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ABSTRACT

This study investigates the spatial and temporal dynamics of wind and solar energy generation across the continental United States, focusing on energy availability, reliability, variability, and cooperation. Using data from the National Renewable Energy Laboratory, we analyze the performance of wind turbines and photovoltaic systems, revealing distinct patterns in energy production and reliability. The classification of wind and solar zones based on energy availability and reliability provides valuable insights for renewable energy planning and grid integration strategies. Overall, this methodology contributes to understanding wind and solar interactions, which will lead to informing effective renewable energy deployment and grid integration efforts.

I. INTRODUCTION

U.S. distribution grids now include significant numbers of small-scale wind turbine (WT) generators[1] in addition to the more commonly found photovoltaic (PV) systems. According to a 2023 report, about 1.104 gigawatts (GW) or 90 000 turbines were actively producing power on distribution networks in 2022.[2] PV, wind's counterpart, represents a much larger market; by 2022, the United States reached a total of about 38 GW of PV on distribution grids.[3] WT integrations are significantly less than PV due to various factors including regulations[4] and other factors.[5] However, optimistic projections of WT integrations exist—by 2035 behind-the-meter installations will reach 919 GWs.[6]

Although WT and PV systems provide many benefits, the oversaturation of these generators on distribution grids will cause electric power systems (EPSs) to suffer. Adding distributed generators (DGs) of any kind causes voltages to increase and if left unmanaged customer equipment could be damaged. In some locations, overgeneration will require excessive congestion management.[7] To avoid grid performance issues and the need to curtail renewable generators, this work proposes an analysis methodology that considers different facets of their outputs.

The methodology, presented here, quantifies and groups locations based on the renewable energy generation availability, reliability, variability, and cooperative operations. The method's threshold-based parser quantifies locations across a region or country using the following metrics:

- Availability: The amount of energy produced by solar or wind resources over an entire year.
- Reliability: The consistency or day-to-day variability of solar and wind resources.
- Variability: Natural changes in renewable energy resource outputs at intra-day intervals.
- Coincidence: The complementary characteristics of wind and solar resources that improve or hinder the integration of the renewable resources.

The evaluation of these metrics provides benefits to industry and the research community. With this knowledge, energy planning and policy developers will make informed strategies for promoting distributed generation developments, setting renewable energy targets, and implementing supportive polices and incentives. It will also help grid planners and operators anticipate the characteristics and potential variability of renewable energy generation in different regions. Not only will they be prepared, but utilities can take an active approach to optimize the deployment of wind and solar resources so that they complement each other and/or directly support the electric grid's needs.

This paper begins by introducing the evaluation approach. It then describes the resources and data useful for studying WT and PV system operations across the United States. To highlight the methodology, this work compares WT and PV system models that each have a capacity of 8.9 kWs. The simulations generated year long, 1 h interval simulations results for locations at 60 km spatial resolution. Data assessments of these results included computations of total energy generation, day-to-day variability, hour-to-hour variability, and the correlation coefficient for the two resources' time series signals at each location.

Up until know, the classification of regions' potential to host wind resources, solar resources, or both has not been assessed to this degree. This paper offers a unique perspective into the interplay between wind and solar resources so that decision makers can evaluate a complete spectrum of operational consequences and opportunities.

II. BACKGROUND

Published studies examine the impacts and challenges associated with wind and solar grid connections. These studies examine large-scale installations[8,9] and small, or micro-wind turbine implementations.[10] It is clear that the integration of wind and solar resources, both independent of one another and together, presents various challenges. A review paper highlights issues associated with the integration of the two resources.[11] Or, WTs alone will also cause similar issues,[12,13] including uncertainty, and voltage instability.

Utilities use various techniques to plan for future renewable energy grid integration levels and scenarios. Most often, it involves production simulations, power flow calculations, stability analysis, and a reliability evaluation.[14] The preparatory evaluations also often include economic assessments.[15] And, before a utility grants an interconnection permit, a hosting capacity assessment must indicate that its impact will not be detrimental.

Hosting capacity approaches represent a common method for studying and estimating the impacts of renewable energy generators on distribution grids.[16,17] These studies subject distribution electric power systems (EPSs) to various implementations,[18] including deterministic,[19] stochastic,[20] and time series simulations.[21] However, little to nothing is done to evaluate the interplay between wind and solar resources as described in this paper.

Studies have examined the impacts of wind and solar on bulk resources system operations.[22] And, published work focuses on hybrid power plant operations.[23,24] However, little has been done to quantify the coincident and non-coincident generation of wind and solar resources on distribution grids and how it varies spatially across the country.

The cooperative dynamics of wind and solar resources provide decision makers with information regarding their most dominant resource, the potential for the two resources to work together, and situations where the two resources could cause grid issues. One interesting study evaluated the correlations between large-scale solar and wind resources for future scenarios in Sweden.[25] Other studies used correlations for co-locating solar and wind resources.[26,27] Another study used spatial-temporal correlations to create a data-driven forecasting methodology.[28] These papers provide interesting examples of when and how wind and solar resources can be evaluated to see how they could potentially work together or against each other. This paper adds to these publications but presents a method for assessing correlations across a larger spatial area. It also evaluates other performance factors, such as availability, consistency, and variability to ultimately identify the dominant resource for a particular location.

III. EXPERIMENT METHODOLOGY

This experiment examines the interplay between PV and WT operations with the objective of classifying regions based on their performance, dynamic nature, and interplay. The overall approach, described in Fig. 1, begins with the acquisition of spatial-temporal weather data. To emulate the most basic operations of WTs and PV systems, the models require irradiance, ambient temperature, and wind speed as inputs. A PVWatts model and a wind power curve emulated the two resources for a full year at 1 h intervals.

After simulating the two resources, four analysis procedures characterize their performance at each location. The first assessment quantifies the overall availability over an entire year, for each resource by calculating the annual energy output. The second and third assessments characterize the locations' reliability, from day to day, and variability on an hourly basis. The final analysis compares the time series signals of the WT and PV systems at each location to estimate coincident operations with the intent of quantifying how the two system types interact on an hourly basis. The results from each of the assessments produce representations useful for classifying each location.

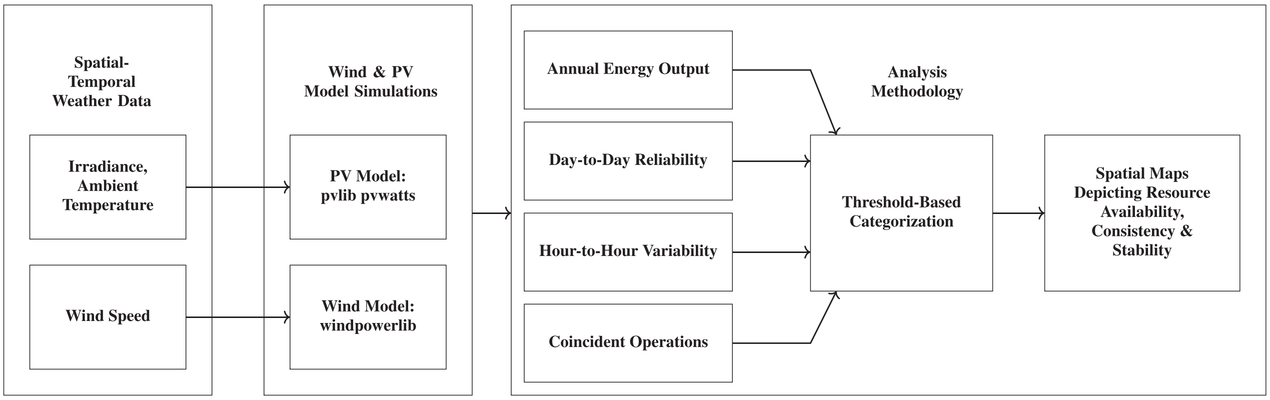

FIG. 1. This block diagram describes analysis methodology used herein. The approach includes the gathering of spatial-temporal data, simulation of PV and wind resources across the country, and evaluation of the renewable energy resources to estimate their availability, consistency, and stability.

A. Spatial-temporal data

National Renewable Energy Laboratory (NREL)'s Highly Scalable Data Service (HSDS) provides access to the Wind Integration National Dataset (WIND).[29] These meteorologic datasets include $2 \times 2\,\text{km}^2$ grid cells at 1 h intervals for years between 2007 and 2013. To avoid extensive computations, not required to provide evidence of the methods' effectiveness, the analysis down-sampled the $2 \times 2\,\text{km}^2$ spatial grid cells to be $60 \times 60\,\text{km}^2$.

B. Test renewable energy system models

An estimate of a WT's operational behavior leveraged an existing Python library called *windpowerlib*.[30] Other research work leveraged this package to assess wind energy, including Ref. 31. For this implementation, the Python library estimates power based on published data and provides the power curve for a Bergey Excel 10 8.9 kW turbine.[32] The top plot in Fig. 2 depicts this turbines power curve.

To emulate the behavior of a grid connected PV array, this work used a PVWatts model developed by the NREL.[33] The model computes power (P) by considering solar radiation and temperature inputs, as described in the following equation:

$$P_{dc} = \frac{G_{poaeff}}{1000} P_{dc0}(1 + \gamma_{pdc}(T_{cell} - T_{ref})), \tag{1}$$

where G_{poaeff} is the plane of array irradiance in units of W/m^2, T_{cell} is the module temperature, T_{ref} is the reference temperature of 25 °C, P_{dc0} is the system's nameplate rating in direct current (DC), and γ_{pdc} is the temperature coefficient in units of 1/C. For this implementation, the PV system's rated capacity matches that of the WT system (8.9 kW). Figure 3 provides a depiction of this PV system's power output at different module temperatures and irradiance conditions.

C. Analysis methodology and objectives

1. Define resource availability

The availability of the wind and solar natural resources directly impacts WTs and PV generator outputs in each geographic location. To produce power, WTs depend on the wind speed, which varies by the season and geographic locations. PV generation depends on the time of day and seasonal changes.

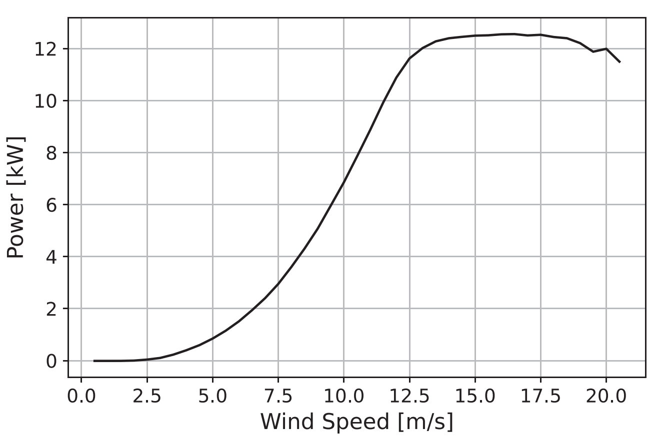

FIG. 2. Depiction of the 8.9 kW wind turbine model's power curve.

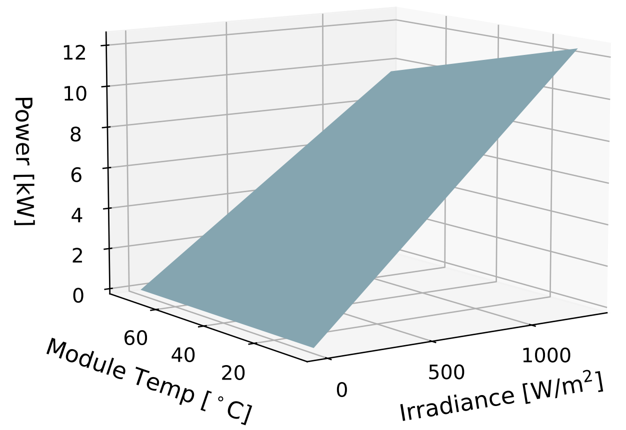

FIG. 3. 8.9 kW PV array's power vs irradiance and temperature.

Interpretation of the spatial resource simulation results involved separation of the locations into the following categories:

(1) High wind, low solar: Locations with abundant wind resources but relatively low sunlight;
Hypothesis—coastal regions or windy plains.
(2) High solar, low wind: Locations with ample solar irradiance but limited wind resources.
Hypothesis—desert regions or sunny plains.
(3) Balanced wind and solar: Locations with moderate to high levels of both wind and solar resources. These regions offer a balanced mix of renewable energy potential.

2. Day-to-day reliability and hour-to-hour variability

Measuring the day-to-day and hour-to-hour changes of the two resources provides an overview of each location's daily reliability and quantifies intra-day intermittent generation behaviors. Generation resources with high reliability, on a day-to-day basis, provide operators with confidence that they can support their near-term loads. In addition to day-ahead preparations, operators must maintain a balance between supply and demand at all times throughout the day. At higher frequencies, intermittency poses challenges associated with the optimal allocation of resources and for grid stability. In preparation, utilities rely on accurate forecasts that anticipate electrical demands. In areas with high penetrations of renewable energy, forecasts of the generation sources provide essential information. Often, forecasts get it wrong and compensating for the uncertainty requires utilities to employ various integration strategies, such as on-demand DER grid services, energy storage, and demand response services.

Relying on grid services to compensate for the uncertainty requires significant investments. In some cases, the high cost of implementing grid services—such as those providing active support to the strained grid through reactive power or other functions—or adding new resources, such as voltage regulators, makes these investments economically unfeasible and poses risks to the grid stability. These added risks and costs often lead utilities to avoid investments or reject permit applications for renewable energy projects within their territories. To avoid such decisions, reliable and stable generation resources or mix of resources will minimize economic and performance related risks.

Quantifying both the daily reliability and intra-day variability for the two resources across the United States begins with computing the change rate (*CR*),

$$CR_i(t) = \frac{x_t - x_{t-1}}{\Delta t}, \tag{2}$$

where x represents the change rate variable. This variable, x, depends on the evaluation type and in this work there are two: (1) day-to-day reliability, where x represents the daily energy (E_d) and t signifies the time step in days, and (2) hour-to-hour variability, where x is the hourly energy (E_h) and t signifies the time step in hours.

Δt is the change in time, which for both cases is 1 since the day-to-day reliability examines changes from one day to the next and the hour-to-hour variability assessment compares values from one hour to the next.

To quantify and compare each location's reliability and variability, this work computed a normalized daily variance. This type of normalization, often referred to as the Coefficient of Variation (CV) describes the spread or dispersion of the data in a manner useful for comparing datasets that have different scales or units. This assessment normalized the CR at each location by comparing the variation [or standard deviation (σ)] with the country's average energy ($\overline{E}$), which in this case is the average across the continental United States,

$$CV_i = \left(\frac{\sigma_{\mathrm{CR,\,i}}}{\overline{E}}\right) \times 100\%. \tag{3}$$

This comparison of each location's *CR* standard deviation with $\overline{E}$ across all locations quantifies both the spatial and temporal consistency and variability. This relative variability assessment defines the fluctuations in energy production with respect to the average level of production. The results provide a temporal understanding of each location's dynamics. When mapped, the spatial patterns indicate regional tendencies.

Further qualification of the daily reliability results involves grouping the locations into the following categories:

(1) Consistent wind, inconsistent solar: Location where stable wind generation patterns exist, but the solar PV generation changes due to cloud cover occur often.
(2) Consistent solar, inconsistent wind: Location characterized by stable PV generation but unstable wind generation.
(3) Consistent solar and wind: Location where both wind and solar generation provide reliable day-to-day energy for the grid.
(4) Inconsistent wind and solar: Location were both wind and solar generation exhibit substantial changes, leading to unpredictable energy output.

For the intra-day generation evaluation, this work characterizes the different location's hour-to-hour variability within the following zones:

(1) Continuous wind, intermittent solar: Location where wind has relatively stable and predictable behavior but solar generation experiences high fluctuations.
(2) Continuous solar, intermittent wind: Location where solar generation has stable operations but wind does not.
(3) Continuous wind, continuous solar: A location where both wind and solar generation have smooth and predictable behavior.
(4) Intermittent wind, intermittent solar: Both wind and solar generation experience high fluctuations in their output.

3. Coincident operations

The simultaneous or non-simultaneous generation of electrical power from the two resources influences grid operations. Clearly, PV generation systems only produce power during the day when sunlight is available. WTs generate power during both daylight and nighttime hours, resulting in either simultaneous or non-simultaneous operations.

The integration of PV systems and WTs on distribution grids has advantages and disadvantages. As a benefit, utilities can diversify their renewable energy portfolios and not rely on a single resource type. Having the two resources work together could lead to stability and smoothing benefits; each resource could experience variability independently and their combined output may lead to a more stable and predictable output signal that reduces any challenges associated with generation variability.

In a negative sense, simultaneous generation of power from PV system and WTs could cause issues in some distribution grids. In locations where infrastructure has not been sized to handle the extra power flows, the power generated by the PV system and WTs could cause thermal overloading. Or the excessive power injections, if left unmitigated, could cause voltages to rise and remain above the ANSI limits for too long and cause damage to connected equipment and machines.

To understand how power from wind and solar resources interact, this work proposes that each time series generation signal be evaluated. The evaluation leverages the Python NumPy correlation coefficient package,[34] which computes the Pearson coefficient matrix, R, for the two one-dimensional arrays X and Y,

$$R = \frac{\mathrm{cov}(X, Y)}{\sigma_X \cdot \sigma_Y}. \tag{4}$$

The formula for computing the covariance [$\mathrm{cov}(X, Y)$] is

$$\mathrm{cov}(X, Y) = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y}), \tag{5}$$

where n is the size of the dataset, X_i and Y_i represent single data points within the set, and $\overline{X}$ and $\overline{Y}$ are the average values for X and Y, respectively.

Computing the standard deviations of both X and Y for Eq. (4) involve the same process but for the respective signals, as shown in the following equation:

$$\sigma_X = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})^2}, \quad \sigma_Y = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Y_i - \overline{Y})^2}. \tag{6}$$

Interpreting the results from this coincident operation's evaluation entails a review of the correlation coefficients. Each of the locations fell within one of the three following categories:

(1) Positive correlation: Locations where the wind and solar generation outputs tend to coincide.

(2) Negative correlation: Locations where the wind and solar outputs have an inverse relationship and tend to produce power at different times in the day.
(3) No correlation: Locations where the two generation types do not correlate. At these locations, the wind and PV power will do both—produce power together and separately.

4. *Wind and solar zone categorization*

The criteria below describe the methodology for determining four distinct zones for the annual energy availability, day-to-day reliability, and hour-to-hour variability evaluations. The zone determination involves calculating and comparing statistical metrics, such as the median and first quantile, for both wind energy [$wind(x)$] and PV energy [$PV(e)$].

$$
\begin{array}{l}
\text{zone(x)} = \\
\{ \\
\quad \begin{array}{lll}
\text{Zone1} & \textbf{if} & \text{wind(x)} > \text{median(wind(x))}, \\
 & & \text{PV(e)} > \text{median(PV(e))}, \\
\text{Zone2} & \textbf{if} & \text{wind(x)} >= \text{median(wind(x))}, \\
 & & \text{PV(e)} <= \text{quartile1(PV(e))}, \\
\text{Zone3} & \textbf{if} & \text{wind(x)} <= \text{quartile1(wind(x))}, \\
 & & \text{PV(e)} >= \text{median(PV(e))}, \\
\text{Zone4} & \text{otherwise.} &
\end{array} \\
\}
\end{array}
$$

IV. DEMONSTRATION RESULTS

A. Annual energy availability

The spatial-temporal WT and PV system model outputs vary across the continental United States. The variation in energy generation includes seasonal differences. For example, PV energy production increases from a low in the winter months to high in the spring and summer. In contrast, the WT average energy production was largest in the spring. The next closest was winter and then fall. The lowest amount of energy production occurred in the summer months for the simulated WTs. PV proved to be a more dominant resource in terms of overall energy production. For each season, the energy production of the PV system had higher outputs than that of the comparable WT.

Spatially, there exist very few locations where the WT's energy exceeded that of the PV system, as shown in Fig. 4. Some notable observations include the following: (1) very small amounts of wind and PV energy were produced in the southeast and northwest; (2) along the Pacific Northwest coast not much energy came from PV system or wind; and (3) the Midwest had slightly more PV energy production but both wind and PV energy were not estimated to be high.

B. Day-to-day reliability

The reliability of each resource depends on its the consistency of day-to-day energy outputs throughout the year. Consistency refers to the degree of stability over time, where lower day-to-day *CV* indicates higher consistency, thus suggesting a more reliable source for energy. Locations with higher *CV* experience less consistency and more significant day-to-day changes in energy production.

To quantify each variability for each resource, the assessment computed the *CV* for each location in the continental United States.

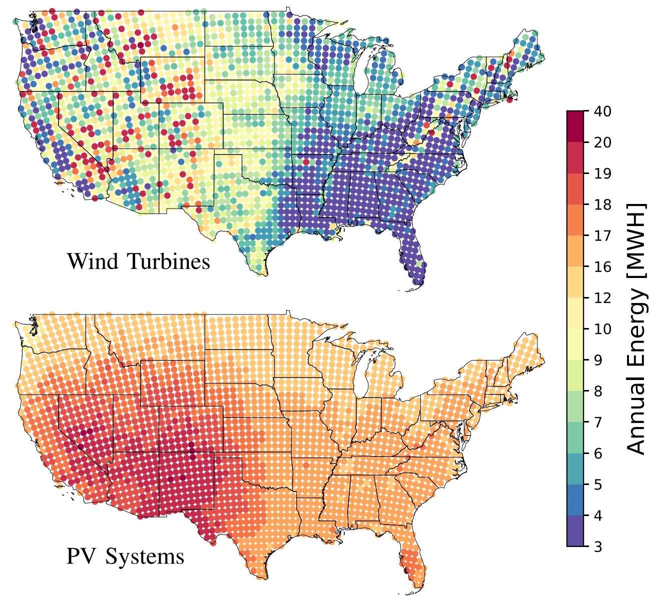

FIG. 4. This figure depicts the annual energy in different locations across the United States for the WT and PV resources.

TABLE I. Day-to-day coefficient of variation for wind and PV systems.

Season	Wind CV (%)	PV CV (%)
Winter	99.2	31.1
Fall	105.4	24.9
Spring	85.1	21.8
Summer	71.7	14.6

Overall, the WT outputs had a much higher *CV*, and a more complete comparison of the seasonal average is shown in Table I.

Figure 5 depicts how each location's WT variations compared with the PV systems over the entire year. States along the west coast (i.e., California, Oregon, and Washington) and in the southeast had the lowest *CV* for wind energy production. Wind conditions in the Rocky Mountain states produced much higher daily *CV*.

Energy from the sun proved to have lower daily *CV*s across the continental United States in comparison to wind. The bottom of Fig. 5 shows that the southwest region had the lowest daily variance, which increased to the north, northeast, and east. Florida, however, exhibited low CV values that were comparable with states in the southwest.

C. Hour-to-hour variability

The results from the second change rate analysis, i.e., hour-to-hour variability, showed evidence of more consistency across seasons compared with the daily-to-day CV results. Table II describes the average seasonal results for the WT and PV systems during the four seasons.

Figure 6 illustrates the hourly CV for wind and PV systems. For WTs, the western United States exhibited high hourly variability, with

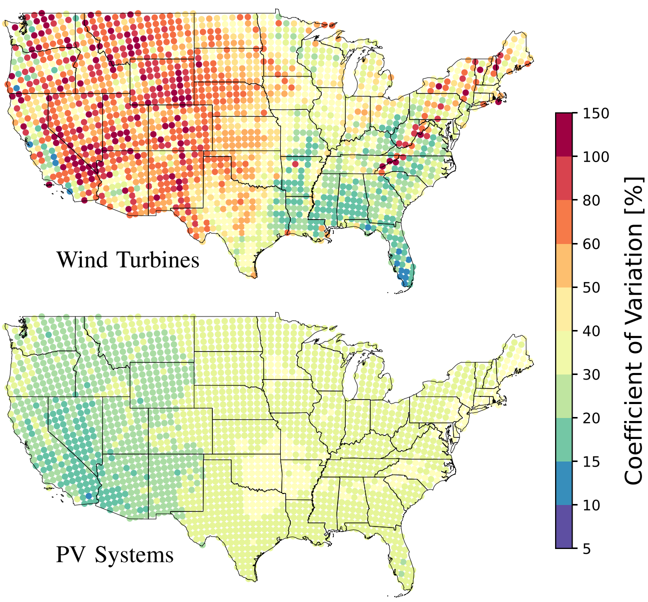

FIG. 5. This figure depicts the day-to-day coefficient of variance for wind and PV generation.

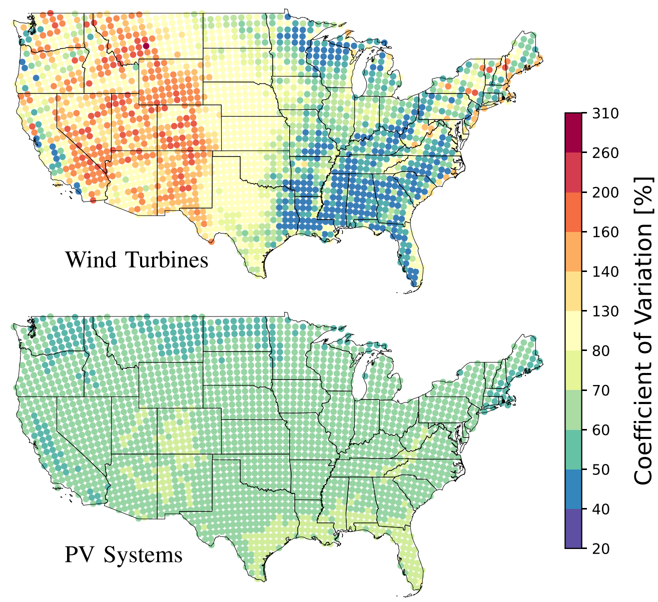

FIG. 6. This figure depicts the hour-to-hour coefficient of variance (*CV*) for both wind and PV resources.

TABLE II. Hour-to-hour coefficient of variation for wind and PV systems.

Season	Wind CV (%)	PV CV (%)
Winter	16.4	47.4
Fall	21.7	50.2
Spring	23.3	41.3
Summer	71.7	14.6

slightly lower CVs in-between Texas and North Dakota. The lowest values are observable in the eastern states with the exception of the higher CV values within the northeastern states and around the Appalachian Mountains.

For PV operations, high hourly CV was observed in the Colorado and New Mexico mountains and along the Gulf of Mexico, while the lowest CVs appeared in the northern states and California's Central Valley. These patterns align with solar variability zones identified through satellite-derived methodologies.[35]

D. Correlation coefficients

The analysis of coincident operations at each location involved a calculation of the correlation coefficients between the temporal signals of the WT and PV resources. Figure 7 illustrates these correlations for each season within a single year. Positive correlation coefficients indicate that PV and wind power generation occurs simultaneously, while negative coefficients suggest that their production times differ. Correlation coefficients near zero signify both concurrent and non-concurrent power production.

During the winter months, correlation coefficients reveal more non-concurrent generation between wind and PV systems compared to other seasons. In the fall, similar patterns are observed, except for a band of concurrent operations across Kansas, Nebraska, and Iowa. Figure 7 shows that in the spring and summer, significant coincident operations occur primarily in states east of the Mississippi, with less non-concurrent generation in the western states compared to winter and fall. Red-shaded areas indicate coincident wind and solar.

While simultaneous generation can be advantageous in areas with high daytime loads, it can present challenges for grid operators, such as congestion, resource curtailment, and infrastructure stress. In regions with non-concurrent wind and PV generation, the grid benefits from the complementary nature of these resources, reducing generation variability and operational challenges. In this case, the need for expensive energy storage systems or backup power plants is reduced, ultimately lowering overall system costs.

V. WIND AND SOLAR ZONES

A. Energy availability and reliability

Using the criteria described earlier, Fig. 8 shows the four zones that segregate energy availability by the dominance of each resource. Zone 1, covering the southwest, has high wind and solar availability. Zone 2, with high wind and low solar availability, is in the northernmost regions. Zone 3, in Florida and parts of California, has low wind and high solar availability, while Zone 4, representing low wind and solar availability, covers much of the eastern United States.

Annual resource availability did not always align with day-to-day reliability. For instance, the southwest consistently has high wind and solar availability on an annual basis, but PV system produced more reliable electrical power on a day-to-day basis compared to wind output, as indicated by Fig. 9. The Midwest shows consistent wind and solar availability, though a patch of inconsistent wind and solar availability stretched from south to north through the middle of the country. Also, in the eastern United States, consistent wind but inconsistent

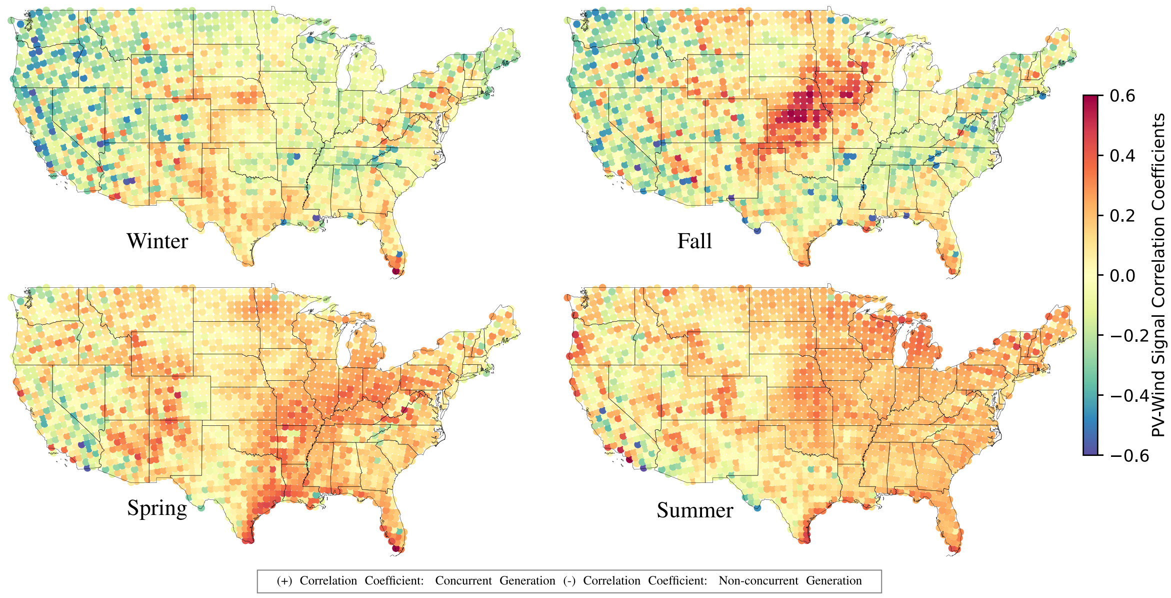

FIG. 7. This figure depicts the correlation coefficients for locations across the United States for the winter, fall, spring, and summer seasons. Positive correlation coefficients indicate concurrent PV and wind generation, while a negative correlation coefficient symbolizes the opposite. Correlations near zero suggest locations experience both concurrent and non-concurrent generation.

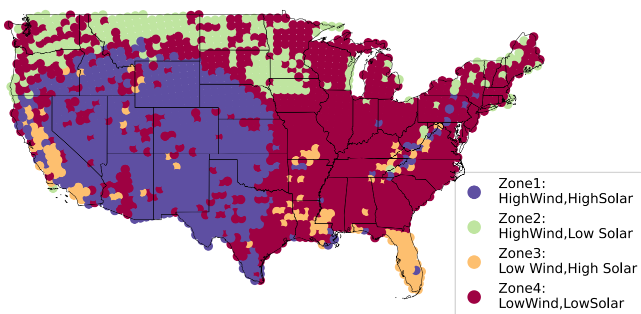

FIG. 8. This map depicts the four zones that delineate regions by the dominant resource by available annual energy.

PV outputs commonly occur, except along the coastal Northeast and in Florida.

B. Power variability

On an hourly timescale, PV and WT power outputs can remain stable with infrequent drastic changes. Figure 10 shows that this stability occurs in Zone 1, covering the Midwest, parts of Texas, California, and some locations in the Northwest. The Southeast generally experiences stable wind but variable solar availability, while the Southeast coastline falls into Zone 4, where both wind and solar outputs are variable.

The Southwest states are also in Zone 4, characterized by variable wind and solar availability, with more frequent hourly changes than Zone 1. Zone 3 includes Washington, Montana, and parts of the Northeast, where PV output is stable, but wind output varies.

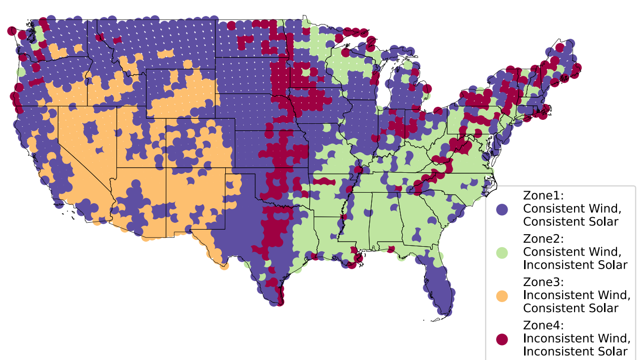

FIG. 9. This map illustrates the zones that represent the day-to-day consistency and reliability of each resource.

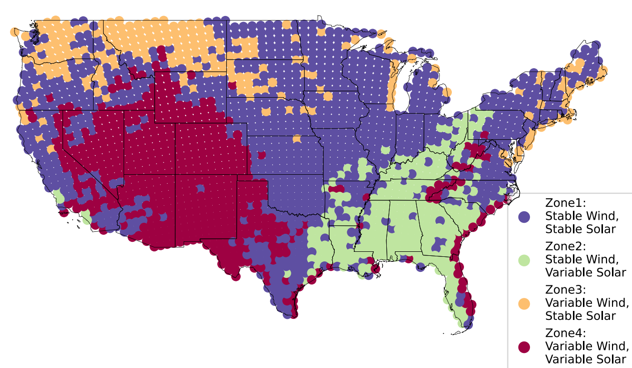

FIG. 10. This map depicts the hourly variability of power from the wind turbines and the PV systems.

VI. DISCUSSION

This methodology provides a framework, along with examples, for how decision makers can gain critical insights into the operations of WT and PV systems. Example use cases include the following:

(1) Energy availability and reliability: Defining the long-term temporal patterns of wind and solar energy can guide the optimal siting of wind and solar generators for consistent energy production.
(2) Variability and cooperation: Grid operators, seeking to manage and mitigate variability of renewable energy, can use this to design hybrid system that maintains a balanced system that reduces the need for backup generation.
(3) Informed policy and strategy development: This methodology supports evidence-based policy making by offering a clearer understanding of renewable energy dynamics, facilitating the development of effective policies and strategies.

Overall, the paper enhances understanding of renewable energy's geographical and temporal characteristics, enabling decision makers to craft more effective renewable energy deployment and grid integration strategies.

VII. CONCLUSIONS

This experiment conducted an in-depth analysis of the interplay between wind and solar resources across the continental United States. The findings provide valuable insights into the spatial and temporal energy availability, reliability, power variability, and cooperation between these two sources.

The results reveal diverse energy landscapes across different regions, with distinct patterns in energy production and reliability. Photovoltaic (PV) systems generally exhibit higher energy output and greater reliability than wind turbines (WTs), particularly in sun-rich regions like the Southwest. WTs demonstrate higher variability, especially in areas with complex terrain, such as the Rocky Mountains. Hourly variability analysis reveals fluctuations in power output for both WTs and PV systems, with differences observed between seasons. PV systems tend to have lower hourly variability, while WTs show significant variability in regions within high wind zones. This underscores the importance of understanding temporal dynamics to anticipate generation challenges and opportunities.

Evaluation of coincident operations between wind and solar resources indicates varying degrees of correlation across regions and seasons. While positive correlations suggest simultaneous generation of power from both resources, negative correlations highlight the potential to leverage complementary characteristics. For instance, in regions where wind power peaks during nighttime and PV dominates during the day, the grid can benefit from reduced generation variability and more consistent overall power output. Grid operators in such regions could prioritize investments in hybrid systems, advanced inverters, or energy storage to optimize this synergy, reducing the need for expensive backup generation or over-reliance on fossil fuel-based peaking plants. Additionally, dynamic load control and demand response programs can align consumption with resource availability, making the grid more resilient and cost-efficient.

The classification of wind and solar zones based on energy availability, reliability, and cooperation provides valuable insights for renewable energy planning and grid integration. For example, regions with non-synchronized generation patterns could explore hybrid renewable energy projects to stabilize outputs, while areas with high coincident generation may require advanced grid infrastructure to manage potential congestion or overgeneration.

Grid operators can also leverage non-complementary WT and PV operations, where the two resources consistently generate power at the same time. In areas where this occurs, the installation and operations of the two resources provide redundant power generation for reliability and resilience in situations where generators fail or the natural resource is not available. Also, the concurrent, day time operations of the two generation resources can provide essential electrical power for grids that support large commercial and industrial demands.

In conclusion, this experiment contributes to the understanding of wind and solar interactions, providing actionable information for effective renewable energy deployment and grid integration strategies. Future work will benefit from assessments that incorporate regional load profiles, economic feasibility analyses, and transmission constraints to further refine these strategies. By expanding on the interplay between wind and solar resources, this research lays the groundwork for a more sustainable and resilient energy future.

VIII. FUTURE WORK

While the current study provides valuable insights into the spatial and temporal dynamics of wind and solar energy, several important topics merit further investigation:

(1) Energy storage integration: Exploring the role of energy storage technologies (e.g., batteries, pumped hydro, and thermal storage) could provide solutions to mitigate the variability of renewable energy sources and align generation with demand.
(2) Economic considerations: Incorporating Levelized Cost of Energy (LCOE) and Return on Investment (ROI) calculations, as well as comparing the costs of renewable and nonrenewable energy sources, would make the findings more actionable for investors and policymakers.
(3) Advanced grid simulations: Simulating grid behavior under scenarios like high renewable penetration or extreme weather events would help validate the robustness of the proposed classifications.

These future directions build upon the methodology presented here, offering opportunities to address the broader implications of renewable energy deployment.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

C. Birk Jones: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Georgios Fragkos:** Conceptualization (supporting); Writing – review & editing (equal). **Rachid Darbali-Zamora:** Funding acquisition (lead).

DATA AVAILABILITY

The data that support the findings of this study are openly available in Wind Integration National Dataset Toolkits at https://www.nrel.gov/grid/wind-toolkit.html.[29]

REFERENCES

[1] A. Tummala, R. K. Velamati, D. K. Sinha, V. Indraja, and V. H. Krishna, "A review on small scale wind turbines," Renewable Sustainable Energy Rev. **56**, 1351–1371 (2016).
[2] *Distributed Wind Market Report: 2023 Edition* (Pacific Northwest National Laboratory, 2023).
[3] U.S. Energy Information Administration (EIA), "Record U.S. small-scale solar capacity was added in 2022," 2024.
[4] N. Teschner and R. Alterman, "Preparing the ground: Regulatory challenges in siting small-scale wind turbines in urban areas," Renewable Sustainable Energy Rev. **81**, 1660–1668 (2018).
[5] G. M. Shafiullah, A. M. T. Oo, A. B. M. Shawkat Ali, and P. Wolfs, "Potential challenges of integrating large-scale wind energy into the power grid–A review," Renewable Sustainable Energy Rev. **20**, 306–321 (2013).
[6] K. McCabe, A. Prasanna, J. Lockshin, P. Bhaskar, T. Bowen *et al.*, "Distributed wind energy futures study," Technical Report No. NREL/TP-7A40-82519, National Renewable Energy Lab. (NREL), Golden, CO, 2022.
[7] S. Islam, "Challenges and opportunities in grid connected commercial scale PV and wind farms," in *2016 9th International Conference on Electrical and Computer Engineering (ICECE)* (IEEE, 2016), pp. 1–7.
[8] J. Kabouris and F. D. Kanellos, "Impacts of large-scale wind penetration on designing and operation of electric power systems," IEEE Trans. Sustainable Energy **1**, 107–114 (2010).
[9] S. R. Abbas, S. A. A. Kazmi, M. Naqvi, A. Javed, S. R. Naqvi *et al.*, "Impact analysis of large-scale wind farms integration in weak transmission grid from technical perspectives," Energies **13**, 5513 (2020).
[10] N.-K. C. Nair and L. Jing, "Power quality analysis for building integrated PV and micro wind turbine in New Zealand," Energy Build. **58**, 302–309 (2013).
[11] V. Kumar, A. S. Pandey, and S. K. Sinha, "Grid integration and power quality issues of wind and solar energy system: A review," in *2016 International Conference on Emerging Trends in Electrical Electronics & Sustainable Energy Systems (ICETEESES)* (IEEE, 2016), pp. 71–80.
[12] A. Hansen, N. A. Cutululis, P. Sorensen, and F. Iov, "Grid integration impacts on wind turbine design and development," in *2009 IEEE Bucharest PowerTech* (IEEE, 2009), pp. 1–7.
[13] S. D. Ahmed, F. S. M. Al-Ismail, M. Shafiullah, F. A. Al-Sulaiman, and I. M. El-Amin, "Grid integration challenges of wind energy: A review," IEEE Access **8**, 10857–10878 (2020).
[14] Y. Li, Y. Chi, X. Wang, X. Tian, and J. Jianqing, "Practices and challenge on planning with large-scale renewable energy grid integration," in *2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2)* (IEEE, 2019), pp. 118–121.
[15] X. Yao, B. Yi, Y. Yu, Y. Fan, and L. Zhu, "Economic analysis of grid integration of variable solar and wind power with conventional power system," Appl. Energy **264**, 114706 (2020).
[16] S. Fatima, V. Püvi, and M. Lehtonen, "Review on the PV hosting capacity in distribution networks," Energies **13**, 4756 (2020).
[17] D. Chathurangi, U. Jayatunga, and S. Perera, "Recent investigations on the evaluation of solar PV hosting capacity in LV distribution networks constrained by voltage rise," Renewable Energy **199**, 11–20 (2022).
[18] E. Mulenga, M. H. J. Bollen, and N. Etherden, "A review of hosting capacity quantification methods for photovoltaics in low-voltage distribution grids," Int. J. Electr. Power Energy Syst. **115**, 105445 (2020).
[19] R. Luthander, D. Lingfors, and J. Widén, "Large-scale integration of photovoltaic power in a distribution grid using power curtailment and energy storage," Sol. Energy **155**, 1319–1325 (2017).
[20] J. W. Smith, R. Dugan, M. Rylander, and T. Key, "Advanced distribution planning tools for high penetration PV deployment," in *2012 IEEE Power and Energy Society General Meeting* (IEEE, 2012), pp. 1–7.
[21] J. Deboever, S. Grijalva, M. J. Reno, and R. J. Broderick, "Fast quasi-static time-series (QSTS) for yearlong PV impact studies using vector quantization," Sol. Energy **159**, 538–547 (2018).
[22] D. Lew, M. Milligan, G. Jordan, L. Freeman, N. Miller *et al.*, "How do wind and solar power affect grid operations: The western wind and solar integration study," Technical Report No. NREL/CP-5500-54684, Energynautics GmbH, Langen, Germany, 2009.
[23] A. Berrada and K. Loudiyi, "Operation, sizing, and economic evaluation of storage for solar and wind power plants," Renewable Sustainable Energy Rev. **59**, 1117–1129 (2016).
[24] H. Zhang, Z. Lu, W. Hu, Y. Wang, L. Dong *et al.*, "Coordinated optimal operation of hydro–wind–solar integrated systems," Appl. Energy **242**, 883–896 (2019).
[25] J. Widen, "Correlations between large-scale solar and wind power in a future scenario for Sweden," IEEE Trans. Sustainable Energy **2**, 177–184 (2011).
[26] N. J. Johannesen, M. L. Kolhe, and A. D. Jacobsen, "Correlation analysis of potential solar photovoltaic power plant integration at wind farm with grid connection limits," in *2023 8th International Conference on Smart and Sustainable Technologies (SpliTech)* (IEEE, 2023), pp. 1–6.
[27] M. Wang, C. Wu, P. Zhang, Z. Fan, and Z. Yu, "Multiscale dynamic correlation analysis of wind-PV power station output based on TDIC," IEEE Access **8**, 200695–200704 (2020).
[28] R. Zhang, H. Ma, W. Hua, T. K. Saha, and X. Zhou, "Data-driven photovoltaic generation forecasting based on a bayesian network with spatial–temporal correlation analysis," IEEE Trans. Ind. Inf. **16**, 1635–1644 (2020).
[29] C. Draxl, A. Clifton, B.-M. Hodge, and J. McCaa, "The wind integration national dataset (WIND) toolkit," Appl. Energy **151**, 355 (2015).
[30] Welcome to the windpowerlib documentation!—Windpowerlib documentation, 2024.
[31] J. Wohland, P. Hoffmann, D. C. A. Lima, M. Breil, O. Asselin *et al.*, "Extrapolation is not enough: Impacts of extreme land-use change on wind profiles and wind energy according to regional climate models," Earth Syst. Dyn. **15**, 1385–1400 (2024).
[32] BergeyExcel10_8.9kW_7 — NREL/turbine-models power curve archive 0 documentation, 2024.
[33] A. P. Dobos, "PVWatts Version 5 Manual," Technical Report No. NREL/TP-6A20-62641 (National Renewable Energy Lab. (NREL), 2014).
[34] C. R. Harris, K. J. Millman, S. J. Van Der Walt, R. Gommers, P. Virtanen *et al.*, "Array programming with NumPy," Nature **585**, 357–362 (2020).
[35] M. Lave, R. J. Broderick, and M. J. Reno, "Solar variability zones: Satellite-derived zones that represent high-frequency ground variability," Sol. Energy **151**, 119–128 (2017).