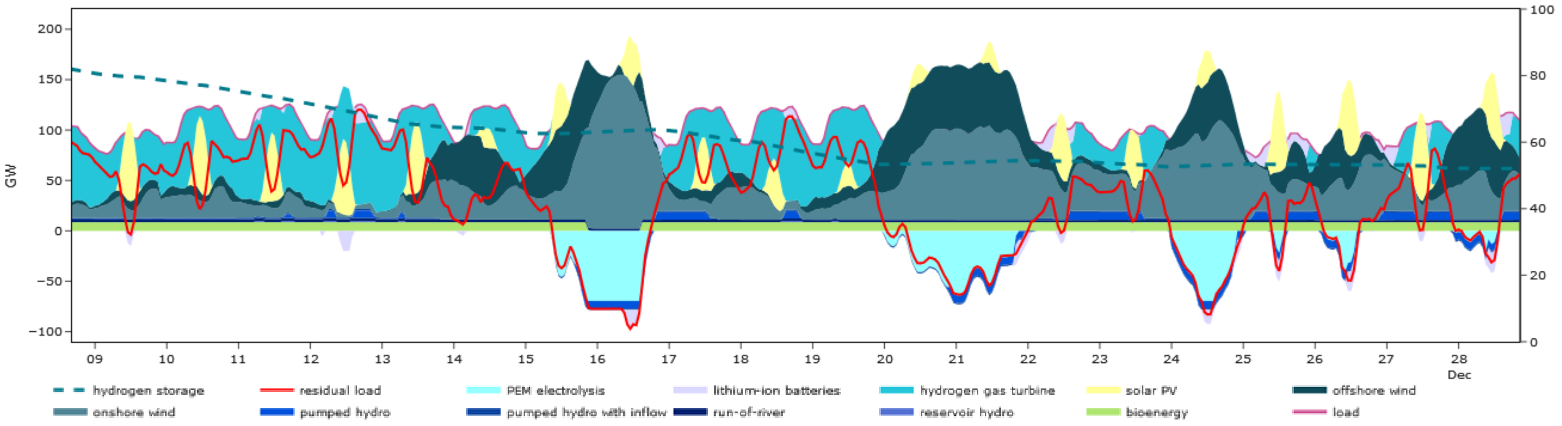
Interaction of flexibility options

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

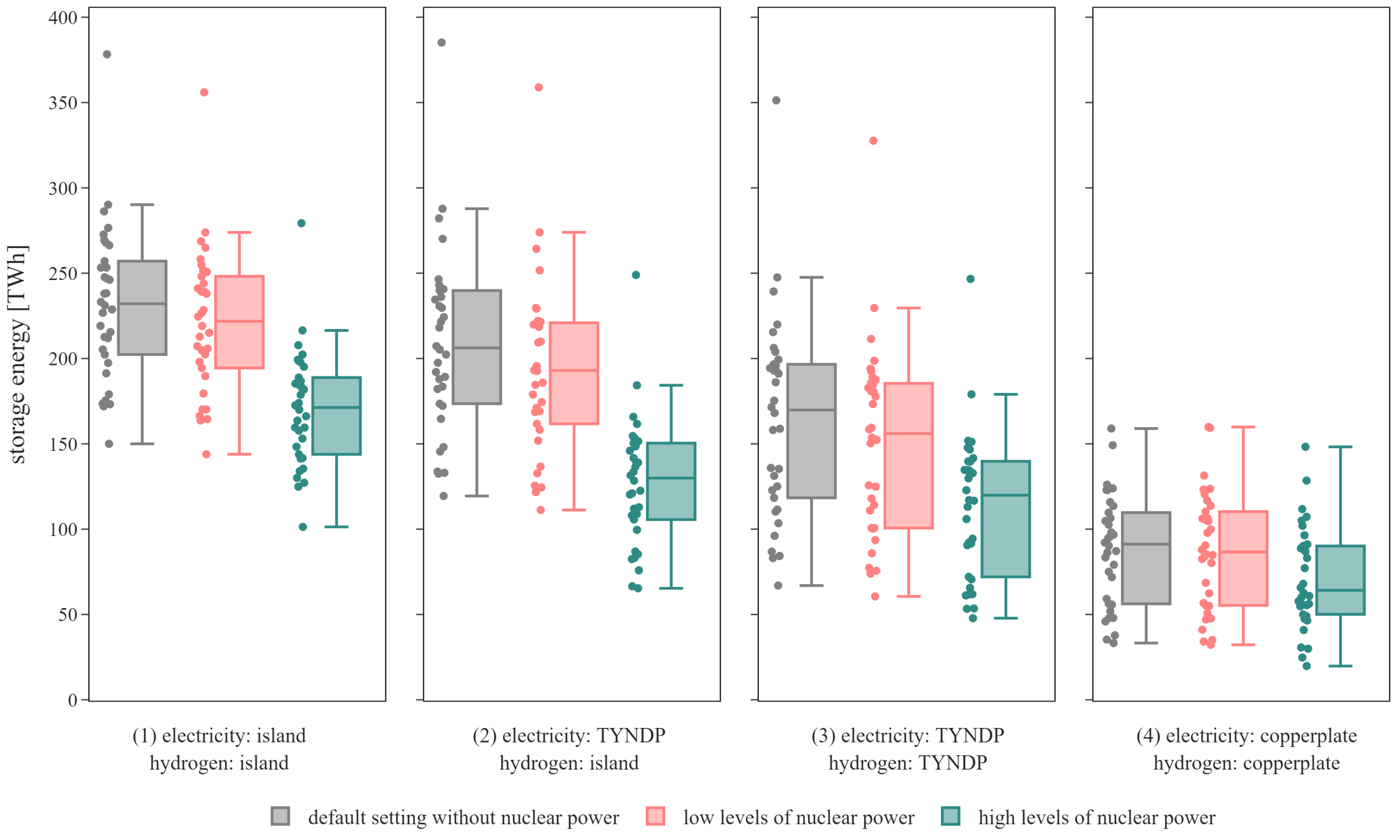
Sensitivity analysis: Impact of nuclear power

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%

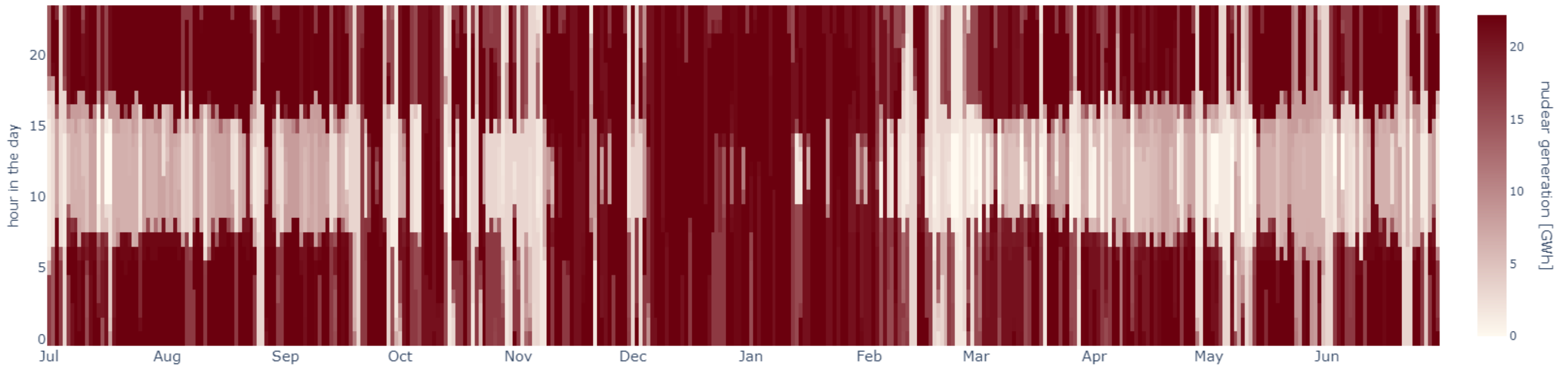


Sensitivity analysis: Impact of nuclear power

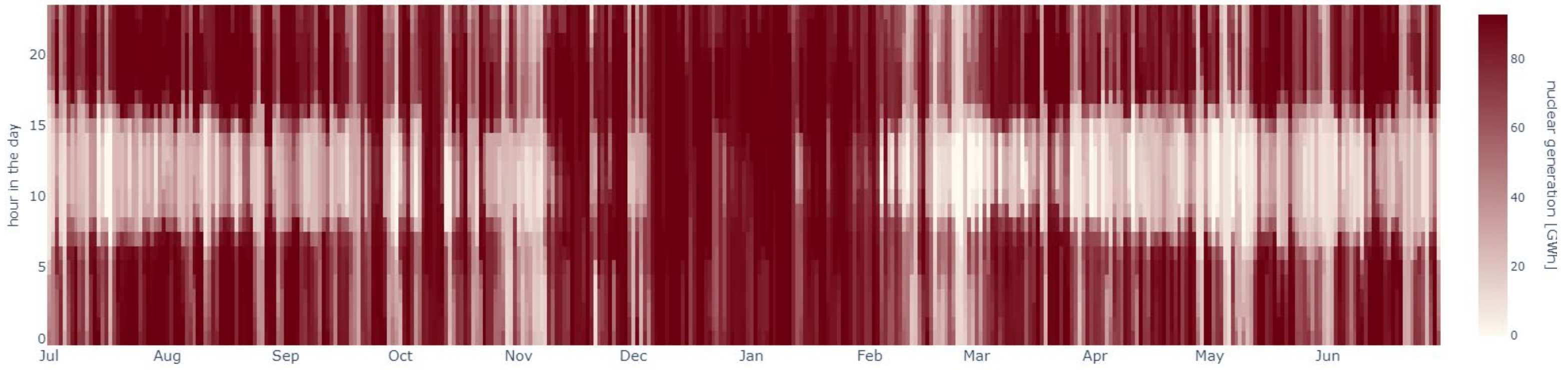
Operational patterns of nuclear power in winter 1996/97 under policy-relevant interconnection (3)

- 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



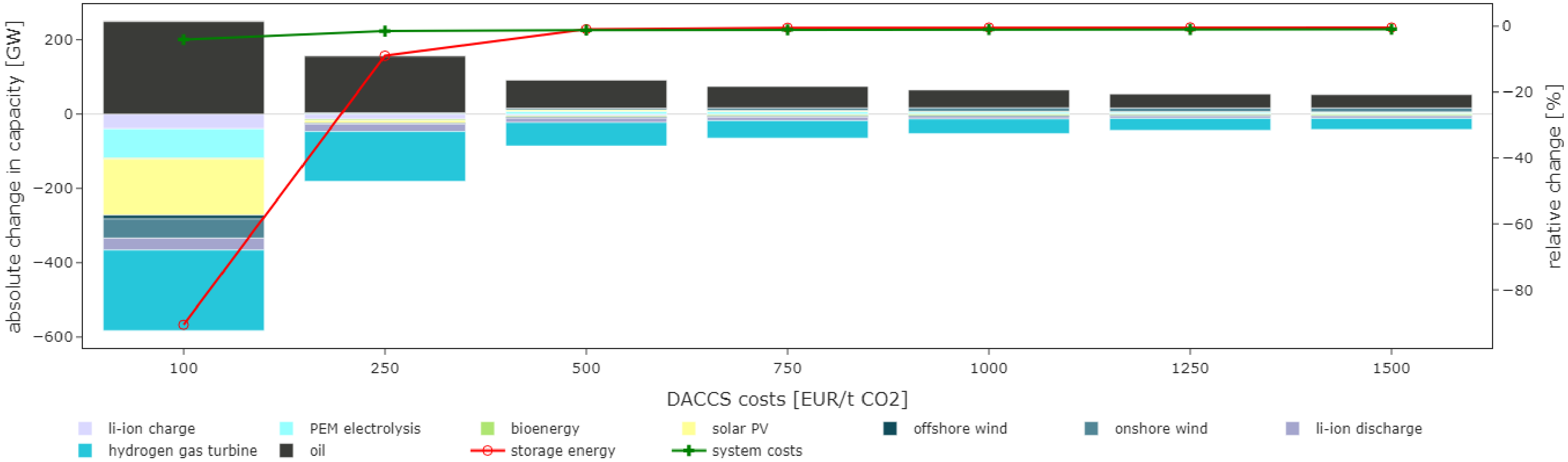
Sensitivity analysis: oil-fired backup capacity with CCS

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 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



5. Add-on: Interactions with electrified heating

Complementary analysis focusing on heat demand and heat storage

Three complementary elements

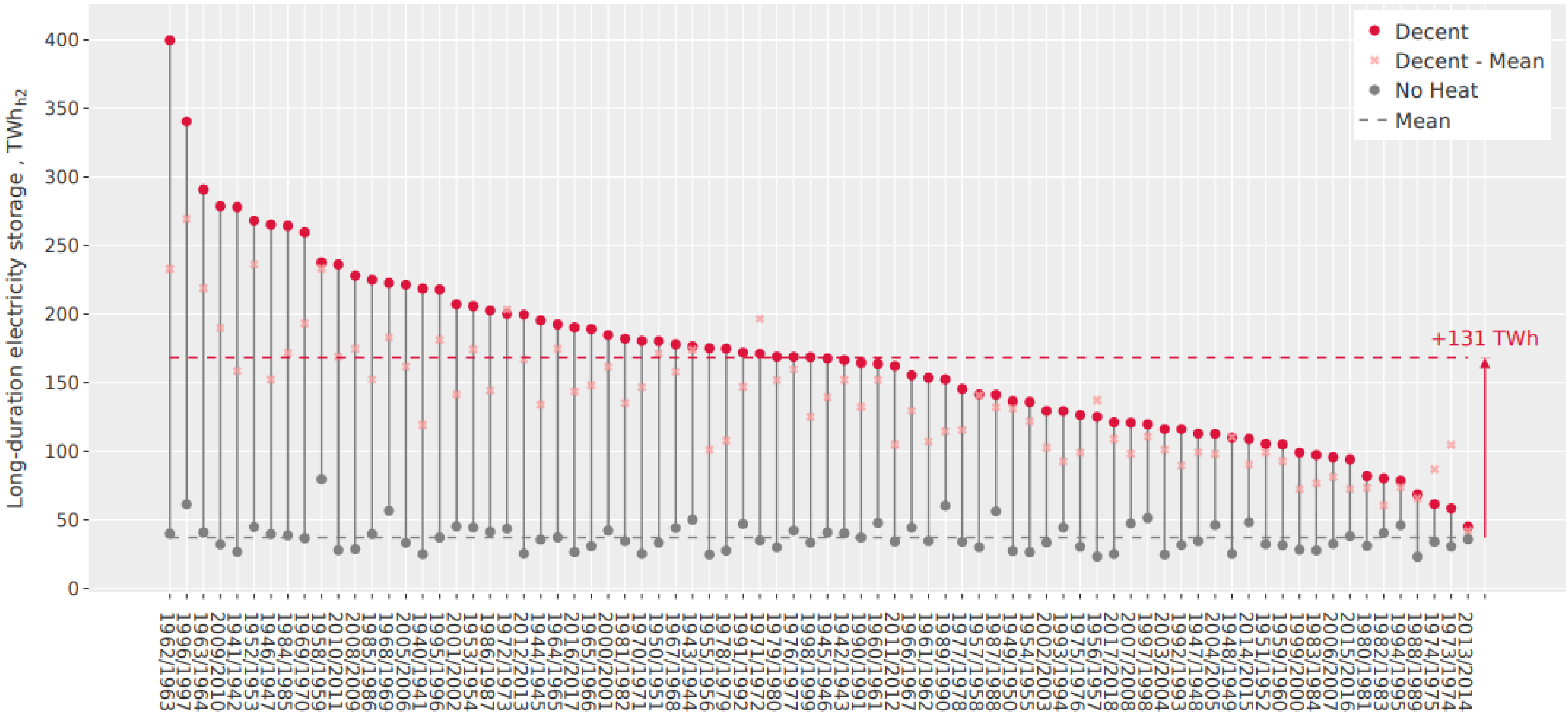
- Effects of additional load for electrified heating
- Effects of long-duration heat storage
- Larger weather year data set (78 years)

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

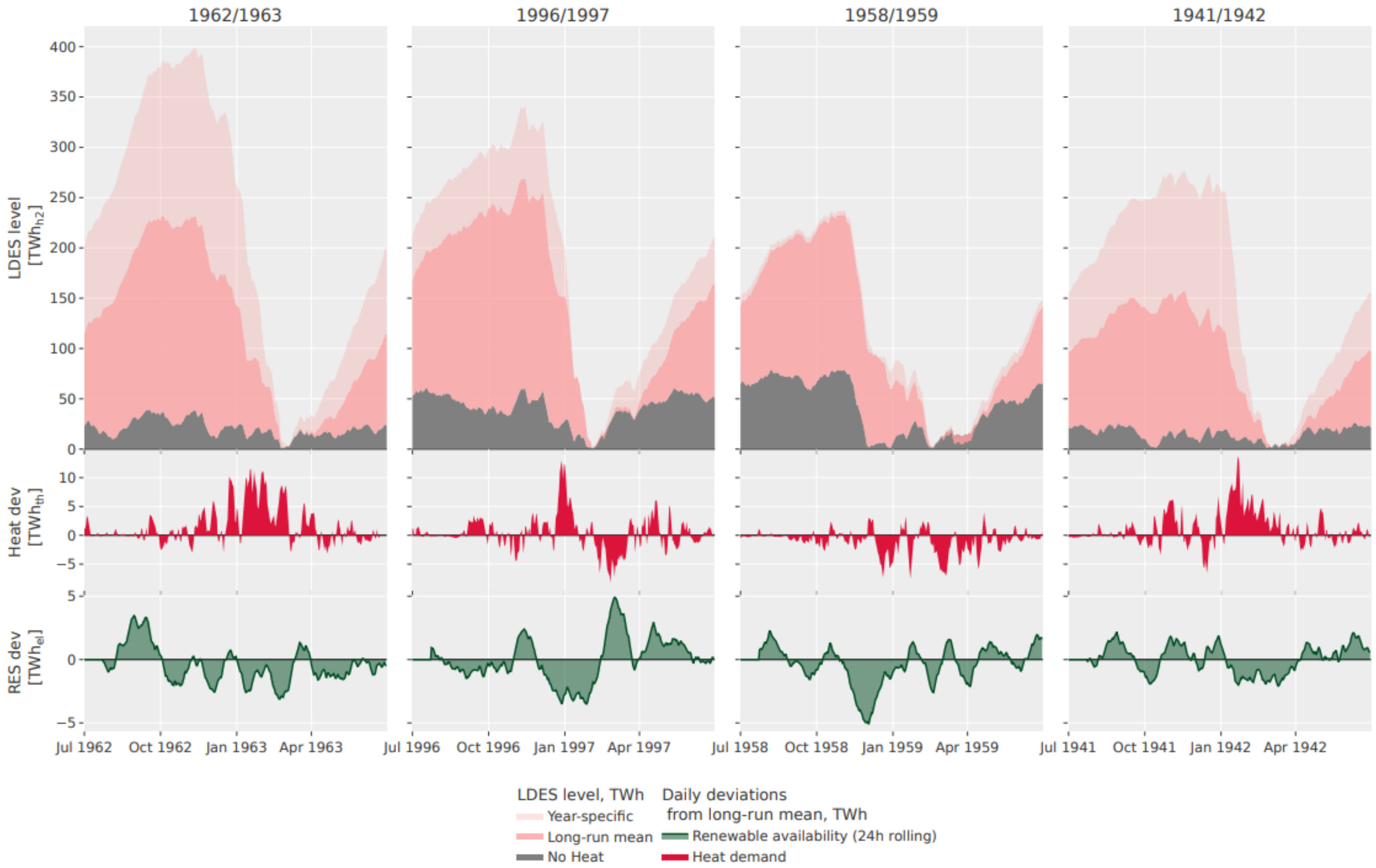
Long-duration electricity storage results for all weather years



→ Electric heating substantially increases LDES needs

→ Large variation between weather years – demand-side variability matters

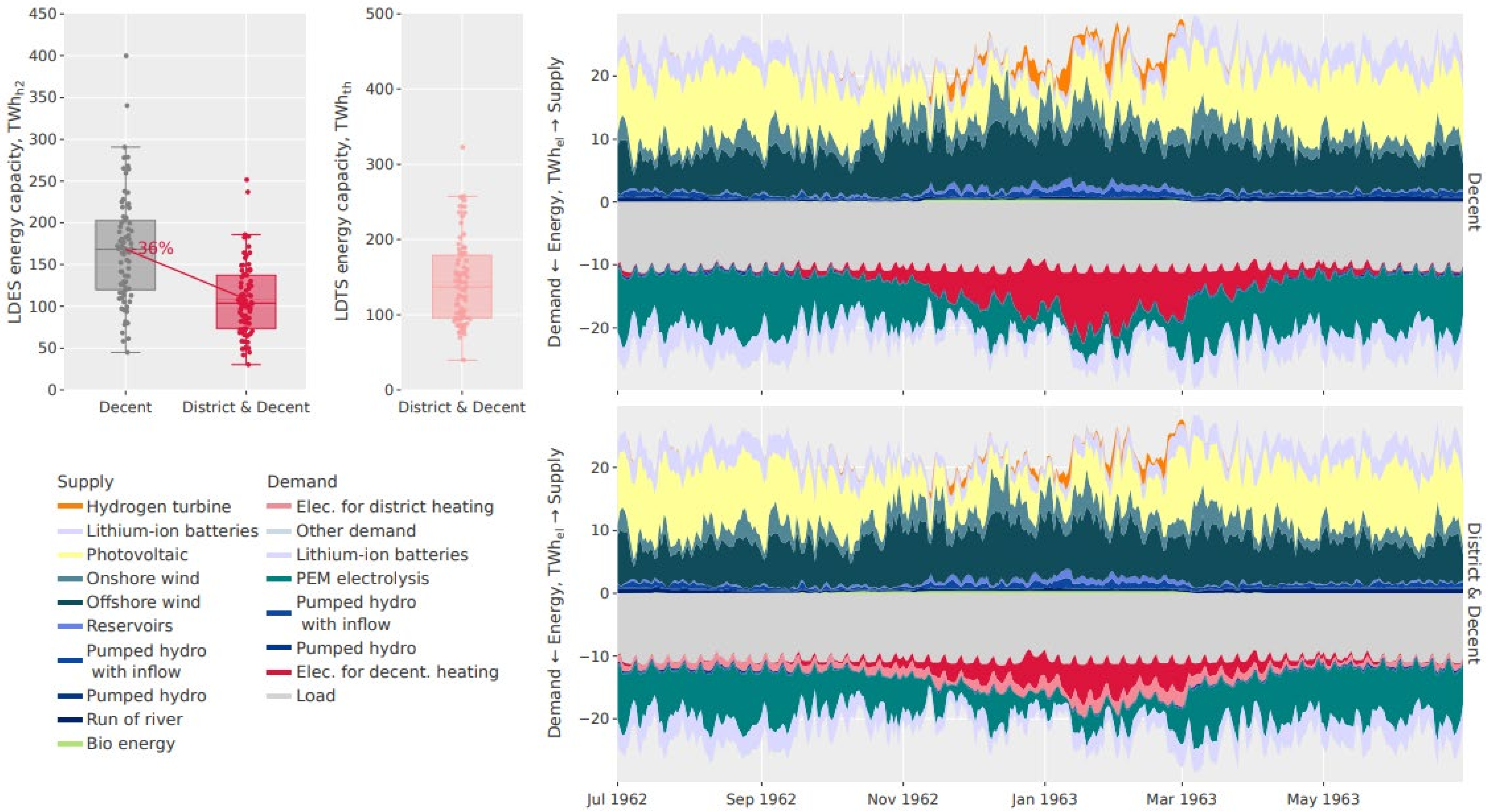
Illustration of effects in four complementary years



→ *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

6. Conclusion

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

Conclusion

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., 2026; Gotske et al., 2024, Schmidt et al., 2025

7. Add-on: Dunkelfaute in Australia

Identification of Dunkelflaute events in Australia

Explanatory short study from 2022

Drought thresholds

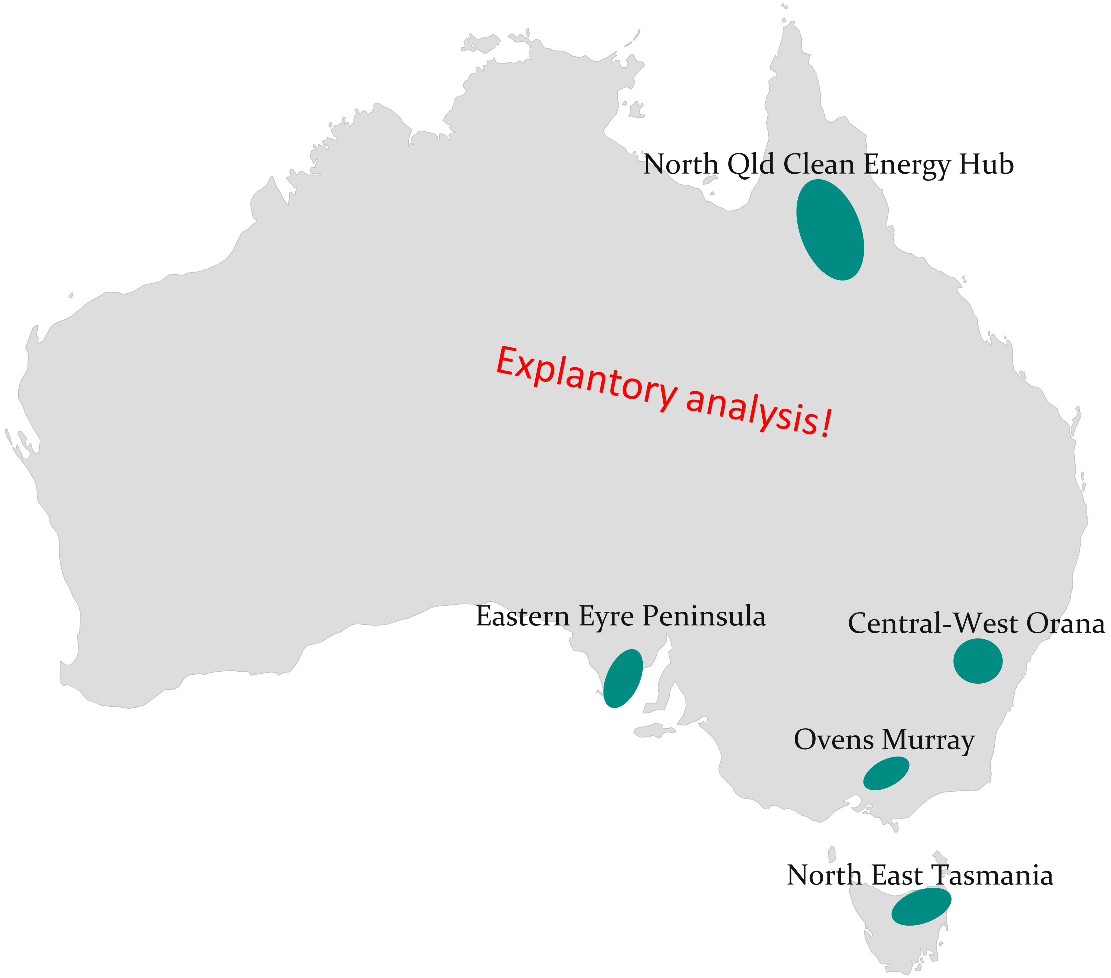
- 2%, 5%, 10% of installed capacity

AEMO Integrated System Planning Report 2022

- renewable energy zones in NEM area
- hourly capacity factors for 2014-2021

Technological scope

- Solar PV
- onshore wind



Identification of Dunkelflaute events in Australia

Most extreme solar PV events per year

- 2017 most extreme → selection of weather year matters
- NSW, QLD, SA with less variation → BUT: short record

Identification of Dunkelflaute events in Australia

Most extreme solar PV events per season

- winter low more pronounced in TAS and VIC
- spatial balancing of long-lasting droughts possible

Identification of Dunkelflaute events in Australia

Most extreme solar PV events per season

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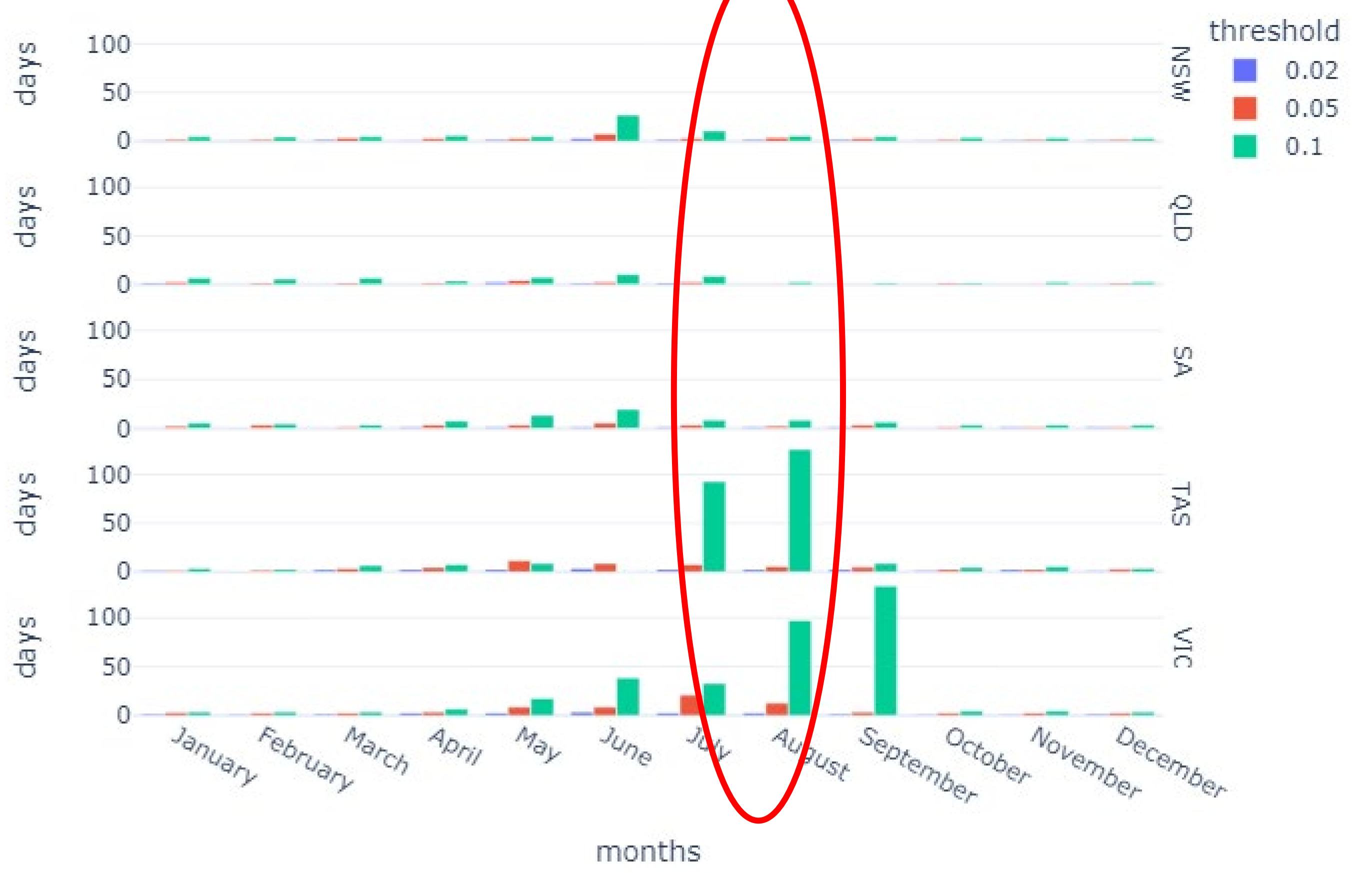
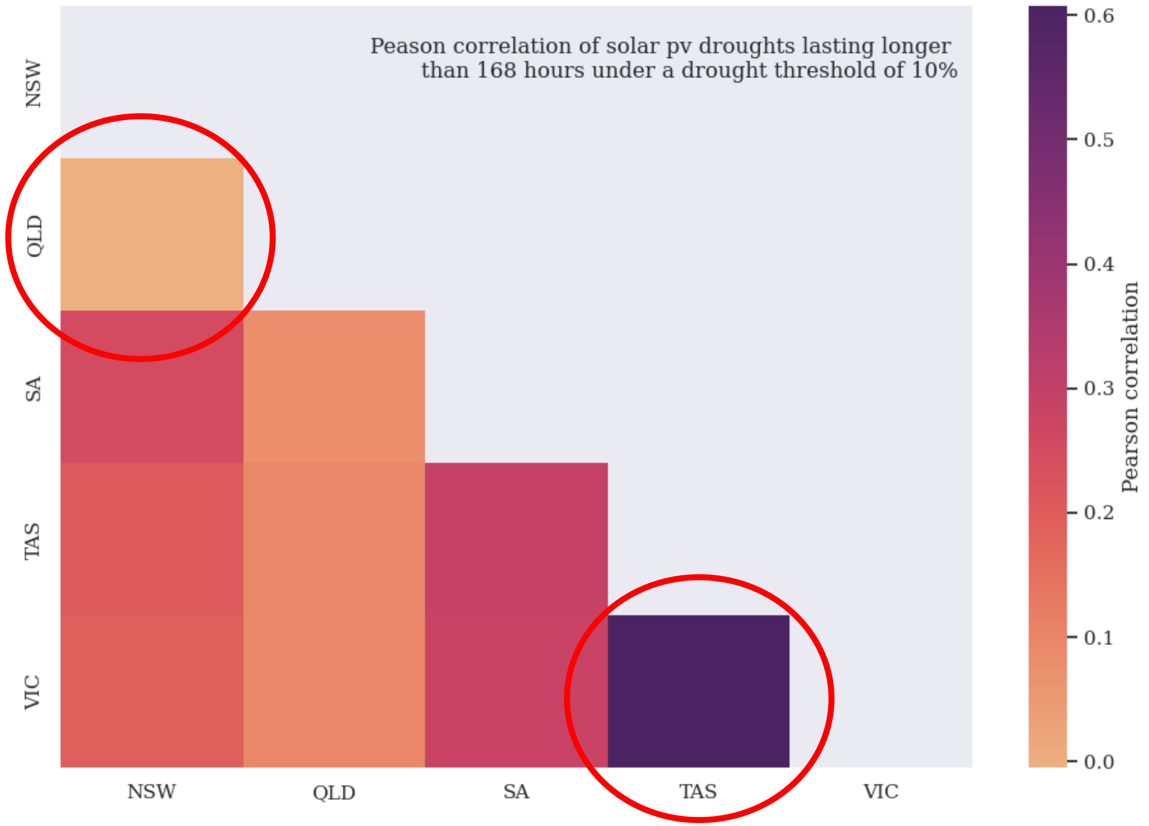


Identification of Dunkelflaute events in Australia

Spatio-temporal correlation of severe solar PV droughts

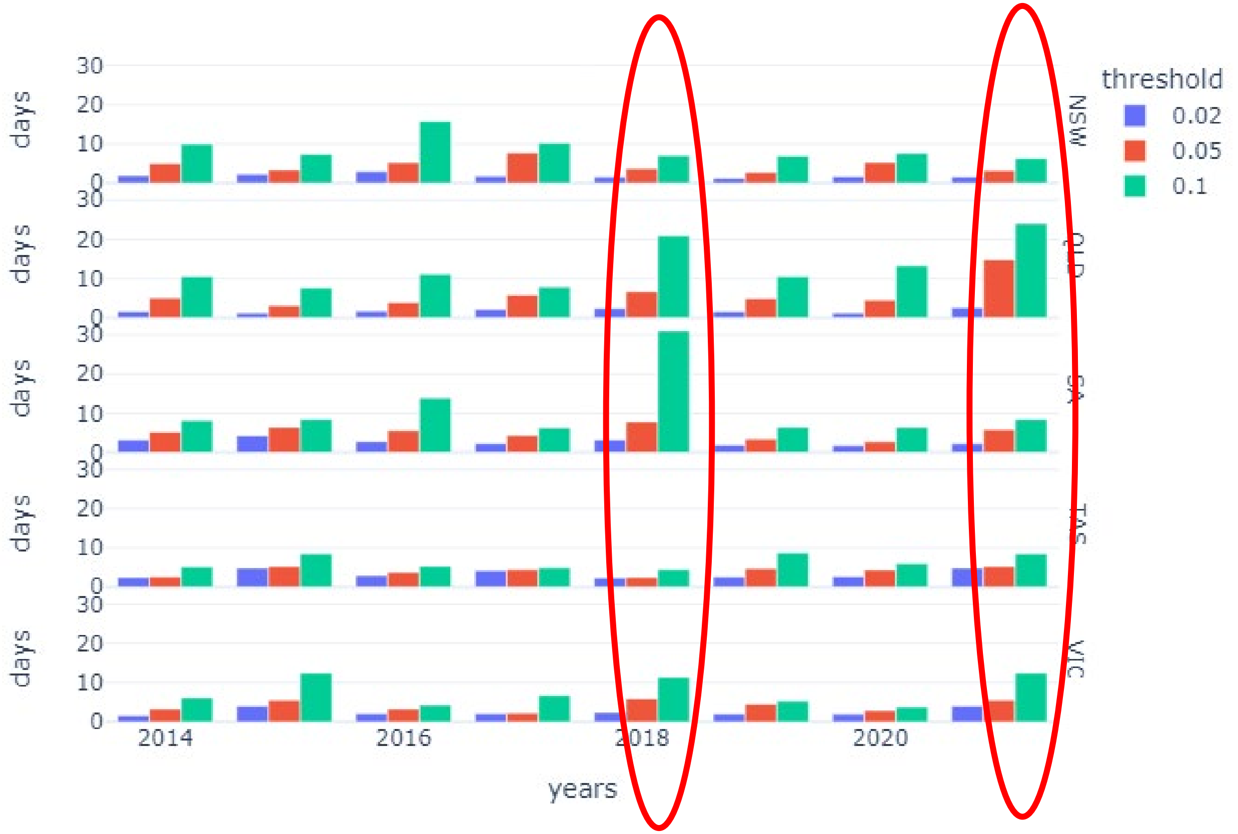
- Strong variations across Australia → different weather regimes
- Electricity exchange to cope with droughts not suitable for some states



Identification of Dunkelflaute events in Australia

Most extreme onshore wind events per year

- More variation than PV
- 2018, 2021 most extreme → selection of weather year matters



Identification of Dunkelflaute events in Australia

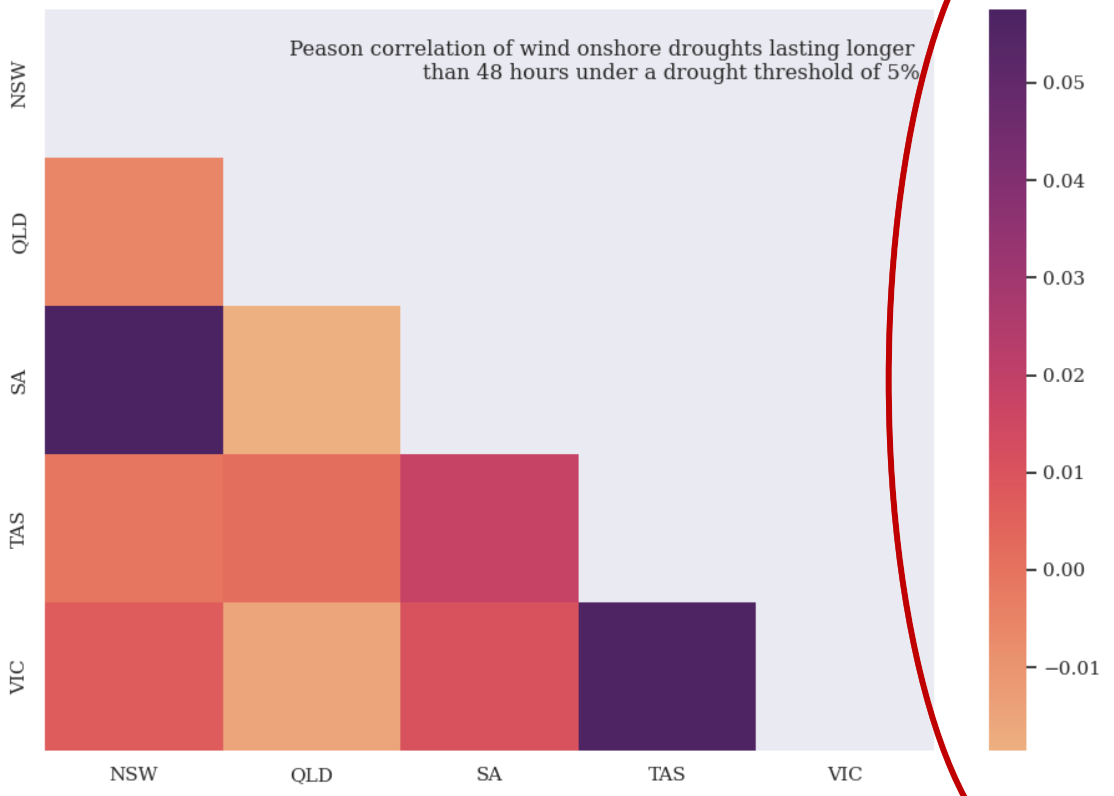
Most extreme onshore wind events per season

- Complementarity of QLD with NSW/SA → strong NEM grid
- TAS & VIC with similar patterns → local storage

Identification of Dunkelflaute events in Australia

Spatio-temporal correlation of extreme onshore wind events

- Strong variations across Australia (very large distances)
- very low correlation, even for lower thresholds and shorter periods



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 & 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

Discussion: Dunkelflaute events in Australia

Research questions

- More stable solar PV availability, increasing wind share
  - Wind drought seasonality, severity?
  - Portfolio drought less pronounced?

- Lower need for seasonal balancing
  - Role of long-duration storage → relevant for steel-making?
  - Other set of flexibility technologies?

Thank you for your attention.

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