Role of long-duration energy storage in solar-wind hybrid systems for energy drought mitigation: case study of Polish energy system

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INTRODUCTION

Ensuring the reliability of power systems largely based on variable renewable energy sources (VRES) requires addressing periods of prolonged low resource availability, known as renewable energy droughts (REDs). These events, marked by simultaneous low solar and wind generation coinciding with high electricity demand, pose significant challenges to achieving full decarbonization. Key strategies for mitigating REDs include the hybridization of VRES, oversizing the system, meaning the installation of VRES capacity exceeding 100% of the annual mean demand, and the deployment of long-duration energy storage (LDES) technologies to bridge the gap between renewable generation and electricity demand during these critical periods.

RESEARCH QUESTION:

What effect does the change in: ① Installed power capacity of VRES, ② Ratio between the amount of demand covered by solar PV and by onshore wind turbines (PV : WT ratio), ③ Energy storage capacity of LDES, have on the occurrence of extreme REDs and associated energy shortages?

ASSUMPTIONS AND DATA

Energy sources:

- Onshore wind turbines (WT): CF_W = 24.7%
- Solar photovoltaics (PV): CF_S =12.1%
- Long-duration energy storage

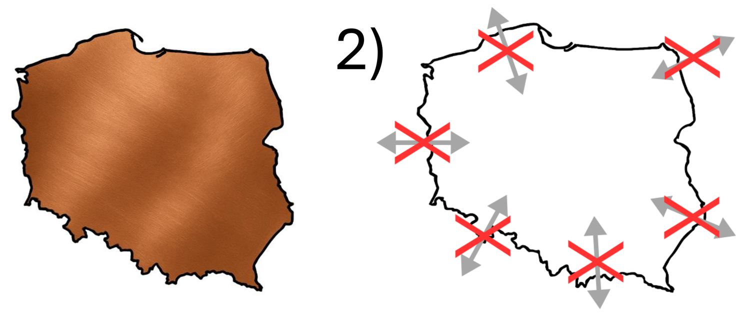
CF – mean capacity factor (1980-2019)

Electrical grid:

1) As 'copperplate' inside the country
2) No interconnection with neighbouring countries

Data:

- Hourly resolution
- Coverage: 1980-2019



Sources

- PV & WT mean capacity factor: MERRA-2 (renewables.ninja)
- Load: ENTSO-e & MERRA-2

METHODS

40 years of hourly electricity demand time series

Artificial Neural Network (ANN) model training: multiple feedforward ANN models in MATLAB trained to simulate hourly electricity demand based on historical inputs and weather variables.

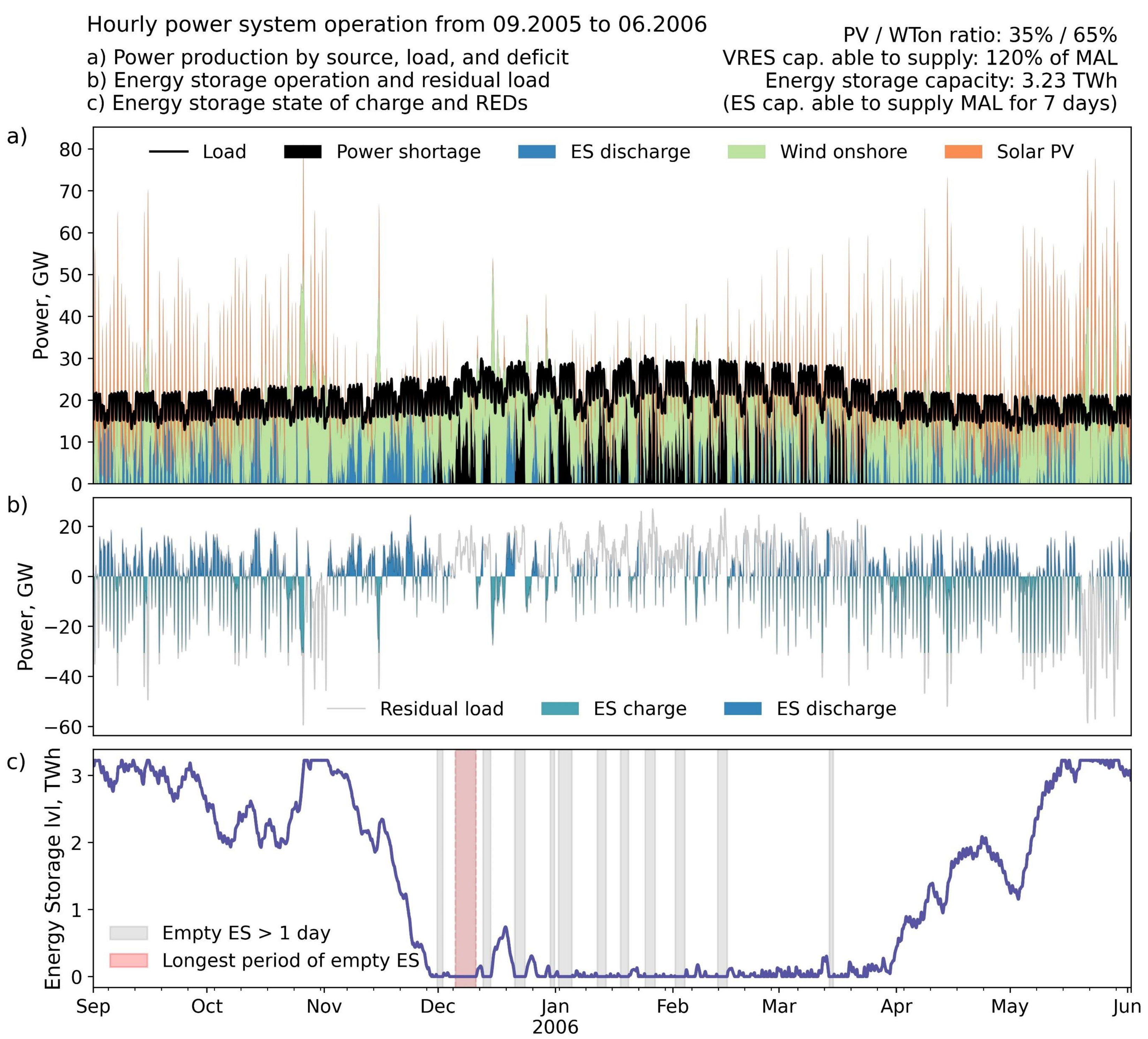
- Historical load data: 2015-2019 (ENTSO-e).
- Weather data: 1980-2019 (MERRA-2, population-weighted).
- Data split: 70% training, 15% validation, 15% testing.
- Hyperparameter tuning: Number of neurons in the hidden layer varied from 1 to 30. Model with minimum MAPE selected.

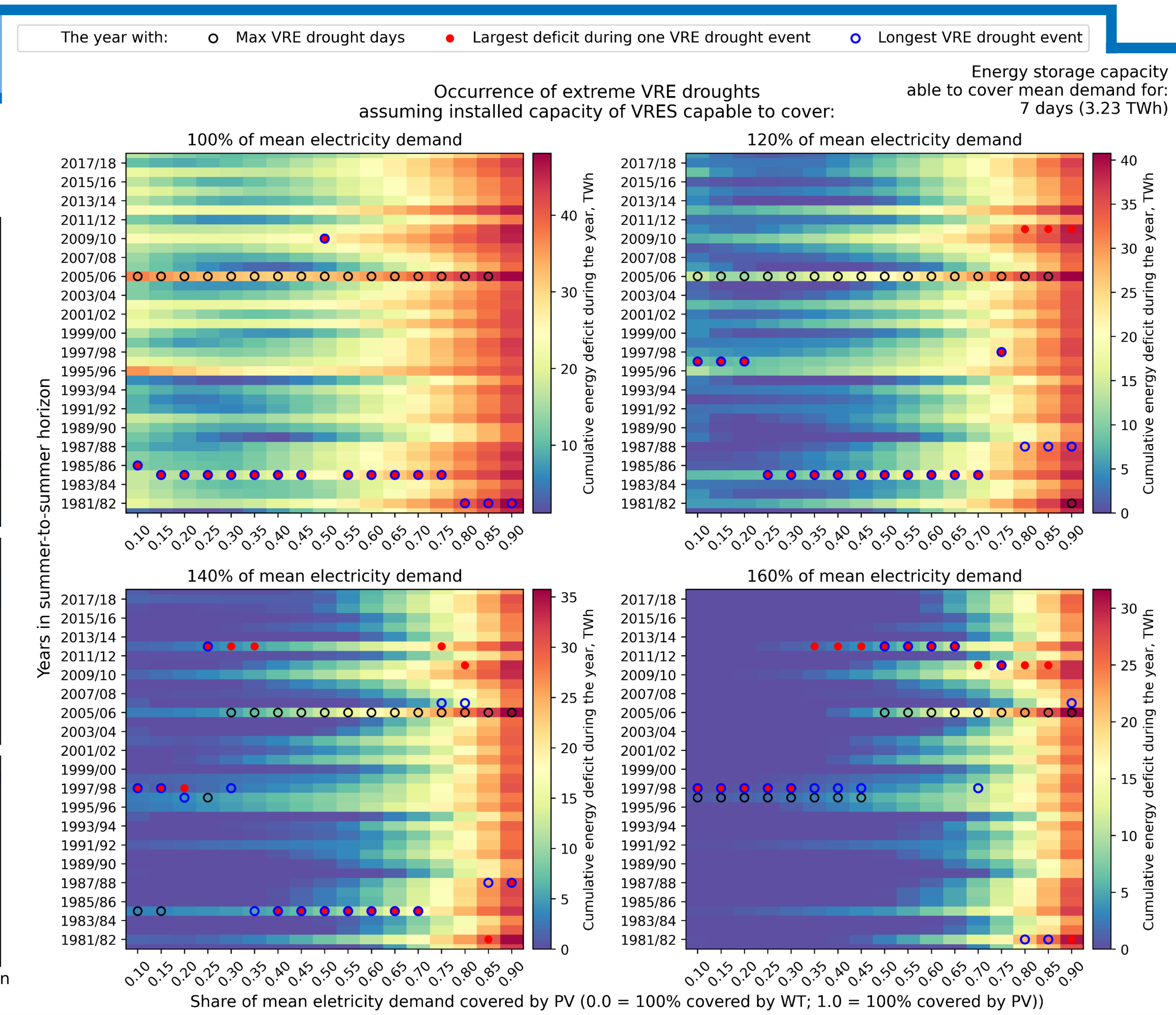
Energy drought metric (*Boston et al., 2022*)

- During periods of **negative residual load** (energy surplus) the algorithm charges the LDES. Charging is constrained by:
  - the available energy storage capacity remaining,
  - the maximum allowable charging power.
- During periods of **positive residual load** (energy deficit) discharges LDES to supply energy to the grid. Discharging is constrained by:
  - the amount of energy available in the storage (accounting for efficiency losses),
  - the maximum allowable discharging power.
- **Unserved energy** is defined as the portion of the positive residual load that remains unmet after the storage is fully discharged (empty).

VRE drought event - uninterrupted period of empty ES over 24 hours

RESULTS AND INSIGHTS





Characteristic data of power system operation assuming:

- VRES demand coverage: 120%;
- PV / WT ratio: 35 / 65%;
- LDES capacity: 3.23 (7 days).

Parameter	Value	Date
$Load_{max}$	30.61 GW	2006-01-24 16:00
RL_{max}	28.53 GW	2010-02-08 17:00
RL_{min}	-77.85 GW	1994-06-23 10:00
$E_{def,sum}$	15.7 TWh	2005/2006
$E_{def,sum}$/ $E_{mean\ annal\ demand}$	9.33%	2005/2006

KEY OBSERVATIONS:

- ✓ In terms of the number of renewable energy drought (RED) hours per year, the most extreme was 2005/06 and 1996/97 in the scenarios studied.
- ✓ The most extreme year or event, in terms of the RED duration or energy deficit, varies depending on the energy system assumptions.
- ✓ With a high share of VRES in demand coverage (>80%), a larger share of the energy produced by wind turbines (>65%), helps to minimize the RED hours per year.
- ✓ With unlimited maximum LDES charging capacity, reducing the occurrence of REDs to 0 would require VRES to cover 160% of long-term mean demand (LTMD), with a 30:70 of PV:WT ratio and LDES capacity able to supply 9 days of LTMD.
- ✓ With limited maximum charging and discharging power to a value equal to the maximum hourly load, it would require VRES to cover 170% of long-term mean demand (LTMD), with a 25:75 of PV:WT ratio and the same LDES capacity.

Acknowledgments & Affiliations

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