DUNKELFLAUTE AND LONG-TERM ELECTRIC ENERGY SHORTAGE EVENTS IN EUROPE

Yvonne Scholz[1], Madhura Yeligeti[1]

[1]*German Aerospace Center (DLR), Institute of Networked Energy Systems, Oldenburg, Germany*

Dunkelflaute and long term shortage events in Europe

- Definitions
  - Residual load = load – PV and wind power generation
  - Shortage = residual load (RL) anomaly, i.e. the RL is below its long term mean
  - Outage = ???
  - Dunkelflaute: event of one day up to 30 days duration
  - Seasonal electric energy shortages: event of one to several months duration
  - Long term electric energy shortages: event of one to several years duration

- Three case studies:
  - Case study 1: Residual load analysis: anomalies of one day to several years duration
  - Case study 2: Resilience assessment of multiple scenarios of energy transition
  - Case study 3: Testing energy shortage events of various intensities and at various times

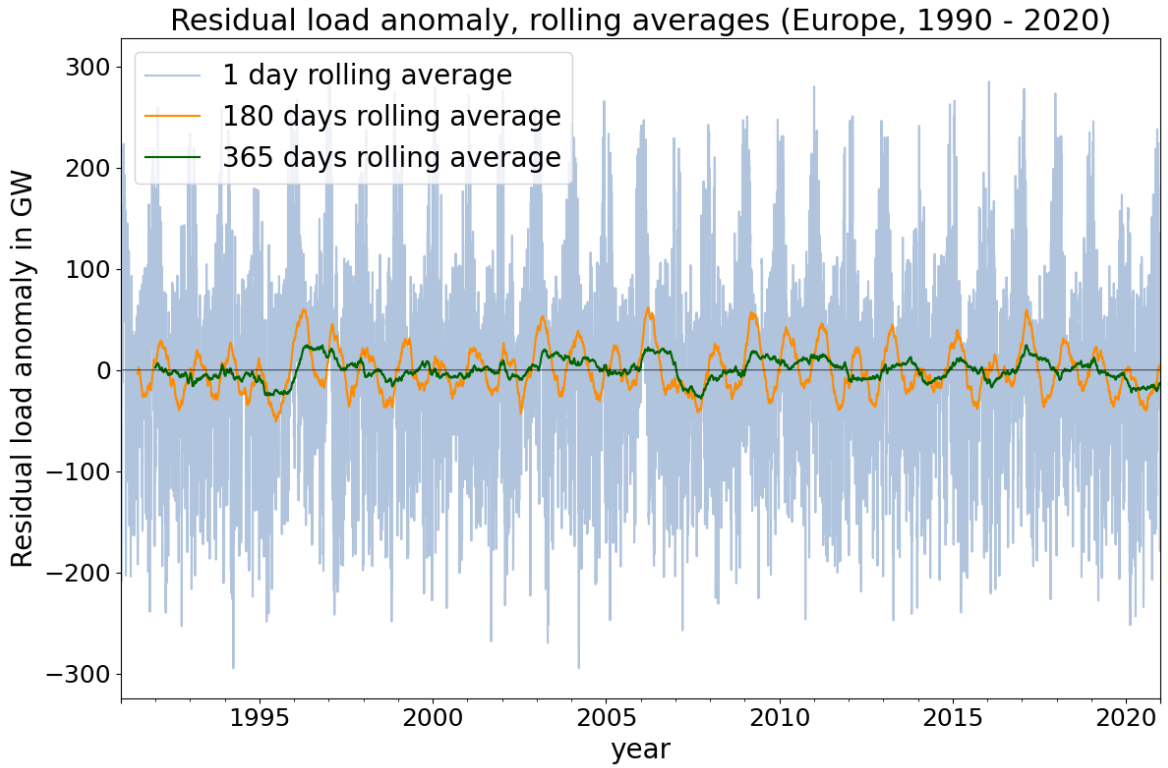
Case study 1: Residual load analysis

Calculate and identify one-day to multi-year anomalies

- Methodology to identify and investigate shortage events:
  - TYNDP Distributed Energy scenario[1]
  - 30 years of ERA5 reanalysis data[2] (1990-2020)
  - Rolling averages of RL anomaly
- Mean load: 410 GW, mean RL: 84 GW

  → 79.5 % VRE

  → 20.5 % non-VRE



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- Maximum one day rolling average of residual load anomaly: 298 GW ≙ 355 % of mean residual load
- 180-day rolling average: distinct seasonal pattern with winter peaks
- One-Year (365-day) rolling average can be above the mean residual load for more than one year in a row

Case study 1: Residual load analysis
Anomaly distributions

A Dunkelflaute (14 days)…

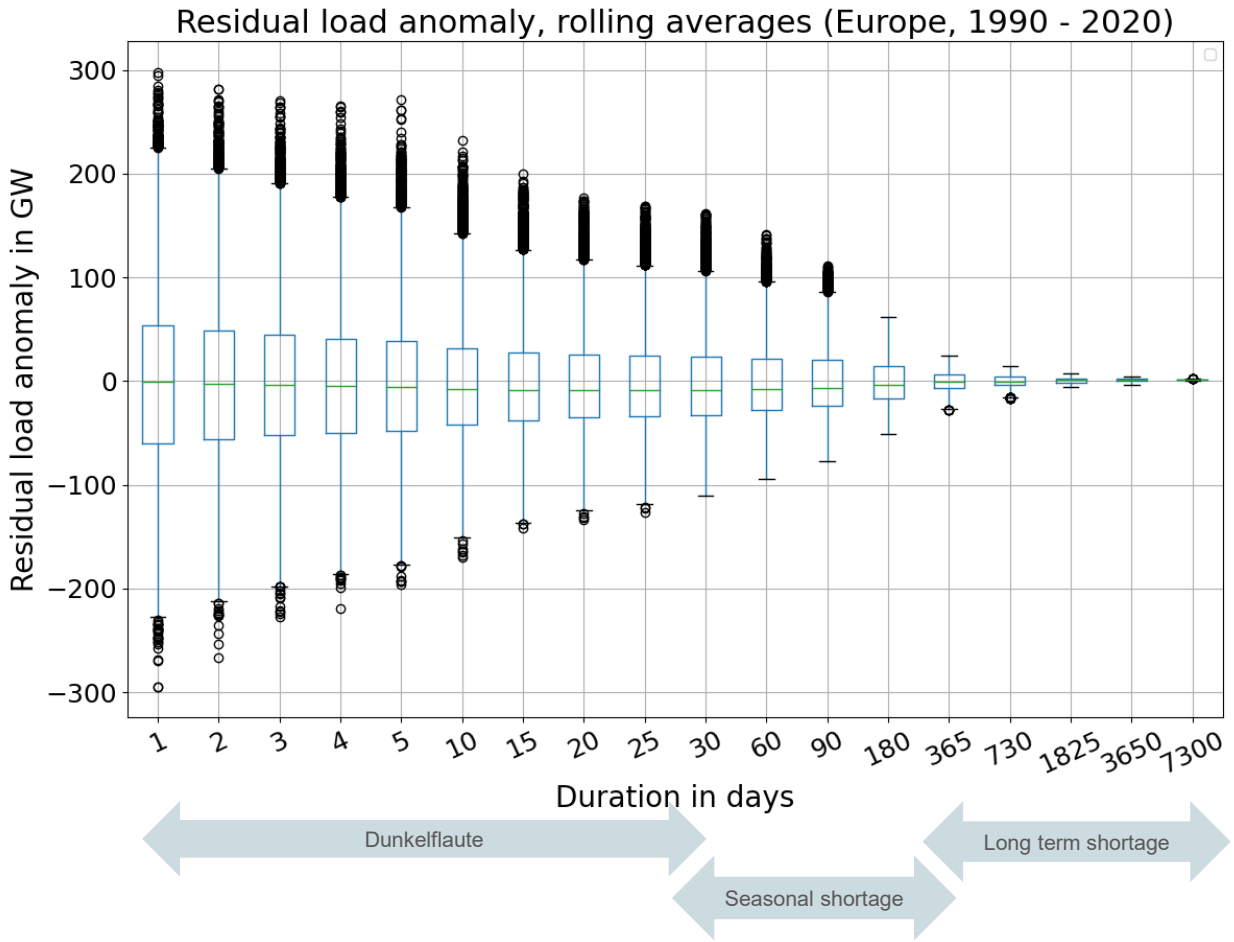
... shows RL anomaly variations of between 207 GW and -144 GW ≙ 246 % and -171 % of mean RL

Less than 4 years averaging…

… is associated with maximum RL anomaly values of more than 10 % of mean RL

A 10 year RL anomaly…

… is still up to +5 % of mean RL



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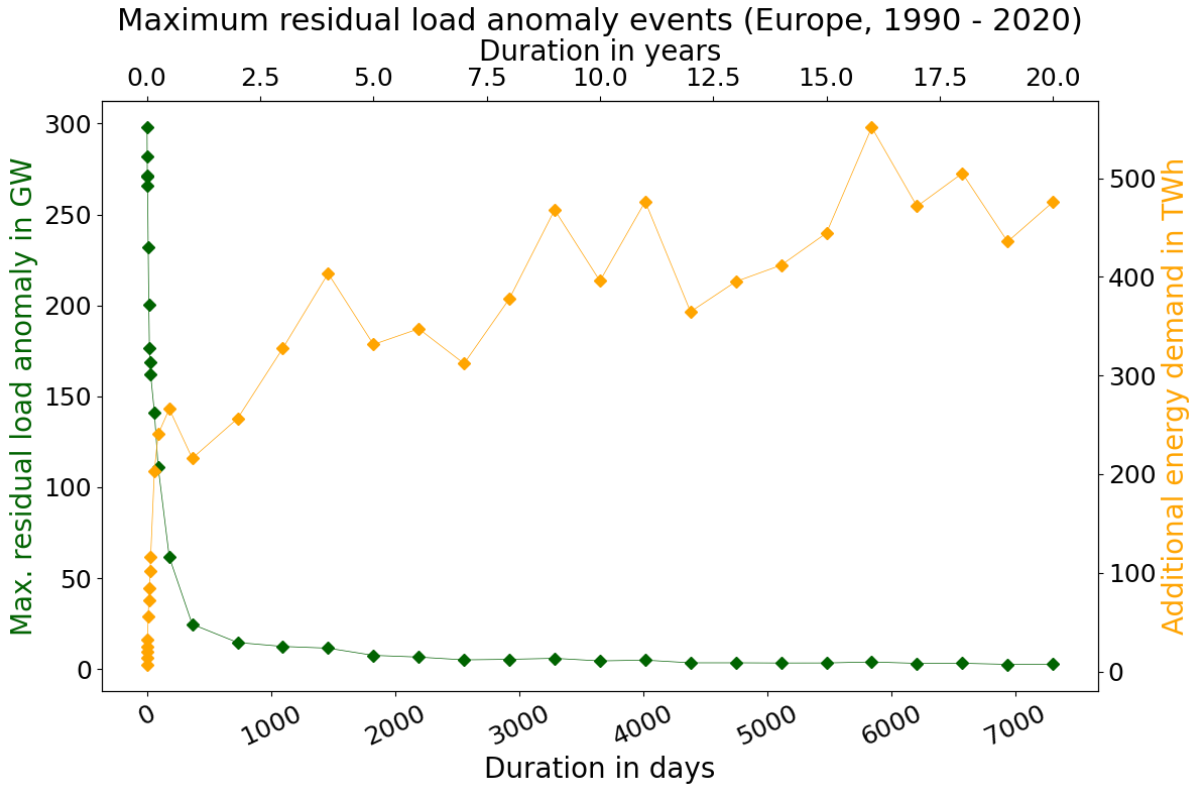
Case study 1: Residual load analysis

Anomaly maxima and corresponding additional energy demand

- In a 10 year period, additional energy demand can add up to ~400 TWh ≙ 5% above average.
- In a 20 year period, it can still amount to around 480 TWh ≙ 3 % above average.



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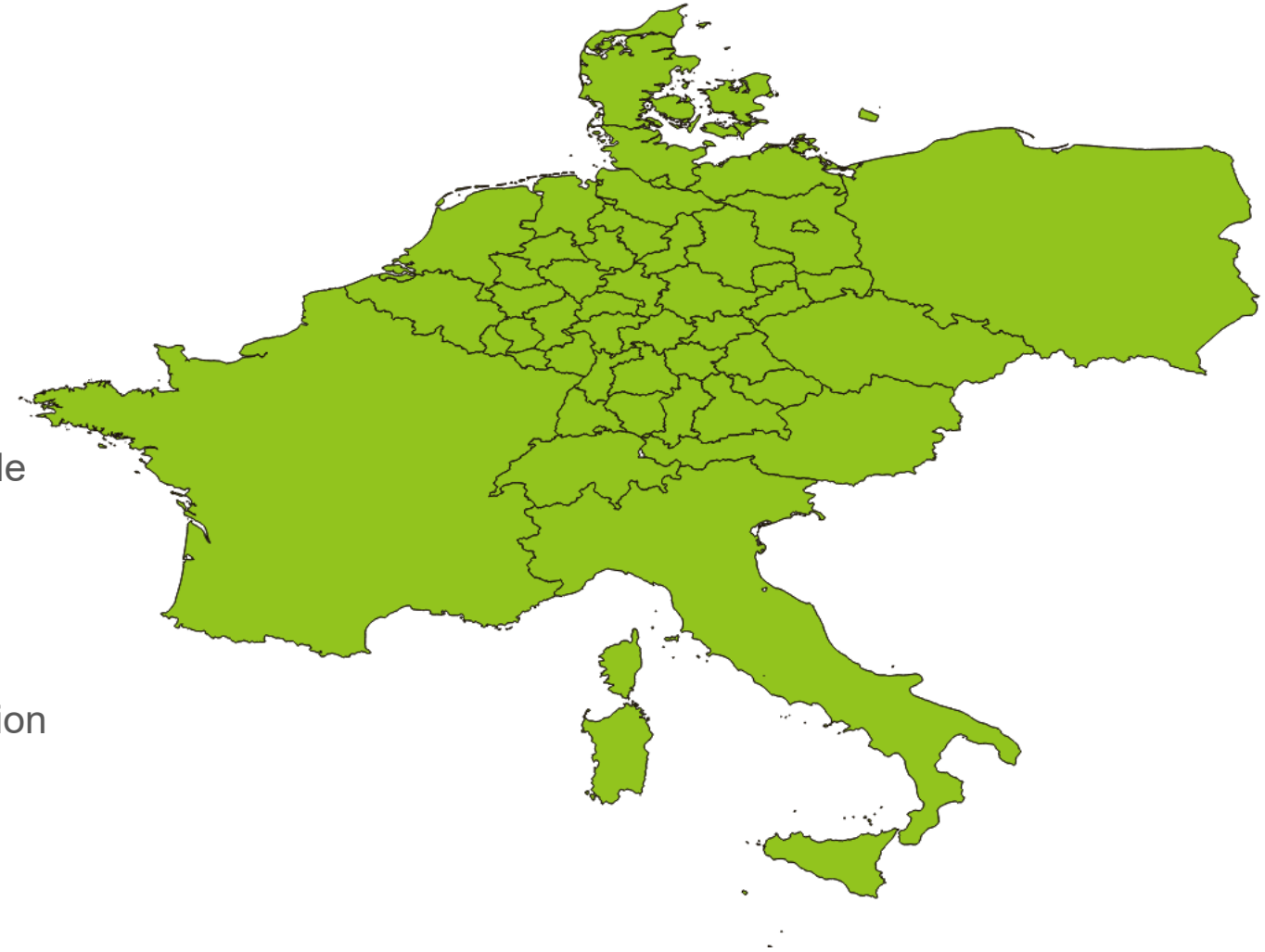
- The additional energy demand must be balanced using imports, storage and/or additional generators,
- The critical time periods can be identified and chosen for further investigation with energy system models.

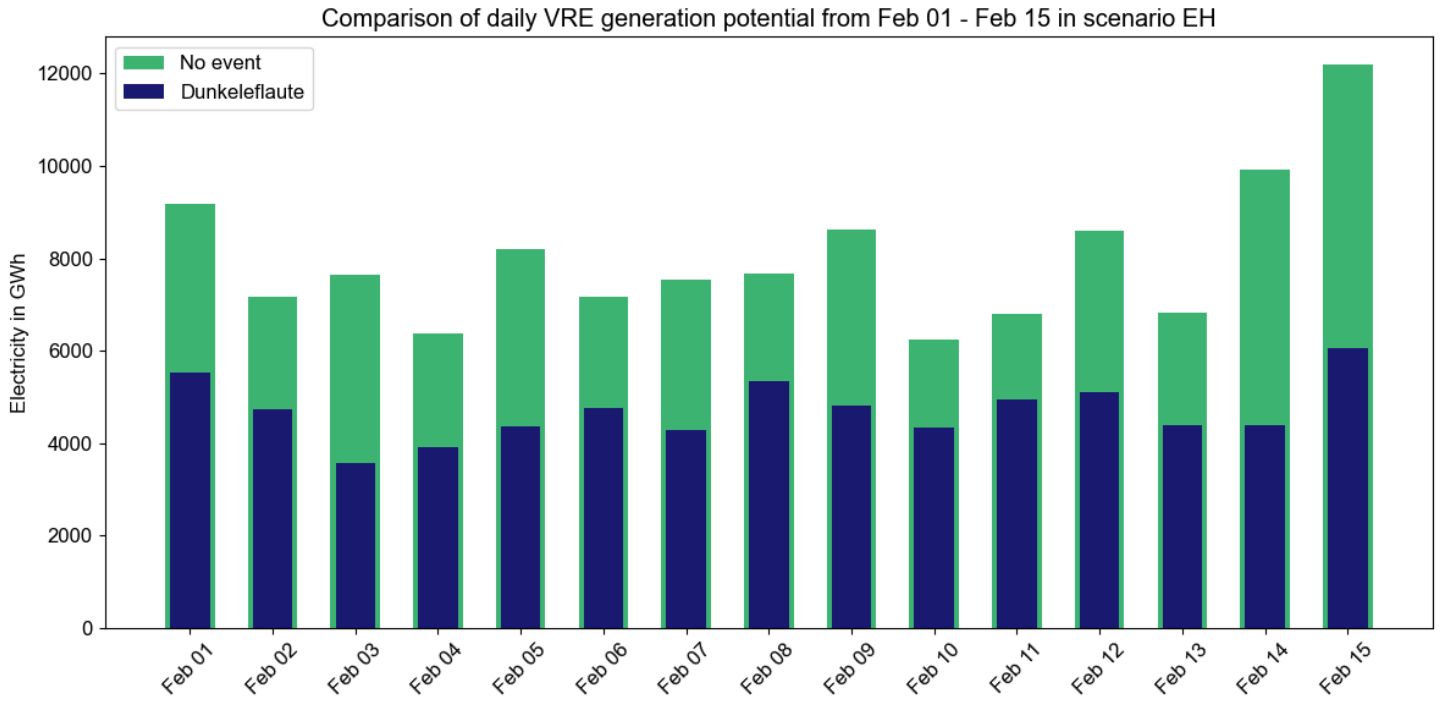
Case-study 2: Resilience assessment
System scope

- CO2-neutral energy system
- 2050 in 8760 time steps
- 48 model regions
- > 70 technologies
- Electricity, natural gas and H2 sectors
- Flexibility of battery-electric vehicles, demand-side management, and heat-sector demands only considered for Germany
- 11 scenarios with variations of European cooperation, grid expansion, extent of electrification in heating, H2-driven applications etc.



Case-study 2: Resilience assessment
Methodology

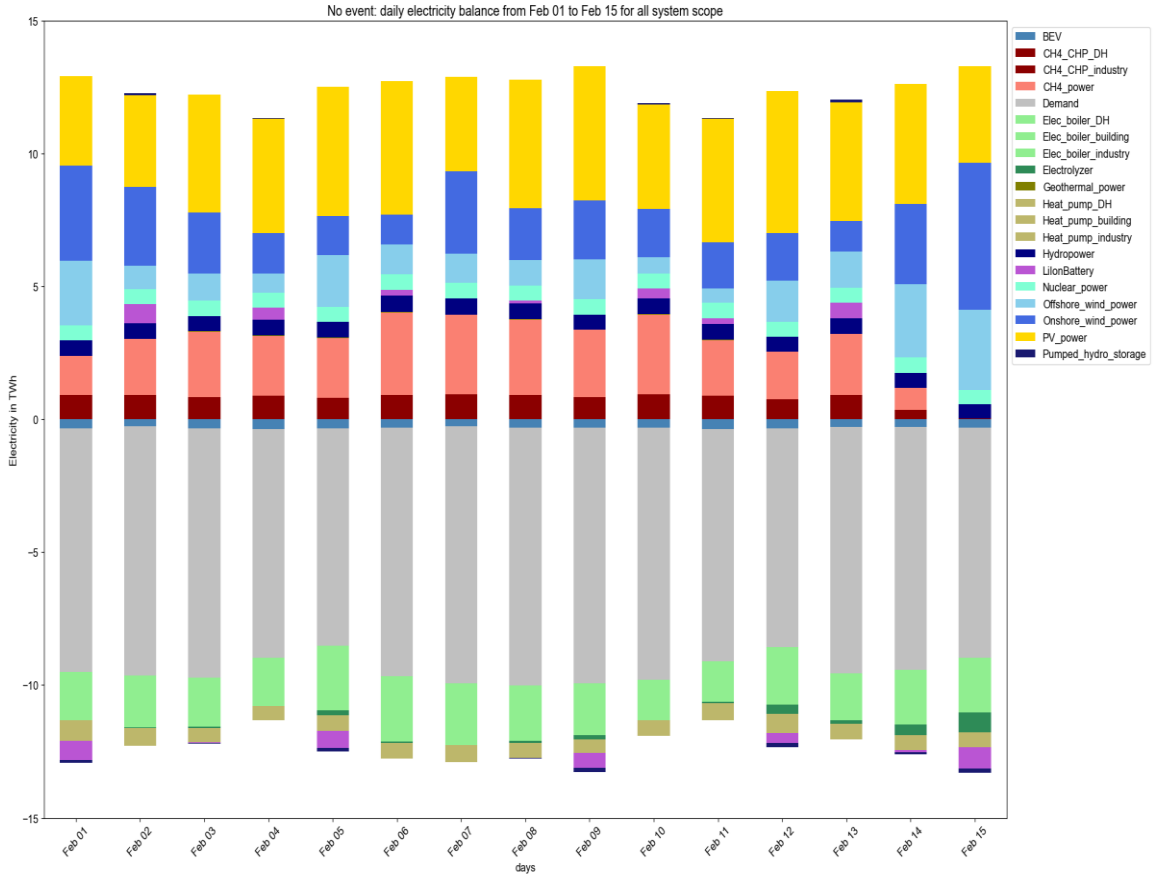
- Step 1: Identification of a 15-day period (10.12.2007-24.12.2007) as the highest 15-day dunkelflaute in Europe between 1990 and 2020.
- Step 2: Optional introduction into the pre-defined period under investigation (01.01 - 15.02.) as outage-factors
- Step 3: Testing with the optimisation framework REMix
  - Capacity expansion without any anomaly
  - Introducing the mapped event and testing system operation with fixed capacities

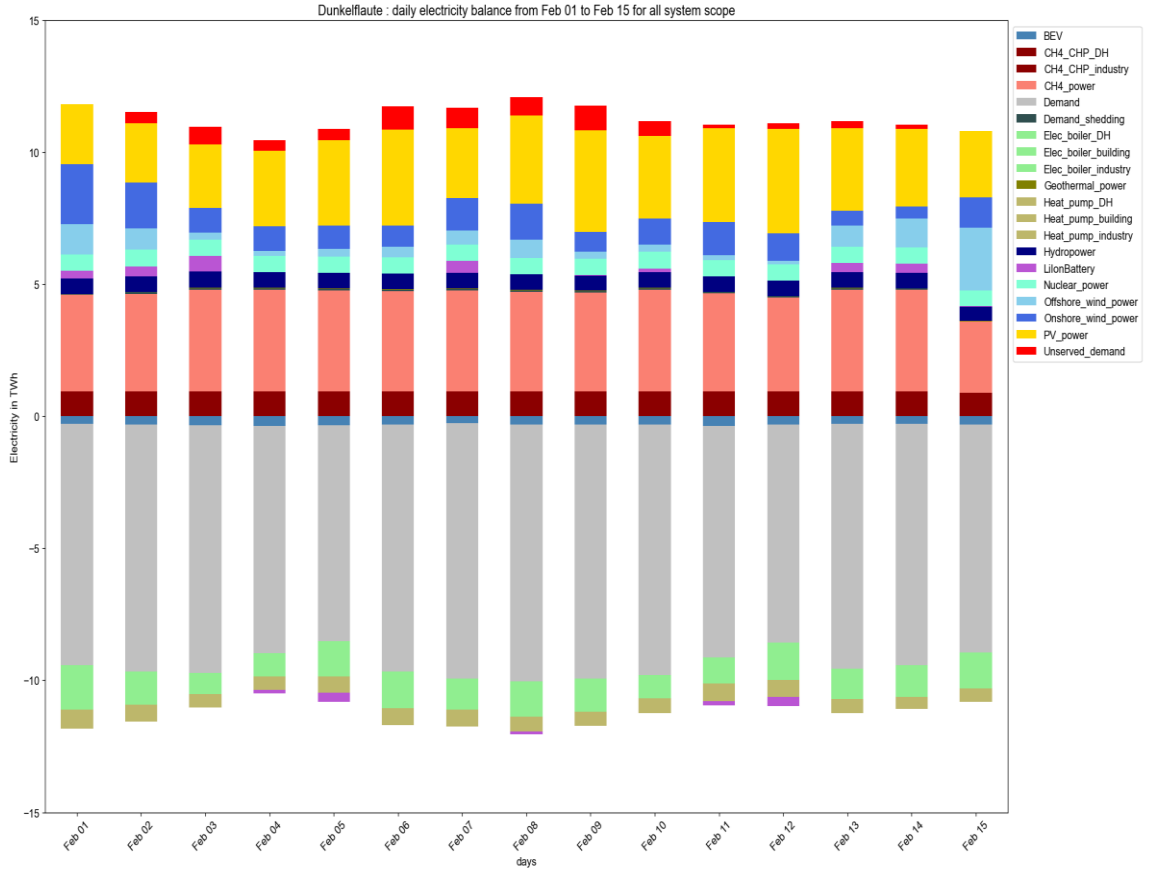


Case-study 2: Resilience assessment

Electricity generation and consumption during dunkelflaute

Scenario EH (Elec-HighRE) characterized by heavy electrification in heat and transport sector and high share of variable renewable energy

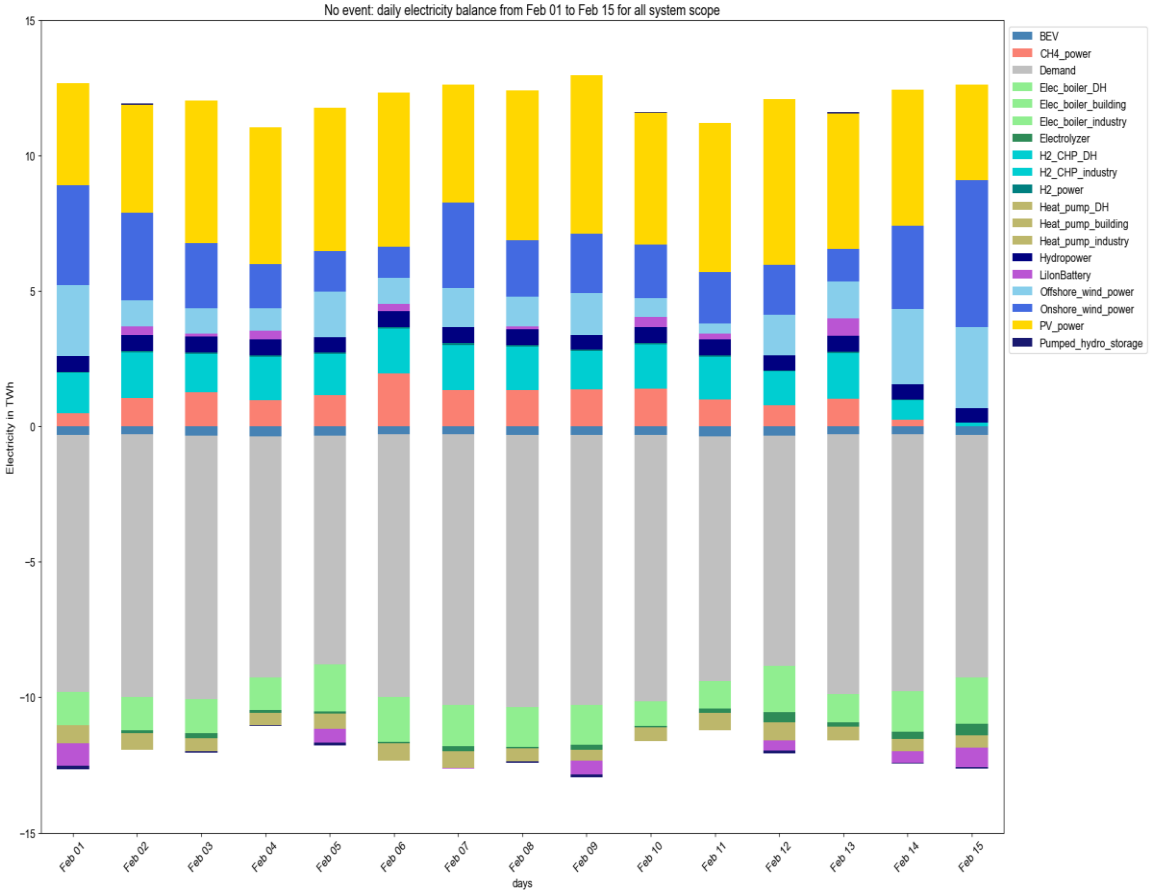


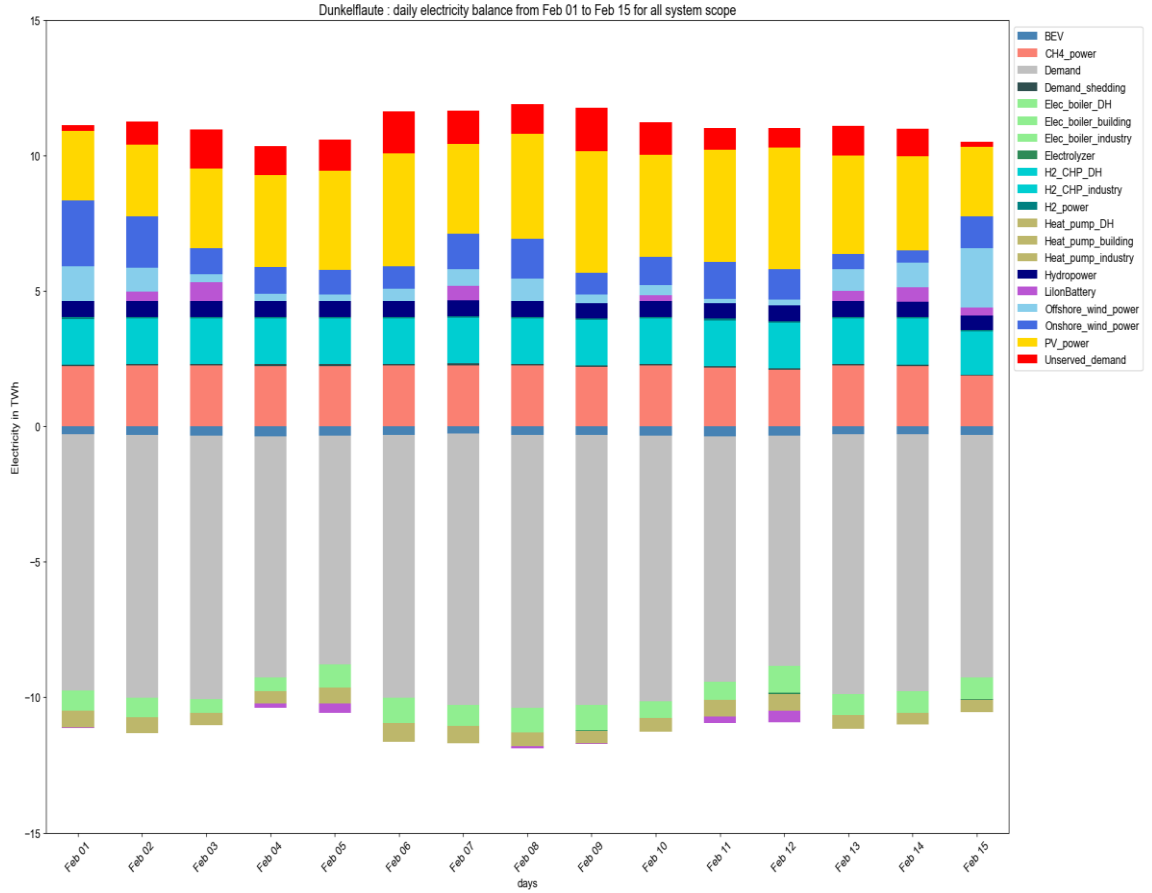


Case-study 2: Resilience assessment

Electricity generation and consumption during dunkelflaute

Scenario MI (Mix- Import) characterized by mixed fuel and electricity shares in heat and transport sectors, high reliance on import



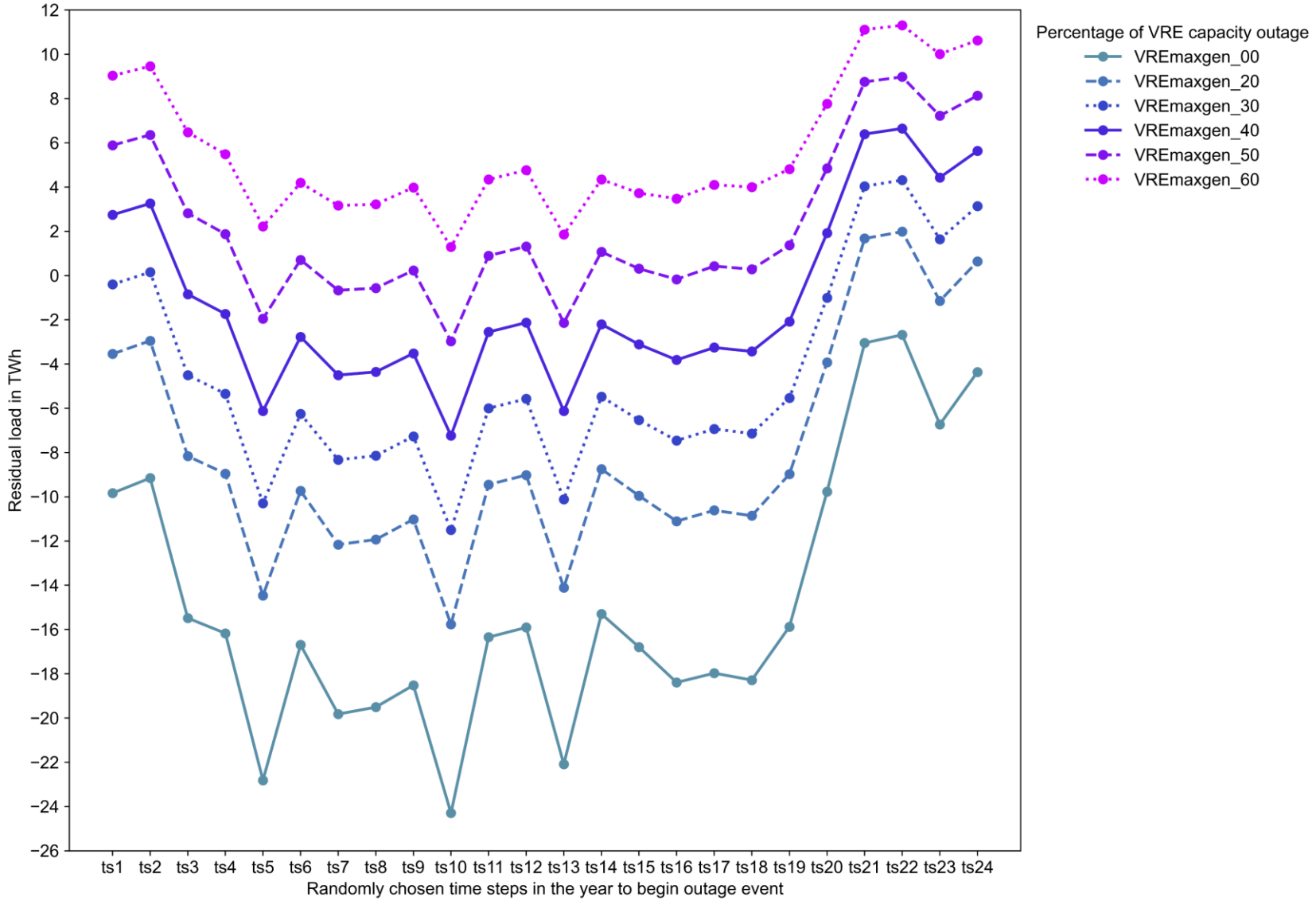


Case-study 3: Different dunkelflaute intensities at various times

- System scope: same as case study 2
- Event: simplified dunkelflaute
  - Duration: fixed to 2 weeks
  - Intensity and place: 20% - 60% outage of all PV and wind power generation in Germany
  - Time of event: 2 randomly selected hours in year = 24 time steps
- Set-up: one system in REMix , capacity expansion without event, testing operation in one event at a time → 360 tests

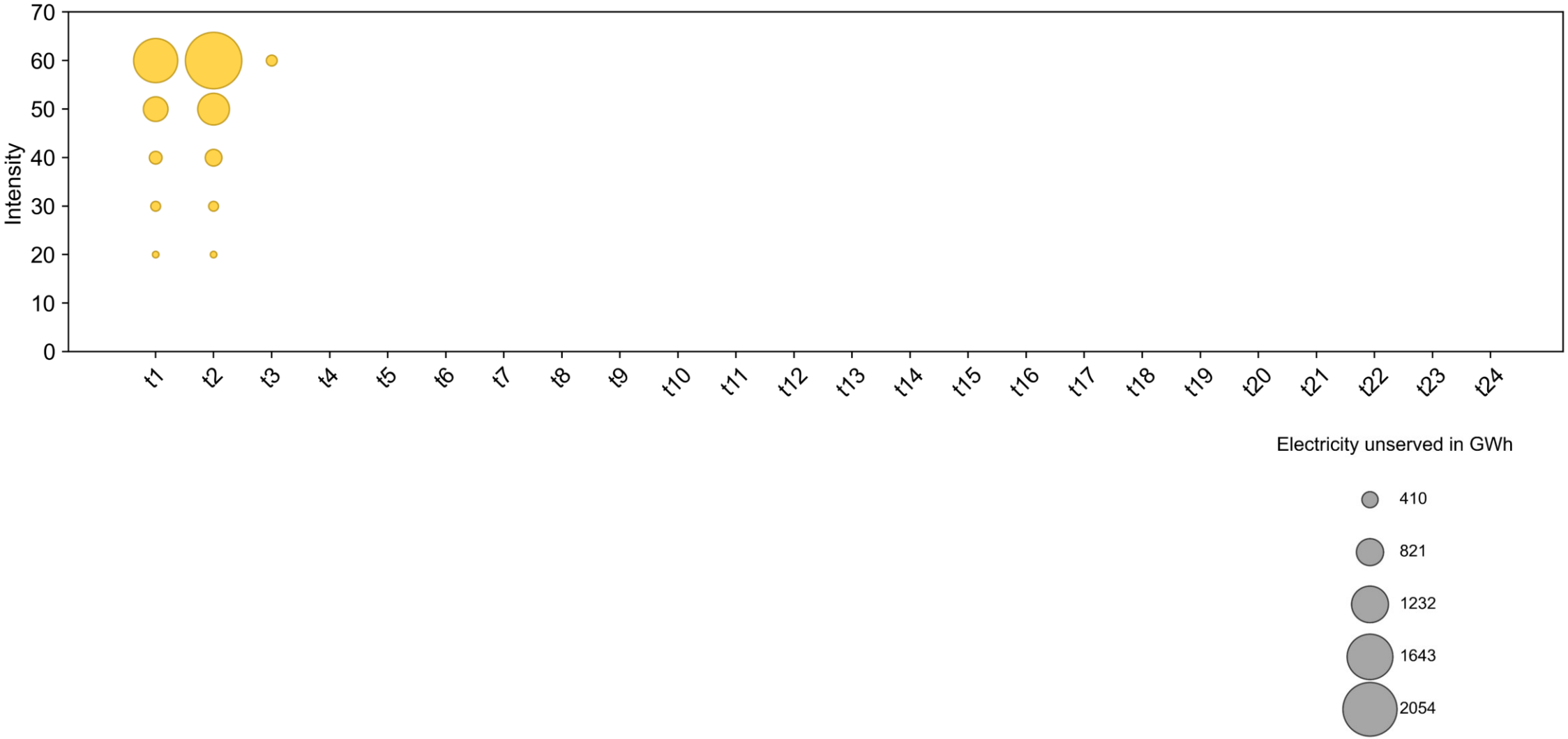
Case-study 3: Different dunkelflaute intensities at various times

Tracing residual load in all tests



Case-study 3: Different dunkelflaute intensities at various times

Results of unserved energy in all tests



Takeaways

- Critical time periods to be further investigated can be identified using residual load analysis
- Residual load and with it energy demand can be elevated by up to ~250 % compared to the mean residual demand in a 14 day period, by up to ~30% in one year and ~5% in ten years,
- Optimally designed energy systems can be inadequate for energy security in case of short extremes like dunkelflaute, and without imports also in case of long term shortages
- The resilience /system response can vary drastically based on the system configuration (i.e. available flexibility options, reserved capacity)
- Storages, demand-side management (load shedding, load shifting), electric-vehicle flexibility have limited benefit for dunkelflaute that lasts for many days
- Timing of events is a significant aspect in testing for energy security

Imprint

Topic:	**Dunkelflaute and long-term electric energy shortage events in Europe**
Date:	2025-09-30
Author:	Yvonne Scholz
Institute:	Institute of Networked Energy Systems
credits:	All figures: „DLR (CC BY-NC-ND 3.0)“, unless otherwise noted

Slido

- What indicators of extreme events do you use or know of? (→ word count)
- What is the geographical extent of extreme events that is most relevant for power supply?
  - Rating each from 1 to 10: local / regional / national / continental
- What are potential hazards to the supply system associated with extreme events?
- Should multi-annual extreme events be considered in energy system planning?
  - Multiple choice:
    - No! There will always be the opportunity to import enough energy carriers.
    - Yes! There can be geopolitical situations where autonomy for several years is important.
    - Maybe.
- Q1 : (who your audience is): e.g. Which category best describes the scope of your work in the energy community? (choice of options : grid operation and maintenance, energy meteorology, systems analysis, energy system modelling, scenario assessment, economics, energy market behaviour…) [finally include an 'Other' option]
- Q2 : (what they are interested in) : e.g. Which of the following aspects of energy security are you most interested in? (choice of options : stability, affordability, adequacy, robustness, overall resilience)
- Q3 : (what kind of energy shortage events they are interested in): e.g. Which of the following types of energy shortage events do you /will like to consider in your work) (multi-choice : short residual load (RL) anomaly, dunkelflaute, seasonal electric shortage events, long term electric shortage events….)
- Q4 : (open ended) What data sources do you use in assessment of energy shortage events ?