

ENERGY FINDINGS

Broad Range of Technologies Could Firm Up Wind and Solar Generation in Net Zero Carbon Dioxide Emission Electricity Systems

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Keywords: energy storage, energy modeling, electricity generation, firm electricity, wind power, solar power

<https://doi.org/10.32866/001c.90391>

Findings

‘Firming’ technologies can be coupled to variable wind and solar generation to meet electricity demand reliably. Options that could participate in this firming role include dispatchable electricity generators, electricity storage technologies, atmospheric carbon dioxide removal, and demand management. In this study, we allow various firming technologies to participate in a stylized net zero CO₂ emission electricity system reliant on wind and solar generation. By examining a series of least-cost systems in which the most valuable firming technologies are sequentially removed, we demonstrate that reliable wind-and-solar-reliant electricity systems do not depend on the feasibility of any particular firming technology.

1. Questions

On-shore wind and solar photovoltaic energy are expected to contribute large fractions of future energy supply (Luderer et al. 2021). The high variability of and geophysical constraints on such energy sources (Tong et al. 2021) creates value for additional firming technologies, defined to be technologies that make electricity available when wind and solar generation is insufficient to meet demand. Because of the vast number of possible technologies, their ability to firm wind-and-solar-reliant electricity systems is typically considered individually or in small sets (Beuttler, Charles, and Wurzbacher 2019; Bistline and Young 2022; Denholm et al. 2012; Jin et al. 2023; Mutke, Plaga, and Bertsch 2023; Sepulveda et al. 2021).

In this study, we use a stylized energy system model and include a large set of different technologies that could improve system reliability. We consecutively remove the technology that contributes the most value to the total system (i.e., the technology that would increase system cost the most if it were removed and the rest of the system were allowed to re-optimize). We address the question: Are there any technologies that are particularly valuable in firming up wind-and-solar-reliant electricity systems, or are there many technologies that could potentially play this firming role?

2. Methods

We define a stylized energy system using PyPSA (Brown, Hörsch, and Schlachtberger 2018) considering a network of 33 generation and storage technologies (Figure 1). We represent the entire US grid with a single node and average wind and solar generation over the areas with the highest capacity factors, reducing variability relative to more realistic representations, decreasing the value of firming technologies.

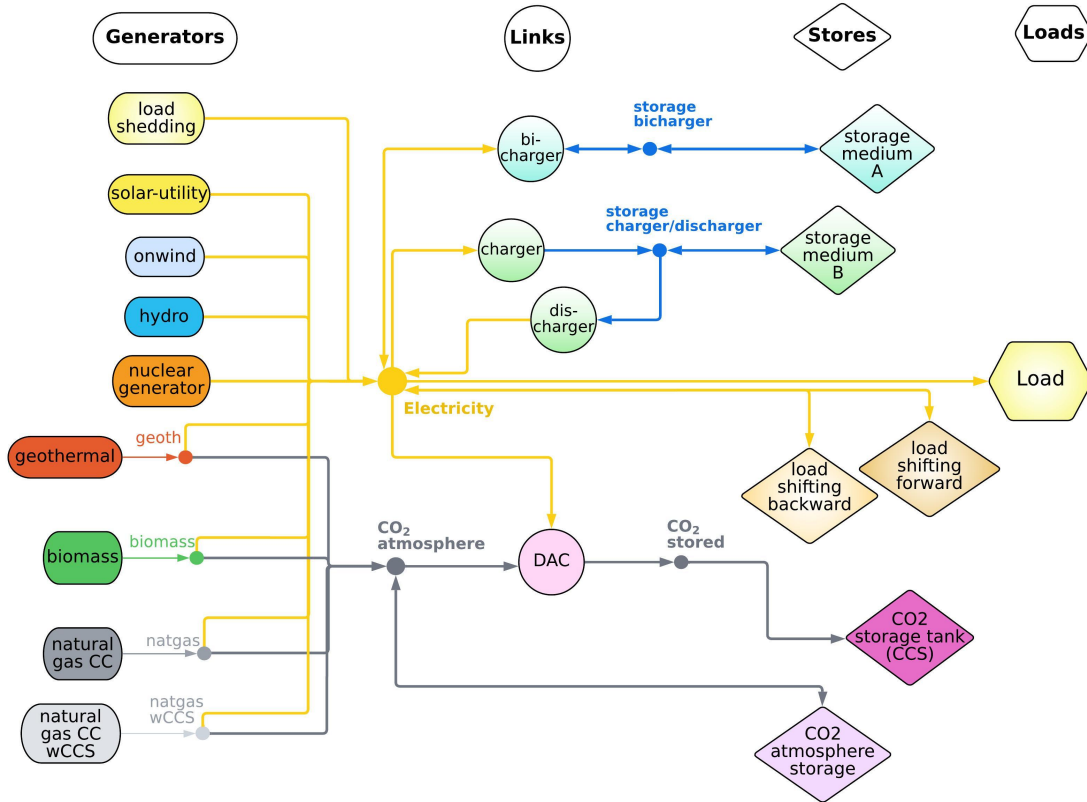


Figure 1. Sketch of the full energy system as defined for the optimization. A generalized storage system for each type in the sketch represents the many different storage technologies.

The generators we consider include (i) firming and emission-free hydro and nuclear generators; (ii) CO₂-emitting natural gas, natural gas with Carbon Capture and Storage (CCS) and geothermal generators; (iii) carbon-removing biomass energy with CCS (BECCS) generator. We use hourly capacity time series for the variable wind and solar generators for the contiguous United States (Ruggles et al. 2023) for one year based on data from ERA5 (Hersbach et al. 2023).

We consider 20 different storage technologies that fall into two different categories (Figure 1): a design with a separate charger and discharger where all components can be sized independently (e.g., hydrogen storage), and a design with a bicharger where the charger and discharger are one component (e.g., Lithium-ion battery). Techno-economic characteristics of all storage technologies are as represented in the PyPSA database (Parzen, Fioriti, and Kiprakis 2023).

Direct Air Capture (DAC) is represented by a process that uses electricity to convert CO₂ in the atmosphere to CO₂ in a storage reservoir. Load shedding is represented as a negative generator, and load shifting is represented as one battery with positive energy storage and one battery with negative energy storage. For the load, we assume hourly demand data for the contiguous United States for one year (Ruggles et al. 2020).

We use estimates of current costs as represented in the PyPSA database (Victoria et al. 2023), first published in 2018 (Hörsch et al. 2018). For technologies not included in the database, values from other sources were used (Denholm et al. 2022; Gerke et al. 2020; Gorman 2022; NREL 2021).

The optimizer minimizes the objective function defined as the system's total cost. The system is constrained to net zero CO₂ emissions, which requires CO₂-emitting technologies to be balanced with CO₂-removing technologies.

We employ an iterative procedure that starts with optimizing the system with all technologies considered allowed to participate. Analyzing the first result, we identify the technology (apart from wind or solar generation) that, when removed, increases the total system cost the most. That “most valuable” firming technology is then removed from the system and system dispatch and capacities, including wind and solar capacities, are reoptimized. The procedure is repeated until only wind and solar generation remains.

For transparency and reproducibility, all model codes, interfaces (Wongel, Hayes, and Caldeira 2023), input data (Ruggles et al. 2023), and analysis results are publicly available and documented (Wongel and Caldeira 2023).

3. Findings

The described removal procedure leads to a series of energy systems ([Figure 2](#)) that starts with a system in which all technologies considered are allowed to participate and ends in a system that consists of only wind and solar generation. Sometimes this procedure allows previously uncompetitive technologies to become competitive.

We present bounding cases where scale of deployment for each technology is either unconstrained or constrained to be zero. More realistic cases might fall between these extremes. When all technologies considered are allowed to participate, the system is dominated by hydropower as the most valuable firming technology. However, hydropower is strongly constrained by geophysical factors (Stoll et al. 2017). After its removal, the next most valuable technology is biomass energy with carbon capture and storage (BECCS), but availability of biofuels is also limited. Its removal also disfavors the use of the geothermal generator because geothermal energy today releases substantial amounts of CO₂ associated with reservoir fluids (Bonalumi, Bombarda, and Invernizzi 2017). After BECCS, the next most valuable firming technologies are compressed air storage and direct air capture of CO₂. All CO₂-emitting generators (natural gas and geothermal) are eliminated from the system in these steps. The most valuable technologies that follow in the series include different combinations of storage technologies used to firm up wind and solar generation. Toward the end of the series, when many storage technologies are already excluded, substantial nuclear energy capacity is built. However, that is mainly utilized to meet load peaks that would otherwise require sizable

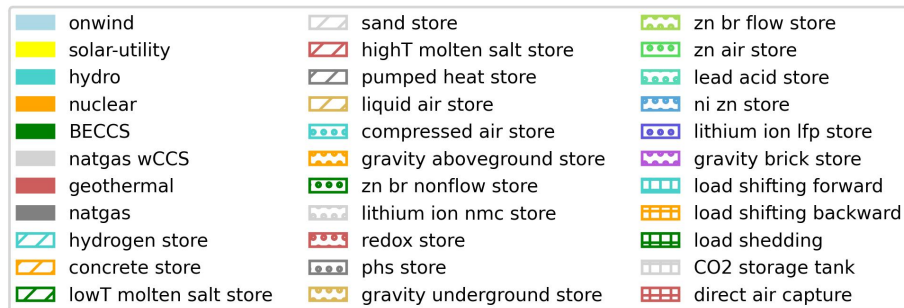
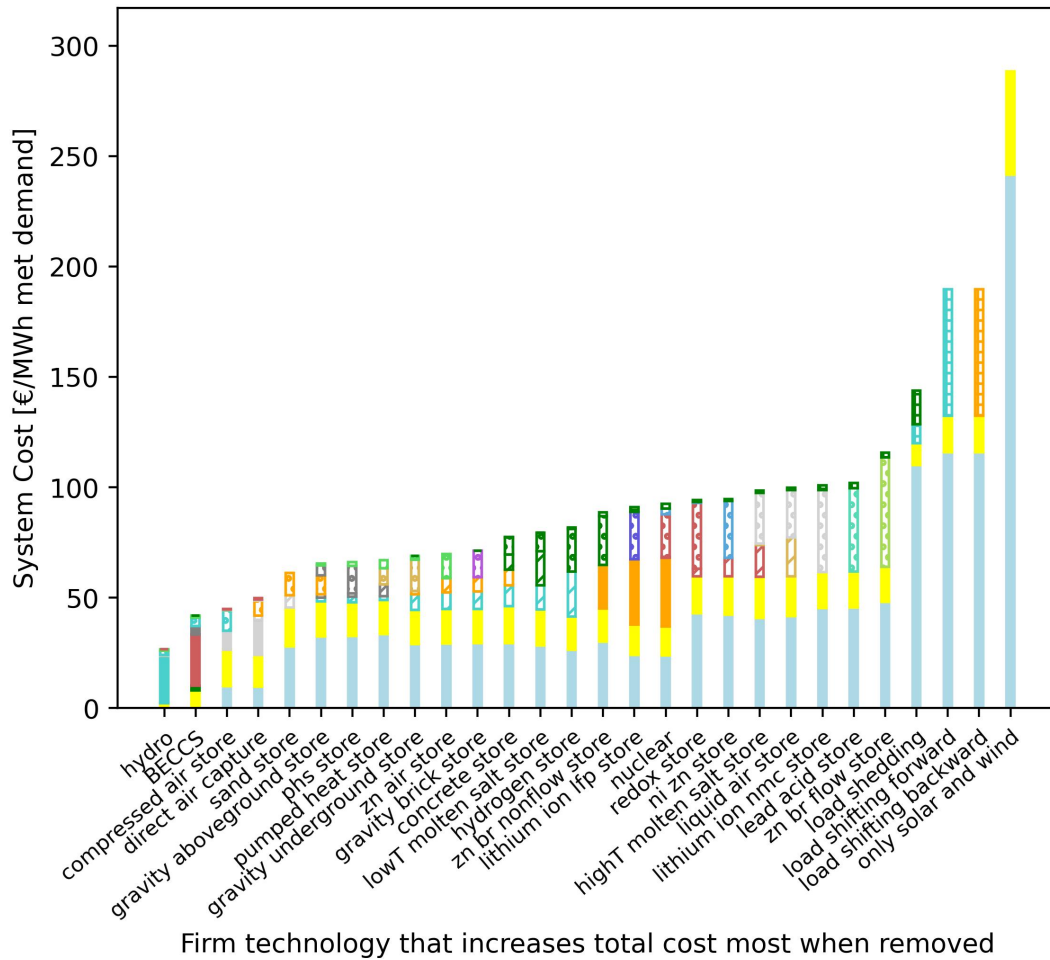


Figure 2. Removal of technology leading to the largest cost increase. The technology that is most valuable to the system at each step is shown on the x-axis. The y-axis shows cost contributions of the different technologies which sum to the total cost of the system per MWh of met demand.

additional wind, solar or storage capacity. The series concludes with only the load-shifting technologies firming the system and, finally, with all demand met by wind and solar generation without firming technologies.

As the more valuable firming technologies are removed from the system, the amount of wind and solar capacity that is built to satisfy loads increases, resulting in increased system cost and increased curtailment of wind and solar generation (Figure 3). When the relatively cost-intensive nuclear power contributes, the amount of unutilized electricity generation is slightly reduced.

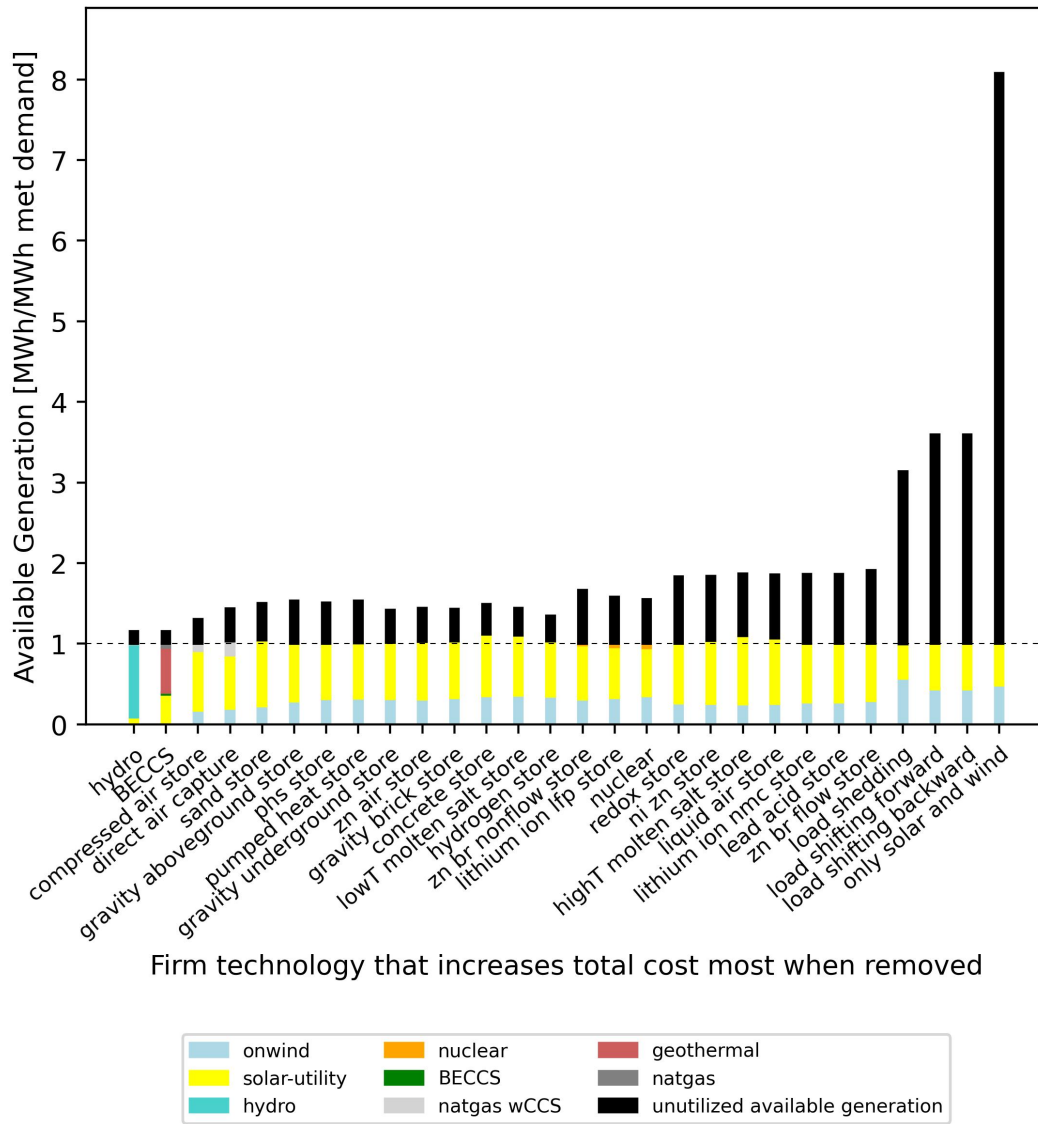


Figure 3. Available generation in energy systems where the most valuable technology is consecutively removed. The y-axis shows the utilized generation of the different technologies and the unutilized available generation summed over all generators. Utilized generation larger than 1 shows storage and other losses.

We observe that the increase in cost between two neighboring steps in the series is often small. In these cases, systems with different contributing firming technologies lead to similar total system costs. The specific ordering of technologies could be influenced by many factors (Duan, Ruggles, and Caldeira 2022; Jenkins, Luke, and Thernstrom 2018; Sepulveda et al. 2018), including electricity transmission, geographical constraints, resource availability, and uncertainties in future cost and technological characteristics.

We find that a broad range of technologies and approaches could contribute to reliability of electricity systems reliant on wind and solar generation. Our results suggest that reliable wind-and-solar-reliant electricity systems do not depend on the feasibility of any particular firming technology.

Acknowledgments

AW acknowledges financial support from Gates Ventures LLC through a gift provided to the Carnegie Institution for Science. We thank Lei Duan and Angelo Carlino for valuable comments and discussion.

Submitted: October 13, 2023 AEDT, Accepted: November 21, 2023 AEDT



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