Journal of Renewable and Sustainable Energy

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Cite as: J. Renewable Sustainable Energy **14**, 023303 (2022); https://doi.org/10.1063/5.0070430
Submitted: 06 September 2021 • Accepted: 08 March 2022 • Published Online: 23 March 2022

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Journal of Renewable and Sustainable Energy | ARTICLE | scitation.org/journal/rse

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Submitted: 6 September 2021 · Accepted: 8 March 2022 ·
Published Online: 23 March 2022

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ABSTRACT

For each geographical region, one of the biggest challenges in reaching a zero-carbon grid is identifying sources of electricity that match the seasonal profile of the load. Summer-dominant solar electricity generation can often be balanced by winter-dominant wind electricity generation. Together with long-duration storage, balanced solar and wind generation are well positioned to provide reliable renewable electricity. However, in some locations the wind may not complement solar energy so well. For example, currently California's wind turbines produce more electricity during summer than winter, raising the question of whether all future wind plants in California will exhibit the same seasonality. As a response to this question, in this paper, we analyzed the generation from existing California wind plants and simulated potential onshore wind resource for the whole state using a metric that reflects the relative wind resource in winter. Our results indicate that the seasonality of the wind can vary for very small spatial difference with more than half of California showing stronger wind resource in the winter compared with the summer despite the current observation of the opposite trend. This study differentiates the seasonality of potential wind resources to inform the creation of a reliable, 100%-renewable-driven grid.

I. INTRODUCTION

The large-scale deployment of renewable electricity resources for the power sector is a major driver of decarbonization and mitigation of climate change. Among renewable technologies, solar and wind have experienced an unparalleled expansion in the last few decades, reaching around 3% and 6% global share of electricity generation, and 38% and 34% of net capacity expansion in 2020, respectively.[1] As variable solar and wind generation has become a larger fraction of the total electricity generation and as goals are set to eliminate emissions of carbon dioxide, an increasing amount of energy storage will be needed to balance the electricity supply and demand. Less storage will be needed if the solar and wind generation can be chosen so as to complement each other both on a diurnal and seasonal time frame.

Multiple researchers have suggested pathways to reaching decarbonized electricity grids.[2–5] The identified pathways vary significantly according to the area of study, but in general, agree that both solar and wind will play key roles as sources of clean and renewable electricity. In locations like Denmark, strong wintertime wind[6] complements summertime solar electricity generation in Germany and Spain, providing a pathway to high penetration of renewable electricity.

Unlike Europe, some regions do not have solar and wind resources which are complementary on a seasonal basis. For example, in California, both wind and solar outputs peak in summer. As shown in the supplementary material, Fig. 4, in the context of 100% renewable driven grid, a seasonal deficit in total renewable output relative to the load provides an additional challenge, as this generation deficit must be met by other, possibly expensive resources, such as long-term storage, capacity overbuild of renewables, fossil generators, or a combination of solutions. The challenge of meeting seasonal minimum renewable production is sometimes reflected in deep decarbonization electric sector simulations. For example, according to the 2035 report[7] which identifies a pathway to 90% decarbonization in the U.S. by 2035, California is suggested to retain natural gas at a higher level (25%) than most other states despite starting with a higher percentage of solar generation and a lower percentage of fossil fuel electricity generation than most states.

While a number of energy storage technologies may enable electricity delivery when wind and solar electricity are not available for short durations, there is not yet consensus for the best approach to addressing the seasonal imbalance between renewable electricity generation and demand for that electricity. A key strategy is adjusting the relative investments in solar and wind.[3,8–10] Adjusting the mix of solar and wind does not completely balance the supply and demand in all seasons because both generation and load vary from year to year. Indeed, some studies conclude that it will not be possible to reach 100% renewable electricity and that reaching full decarbonization will require a dispatchable carbon-free generator such as nuclear or natural gas coupled with carbon capture and sequestration.[11,12] Nevertheless, studies agree that an optimal mixture of solar and wind generation can reduce the cost of decarbonizing a grid. In many locations, including the western U.S., the best wind resource is strong in winter and spring, complementing stronger solar generation in the summer,[2,4] but, curiously, California's reported wind generation is highest in the summer rather than in the winter, preventing solar and wind from being seasonally complementary and suggesting that California may be most challenged to deliver adequate electricity in wintertime after the grid is decarbonized.[13] When wind blows, it often blows across very large regions. California, as well as many other regions of the world, has multiple mountain ranges. The interaction between meso-scale weather systems and orographic forcing can lead to a highly nonuniform wind resource. For example, this is observed in California.[14] The variability of wind resource in the vicinity of mountains is well known, but the effect of the mountains on the seasonal characteristics of wind resource has not been well explored. A majority of on-line wind resource maps provide annual rather than monthly wind resource, so understanding the seasonal characteristics requires a more in-depth study, as we present here.

To our knowledge, studies have not differentiated onshore wind that could generate more electricity in California during winter, which would help to reduce the need for seasonal storage. In this paper, we focus on the seasonality of the wind generation to better understand its capability to complement solar in a zero-carbon grid. We believe that this analysis will better define the types of wind generation profiles that should be used for a broader study of how renewable electricity and long duration storage may be designed to most effectively meet the decarbonization goals and to draw attention to the strong variations in temporal characteristics that can be seen on relatively short distances. In Sec. II, we review the existing wind and solar generation profiles for Colorado and California to explain the desirability of winter-dominant wind resources in California. In Sec. III, we describe the sources of data, parameters used for our simulations, and metrics used in the analysis. In Sec. IV, we present the current wind plant statistics and maps of simulated wind potential. We apply exclusions to the simulated data to better understand why today's generation differs from the total potential. Finally, in Sec. V, we summarize the potential we found for winter-dominant wind and discuss the implications of the results as wind resources are identified for use in capacity expansion modeling.

II. BACKGROUND

Throughout the globe, leaders in wind energy capacity like China and Germany produce more wind electricity in winter than in summer. In the U.S., most of the states show a similar trend by generating higher winter wind electricity, but California is somehow different.[15,16] To exemplify, the historical monthly solar and wind generation for California and Colorado for 2015–2020 are shown in the supplementary material, Fig. 3. We can clearly see a complementary seasonal behavior of solar and wind generation for Colorado, but for California both solar and wind generation peak in the summer and drop during the winter months. As discussed in the introduction, for locations like Colorado, solar and wind plants can be deployed in a ratio that optimally meets the demand in summer and winter. However, in California, increasing the generation from wind as shown in Fig. 1 does not help with matching generation and load in all seasons.

To complement solar generation, offshore wind can be a great option.[13] Offshore wind is being explored for floating systems that can function even in the deep waters off of California's coast. The first California offshore deployments are anticipated in about 2026 or 2027.[17]

Alternatively, transmission lines from Colorado and Wyoming (which also has strong generation from wind during the winter) are also a good option for bringing more wintertime renewable electricity to California. However, the high costs of offshore wind, long-distance transmission for wind coming from Wyoming and Colorado, and the question of whether California can count on imports during a widespread high-load event motivate further exploration of onshore wintertime wind potential in California. Understanding the seasonality of wind may be relevant to many locations in the world. Within the U.S., all of the states that touch the Pacific Ocean exhibit summer-dominant winds.[18] Summer dominant winds are also observed elsewhere in the world, such as in western parts of India.

In addition to seasonally complementing solar, wind electricity generation often complements solar's daytime generation with its higher output during the night. To our knowledge, the seasonality of the wind resource in California has not been a focus for siting wind systems. In fact, California is currently more interested in increasing capacity during the summer because the highest loads occur during August and September timeframe. Thus, California is currently motivated to select generators that perform well during the summer, especially at night, with little concern for the performance during the winter.

In the future, as solar supplies a greater fraction of electricity generation in California,[20] it may lead to an imbalance of electricity during the winter and summer as solar generation in summer months is about twice that in December or January. This seasonal imbalance could result in a shortage during the winter and motivates study of wintertime electricity generation. Additionally, building electrification will increase the use of heat pumps, increasing winter load. These observations motivate study of the seasonal variations of wind resource, especially in the peculiar areas like California that have sites with winter- and summer-dominant wind generation intermixed in relatively small geographical regions.

III. DATA AND METHODOLOGY

This study explores the juxtaposition of summer- and winter-dominant wind resource in California where the wind is irregular and

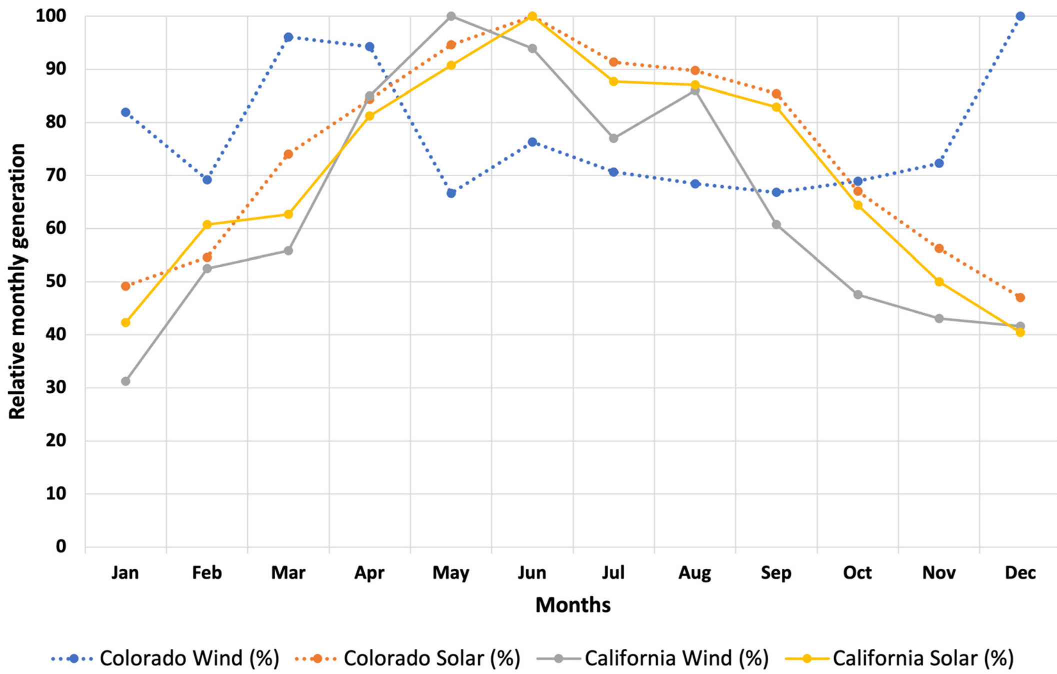

FIG. 1. Seasonality of solar and wind generation for Colorado and California.[15,19]

electricity generation from wind is more in summer months. First, we analyze the seasonal generation trend of existing wind power plants in California using the measured monthly generation data. Second, we examine the seasonal trend and resource quality of wind power of the entire state using a 5-min resolution wind-speed simulation. Finally, we estimate potential high capacity factor (CF) winter-dominant wind sites in California after excluding protected areas and areas with slopes >20%. We propose a metric, relative winter-to-summer difference (W–S difference), as a measure of ability to complement the seasonal trend of solar PV generation. We calculate the capacity factor to assess the wind resource quality of each plant and site, assuming an onshore wind turbine power curve with a cut-in speed of 2 m/s, reaching rated power at 11 m/s.

We use the California Energy Commission's CEC-1304 Power Plant Owner Reporting Database[19] as a primary dataset for obtaining the measured generation and nameplate capacity from the existing power plants in California. The CEC-1304 database provides the monthly generation data of power plants whose nameplate capacity is larger than 1 MW within California or located within a control area with the end users within California. Each record contains detailed information of each of the power plants and its geographical location. From this dataset, we extracted only the wind power plants located in California. Additionally, we used the EIA 860 (nameplate capacity)[16] and EIA 923 (electricity generation)[15] to complement the monthly generation data of wind power plants that are not covered in the CEC-1304 database. Out of 99 plant level monthly data, 96 plant data are from CEC-1304, and three plant data are from EIA860/EIA923.

Many of the EIA 923 monthly generation datasets are estimated from reported annual generation data using a monthly profile derived from a small sampling of plant data each year. EIA's choice of generators for which to report measured vs estimated data varies from year to year as shown in supplementary material, Fig. 1. The CEC-1304 always reports measured data. We carefully sorted the measured and estimated EIA data and only used results for measured data, using the measured CEC data when it was available and only supplementing with EIA data when those data were measured instead of estimation. We did not consider wind curtailment in our analysis as we find that the annual wind curtailment is less than 0.3% relative to the annual wind generation.[21]

From these three datasets, the W–S difference was calculated for each plant as shown in Eq. (1). Here, winter refers to the months of December, January, and February, and summer indicates June, July, and August. These months were chosen based on the seasonal wind generation trends in California from 2015 to 2020 as shown in supplementary material, Fig. 3. The W–S difference is defined as the ratio of the difference in the mean capacity factor between winter and summer months to annual capacity factor. Thus, W–S difference greater than 0 indicates winter-dominant sites where winter generation is higher than summer generation.

$$\text{W–S difference} = \frac{\text{difference in CF between winter and summer months}}{\text{annual CF}}. \quad (1)$$

For the wind resource, we used the open-access data from the NREL WIND Toolkit.[22] From this dataset, the wind speed was taken at 100 m using 5-min interval data. The simulated capacity factors are calculated from those wind speeds using a wind power curve for a GE 2.5–120 turbine. Although in practice the wind turbine is selected to be optimal for the wind speed, for simplicity and ease of comparison, we used a single power curve for most of our calculations. We also explored the results using other power curves and, as expected, both

TABLE I. Summary statistics of operating wind power plants in California for 2020. Nameplate capacity of each plant is used for the weights of weighted means.

Type	Number of plants	Operating capacity (MW)	Weighted mean of W–S diff (-)	Weighted mean of annual CF (-)
Total	71	5806	−0.84	0.258
Winter-dominant plants	3	282	0.382	0.269
Summer-dominant plants	68	5524	−0.84	0.258

the capacity factor and the seasonality change a little as shown in the supplementary material, Fig. 10. Although the quantitative results are dependent on the power curve used for the simulation, the choice of power curve does not change the conclusion that the seasonality of California's wind resource is highly variable.

The grid size was taken as 0.02 decimal degree (DD) × 0.02 decimal degree points (approximately 2.22 × 1.88 km^2), resulting in 97 650 locations analyzed in total providing the finest resolution of the NREL WIND Toolkit dataset. The two metrics, annual capacity factor (CF) and W–S difference, were used together to create the map of potential "good" winter sites that have W–S difference greater than 0 and annual capacity factor greater than 0.4, an arbitrary value representing wind resource of respectable quality.

Recognizing that not all of these sites would welcome installation of wind turbines, we estimate winter-dominant high-quality wind resources in California with and without the exclusion of various protected areas based on the California Protected Areas Database (CPAD).[23] The CPAD is a shapefile that includes national/state/regional parks, forests, preserves, and wildlife areas, large and small urban parks, land trust preserves, and special district open space lands (watershed, recreation, etc.). We also excluded the regions where the slope is greater than 20°. Wind power capacity and annual generation are estimated using Eqs. (2)–(4). To estimate the wind power capacity, we used capacity density of 3 MW/km^2 based on onshore wind power studies.[24]

$$\text{Capacity} = \sum_{i \in W} (CD \times a_i), \tag{2}$$

$$\text{Annual Generation} = \sum_{i \in W} (CD \times a_i \times CF_i \times 8760), \tag{3}$$

$$W\,(CF_i > 0.4) \cap (W - S_i > 0), \quad i = \{1, 2, \ldots, 97650\}, \tag{4}$$

where CD represents capacity density in MW/km^2, a_i represents area that satisfies W–S difference and CF criteria in km^2, CF_i, and $W - S_i$ represent capacity factor and W–S difference in site i, respectively.

IV. RESULTS AND DISCUSSION

A. Monthly generation of existing wind power plants

Although today's overall wind generation seasonal pattern in California is summer-peaking as shown in Fig. 1, some plants show a winter-dominant generation pattern, as tabulated in Table I. The performance of a wind plant is site-specific, depending primarily on the wind speed. Table I shows that the vast majority of the wind plants in California provide more generation in summer (labeled as "Summer-dominant plants"). The capacity factors observed for these summer- and winter-dominant plants are similar.

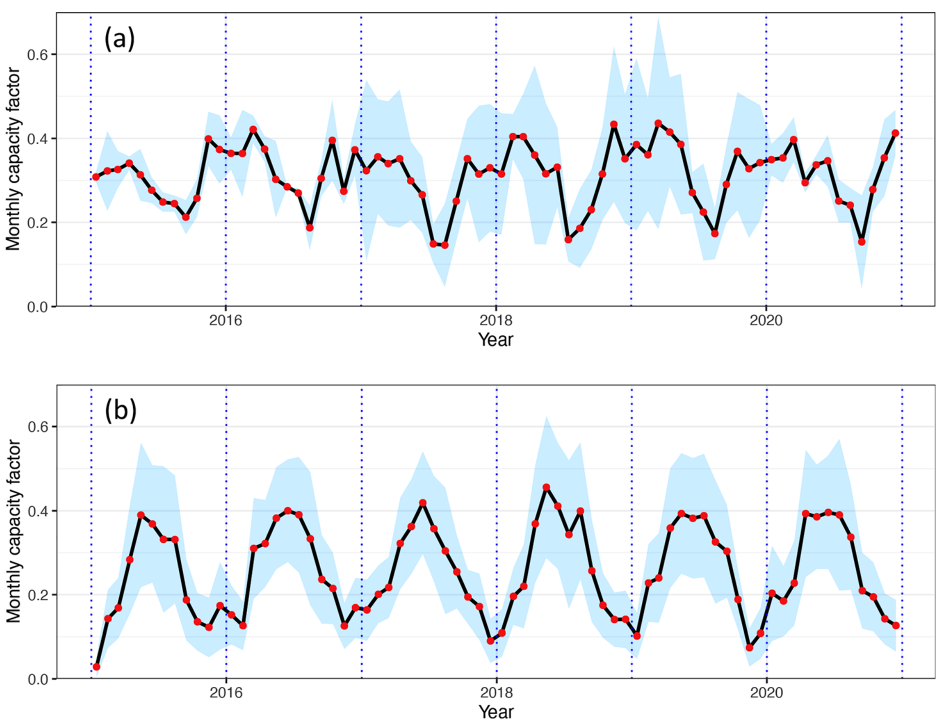

FIG. 2. Monthly capacity factor (vertical dashed lines indicate January) for (a) winter-dominant and (b) summer-dominant wind plants in California from 2015 to 2020. The solid lines and blue shaded regions represent the mean and one standard deviation of all of the analyzed plants, respectively, as calculated for each month.[15,19]

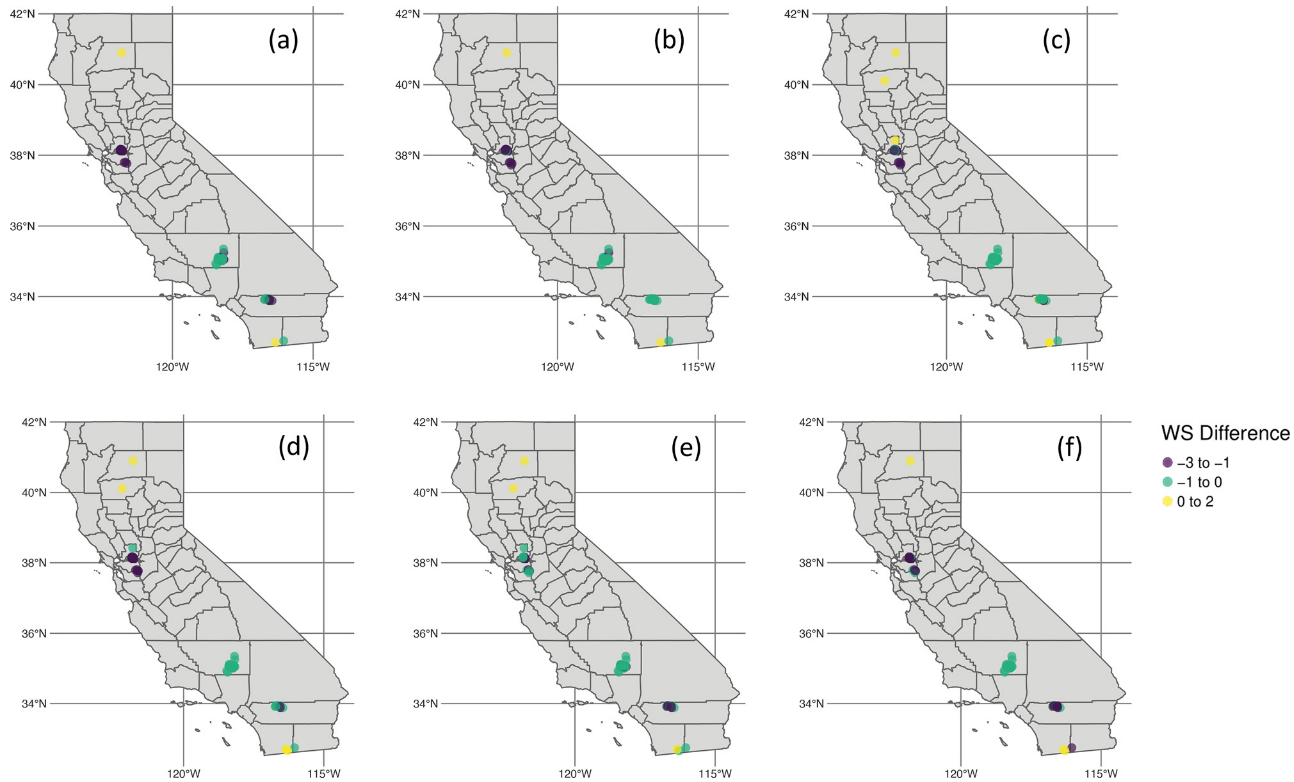

FIG. 3. W–S difference of measured generation for the existing plants in California for (a) 2015, (b) 2016, (c) 2017, (d) 2018, (e) 2019, and (f) 2020.

Figure 2 shows monthly capacity factor of both types of wind power plants in California from 2015 to 2020. The number of plants in the graph varies year by year due to new construction and retirements of power plants. Also, some plants in the EIA923 dataset report actual data in some years and estimated data in the other years. Only the actual data are reported here. Statistics for the California wind plants studied for Fig. 2 are summarized in Table I in the supplementary material.

The monthly measured capacity factors in Fig. 2(b) show similar seasonality as shown in Fig. 1 for California. In Fig. 2, monthly capacity factors of California wind plants show that the capacity factor ranges between 0.2 and 0.4 approximately for all the years. However, some plants generate more electricity in winter, as indicated in Fig. 2(a). The seasonal behavior is duplicated over the six years as shown here. Further analysis of these data shows that the wide variability in Fig. 2 (as reflected by the blue shaded area) arises from variations from plant to plant, perhaps because of different wind resource or wind technology, rather than variability from year to year. Normalization of the data demonstrates this, as shown in Fig. 2 of the supplementary material.

The reported W–S differences and annual capacity factors are shown for existing California wind plants in Figs. 3 and 4, respectively. As noted above, these data were taken from the CEC database and the EIA 923/860 data.[15,16,19]

The maps shown in Fig. 3 demonstrate the existence of winter-dominant wind plants in California, while confirming that most wind plants generate more in summer. The winter-dominant wind plants tend to be found in northern California or near the border with Mexico. Surprisingly, winter- and summer-dominant sites may be found in close proximity as seen for the two sites near Mexico. The reported annual capacity factors shown in Fig. 4 vary with year, possibly due to variations in weather, routine maintenance, repair, etc.

B. Simulated data analysis

We simulated the 2012 monthly capacity factors for a number of winter-dominant and summer-dominant plants using 100-m wind speed data from the NREL WIND Toolkit. An example of the results is shown in Fig. 5 for one summer-dominant and one winter-dominant plant. Additional examples are shown in the supplementary material, Fig. 6. The simulations were run with multiple power curves as represented in the supplementary material, Fig. 5; in each case, two simulations are shown, as noted.

In Fig. 5, Shiloh I wind plant represents a summer-dominant wind resource having W–S difference of -1.16, whereas Kumeyaay wind plant is winter-dominant with W–S difference of 0.82. The measured and simulated monthly capacity factors shown in Fig. 5 are quite similar in shape. These simulations clearly differentiate winter-dominant and summer-dominant actual wind generation profiles. As indicated by Fig. 5, the GE 2.5–120 turbines are simulated to extract more power because of having a lower cut-in wind speed than the Gamesa G87–2000 power curve. In both cases, the simulated data show consistently higher capacity factors than the reported wind data,

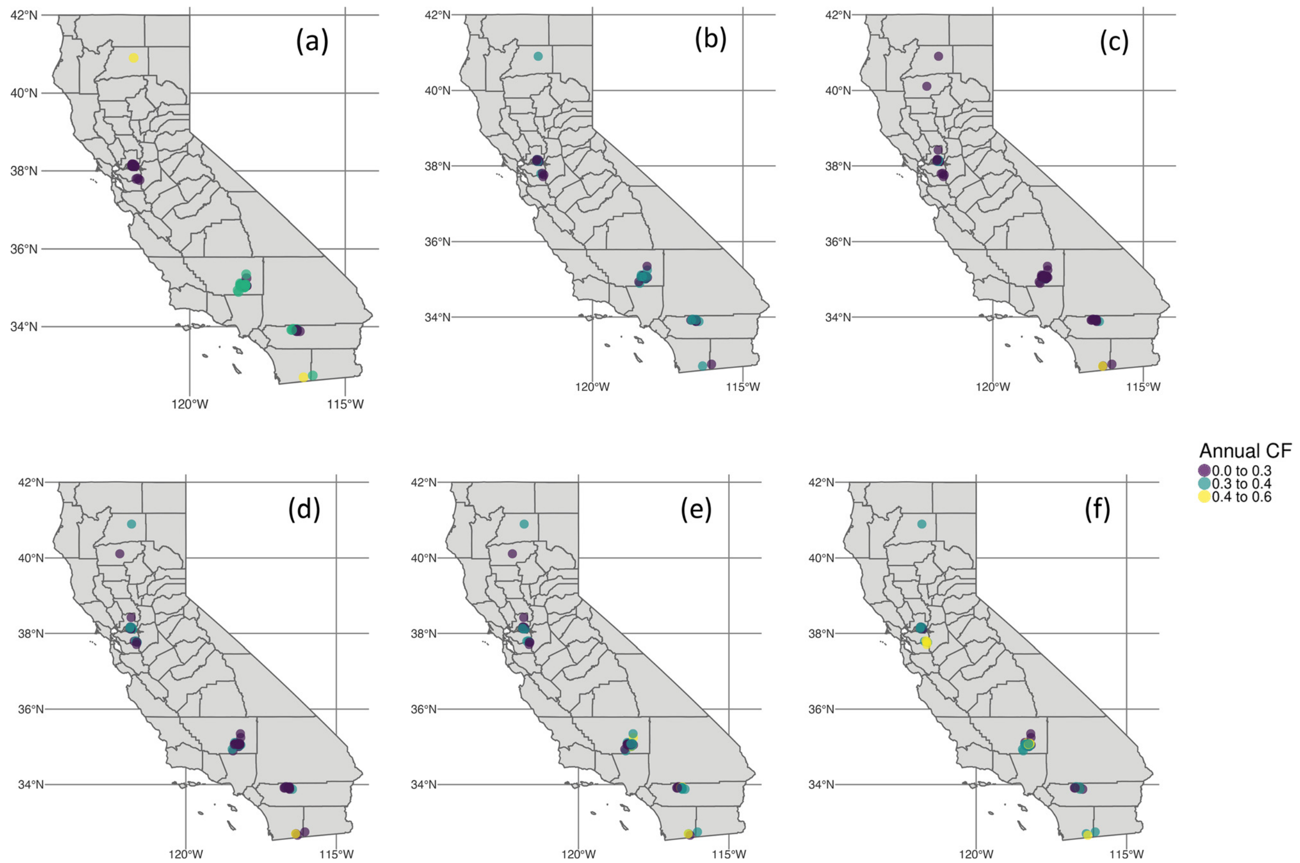

FIG. 4. Measured capacity factor for the existing wind plants in California for (a) 2015, (b) 2016, (c) 2017, (d) 2018, (e) 2019, and (f) 2020.

perhaps due to some combination of bias in the modeled wind speeds (the WIND Toolkit data vs the wind speeds experienced across the blades of the generator) and losses (wake losses, electrical losses, maintenance, etc.), but demonstrate that the simulations track trends even though the reported numbers are not exactly duplicate. Based on this verification of the relevance of the simulation to what has been observed in the field, we used this simulation technique to create a map of wind potential in California as shown in Fig. 6.

In Fig. 6, the left map shows the W–S difference of wind resources. The map is categorized depending on the value of the W–S difference. Around 25% of the onshore land has W–S difference less than 0 while 45% with W–S difference between 0 and 1, and 30% of the state holds W–S difference greater than 1. The figure in the middle shows the annual capacity factor and how it varies spatially. About 47% of California has wind resource capacity factor larger than 30% while 17% of California has wind resource with capacity factor more than 40%. Sites that are good for winter generation have high values for both the W–S difference and the capacity factor as shown in the right map marking the good winter sites. The highlighted area represents 8.8% of California onshore area. This third map does not consider land exclusions such as national/state parks, sensitive habitat, and terrain that is not feasible to build on, which eliminate many of the indicated regions from contention, as discussed next.

C. Winter-dominant high-quality wind resource estimates

Using Eq. (2)–(4), we find substantial winter-dominant, high-quality wind resources in California, as summarized in Table II and in Fig. 6. The total potential and the potential in the available areas are 107 and 25 GW, respectively. Further excluding areas with slope >20% reduced the viable potential to 22 GW as represented in Fig. 8. We anticipate that additional practical considerations would further reduce this potential. In comparison, the current wind power capacity is 6.0 GW as of the end of 2020. The annual generation potential in available areas is 100 TWh/year, which is 37% of the total electricity consumption, 272 TWh/year, in California in 2019.[19] The seasonal pattern of wind power generation will be different from the current summer-dominant pattern if even a fraction of these materialize since addition of 24% of the potential in available areas we identify here could double the wind capacity in California. In the supplementary material, we also conducted sensitivity analysis of the cutoff values of annual capacity factor on the potential and annual generation in Figs. 7 and 8.

To better understand the relationships between the W–S difference and the capacity factor and to understand why most of the existing plants are summer dominant when 60% of the area is found to have winter-dominant wind resource, we created two heat maps to

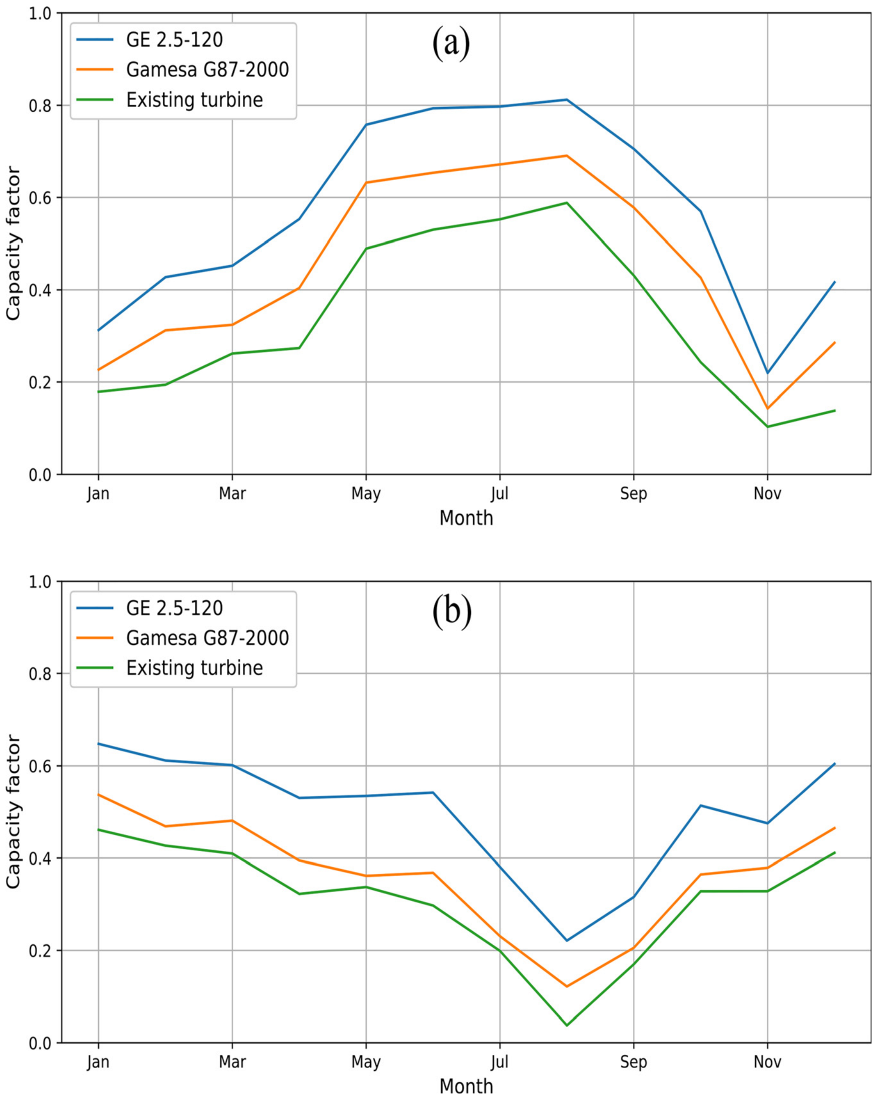

FIG. 5. Comparison of monthly capacity factor for simulated and actual generation for (a) Shiloh I wind project (summer dominant) and (b) Kumeyaay wind farm (winter dominant) for 2012.

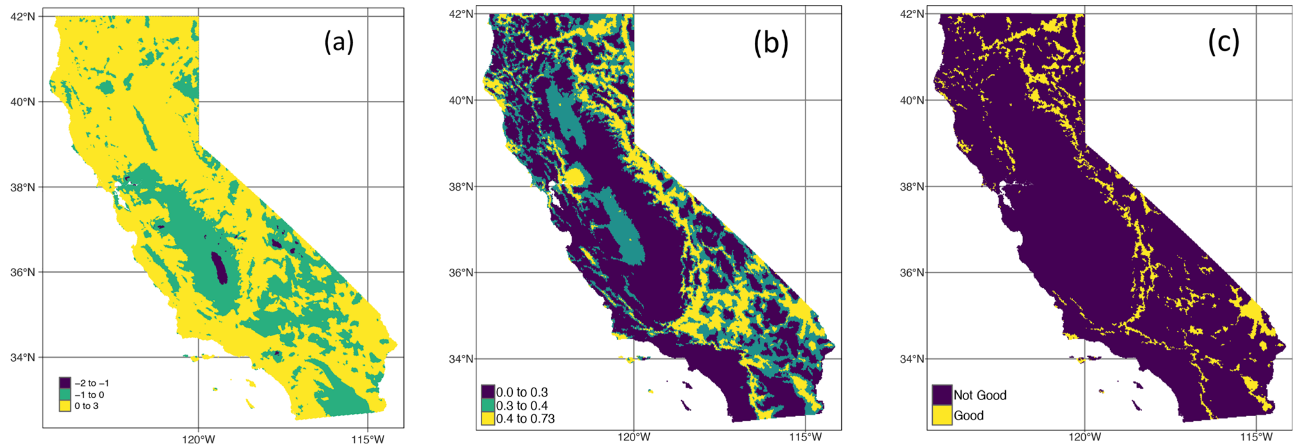

FIG. 6. Wind maps for the (a) W–S difference, (b) annual capacity factor, and (c) Good winter sites with CF > 0.4 and W–S difference > 0 in California.

TABLE II. Simulated wind power potential for California winter-dominant, high-quality wind resource areas.

Types	Potential (GW)	Annual generation (TWh/year)	Mean CF (-)	Mean W–S diff (-)	Area (km^2)
Total potential	107	428	0.46	0.35	35 664
Potential in available areas	25	100	0.45	0.34	8396
Potential in available areas excl. steep slope areas	22	74	0.45	0.34	6437

show the number of points that were identified with each combination of W–S difference and capacity factor, as shown in Fig. 7 for available areas on the left and excluded areas on the right. Of the available locations estimated to have good wind resource (capacity factor > 0.4) we see that the majority of locations are summer dominant. This is consistent with the statistics we share in Table I. On the other hand, the excluded areas show closer to equal numbers of locations with winter- and summer-dominant generation. Thus, Fig. 7 explains the puzzle as to why California generates more wind electricity in the summer than in the winter when the calculated potential shows the winter-dominant wind to be more prevalent. This could happen elsewhere, motivating exploration of the seasonality of wind in other parts of the world to identify sites that have the desired seasonality as well as diurnal behavior.

The winter-dominant, high-quality wind resources represented in Fig. 7 are distributed in multiple locations across the state, as shown in Fig. 8 for the available areas. Further exploration will be needed to identify which of these sites can be economically viable. Many of them are in remote parts of the state that would require new transmission lines or may be in rugged areas that do not have the needed access for construction of wind plants. The economic analysis is outside of the scope of our study and could change as technology develops and as we move closer to a decarbonized grid.

V. CONCLUSION

As efforts to decarbonize energy systems accelerate, the ability to balance summer and winter loads by balancing solar and wind generation will be increasingly important for reducing needs for seasonal storage. This paper shows that the selection of specific wind sites can have a large effect on the seasonality of the associated electricity generation. Surprisingly, the seasonality may change from >20% more wind in winter to 40% more wind in summer for nearly located sites and the geographical variation of the seasonality can be quite complex, apparently associated with local topography. The seasonality can vary from twice as much wind in winter as in summer to five times as much wind in summer as in winter.

The seasonal pattern of existing California wind generation closely follows that of the solar generation, showing summer generation about twice the winter generation, with less than a handful of wind plants that generate more electricity during the winter than during the summer. Our analysis shows that almost 60% of the state has wind resource that is stronger in winter than in summer, despite today's observation of strongly summer-peaking wind electricity generation.

Exclusion of protected areas greatly reduces the number of sites that have adequate capacity factor while still showing winter-dominant generation. Disregarding the economic feasibility, we estimate about

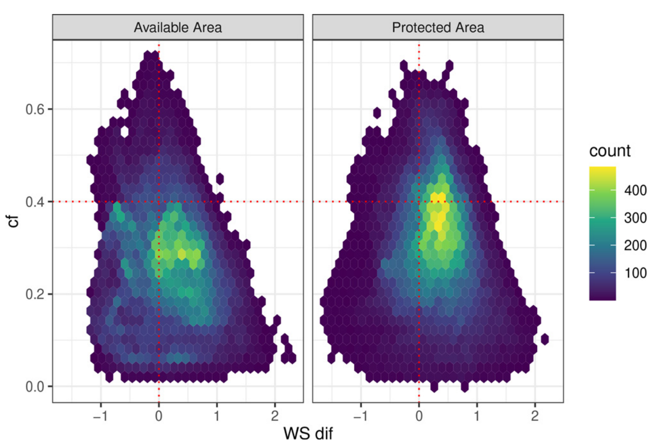

FIG. 7. W–S difference and capacity factor heat maps for available and protected areas.

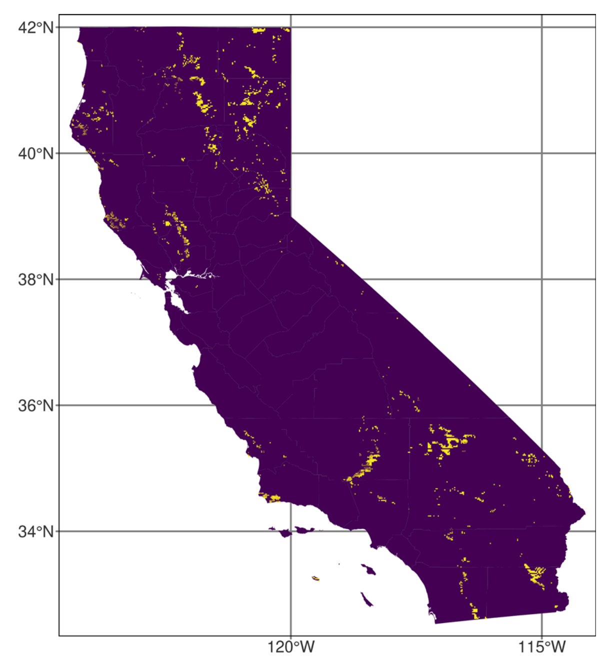

FIG. 8. High-CF, winter-dominant, available wind power potential (CF > 0.4, W–S difference > 0, excluding regions with slope $> 20°$, and protected areas.).

22 GW of winter-dominant plants could be sited on available land. These represent 23% of the total potential. For these 22 GW, the weighted mean of W–S difference is 0.34 and the mean of annual capacity factor is 0.45. The locations extend through much of the state.

On the way to decarbonizing the grid, wintertime electricity generation will be crucial. Onshore wind with stronger generation in winter than in summer would reduce the need for seasonal storage. As the focus shifts from summer to winter electricity generation, the option of onshore winter-dominant wind resources should be considered in comparison to transmission lines for out-of-state wind and offshore wind. Investments in technical advancement and changes in policy that would enable deployment of wind turbines in locations with strong winter wind may be pivotal toward enabling a renewable-electricity-based, resilient pathway to a low-cost, zero-carbon grid.

SUPPLEMENTARY MATERIAL

See the supplementary material for additional tables and graphs for both historical and simulated data. The historical data analysis includes monthly and annual wind electricity generation and a typical California load profile compared with solar and wind generation profiles. The simulation methodology is demonstrated in comparison with historical data using two power curves. The statistics for the wind resource as a function of the simulated capacity factor is shown from multiple perspectives. Finally, the effect of using a different power curve for simulation of seasonal wind resource is shown for all of California.

ACKNOWLEDGMENTS

The authors thank D. Kammen for useful comments on the manuscript. We are also indebted to NREL for making wind data available through the NREL Wind Toolkit. Author D.M. was supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231. The U.S. Government retains, and the publisher, by accepting the article for publication, acknowledges, that the U.S. Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

This work was supported by the California Energy Commission (No. EPC-19-060). This document was prepared as a result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees, or the State of California. The Energy Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this document; nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Energy Commission nor has the Energy Commission passed upon the accuracy of the information in this report.

AUTHOR DECLARATIONS

Conflicts of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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