LOCALIZED, COST-EFFECTIVE, 100% RENEWABLE FIRM POWER GENERATION

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Abstract

Solar photovoltaic (PV) and wind energy are now the most scalable and cost-effective electricity sources. However, their weather-dependent variability raises concerns about their ability to provide reliable, continuous power. The concept of firm power—the ability to meet demand 24/7/365 ─ is central to addressing this challenge. Research from IEA PVPS Task 16 shows that PV and wind can deliver firm power cost-effectively when combined with battery energy storage systems (BESS), dynamic curtailment (aka implicit storage), and a small share of dispatchable thermal generation using GHG-free e-fuels. This paper quantifies how the cost of firm PV/wind power varies with the geographic scale of the generation footprint across the continental U.S., assuming a flat baseload and 5% e-fuel flexibility. Results show that localized, self-contained firm power systems within areas smaller than 50,000 km² are economically viable, with projected 2050 levelized costs ranging from 4.25 to 6.25 ¢/kWh ─ challenging the assumption that large-scale transmission is essential for reliable renewable power. The study also explores optimal PV/wind mixes, storage requirements, and how these evolve with footprint size.

1   Introduction

1.1 Firm VRE power Generation

Photovoltaic (PV) and wind energy are variable renewable energy (VRE) sources whose output depends on weather conditions, making them inherently intermittent and unable to meet firm power requirements on their own. However, research from the IEA [1–4] shows that VREs can be economically transformed into firm power sources ─ capable of reliably supplying electricity 24/7 ─ through a strategic combination of technologies. This transformation involves coupling solar and wind generation with battery energy storage systems (BESS), overbuilding generation capacity, and dynamically curtailing excess output. The latter approach, sometimes referred to as implicit storage, reduces the need for large-scale physical storage. Additionally, incorporating a small share of dispatchable thermal generation powered by clean e-fuels can further enhance system flexibility and reliability. Together, these strategies have been shown to enable cost-effective firm power generation from VREs, paving the way for a gradual and seamless transition away from conventional energy sources.

1.2 VRE footprint

Studies conducted in Switzerland [2] and the Midcontinent Independent System Operator (MISO) in the US [3] demonstrate that firm power solutions can be achieved entirely within localized geographic areas. These localized systems incur only a modest cost premium compared to continent-wide interconnected solutions ─ and that is even before accounting for the additional expenses that would be associated with building and maintaining long-distance transmission infrastructure.

In this study, we systematically evaluate these observations. Focusing on the continental United States (CONUS), we analyse how the cost of firm PV/wind power evolves as the geographic footprint of renewable generation expands ─ from a single localized point to progressively larger regions, up to a subcontinental scale. This approach allows us to quantify the relationship between spatial aggregation and cost-effectiveness, providing insights into how localized renewable systems can contribute to dependable, 24/7 power supply without the need for extensive grid expansion.

2   Methodology

2.1 Spatial Scaling of VRE Capacity Factors Across Continental U.S. Using High-Resolution Simulation Data

We selected 36 centroids across the continental United States (CONUS), as shown in the top-left panel of Figure 1. Around each centroid, we defined variable renewable energy (VRE) generating areas of increasing size, starting from a single 0.1° × 0.1° latitude-longitude cell and expanding outward in concentric grids of 3×3, 9×9, 21×21, 39×39, 69×69, 123×123, and 249×249 cells. The largest configuration spans 6 million square kilometres.

Hourly, site-specific nominal wind and PV production data for 2022 were simulated using SolarAnywhere surface irradiance and meteorological inputs [5], along with ERA5 wind speed data at 100 meters [6]. PV systems were modeled with a fixed
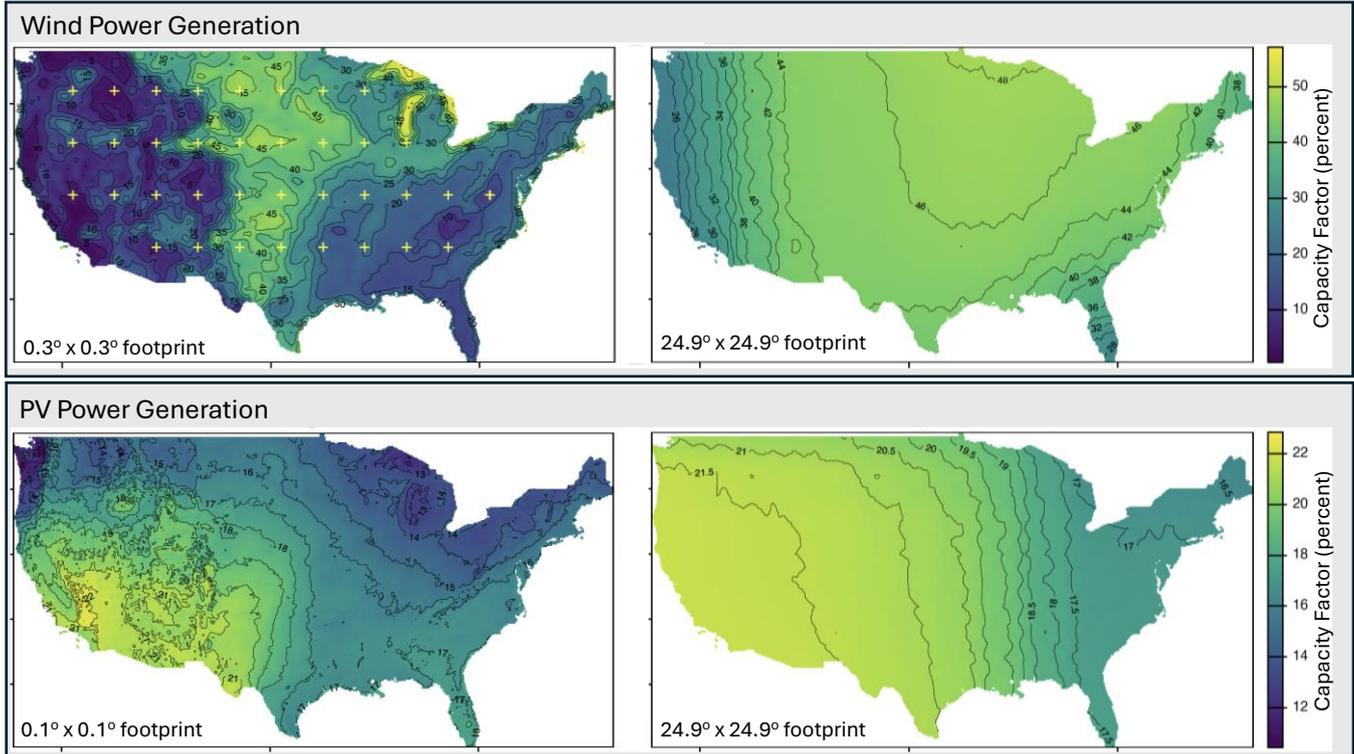
Fig. 1 Location of the regional centroids (top left). Mean PV and Wind capacity factors for the smallest considered regions (left) and the largest subcontinental regions (right). Note that the colour scale is different for wind and PV.

30° south-facing tilt configuration, while wind generation assumed land-based wind farms (100-meter-high turbines) incorporating wake effects [7].

For each generating area, we calculated the average wind and solar output based on the top 10% of single-cell capacity factors within any given area. Figure 1 maps the resulting area-wide capacity factors for both the smallest (single cell) and largest (249×249 cells) footprints around each centroid.

2.1 Firm power simulations & assumptions

To identify the lowest levelized cost of electricity (LCOE) for firm power generation, we applied the Clean Power Transformation model [8] across all defined areas. This model optimizes the configuration of PV, wind, battery BESS, and curtailment to minimize firm generation costs. Financial assumptions were aligned with those used in multiple IEA studies, including a 30-year system lifetime and a 4% weighted average cost of capital representative of the US utility industry. Optimal firm power configurations are influenced by the capital and operating expenses (capex and opex) of each technology, the temporal alignment of PV and wind generation with the target load, and the flexibility of that load. For this analysis, we assumed a constant 24/7 load profile — representative of a nuclear generator with zero downtime — to be served firmly at all times. To introduce a degree of supply-side flexibility, we allowed 5% of the load to be met by dispatchable thermal generation powered by 100% renewable GHG-free e-fuels. Although costly, this dispatchable component has a catalytic effect: it significantly lowers the overall cost of firm power by reducing the need for extensive storage and curtailment. Moreover, it provides a fail-safe guaranty mechanism against rare but impactful VRE droughts, thereby justifying the use of a single meteorological year (2022) for optimization and cost estimation.

Capital and operating cost assumptions for PV, wind, BESS, and e-fuel flexibility are detailed in Table 1. These values are based on the 2020 NREL Annual Technology Baseline (ATB) [9], specifically the projections for advanced development by 2050.

Table 1 Capex and opex of considered firm power technologies.

CapEx	PV	$ 465/kW
	Wind Onshore	$ 525/kW
	Battery	$ 65/kWh
		$ 49/kW
	e-fuel Thermal Gen	$ 850/kW
OpEx	PV	$ 11/kW/yr
	Wind Onshore	$ 24/kW/yr
	Battery	$ 1.63/kWh/yr
		$ 1.23/kW/yr
	e-fuel Thermal Gen	¢ 0.18/kWh

These same figures have been adopted in several IEA studies [1–3]. Notably, the 2024 ATB [10] revised BESS energy capacity capital costs upward by nearly 100%, a change that contrasts sharply with other independent sources such as

Bloomberg, which report significantly lower estimates even for current or near-term market conditions [11]. It should be noted, however, that such an increase in BESS capex, can be compensated by shifting the optimal firm power balance between physical and implicit storage as shown in [13].

3   Results

3.1 Impact of Spatial Footprint on Firm Power Cost and System Configuration

Figure 2 illustrates how the size of the VRE generation footprint influences several key metrics in firm power system design:

- Levelized Cost of Electricity (LCOE) for firm power.
- Optimal blend of wind and solar generation
- Installed renewable energy (RE) capacity, expressed as multiples of the served baseload.
- Nominal battery energy storage system (BESS) capacity

- Implicit storage, i.e., optimally curtailed VRE output.
- Implicit storage effectiveness at reducing firm power costs – specifically, the LCOE reduction achieved by allowing optimal curtailment of variable renewable energy vs. entirely avoiding curtailment.

Across small regions, LCOE values vary widely, with up to a 300% difference between the most and least cost-effective regions. However, this region-to-region variation narrows significantly as the footprint expands to approximately 40,000–50,000 km², where average LCOEs stabilize around 5 ¢/kWh, with a national range of 4–6 ¢/kWh. While further cost reductions are observed with larger footprints, it is important to note that these gains would come at the expense of increased transmission infrastructure, reduced local resilience, and diminished use from distributed grid resources. This last point is particularly important because regional firm power PV and BESS resources can be effectively deployed locally below distribution substations, incidentally, also helping to mitigate hosting capacity constraints on these circuits [12].
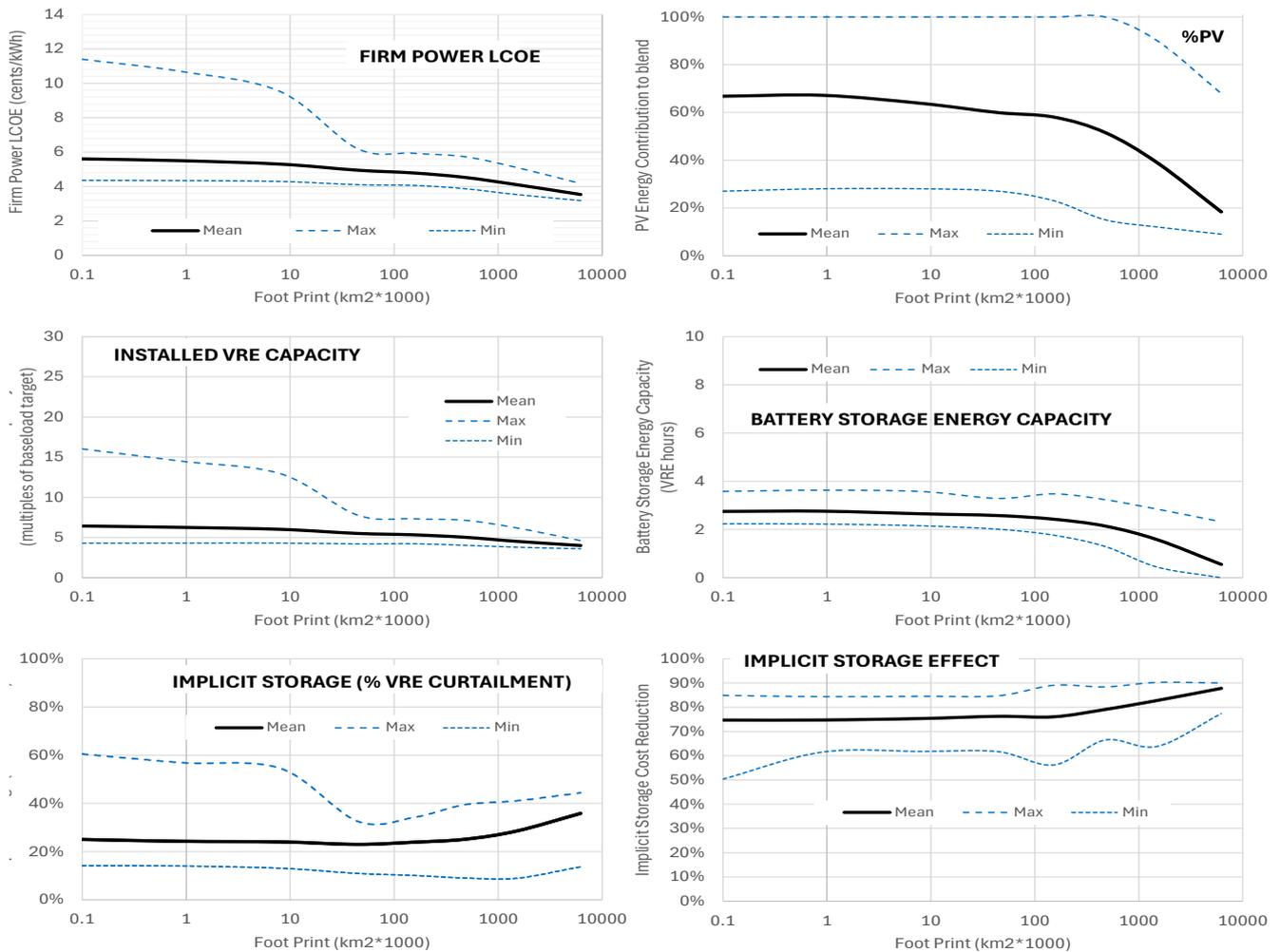

Fig. 2 Footprint dependence of firm power LCOE (top left), proportion of PV in the VRE blend (top right), Installed VRE capacity in multiples of load (middle left), BESS energy capacity in VRE-hours (middle right), Implicit Storage ― % dynamic VRE curtailment (bottom right), and firm power cost reduction enabled by implicit storage (bottom right).

In most regions ─ except the largest ones where distant high-capacity wind resources can be accessed ─ the optimal VRE mix is PV-dominant, despite PV's lower capacity factor. This trend varies by location, as reflected in the wide min-max ranges shown in the figure.

Installed VRE capacity typically ranges from 4 to 6 times the constant load, a ratio that aligns with LCOE sensitivity, given that VRE costs are a major driver of firm power economics.

BESS requirements average around 2.5 VRE-hours (equivalent to 10–15 load-hours) and remain stable across regions. Exceptions occur in the largest footprints, where wind variability and higher wind capacity factors begin to influence storage needs. Curtailment levels also remain consistent at approximately 25%, except in the largest regions, which tend to be wind-dominant and more variable ─ leading to increased reliance on oversizing and curtailment.

3.2 Flexibility and Grid Integration

The firm power configurations considered in this analysis include a modest amount of newly built supply-side flexibility ─ amounting to 5% of the total generated electrical energy. This dispatchable flexible thermoelectric generation is operated with clean, 100% GHG-free e-fuels, Although this resource is extremely expensive per se (with an opex five times higher than that of natural gas) it has been shown to have a catalytic effect that delivers overall firm power LCOEs that are considerably lower than would be achieved without flexibility when sparingly applied. Figure 3 compares the mean LCOEs achieved in the US with and without flexibility as a function of generation footprint.

In addition to positively impacting overall firm power generation costs, adding clean supply-side flexibility into firm power configurations also has the advantages of:

(1) offering guaranties against any extended VRE droughts. This is unlike demand-side flexibility that would have a more limited expandability beyond intraday --- indeed while amounting to 5% in terms of energy, the capacity of optimized flexible resources typically amount to the served peak load [13].

(2) offering near-term logistical guaranties to grid operators who are currently struggling to meet renewable mandates and absorb growing amounts of unconstrained VREs. Operators are actively petitioning to keep/build new thermoelectric (natural gas) generation [14]. Such natural gas resources can function as a bridge today to enable a smoother transition high VRE penetration. Most importantly, these resources can eventually be fully converted to clean electro fuels and actively contribute to deliver optimally priced firm renewable power generation.

In terms of grid integration, the present findings suggest that extensive transmission build-out beyond small, resilient regions may not be necessary to achieve cost-effective 100% VRE firm and reliable solutions commensurate with current generation costs.

Figure 4 contrast the mean LCOE achievable in 2050 for footprints of 50,000 km^2 in the US to the current generation cost in major US TSO regions. Note that these regions are larger than 50,000 km^2 (the smallest one being NYISO at 122,000 km^2) and could thus accommodate several electrically independent subregions capable of supplying low renewable firm power while maximizing localized resiliency.

Importantly:
(1) these results do not consider any subsidies for the firm VRE solutions (tax-based or otherwise). If one assumes that the probability for such subsidies is substantial the coming years (e.g., from environmental and societal pressures), the renewable LCOEs could be lower than current generation while also offering very long-term guarantees of cost/supply stability.
(2) The considered TSOs wholesale costs are for energy only. Actual wholesale electricity also includes a capacity component that would typically make these figures 20-30% higher. The firm VRE LCOEs include built-in guaranteed capacity.
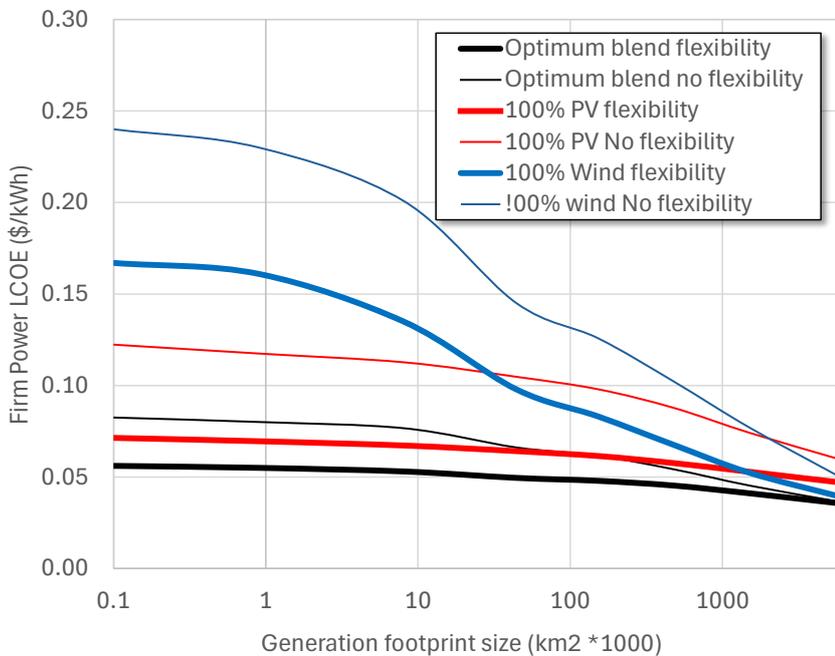

Fig. 3 Firm power generation LCOE as a function of footprint, VRE blend and flexibility.
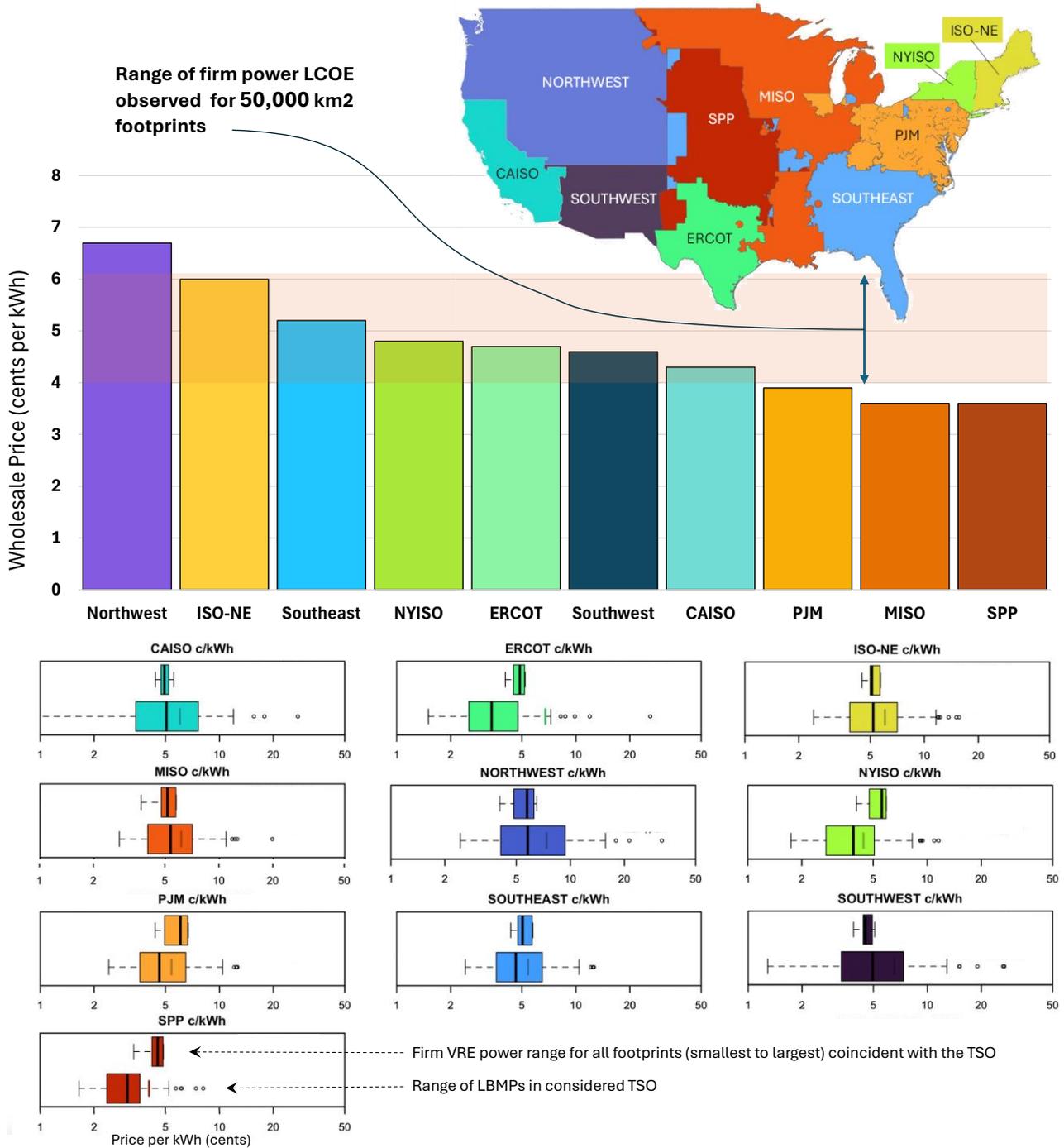
Fig. 4 The top bar chart contrasts the range of future firm power LCOEs for 50,000 km2 footprints to the 2024 mean wholesale electrical energy cost for US TSOs. The bottom set of plots compares the range of hourly wholesale energy generation transacted on these TSOs against the range of firm VRE power observed for each footprint --- 1x1 to 249x249 --- included in or overlapping with each TSO (note: we selected the lowest cost area for each size)

4   Conclusion

This study demonstrates that localized, 100% renewable firm power systems—built around solar, wind, storage, and a touch of clean dispatchable flexibility—can be both cost-effective and resilient. By analysing spatial footprints across the U.S., we show that areas under 50,000 km² can reliably deliver firm power at competitive costs, without relying on long-distance transmission infrastructure. These findings challenge the conventional wisdom that large-scale interconnection is essential for reliability and highlight the potential of

distributed, locally optimized solutions. As technology costs evolve and policy support grows, localized firm VRE systems could become a cornerstone of a stable, affordable, and sustainable energy future.

5 Acknowledgements

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