Online Workshop | ETH & DIW

Coping with the Dunkelflaute

Power sector implications of variable renewable energy droughts in Europe

Martin Kittel, Alexander Roth, Wolf-Peter Schill
Berlin, 22 October 2025

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1. Research questions and design

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)

DIETER

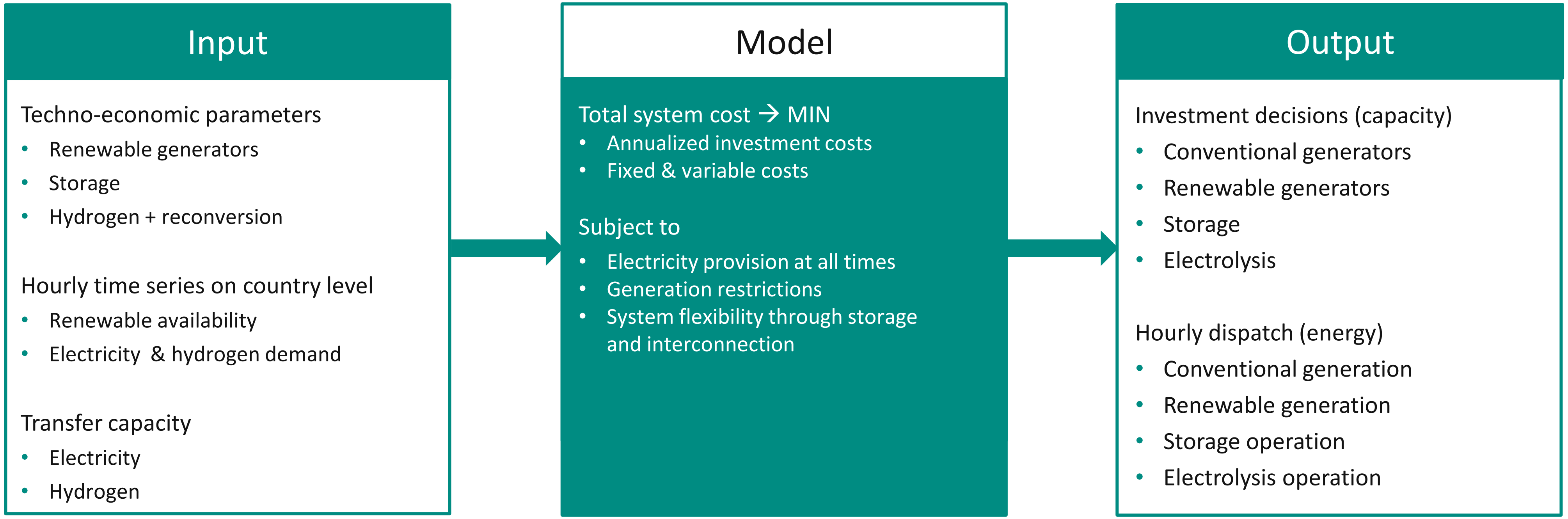
European power sector implications of extreme Dunkelflaute events

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? 4. Are there critical historical weather years?	Kittel, Roth, and Schill (2024)
5. Impact of electrified space heating and interactions with long-duration heat storage?	Schmidt, Roth, and Schill (2025)

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

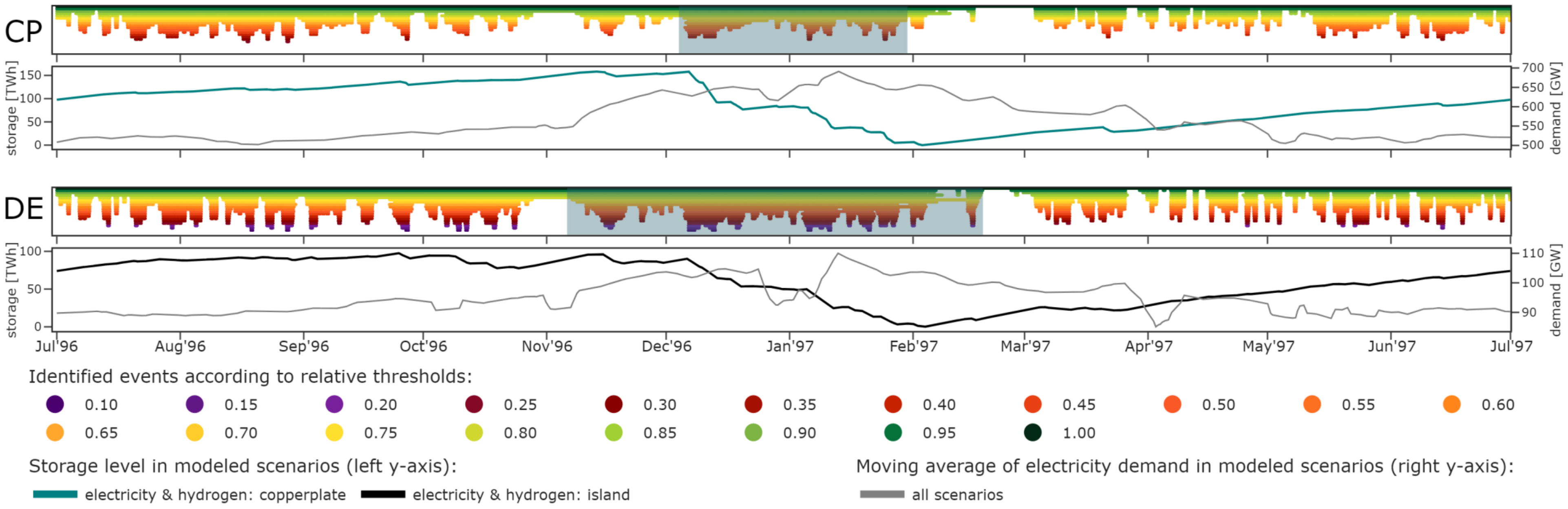
2. Key insights

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

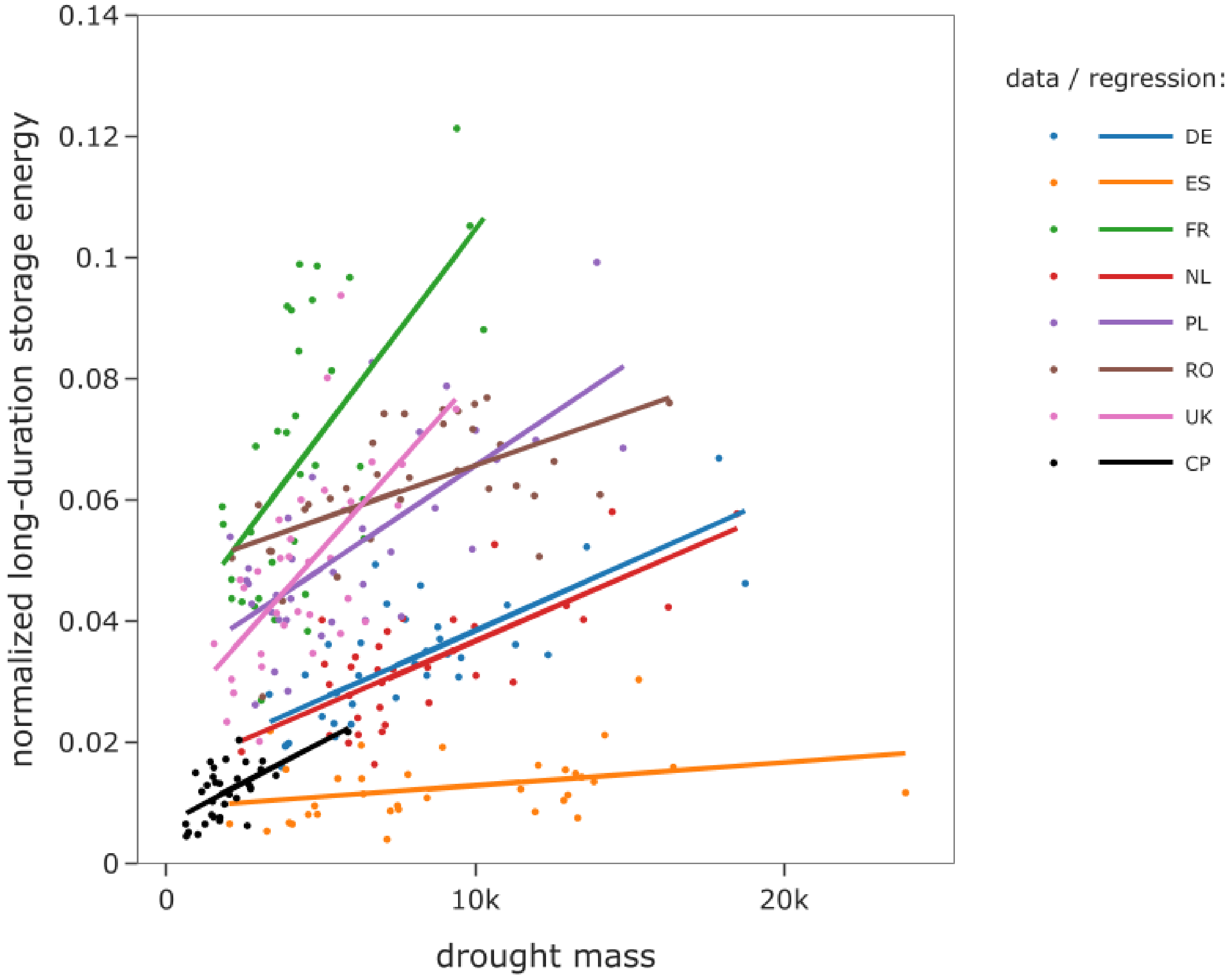
winter 1996/97



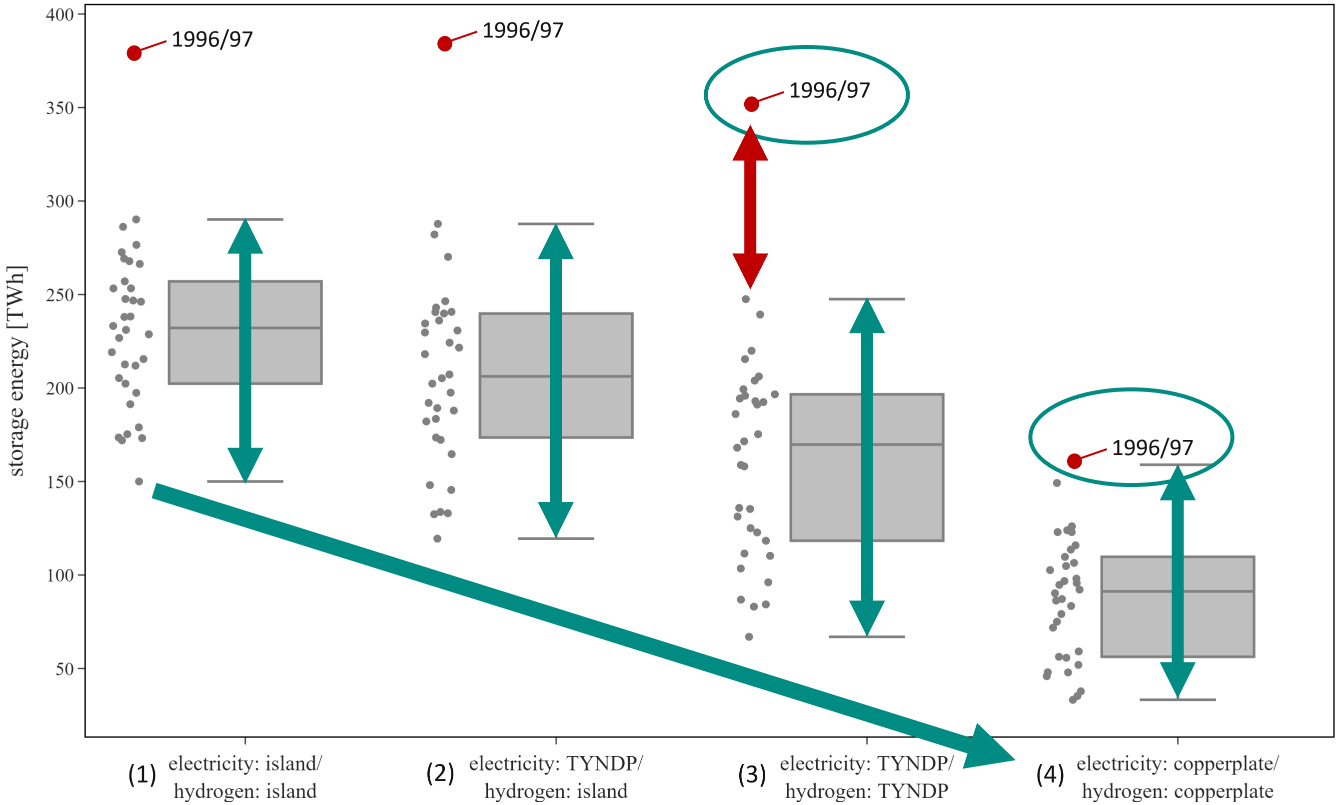
Long-duration electricity storage investment

- 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

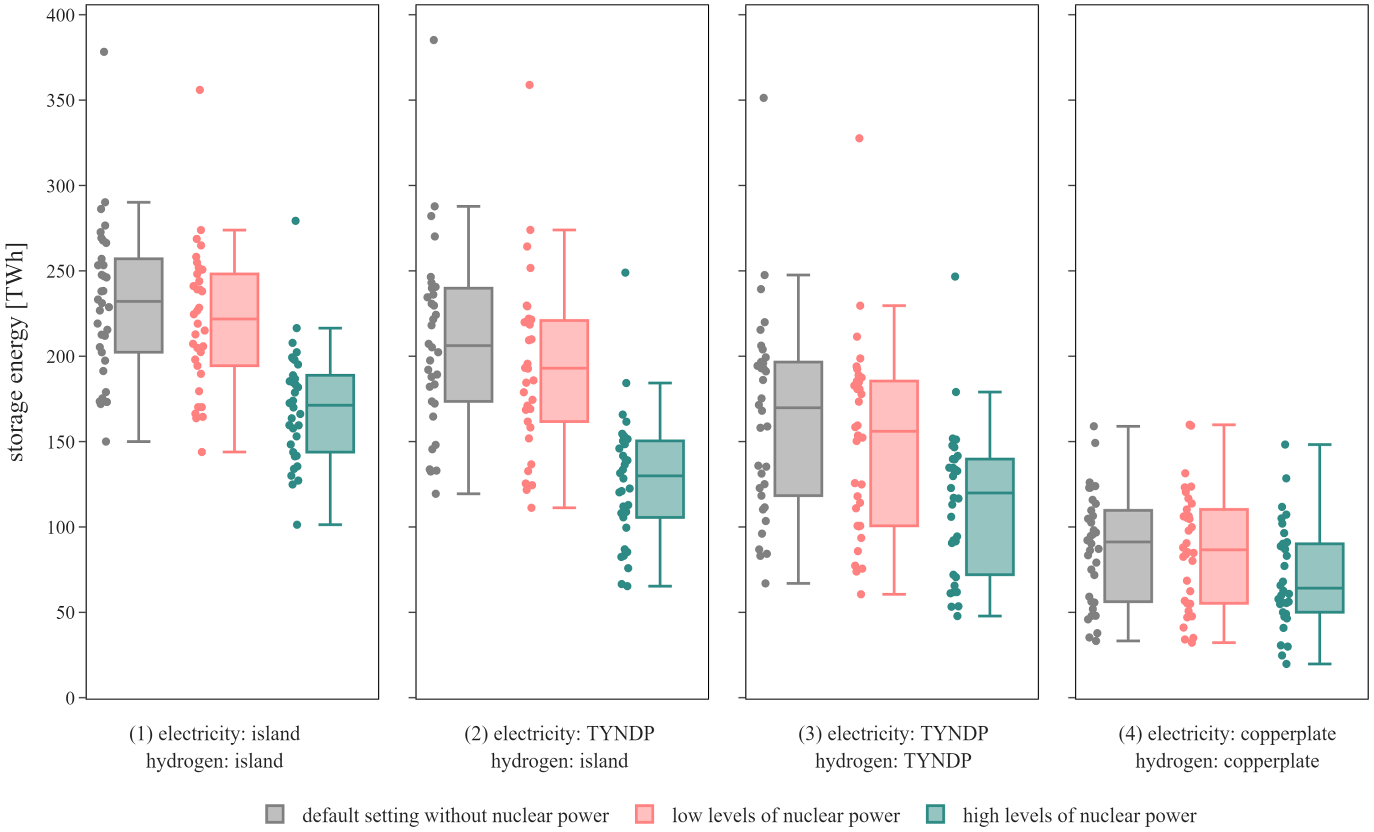
Exogenous nuclear capacity

- 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



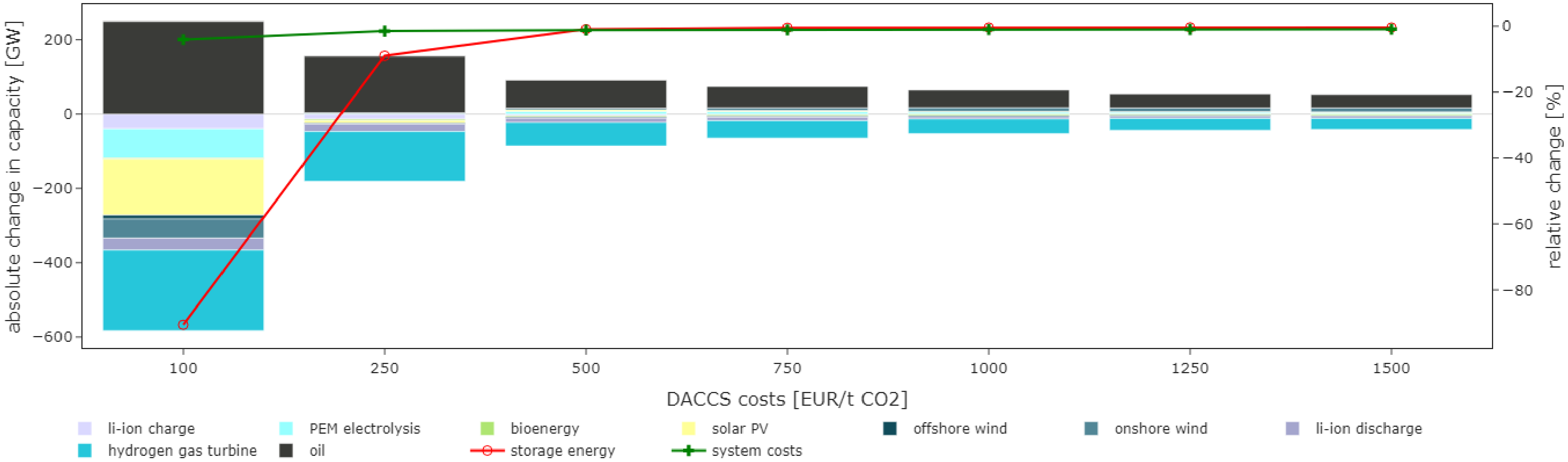
Sensitivity analysis: oil-fired backup capacity with CCS

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



3. 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

Thank you for your attention.

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

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