IAEE 2025

Coping with the Dunkelflaute

Power sector implications of variable renewable energy droughts in Europe

Martin Kittel, Alexander Roth, and Wolf-Peter Schill
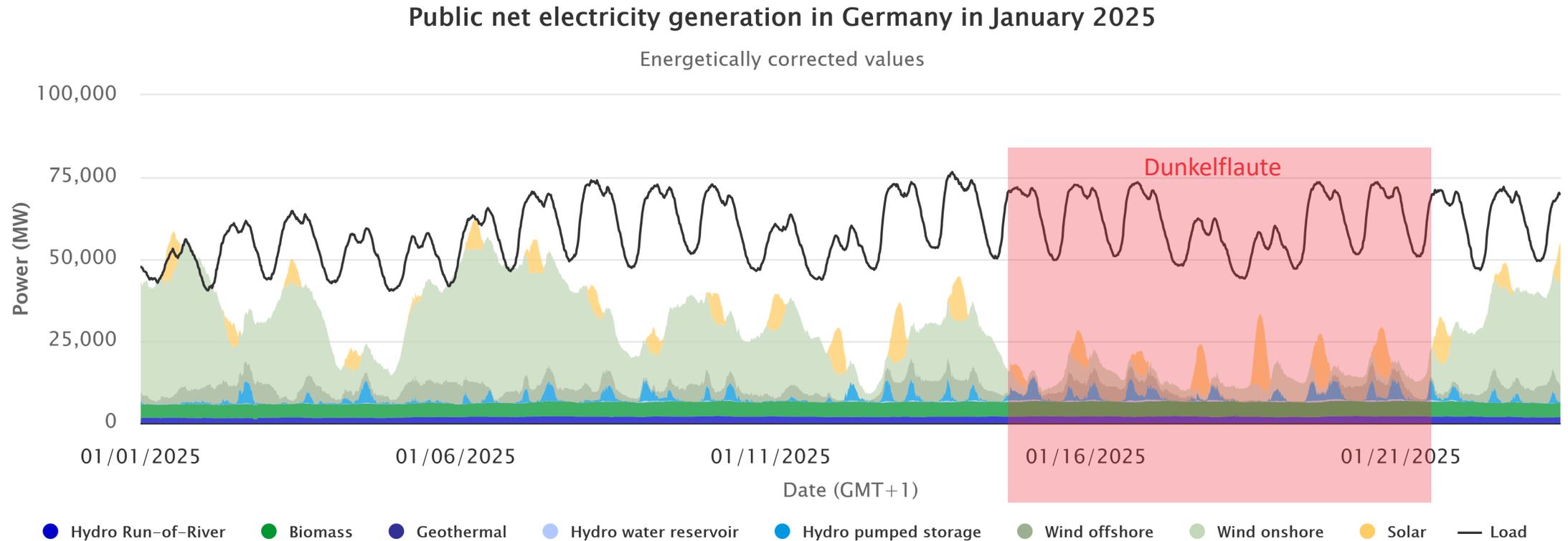Paris, 17 June 2025

Content

1. Motivation

Recent Dunkelflaute event in Germany

Public net electricity generation in Germany in January 2025

Energetically corrected values

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

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Relevance

Dunkelflaute events in public, policy, and academic discourse

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Research Questions

VREDA

Characterization of European Dunkelflaute events

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

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European power sector implications of extreme Dunkelflaute events

1. What is the impact on long-duration storage operation and investment?	
2. What is the value of cross-country electricity and hydrogen exchange?	
3. How do flexibility options interact?	Kittel, Roth, and Schill (2024)
4. Are there critical historical weather years?	

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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)

Input	Model	Output
Techno-economic parameters • Renewable generators • Storage • Hydrogen + reconversion **Hourly time series on country level** • Renewable availability • Electricity & hydrogen demand **Transfer capacity** • Electricity • Hydrogen	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	Investment decisions (capacity) • Conventional generators • Renewable generators • Storage • Electrolysis Hourly dispatch (energy) • Conventional generation • Renewable generation • Storage operation • Electrolysis operation

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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

- 36 independent runs based on 36 historical weather years (1982 – 2016)
- Source: Pan-European Climate Database 2021.3

Scenarios: spatial dimension

- Different interconnection levels

Interconnection

Island ──► European copperplate (CP)

(1)	(2)	(3)	(4)
Electricity: no	Electricity: TYNDP	Electricity: TYNDP	Electricity: copperplate
Hydrogen: no	Hydrogen: no	Hydrogen: TYNDP	Hydrogen: copperplate

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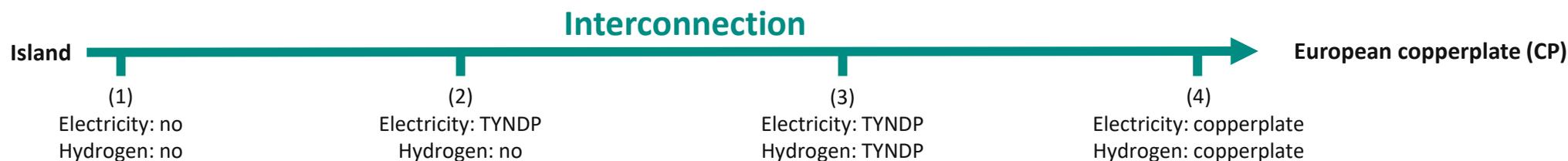
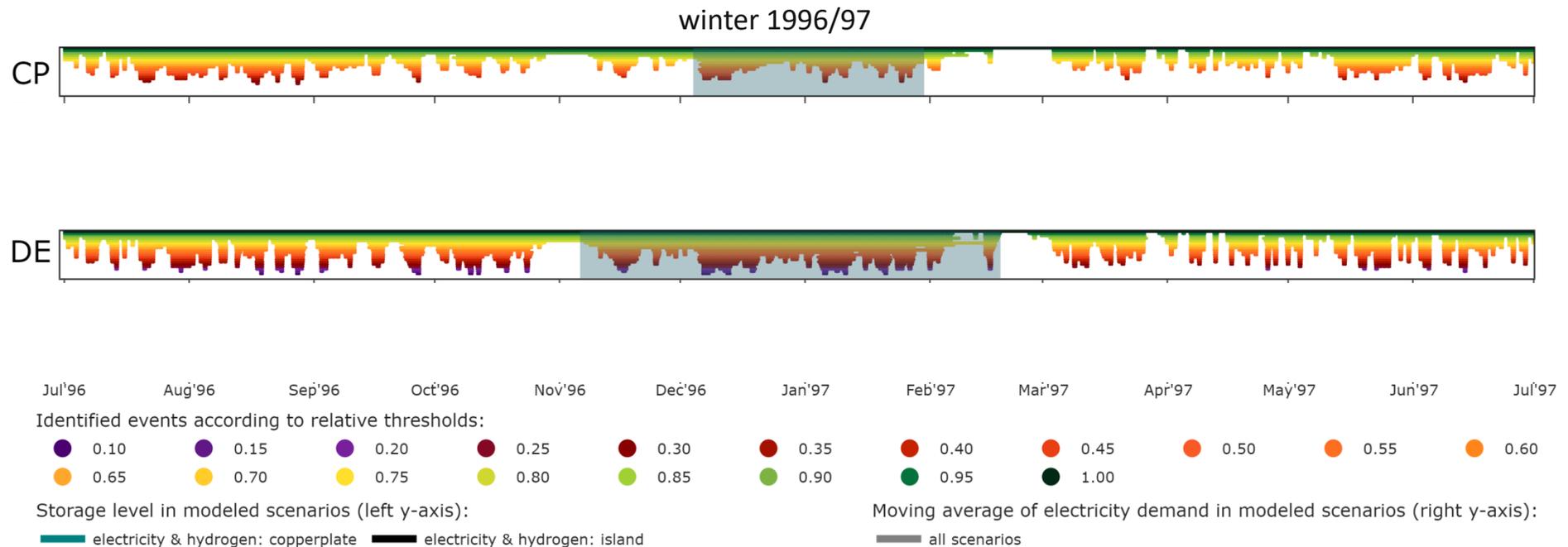# 3. Key insights
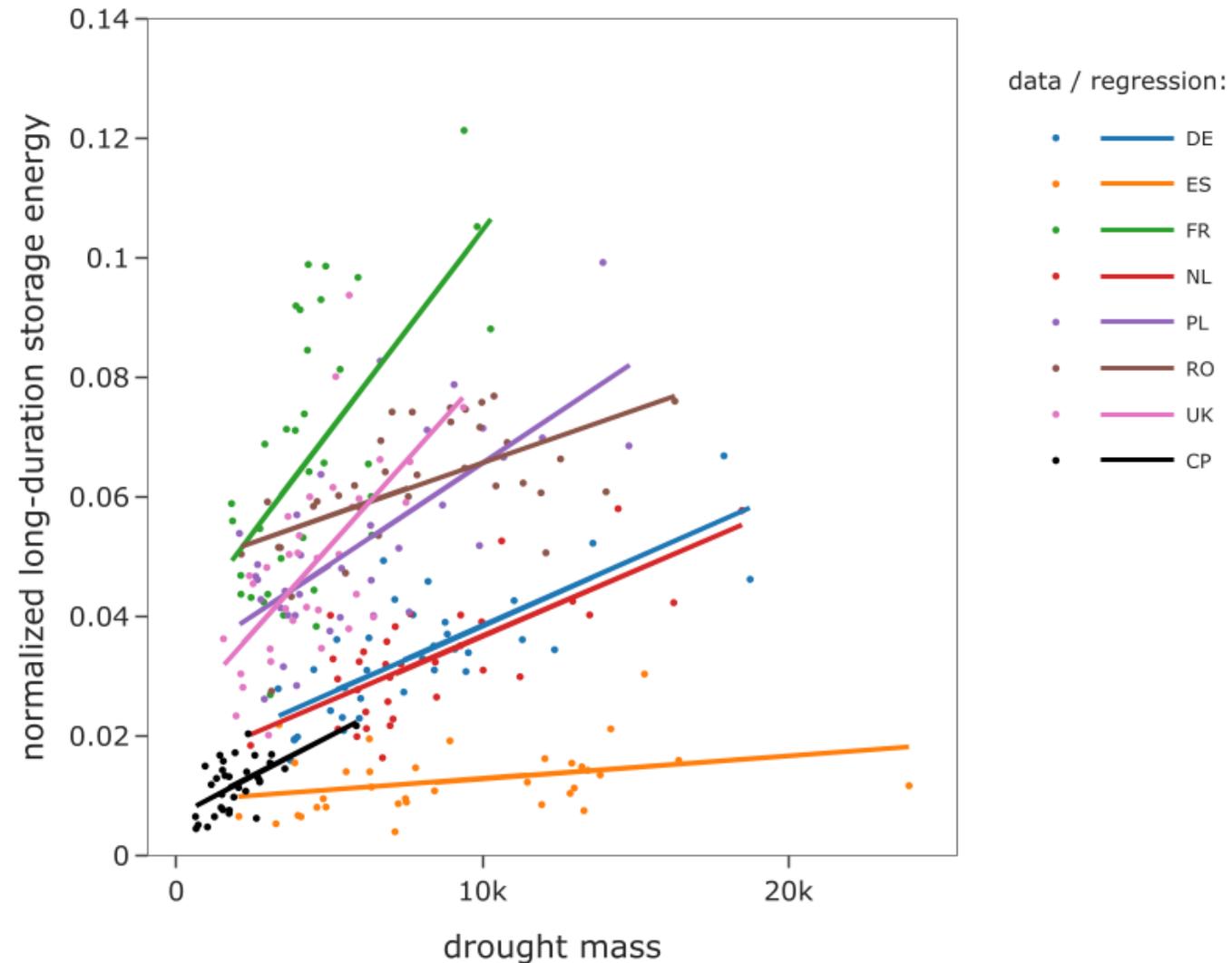
Identification of extreme Dunkelflaute events

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

winter 1996/97

Identified events according to relative thresholds:

0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60
0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00			

Storage level in modeled scenarios (left y-axis):
electricity & hydrogen: copperplate   electricity & hydrogen: island

Moving average of electricity demand in modeled scenarios (right y-axis):
all scenarios

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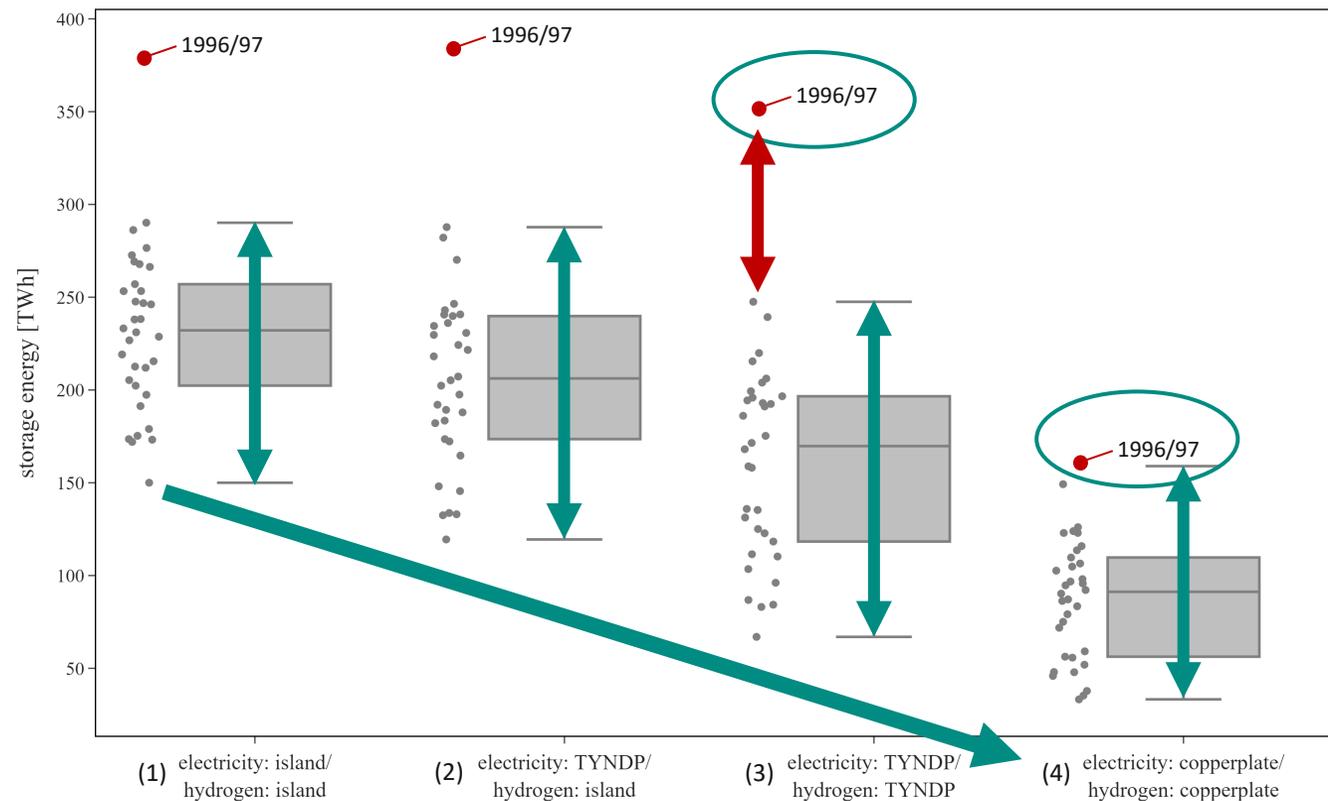Martin Kittel, Paris, 17 June 2025

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Long-duration storage investment

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

- Further drivers
  - Other flexibility options
  - Demand seasonality

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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%

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4. Conclusion

Conclusion

Policy implications

- Dunkelflaute events drive long-duration storage operation and investment

- European cooperation beneficial for coping with Dunkelflaute events

- Long-duration storage indispensable for renewable energy system

- 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

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Thank you for your attention.

**DIW Berlin — German Institute
for Economic Research**
Mohrenstraße 58, 10117 Berlin
www.diw.de   LinkedIn: DIW Berlin

Martin Kittel
Department Energy, Environment, Transport
mkittel@diw.de

Literature

- 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.

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