ECEMP 2025

Coping with the Dunkelflaute

Power sector implications of variable renewable energy droughts in Europe

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Berlin, 16 October 2025

KOPERNIKUS PROJEKTE
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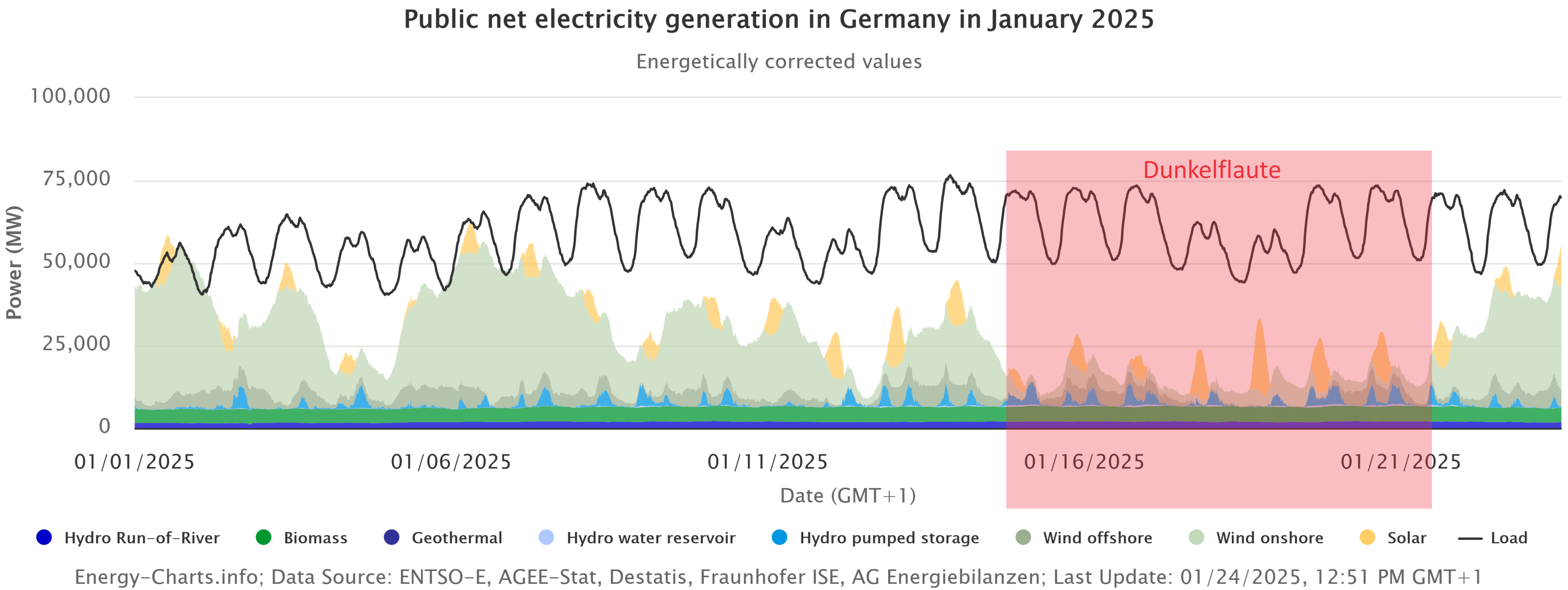
Content

1. Motivation

Recent Dunkelflaute event in Germany

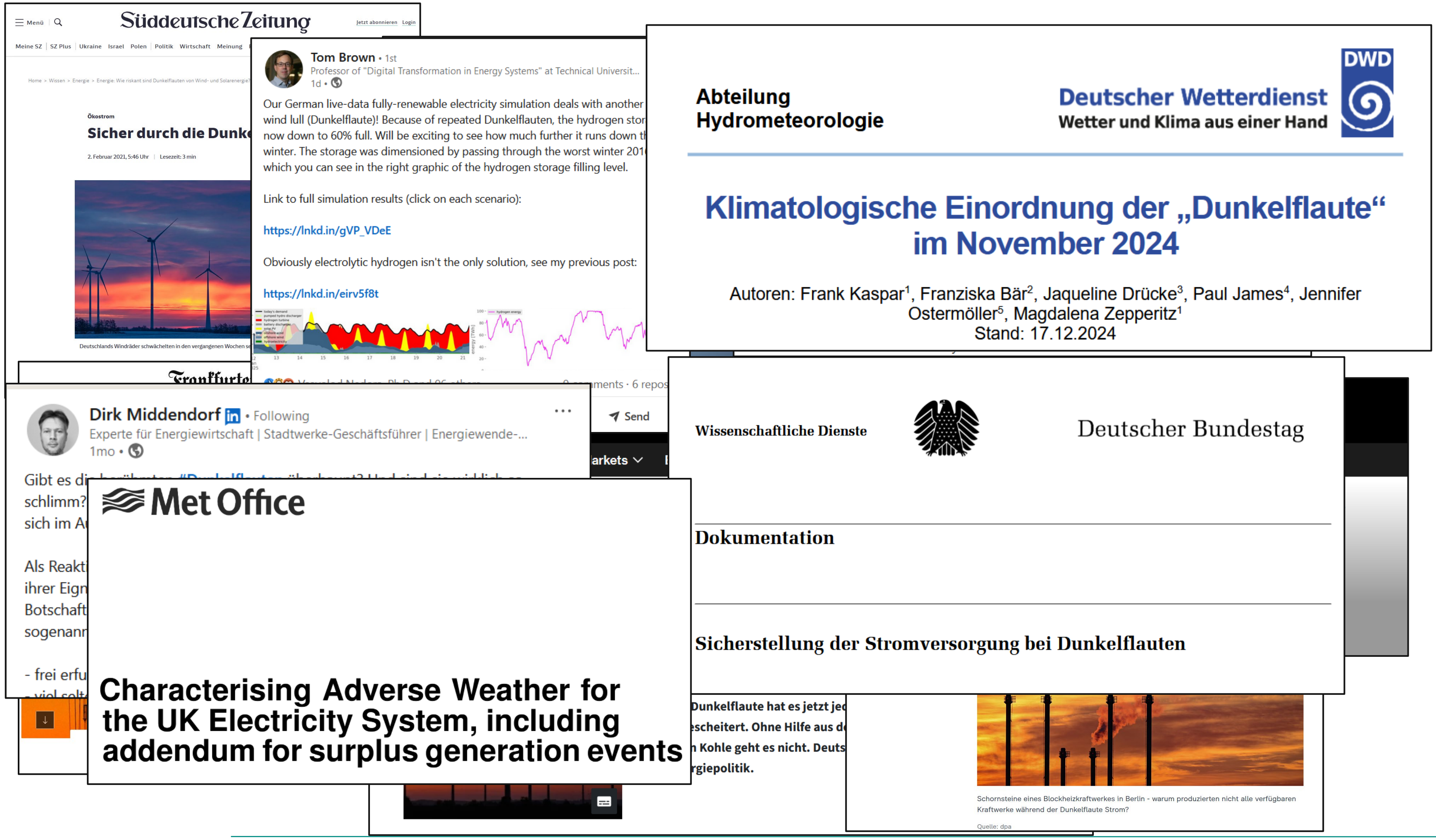


Variable renewable energy (VRE) drought or German term "Dunkelflaute"

- Extended period with low renewable availability
- Increasing reliance on VRE → Dunkelflaute events become key challenge for realizing energy transition
- Temporal and spatial flexibility for dealing with these periods

Relevance

Dunkelflaute events in public, policy, and academic discourse



Research Questions

European power sector implications of extreme Dunkelflaute events

VREDA

1. What are most extreme Dunkelflaute events? Kittel & Schill (2024a), Kittel & Schill (2024b)

DIETER

2. What is their impact on long-duration storage operation and investment?
3. What is the value of alternative flexibility in terms of…
   - Cross-country electricity and hydrogen exchange?
   - Interaction of various flexibility options?
   - Firm zero-emission capacity?
   - Fossil-based backup capacity with CSS?
4. Are there critical historical weather years?

Kittel, Roth, and Schill (2024)

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

Interconnection

Island → **European copperplate (CP)**

(1)
Electricity: no
Hydrogen: no

(2)
Electricity: TYNDP
Hydrogen: no

(3)
Electricity: TYNDP
Hydrogen: TYNDP

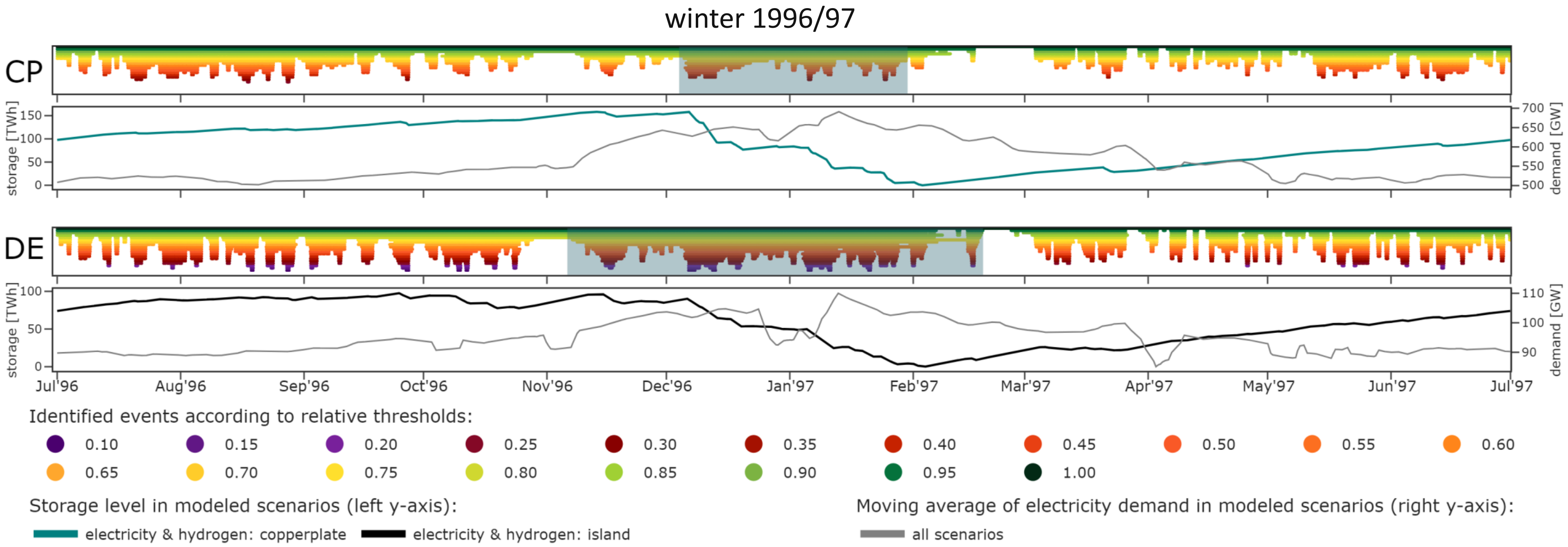
(4)
Electricity: copperplate
Hydrogen: copperplate

3. Key insights

Identification of extreme Dunkelflaute events

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

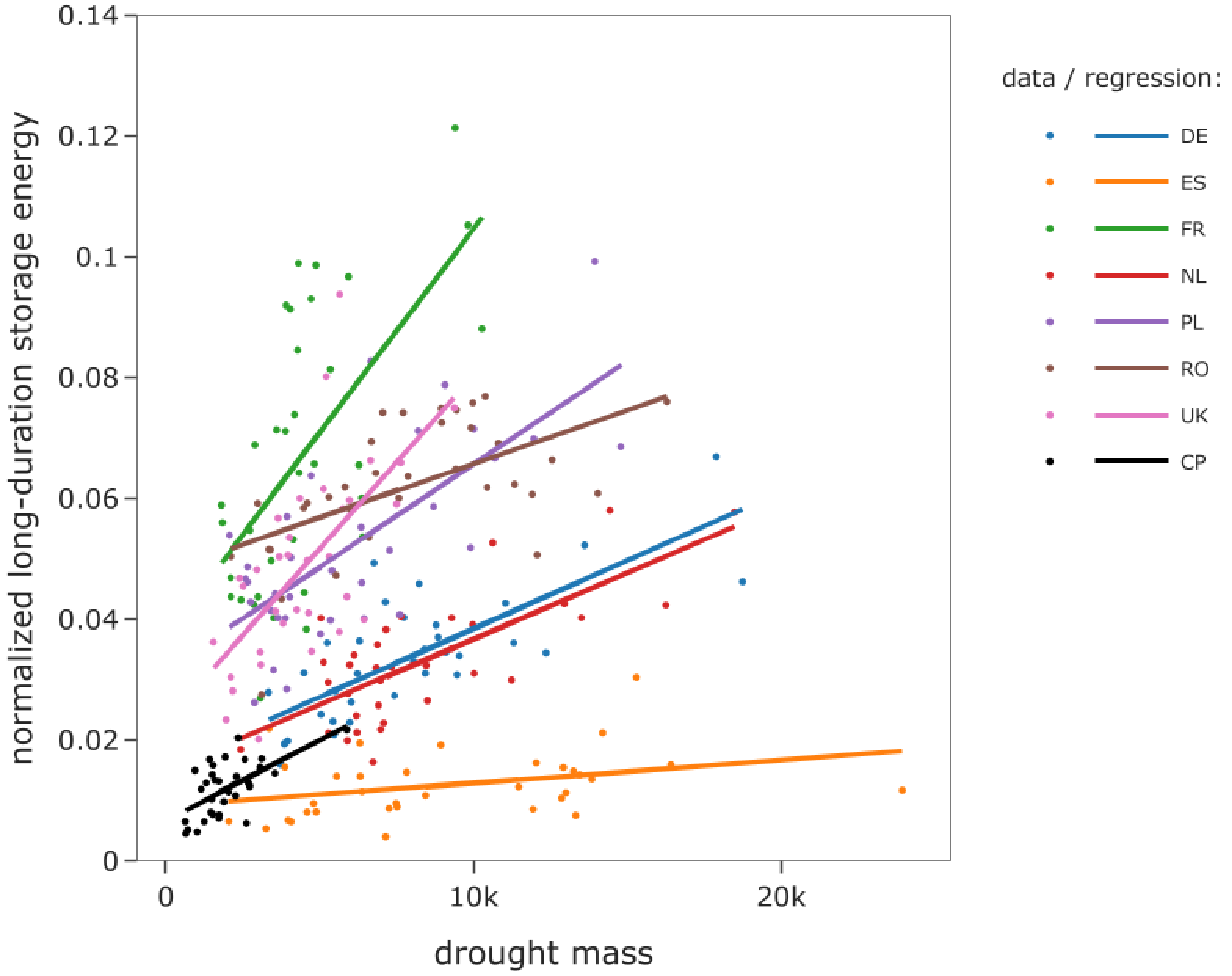
- No meaningful definition for extreme Dunkelflaute events
- Drought mass metric to find events that drive long-duration storage discharge
- Sequence of severe shortage events within a long-lasting, contiguous low-availability period
- Span across turn of year
- Most extreme European event in the data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



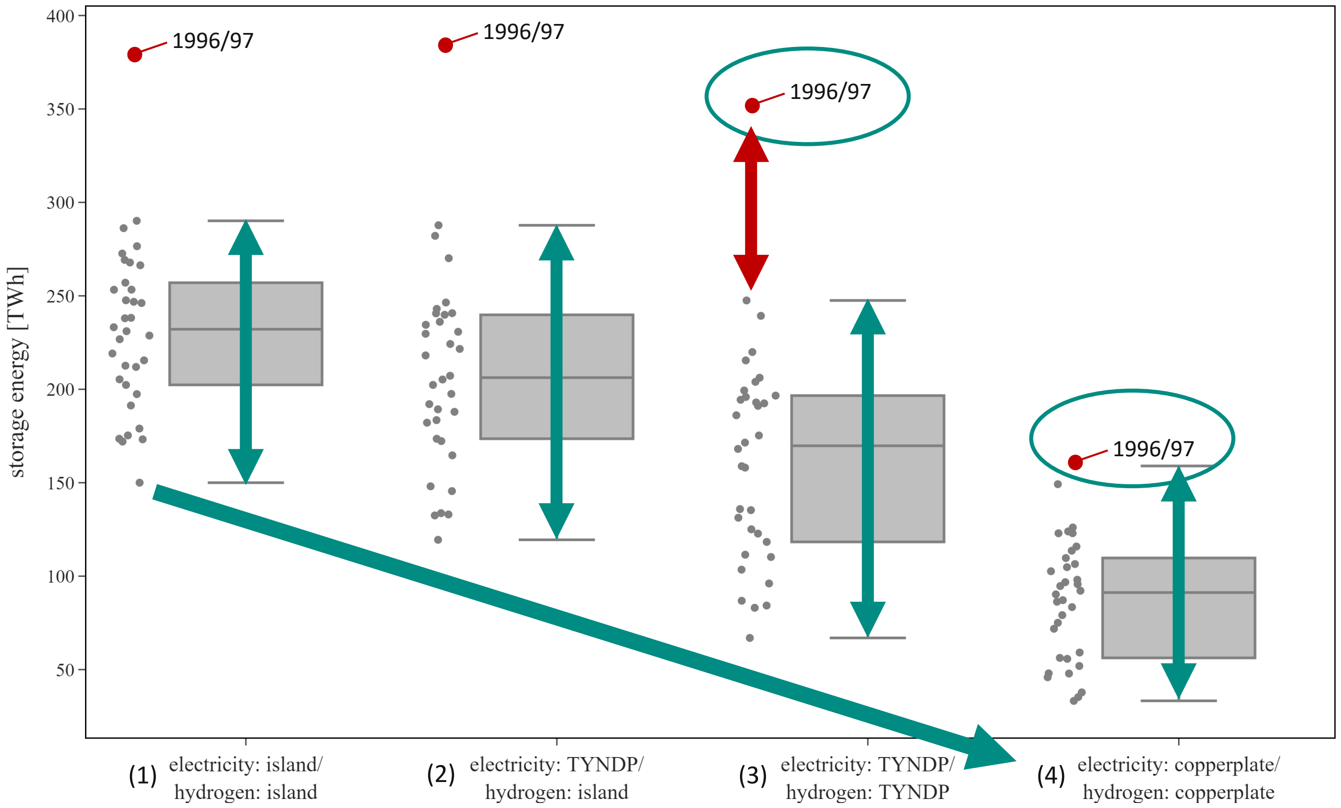
Long-duration electricity storage investment

- 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%

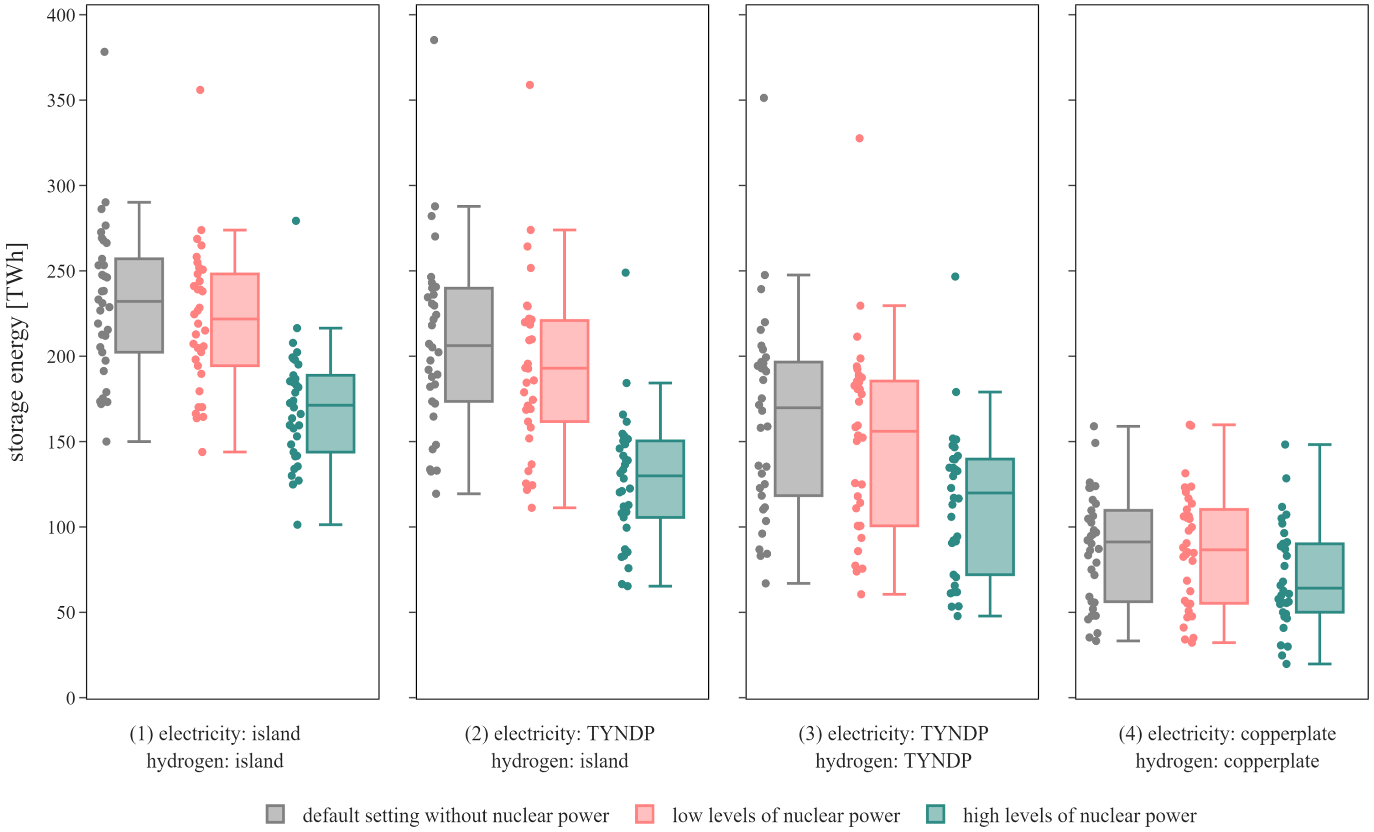
Sensitivity analysis: Impact of nuclear power

Exogenous nuclear capacity

- Low (24 GW) and high (102 GW) levels of nuclear power acc. to TYNDP 2022

General effects

- Nuclear provides firm generation during extreme Dunkelflaute events
- Nuclear displaces optimal investment in wind and solar, decreasing the system's flexibility need
- Mitigation of storage needs under policy-relevant interconnection (3)
    - Low: 8/7% mean/max reduction
    - High: 29/30% mean/max reduction



5. Conclusion

Conclusion

Policy implications

- Dunkelflaute events drive long-duration storage operation and investment
- Extreme years with substantially higher storage needs
- Interconnection can mitigate storage needs to a limited extent
- Nuclear power can mitigate storage needs
- Fossil backup capacity incl. DACCS or load shedding unlikely to mitigate storage needs

- Long-duration storage indispensable for renewable energy system
  - 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 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, code, and data

- 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.

Thank you for your attention.

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