Long-duration electricity storage needs for coping with Dunkelflaute events in Europe

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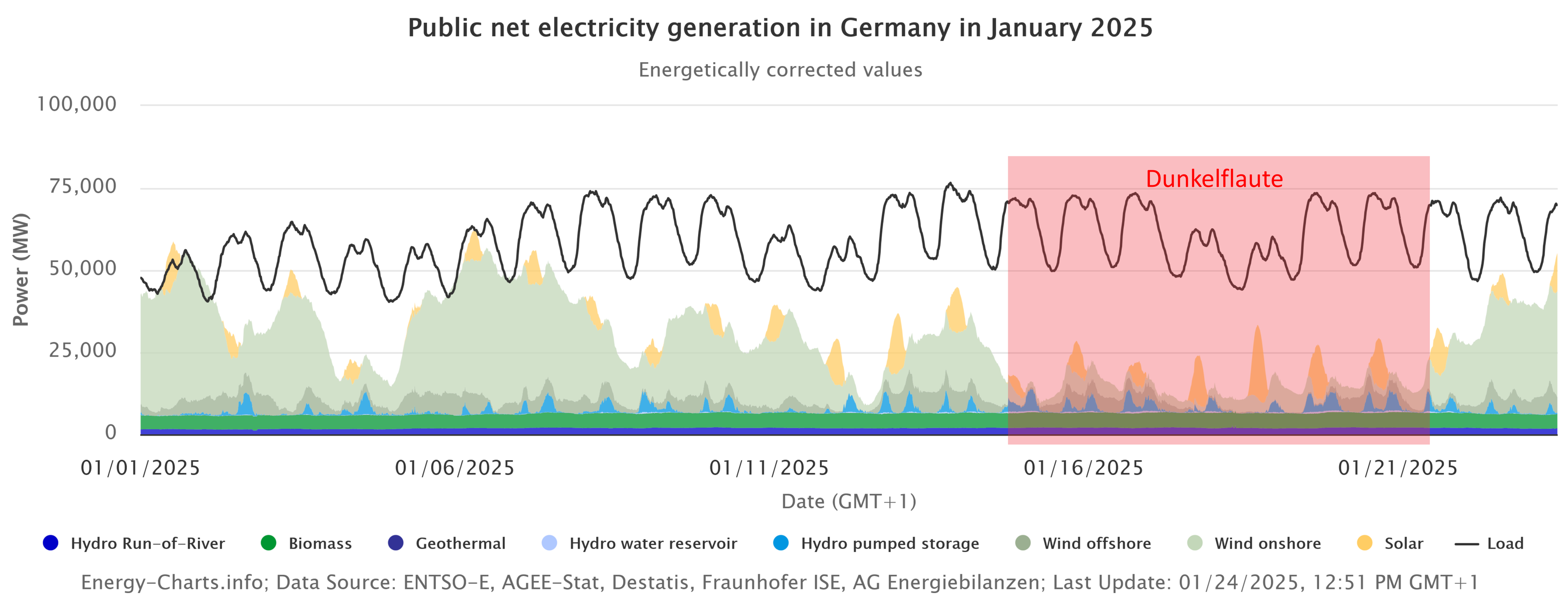
MOTIVATION

While wind and solar power are key for decarbonizing economies, energy systems become increasingly exposed to weather variability with rising shares of these variable renewable energy sources. Prolonged periods of low availability of wind and solar power, also referred to as "Dunkelflaute" or variable renewable energy droughts, emerges as a key challenge for realizing a decarbonized European energy system based on renewable energy. Here we investigate the role of long-duration electricity storage and geographical balancing in dealing with extreme variable renewable energy droughts. Power system implications are crucial for weather-resilient energy system planning, energy policy, and the design of energy markets and support instruments.



RESEARCH DESIGN AND SCENARIOS

Fully renewable European power sector

- No fossil fuels, CCS, or nuclear but import of green hydrogen
- Largely parameterized to TYNDP 2022 (Distributed Energy)
- Sector-coupling "light"
- Sensitivity: nuclear power, fossil backup combined with CCS

Scenarios: temporal dimension

- 35 independent runs based on 35 historical weather years (1982 – 2016) from Pan-European Climate Database 2021.3

Scenarios: spatial dimension

- Increasing levels of interconnection (electricity and hydrogen): no exchange, policy-oriented exchange, European copperplate

METHODS

Dunkelflaute identification using VREDA

- Based on wind and solar energy availability time series
- Advanced identification method VMBT (Kittel & Schill, 2024)
- Drought mass metric to identify extreme events (Kittel & Schill, 2026)

Power sector modeling DIETER

- Cost-minimizing, open-source model of European power sector (Zerrahn & Schill, 2017) incl. green hydrogen generation, storage, and reconversion
- Summer-to-summer planning horizon

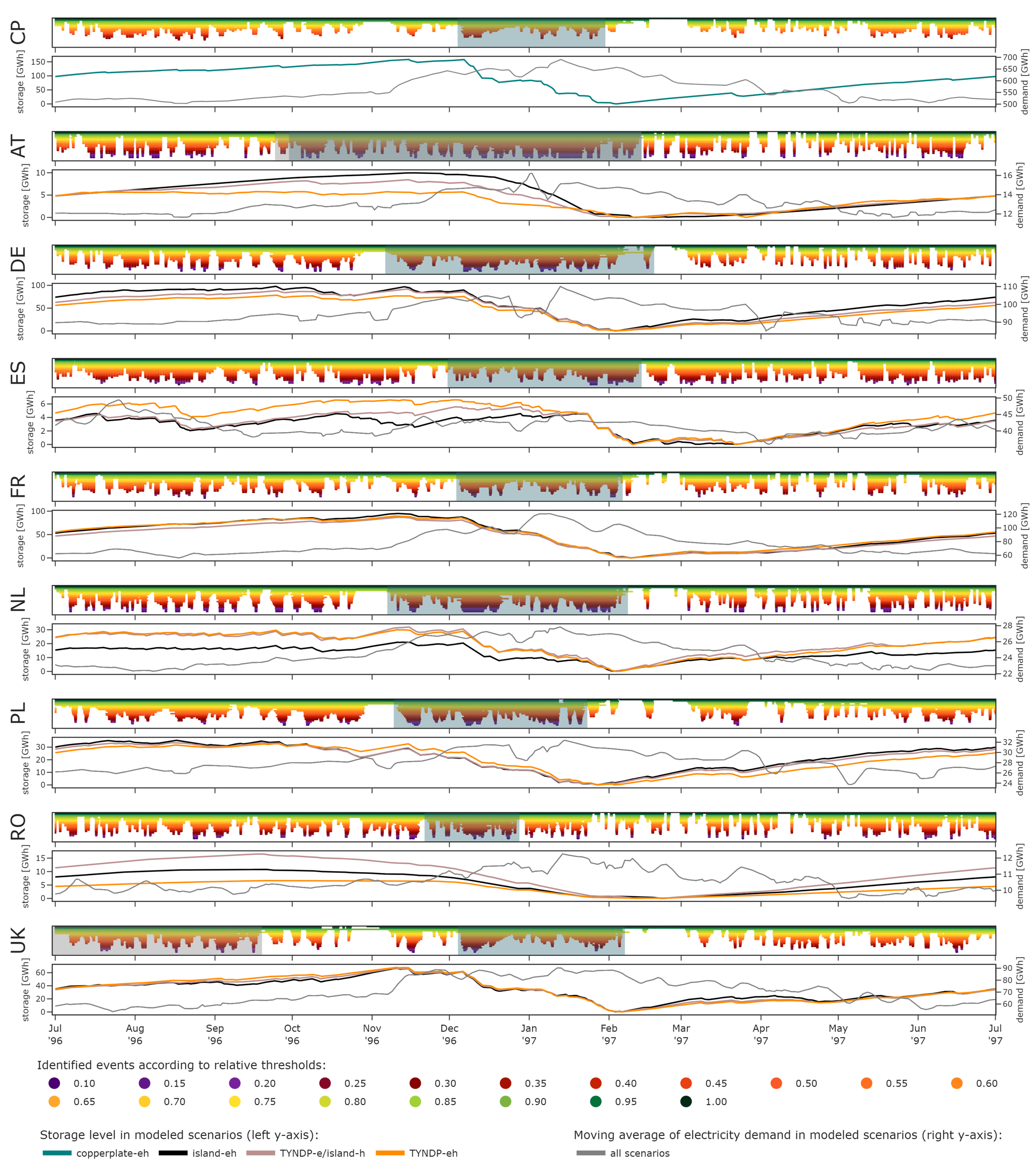
RESEARCH QUESTIONS

- What is the impact of extreme Dunkelflaute events on long-duration electricity storage operation and investment?
- What is the value of cross-country electricity and hydrogen exchange in dealing with such events?
- How do flexibility options interact to cope with such events?
- How can zero-emission and fossil-fueled backup with CCS contribute to dealing with such events?
- Are there critical historical weather relevant for energy system analysis?

KEY RESULTS

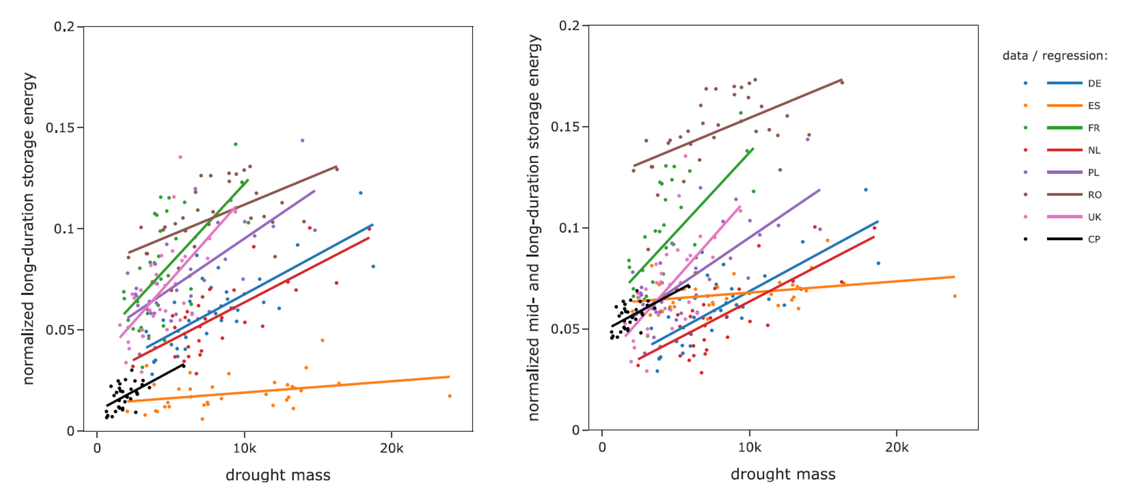
Most extreme Dunkelflaute events

- Drive long-duration electricity storage discharge periods
- Sequence of severe events within a long-lasting, contiguous low-availability period
- Span across turn of years
- Most extreme European event in winter 1996/97, affecting many countries simultaneously



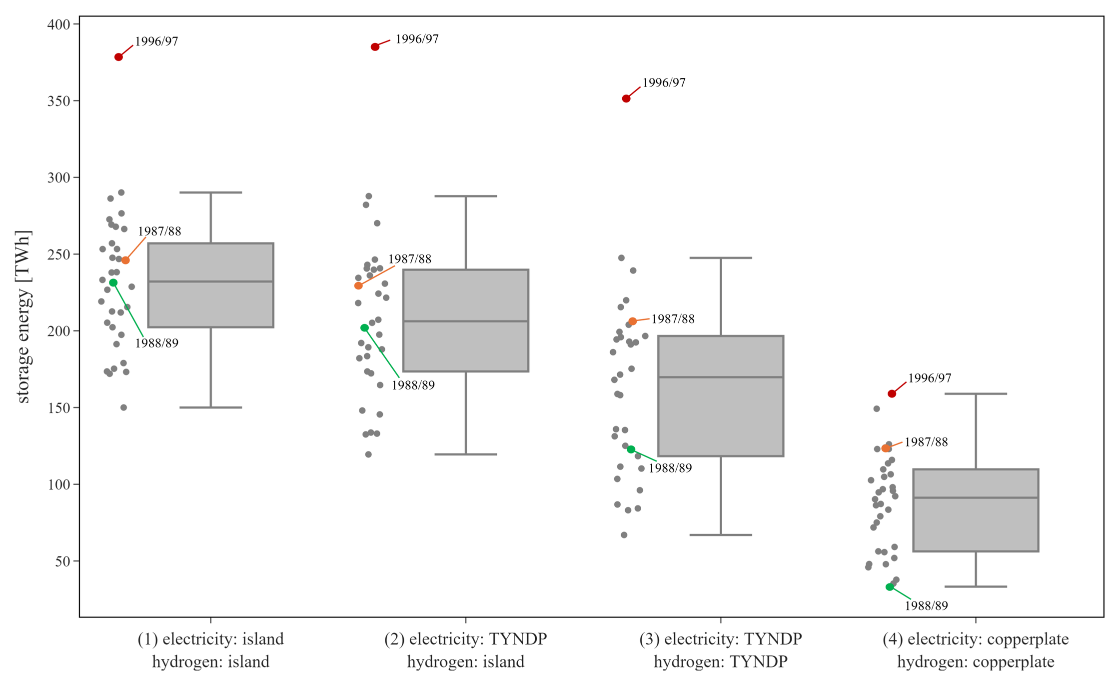
Drivers of long-duration storage energy investment

- Most extreme Dunkelflaute events
- Availability of flexibility options
- Electricity demand seasonality



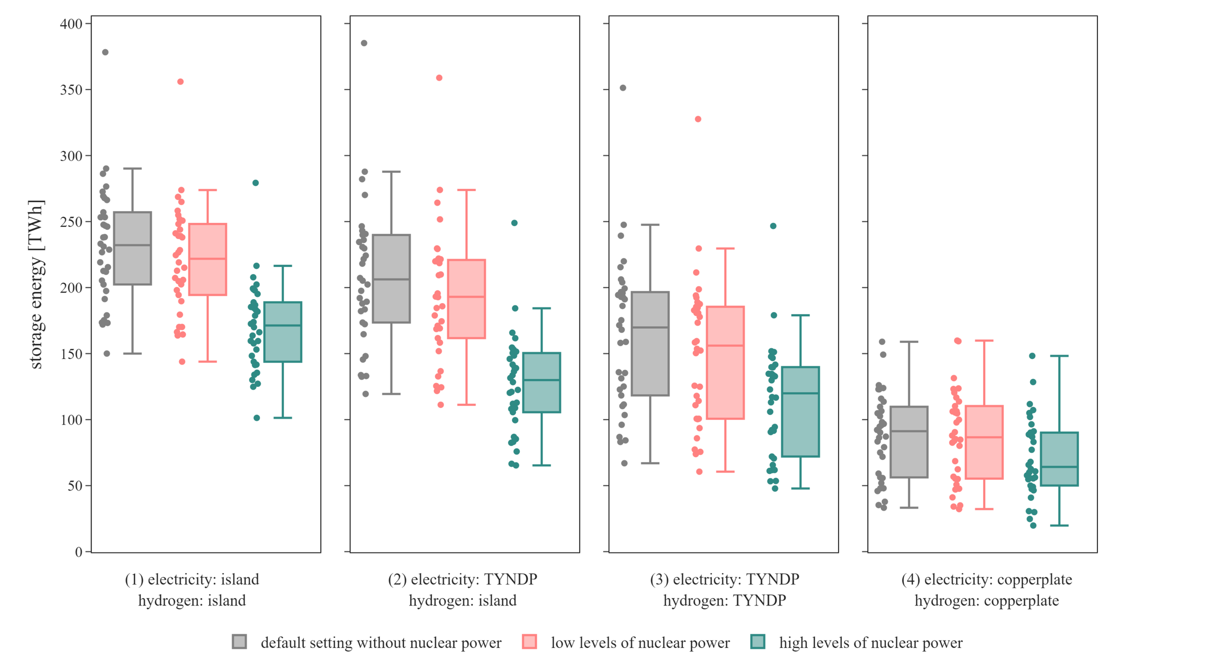
Long-duration storage needs and interconnection

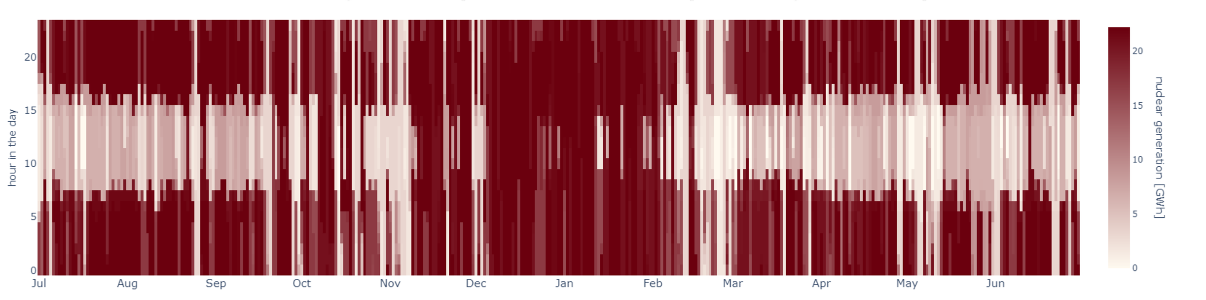
- Geographical balancing decreases Dunkelflaute impact, but significant storage needs remain
- Substantial inter-annual variation
- Highest storage needs in 1996/97 due to European scale of most extreme Dunkelflaute event
- Copperplate scenario (4): 159 TWh as minimum investment
- Policy-relevant scenario (3): 351 TWh as upper bound (7% of annual electricity demand), exceeding next highest storage need by 42%



Impact of nuclear power

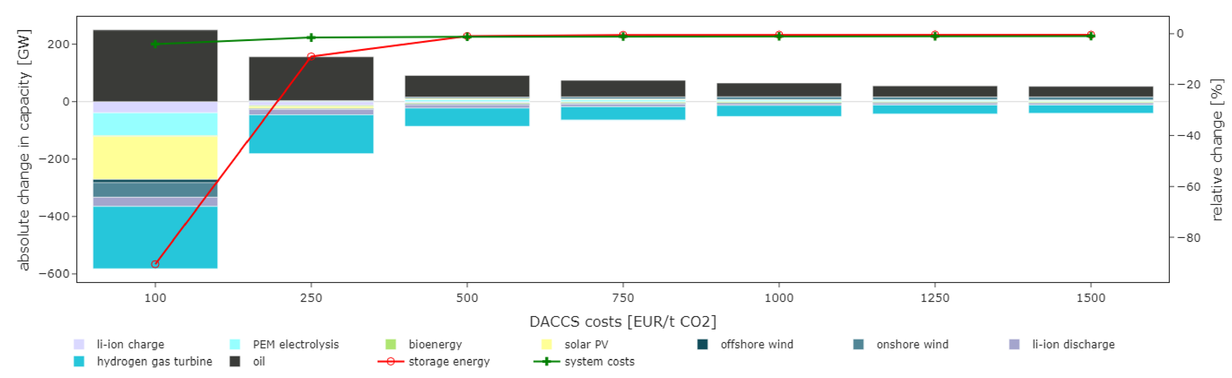
- Nuclear power provides electricity during extreme Dunkelflaute event, which mitigates storage needs
- Prerequisite: flexible operation (diurnal and seasonal)





Impact of fossil backup combined with CCS

- Oil without capital-intensive infrastructure requirements
- DACCS with low TRL and very uncertain costs
- Very low DACCS costs: some substitution effects and system cost decrease
- Higher DACCS costs: substitution of storage discharging capacity, storage energy capacity needs unaffected



CONCLUSIONS

- **Long-duration electricity storage is indispensable** for realizing a renewable European energy system. **Dealing with the most extreme Dunkelflaute** that occurred in winter 1996/97 **requires several hundred TWh storage capacity** in Europe.
- Underground hydrogen storage projects have long lead times (5-15 years). **Policymakers should prioritize investments** and consider **additional deployment incentives** to ensure sufficient storage capacity for dealing with very extreme Dunkelflaute events.
- Modeling **multiple weather years** including 1996/97 and **planning horizons maintaining complete winter periods** that capture long-lasting Dunkelflaute events are required for weather resilient energy system modeling.
- Dunkelflaute detection based on variable renewable energy availability helps identifying relevant weather years.

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- Variable Renewable Energy Drought Analyzer (VREDA): https://gitlab.com/diw-evu/variable_renewable_energy_droughts_analyzer

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