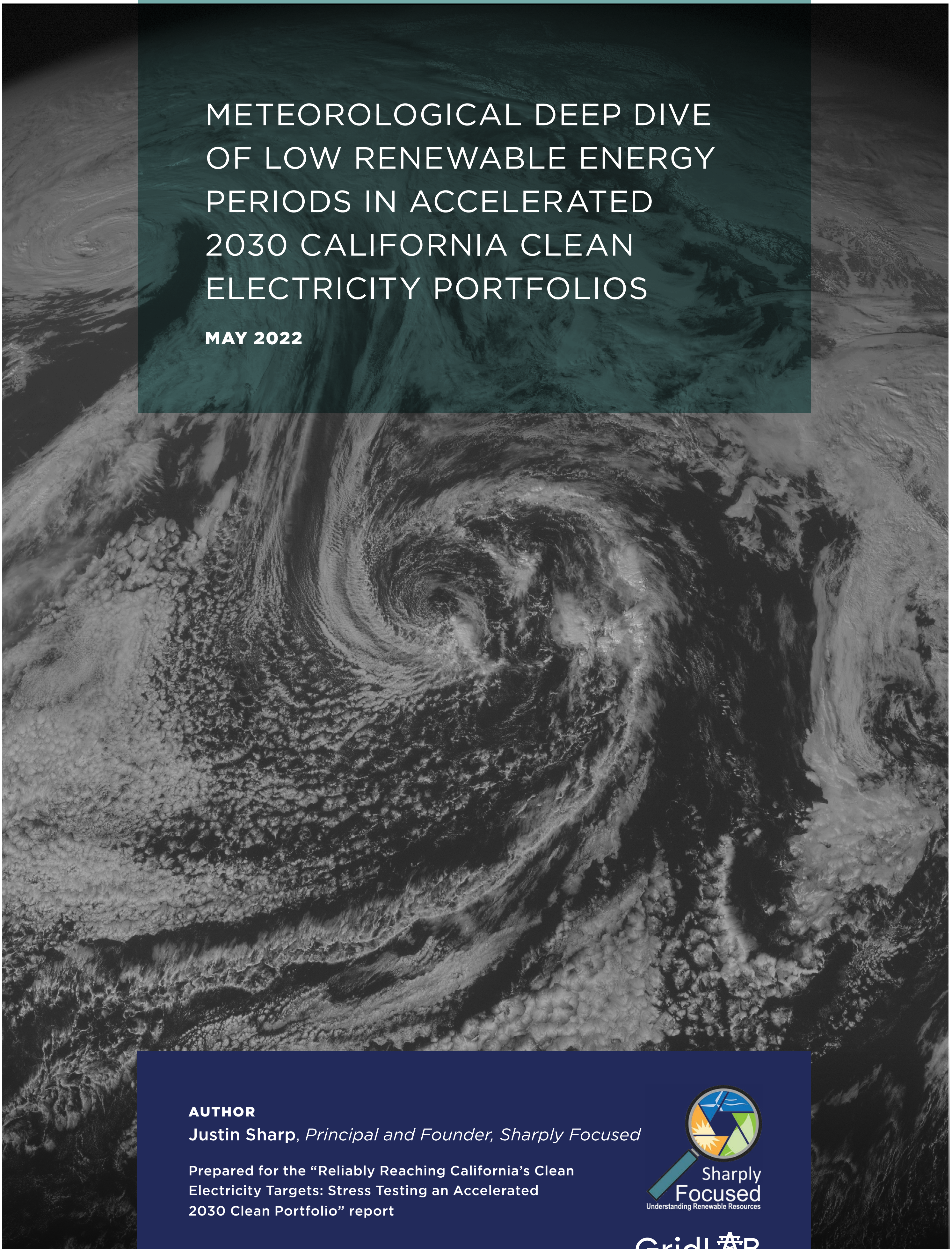


METEOROLOGICAL DEEP DIVE OF LOW RENEWABLE ENERGY PERIODS IN ACCELERATED 2030 CALIFORNIA CLEAN ELECTRICITY PORTFOLIOS

MAY 2022

AUTHOR

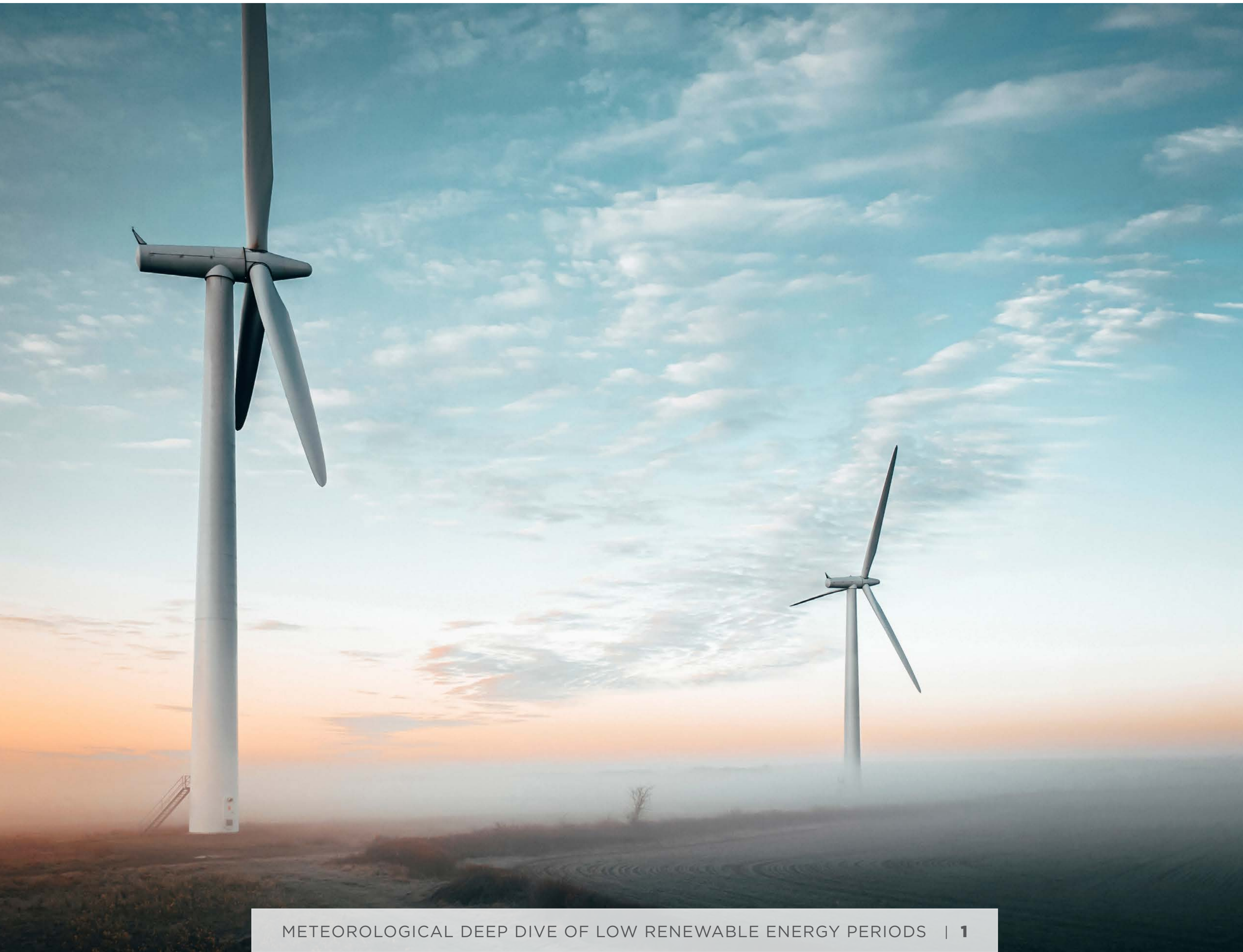
Justin Sharp, *Principal and Founder, Sharply Focused*

Prepared for the “Reliably Reaching California’s Clean Electricity Targets: Stress Testing an Accelerated 2030 Clean Portfolio” report

Sharply Focused
Understanding Renewable Resources

GridLAB

As part of the “Reliably Reaching California’s Clean Electricity Targets” study, concurrent wind and solar resource data was used to project the generation at renewable energy sites throughout California and the broader WECC area. The concurrent data spanned the period 2007 through 2014. During this period, when projected renewable generation was compared with expected load, three periods stood out starkly as having an average California renewable generation capability of less than 20% of estimated load over at least three days. These periods were January 21-23, 2009, December 20-22, 2010, and January 23-25, 2013. Sharply Focused was asked to evaluate the weather driving these low resource periods, to provide historical context of the events and provide insight on the nature of the regional pattern. Sharply Focused analyzed features such as how the weather patterns impacted renewables within California and more broadly across the western interconnect and used expert knowledge of Western weather to give a qualitative view on the events and how they might be mitigated.



DATA USED

Telos provided Sharply Focused with hourly resource data for 2007 through 2014 for twenty-six different western sub-regions, including eight within California, which was derived from the Wind Integration National Dataset (WIND Toolkit) and the NREL National Solar Resource Database (NSRDB). For the purposes of discussing regional weather regimes in this supplemental report, the twenty-six sub-regions were combined into eight broader regions that often experience similar weather regimes. The names of these regions and the sub-regions defining them are given in Table 1. Telos also provided a single typical load year.

TABLE 1.

Components of aggregated regions used in weather discussions.

AGGREGATE REGION	COMPONENT REGIONS
Canada	Alberta, British Columbia
Desert Southwest	Arizona (AZPS, SRP, TEPC, WALC), and New Mexico
California	BANC, IID, IV-NG, LADWP, PG&E, SCE, SDGE, TIDC
Baja	CFE
Great Basin	Idaho, Nevada (Nevada Power, Sierra Pacific Power), Utah (PAUT)
Rockies	Colorado East, Montana (NEW, WAUW), Wyoming (PacEast, WP Colorado/Missouri)
PNW	BPA, PacWest and all other Pacific Northwest BA's

Sharply Focused obtained Grib2 archive data for the dates in question from NOAA for the North American Mesoscale Forecast system (NAM) which provides output of key weather variables on a 12-km grid. Grib2 is a binary format used to efficiently store large amounts of weather data. The Grid Analysis and Display System (GrADS) was used to extract the archive and plot historical maps to allow us to gain insight into the weather during these three periods. NREL WIND Toolkit data was used to generate the national wind and solar deviation maps that are shown in each section using the same method that Sharply Focused and NREL used for their paper, "The Evolving Role of Extreme Weather Events in the U.S. Power System with High Variable Generation Penetrations". Lastly, we downloaded archived weather maps and satellite imagery from NOAA and academic data repositories for the dates.

GENERAL OBSERVATIONS

Two of the three events studied presented as rather benign from the perspective of the type of weather that normally makes news. However, the December 2010 event came at the end of a period of heavy rain across California, the focus of which moved from north to south during the period. All three events led to three consecutive days of below normal wind resource across not only California, but the entire west, with the average west wide wind generation estimated at below 25% of installed capacity on the worst days (16.9% in the worst case on January 23, 2009). On the lowest resource days, this equates to *aggregated total* west wide wind generation falling as low as 48% of the average expected for the months when the events occurred, with low resource also seen during surrounding days. All three events share some similarities in respect to their atmospheric dynamics. In all cases there is a high amplitude ridge in place with the axis located somewhere between the Great Basin and the Rocky Mountains. This ridge blocks the progress of incoming weather systems and weakens them. In cases where a ridge like this is further to the west, the result is generally sunny weather and there is plenty of solar resource which offsets the wind resource typically being lower than normal. However, in cases like those examined here, the ridge migrates inland and storms can impact the west bringing widespread and slow-moving cloudiness that results in days of low solar resource across California and the entire western interconnect. West-wide solar capacity factors, already low in the winter months (15.7% and 17% for December and January respectively) dropped below 10%, with values below 6% in December 2010. California solar resource capacity values were similarly depressed. Thus, both west wide and California solar resource dropped as low as 1/3 of the typical wintertime values.

The overall surface pressure distribution seen in all three events wasn't conducive to generation at many of the California locations where wind is commonly built, and where it was conducive, the atmospheric dynamics were weak and produced poor generation, though in December 2010 the poorest California wind potential occurred after the solar resource started to improve. Further north, the modeled wind data used to estimate generation indicates some recovery in PNW wind as west-wide solar resource decreases. However, we found that in all cases the weather observations suggested offshore flow, and when we examined BPA historical generation, we found that model generation was overstated. This is explained in detail later. We believe this will be a common failure mode for similar events in the WIND Toolkit dataset.

In some respects, the January 2013 event is like the January 2009 event. There is significant nuance in the details, but both are the result of an amplified ridge pattern. In one case the pattern is almost stationary and blocked, in the other it is moving slowly through the region, but the net effect is the same. The storm track is moving through to the north of the region and when it does finally arrive at the coast, it is slow moving, weak and stretched out. The results in copious clouds that dramatically impact solar generation but weak dynamics for wind generation.

The December 2010 event is different. In this case the dynamics are much stronger, with the jetstream diving south in the eastern Pacific with a strong storm track developing across the southern states. This is much more conducive to offshore wind generation, and wind generation in the southwest and Baja. However, the pattern leads an even more extended period of low solar generation and weak wind generation further north.

All the events were associated with temperature patterns across the west that were likely associated with lower than normal or near normal electricity usage. That is, the weather was generally normal or warmer than normal, but not warm enough to result in air conditioning load in the southwest.

We believe that both patterns are relatively common. The January 2009/2013 patterns occur frequently, and we expect that similar low resource periods will occur once every two to four years in the severity seen here. The December 2010 pattern is less frequent and thus more difficult to quantify the return interval on, but we speculate that it is not particularly uncommon and will occur at least every five to ten years in the severity seen here. Note however, that these statements are speculative based on Dr. Sharp's experience of west coast weather and are not the result of rigorous data analysis. Based on that same experience, it is speculated that a pattern could develop that will be similar to one of the two seen here that could be coincident with cooler temperatures and frozen precipitation, and could last a day or two longer. This would dramatically increase the impact on the electric system. However, such a pattern was not present in the time interval analyzed.

For the study being conducted for CEC, where the intent is to evaluate the reliability of a system attaining an accelerated 75% clean energy target by 2030, while assuming renewable development continues in the rest of the western region according to current plans, modeling results indicate that while these concurrent low wind and solar resource periods will result in some supply tightness, resource adequacy can be maintained by utilizing existing gas capacity to ride through the difficult period. However, in the bigger picture of west-wide deep decarbonization, the events described below, as well as several days surrounding them, suggest that even for a footprint as large as the WECC region, that several times per decade there will be periods of several days to two weeks where renewable resources will not be able to reliably serve load if resources are built out as currently planned. It is crucial to note though that several options are available to mitigate this. These include obvious answers like ensuring enough existing gas generation remains available as a rarely used capacity resource or developing cost effective weekly time frame storage. Another less frequently considered answer is to change the way wind and solar are deployed to incentivize projects that have lower overall annual energy production but a high capacity value during periods where supply is tight. While the weather patterns producing low resource periods in this study leave little option for mitigating solar deployments unless the solar power was imported from other interconnections, they do exhibit good wind resources in some locations not currently favored for wind development, that are concurrent with the times that "typical" wind regions experience low winds. More analysis and better weather datasets geared explicitly to this type of planning optimization are needed to make a definitive assessment of this option, but examples where "peaking" wind could be deployed include the desert southwest, Baja, and on the west side of the Cascades and Sierra Nevada.

JANUARY 21-23, 2009

TABLE 2.

Modeled resource for different western areas for the period of interest. Solar generation is derived from NSRDB data and wind from the WIND Toolkit dataset. Percentages of California load are based on January average load provided by Telos.

	WIND								SOLAR								BULK RESOURCE STATS			
	Cali OSW	CALI	CFE	BC/AB	DSW	IMW	ROCKIES	PNW	Cali BTM	CALI	CFE	CANA	DSW	IMW	ROCKIES	PNW	Cali VRE CF%	Total VRE CF%	CA Load by CA VRE	CA Load by All VRE
Jan 2009 Ave	33%	19%	40%	55%	40%	26%	54%	32%	16%	19%	21%	16%	20%	19%	18%	15%	19%	27%	37%	106%
Overall Jan Ave	34%	20%	36%	46%	36%	25%	47%	28%	15%	18%	20%	14%	19%	19%	18%	13%	18%	25%	36%	97%
18-Jan-09	4%	14%	35%	68%	22%	8%	67%	16%	21%	22%	21%	19%	21%	23%	21%	17%	20%	27%	38%	105%
19-Jan-09	6%	13%	17%	48%	35%	6%	64%	9%	18%	19%	20%	20%	21%	21%	24%	17%	17%	24%	33%	95%
20-Jan-09	4%	9%	15%	57%	30%	9%	60%	4%	18%	20%	20%	18%	21%	22%	24%	17%	17%	23%	33%	92%
21-Jan-09	7%	10%	1%	64%	39%	5%	54%	3%	7%	10%	15%	9%	16%	17%	23%	8%	9%	19%	18%	73%
22-Jan-09	4%	4%	5%	61%	53%	10%	58%	2%	4%	9%	15%	5%	13%	15%	15%	5%	6%	18%	12%	69%
23-Jan-09	13%	7%	3%	10%	47%	11%	18%	10%	3%	7%	14%	11%	8%	6%	14%	10%	6%	11%	12%	42%
24-Jan-09	22%	37%	24%	3%	34%	32%	29%	3%	7%	16%	22%	6%	21%	15%	17%	5%	16%	17%	32%	67%
25-Jan-09	70%	58%	80%	23%	58%	30%	18%	23%	13%	18%	23%	9%	22%	20%	15%	8%	25%	25%	49%	99%

As can be seen in Table 2 and Figure 1, the period from January 21-23, 2009 was characterized by dramatically lower than normal wind and solar resource in California, especially on the 22^{nd} and 23^{rd} when it is estimated that California Variable Renewable Energy (VRE) resources had capacity factors of 5.9% and 6.2% respectively compared to a January average of 18.1%. This would allow California renewables to meet only about 11 to 12% of California load compared to the mean of about 35.7% for the month of January. We also see in the table and the plots that this VRE deficit is not limited to California. The entire western interconnect on average has well below normal renewable resources, with January 23 seeing a region wide VRE capacity factor estimated at 10.8% of installed capacity, while the 22^{nd} and 24^{th} were both under 18%, compared to regional January average of 24.6%. The objective of the following section will be to provide some color around the meteorological reasons for this. It is worth noting that this is an event where renewable resources are above normal in the eastern part of the country. Wind resource is way above normal in the east on the 23^{rd}, and solar resource has positive deviation on the 22^{nd}. The nature of the continental scale weather systems occurring during this period will hopefully help illustrate some of the physical reasons why it will become increasingly important to plan across interconnections as VRE penetration increases.

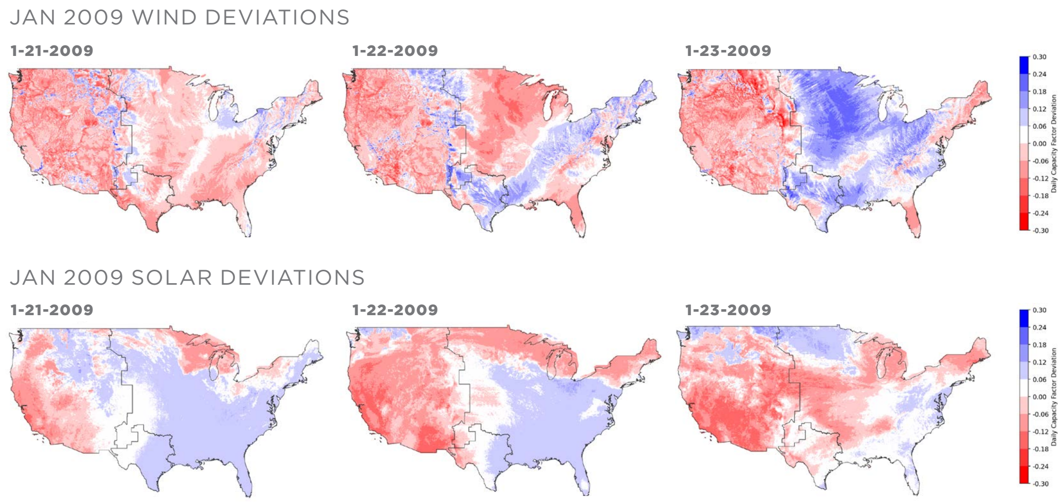


FIGURE 1.

Deviation from mean wind and solar capacity factors based on WIND Toolkit data and standard power curves. The mean is a seven day window centered on the day of interest and averaged across all years in the dataset. Darker blues indicate higher than normal resource, white is average, and darker reds show lower than normal resource.

The second half of January 2009 was dominated by what meteorologists call a high amplitude wave pattern that evolved and moved slowly. In essence, the jetstream was very wavy, meandering far to the north over Alaska and diving south all the way to Mississippi, and again north all the way to Greenland. This can be seen in Figure 2, which shows contours of constant geopotential height and winds on a 500 mb pressure surface. The region where the lines are close together is where the jetstream is located at that pressure level and the closer the lines the faster the flow. This pattern began to set up around January 10, and strengthened while translating slowly east, reaching its peak amplitude around January 19, after which it slowly decayed. In this type of pattern, storms in the Pacific move north along the

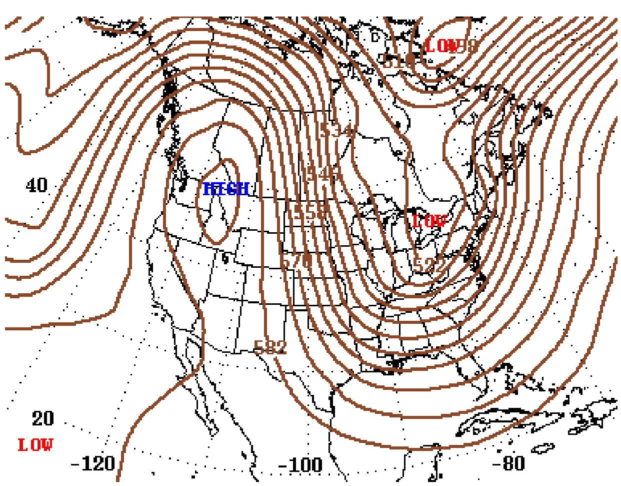


FIGURE 2.

500mb geopotential height and wind field for January 19, 2009, highlighting the high amplitude flow and east-west weather split.

jetstream and weaken as they encounter anticyclonic flow and generally subsiding air and are blocked from impacting the west coast, and warm air is transported into Alaska. Meanwhile, the same pattern is conducive to clearing skies across the entire west. When this happens in the wintertime, the outcome is governed by whether nighttime cooling offsets the warming of the short days, and whether the ridge is oriented such that it will draw cold surface area south from Canada or pull warm air north from the desert southwest. In this case, the surface high pressure system was well inland, and the result was generally above average temperatures during this period for most of the west, especially the southwest. These warmer temperatures would have reduced heating loads in most of California, Nevada and the four corners. The exception was the NW where nighttime cooling predominated, and the formation of fog led to cool days in the Columbia Basin with temperatures slightly below normal in load centers like Portland, Seattle and Boise. It is worth noting that the same pattern triggered two moderate cold waves east of the Rockies, one beginning on the 14th and a second beginning on the 24th. Sinking air associated with such a pattern generally means clear skies, and the offshore (from continent towards ocean) flow yields further sinking off the Cascades and Sierra Nevada so that the US west coast was completely cloud free for several days. Aside from giving people living west of the Cascades and Sierra some welcome winter sunshine, the offshore pattern is known for strong, dry winds on the western side of the Cascades and Sierra. However, during an offshore pattern, windy locations where wind facilities are typically built see weak or even calm winds. Few if any wind energy facilities are typically found in regions where wind is strong during this offshore regime as the resource is not nearly as high as other locations when a more typical pattern is present. This is especially true in the PNW and the Great Basin, where the inversion that is present during these wintertime cases will further decouple momentum aloft from the surface layer, leading to days with almost no generation at all. We see in Table 2 that this case is no exception. We also see that solar resource is of course well above average leading into the low resource period. However, as with everything weather, there is nuance to this story, and east of the Cascades and Sierra, and later as the pressure gradients relax, even in sheltered valleys west of the mountains, low clouds and fog become more prevalent. This is because east of the mountains, where winds were slack and the air bound by terrain, a strong subsidence inversion formed that prevented any mixing of the surface layer with air above. As the layer continued to cool and pick up surface moisture, fog formed in many valleys and became persistent throughout the day in much of the Great Basin. This is common whenever the western US is under the influence of a strong upper-level ridge at this time of year. By January 20, fog was widespread (Figure 3 left) in western valleys, but fortunately was not coincident with where the majority of the solar generation currently exists and thus didn't have a profound impact in this case.

Around January 20, the upper-level high pressure ridge was beginning to break down, and weak westerly flow was re-establishing itself in the eastern Pacific. The change in upper air conditions combined with the sharp contrast between warm maritime air meeting the cold continental air just offshore was enough to form a weak frontal system that began to spread mid- to high-level cloud over Southern California and the desert southwest (DSW) by early morning on January 21. The

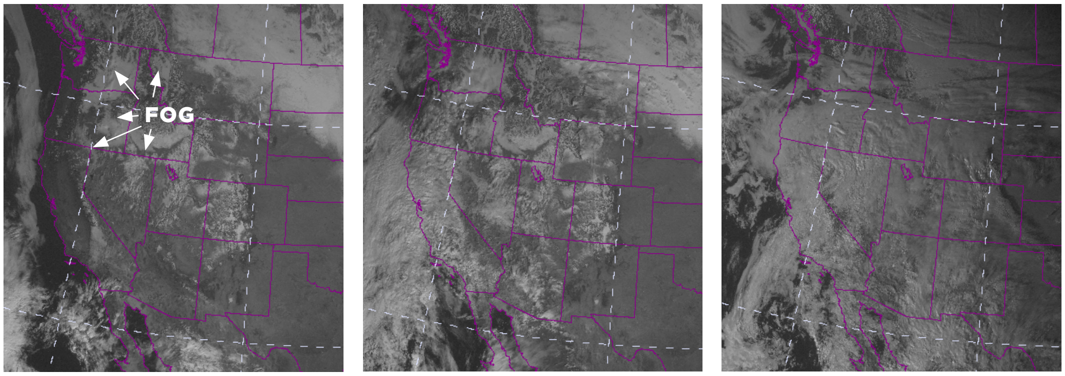


FIGURE 3.

Visible satellite imagery for January 20 at 10 am PST (left), January 21 at 10 am PST (middle) and January 22 at 3 pm PST. Widespread cloud remained on the January 23, with similar coverage to January 22 (not shown).

system was too weak to raise the wind resource, even offshore, but it greatly impacted the available solar resource, not just in California, but across much of the western interconnection (see Table 2 and Figure 3, middle). By the evening of the 21st, most of the west through to the Rocky Mountain crest was cloud covered.

While the weather approaching from the west was weak and, from a traditional weather perspective would be viewed as benign, from a renewable energy perspective the implications were severe. Because the upper air pattern was still blocked downstream, and the atmospheric dynamics were very weak, the weather evolved very slowly with weak impulses rotating onshore reinforcing the clouds and intervals of rain, while not providing the vigor to clear out the inversion in the northwest and the inner mountain west. On the 22nd and 23rd, this led to coincident weak wind resource offshore, a lack of wind resource in the key wind generating areas of the Northwest and California and two days of very poor solar resource across the entire west.. Indeed, based on model estimates, ALL the VRE generation in the western region on January 23, 2009 would only meet 41.4% of the average California load for a January day. Actual load data is not available but given major load centers in the southwest and inner mountain west were warmer than typical, loads were probably a little below average there. This will have been offset to some degree by below normal temperatures in the northwest population centers of Oregon, Washington and Idaho. Thus, both actual California and actual west wide load was likely below normal, but not by nearly enough to offset the extreme deficit in renewable resource availability across the entire west. Also, while the values in Table 2 indicate a recovery in the wind resource in the Pacific Northwest on the 23rd as low pressure moves inland, weather maps indicated that this recovery did not occur. We downloaded wind data for the BPA control area for the period and found that wind generation never got above 20 MW (out of an installed capacity of about to 1700 MW) on January 23, so we must conclude that west wide resource was likely even lower than modeled. This is a common failure mode for numerical weather prediction (NWP). The models scour out the inversion too quickly, leading to momentum from aloft mixing down and providing some wind. Because of the importance of this type of event, we recommend that time be spent doing a robust validation of the accuracy of the WIND Toolkit data, and any similar datsets, during this type of offshore regime that is common in the wintertime. This includes checking against actual wind farm generation and met-towers, as the data might be an over-estimate for many days, especially in the PNW and Great Basin. In addition, because the weather system was so weak and cold air was entrenched throughout the Northwest region there is a risk that icing may have had some impact on resource availability for both wind and solar especially in sheltered valleys where temperatures remained below freezing throughout the precipitation event. Based on the NAM model data, and weather maps it looks like rain fell in some areas while temperatures were below freezing, but the actual station data needs to be evaluated to confirm this.

Even though resources were coincidentally low in many places, and were perhaps even lower than the model data is suggesting, the event exhibits the importance of geographic diversity. Because the jetstream split, while the weather that did finally move inland didn't yield much wind in the typical locations, it did bring healthy resource to the desert southwest. Though the amount of wind installed there is low in this study, this region does have a moderately good wintertime capacity factor and it would be useful to learn more how reliable it is in similar situations where west wide solar is impacted by broadscale cloudiness, and California/PNW wind is low due to lack of weather dynamics. Similarly, the regions east of the Continental Divide (Alberta, MT, WY, CO) exhibit generally above normal wind capacity factors during the time leading into the event. But note, these winds collapse as the pattern shifts and weather moves inland, and it is the loss of this wind that leads to the lowest overall west resource day on January 23. It will be crucial to understand the robustness of any correlations between this low resource pattern in the west and possible compensatory resource in the desert southwest, and to examine what typically happens to the wind in the Rocky Mountain areas in similar situations. From a physics perspective it seems reasonable that regions in the Desert Southwest will generally do well in an event like this and that the Rocky Mountains will see robust winds days in the pattern leading up to this event. It is less clear, if the concurrent collapse of the Rocky Mountain wind will typically be as severe.

While this event produced the lowest California VRE resource across a three-day rolling period and produced several days of very low west wide resource, it is important to note that it was not an extreme weather event or exceptionally unusual. The combination of stagnant conditions followed by a weak, slow moving weather system breaking through occurs every year, and while this case produced the lowest resource in the dataset, such a weather pattern is not unusual and does **not**, in Sharply Focused professional opinion, represent a situation with long return time expectation. Longer datasets need to be produced and analyzed to determine how frequent low resource periods like this will be. The eight-year dataset being examined contains two other events that are only slightly less severe. Each has its own unique characteristics that we will examine next, along with comments about their similarities.

DECEMBER 20-22, 2010

TABLE 3.

Modeled resource for different western areas for the period of interest.

	WIND								SOLAR								BULK RESOURCE STATS			
	Cali OSW	CALI	CFE	BC/AB	DSW	IMW	ROCKIES	PNW	Cali BTM	CALI	CFE	CANA	DSW	IMW	ROCKIES	PNW	Cali VRE CF%	Total VRE CF%	CA Load by CA VRE	CA Load by All VRE
Dec 2010 Ave	43%	23%	35%	30%	40%	30%	39%	26%	11%	14%	16%	9%	16%	14%	15%	9%	16%	21%	31%	83%
Overall Dec Ave	36%	22%	34%	43%	38%	28%	45%	29%	14%	17%	18%	12%	17%	17%	16%	11%	18%	24%	35%	93%
15-Dec-10	22%	44%	46%	71%	65%	22%	34%	27%	9%	11%	12%	18%	13%	9%	11%	17%	16%	23%	30%	91%
16-Dec-10	6%	31%	57%	23%	25%	10%	12%	15%	13%	14%	12%	21%	7%	12%	10%	19%	16%	15%	31%	60%
17-Dec-10	75%	23%	41%	3%	12%	27%	6%	26%	4%	6%	12%	21%	15%	6%	9%	19%	12%	12%	23%	48%
18-Dec-10	75%	53%	66%	3%	58%	46%	23%	27%	3%	6%	12%	4%	15%	4%	11%	4%	16%	19%	31%	74%
19-Dec-10	64%	61%	62%	3%	64%	50%	34%	21%	3%	5%	11%	4%	15%	8%	12%	3%	16%	20%	31%	79%
20-Dec-10	21%	25%	83%	14%	66%	31%	41%	15%	4%	5%	8%	8%	11%	4%	15%	7%	8%	17%	16%	65%
21-Dec-10	58%	15%	83%	10%	51%	15%	9%	22%	6%	6%	3%	4%	6%	4%	14%	3%	11%	13%	21%	52%
22-Dec-10	42%	19%	83%	9%	21%	25%	20%	9%	5%	6%	5%	9%	6%	2%	7%	8%	9%	11%	18%	42%
23-Dec-10	33%	19%	27%	30%	25%	5%	30%	6%	13%	18%	20%	6%	16%	16%	12%	6%	17%	18%	33%	70%
24-Dec-10	8%	8%	28%	21%	33%	6%	33%	16%	15%	17%	21%	6%	20%	17%	18%	5%	14%	18%	28%	72%
25-Dec-10	42%	25%	25%	9%	6%	30%	16%	22%	8%	14%	18%	11%	19%	14%	20%	10%	15%	16%	29%	60%
26-Dec-10	29%	47%	32%	45%	47%	41%	50%	48%	14%	14%	12%	9%	15%	14%	15%	8%	20%	28%	38%	108%

As can be seen in Table 3, the third and fourth weeks of December 2010 represent an extended period of below average VRE resource across California and the entire western footprint, with resource below the December average for the eight-year dataset every day from December 15 through December 25, and a particularly low three-day period on Dec 20-22. Exceptionally low resources were also seen west wide on December 16 and 17. While the lack of solar resource really stands out in this event, there are only a few pockets of wind resource too. Understanding if a physical correlation with robust causation typically exists between these areas with good wind resource and west wide cloud cover events like this one will be critical to determining if they can be relied upon to provide some mitigation such events.

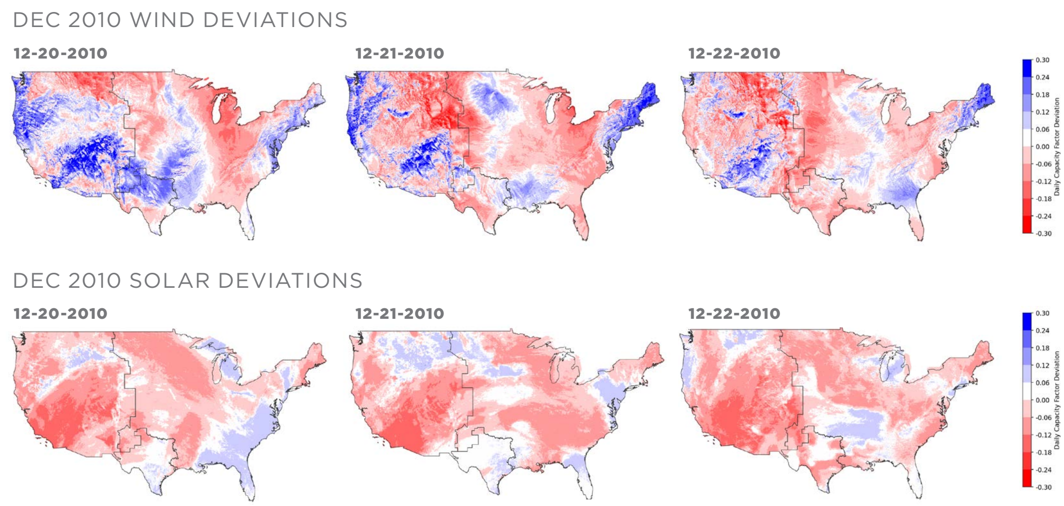


FIGURE 4.

Deviation from mean wind and solar capacity factors based on WIND Toolkit data and standard power curves.

The poor resources also show up in Figure 4 which shows the geographic deviation of wind and solar resources from the average for the same time of year. Note, however, the area of stronger wind resource in the southwest. Also, note the strong wind resource along the northwest coastal areas especially on the 21st. This is due to the proximity of low pressure offshore and impacts an area where little wind energy is deployed. Some of this energy is indicated as reaching inland to the Columbia Basin where there is significant installed capacity. We will see later that the model is erroneously bringing too much momentum to the surface in the Columbia Basin region.

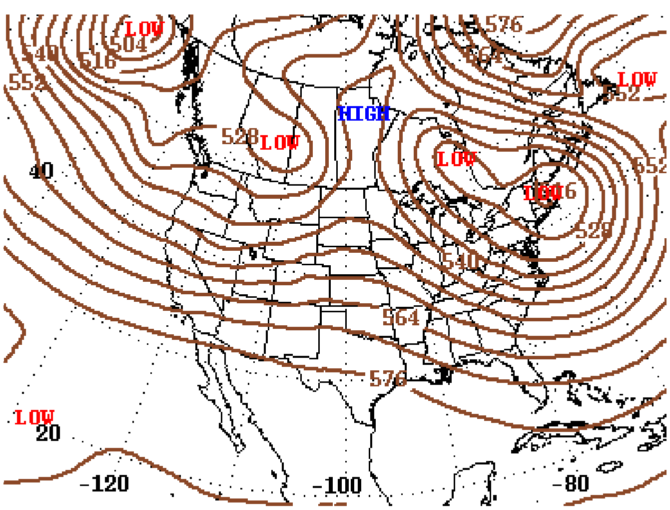


FIGURE 5.

500mb geopotential height and wind field for December 15, 2010, highlighting the Omega block pattern in the northern portion with a strong progressive jet over the southern US.

The weather pattern across North America during this period was dominated by "blocking". This is what meteorologists call a high amplitude upper air wave pattern that tends to prevent the evolution and translation of short-wave ridges (zones of high pressure aloft) and troughs (zones of low pressure aloft) that drive our surface weather. The pattern began with a building upper-level ridge along the west coast on December 11, that slowly migrated east through December 15. Upper-level low pressure strengthened either side of the ridge, driving the northern branch of the jetstream south where it merged with the subtropical jet. By the 15th, the ridge axis was in the mid-section of the US and Canada and formed a classic omega block, so called because the flow looks like the Greek letter, Ω (see Figure 5), that was undercut in the southern US by a strong jetstream. Storms rotated around the long wave pattern, weakening as they moved into anticyclonic (clockwise in the N. Hemisphere) flow. This led to a quasi-stationary area of low pressure off the coast of Oregon and Washington, where storms were decaying, and to the south, where upper-level dynamics were supportive, the storms would break under the block and quickly transition across the southwest. For the next ten days weather systems split and rode this strong jet along the southern tier of the US, while further north and throughout Canada, the weather was essentially stagnant. Thus, wind speeds in the southern US were variable and well above normal on average, while further north they were generally low. California offshore wind resource was variable but above average as systems rotated around the offshore upper level low. The data in Table 3 indicates that winds in the PNW were close to normal during this period, however, actual wind generation data from the BPA area indicate that the generation was considerably lower during this period, with capacity factors 3 to 8 times less than indicated in WIND Toolkit data during the December 20-22 period, and even greater differences later in the period. This is for the same reason discussed in the last section. Energy from storms rotating around the upper-level low is being mixed to the surface by the model creating the resource data, but in reality it remained aloft. This is starkly shown in Table 4.

TABLE 4.

Table of differences between observed and modeled capacity factor for the BPA region

DATE	BPA CF	MODEL CF	DIFFERENCE
12/19/2010	4.7%	20.9%	441%
12/20/2010	2.5%	14.9%	604%
12/21/2010	6.5%	21.7%	336%
12/22/2010	1.0%	8.8%	888%
12/23/2010	0.6%	6.1%	1017%
12/24/2010	1.1%	15.7%	1379%
12/25/2010	8.4%	22.4%	268%

The storminess off the west coast, coupled with the strong cyclonic southern jetstream, with frontal systems pushing inland on it into the southwest, led to persistent cloudiness in regions that normally favor solar generation. This lasted for close to a week, three days of which can be seen in the visible satellite imagery for December 20 through 22 shown in Figure 6. Looking at Figure 6 it is not surprising that solar output was well below normal. With the exception of New Mexico, and, on the 20th, SE Arizona, the entire west is mostly overcast.

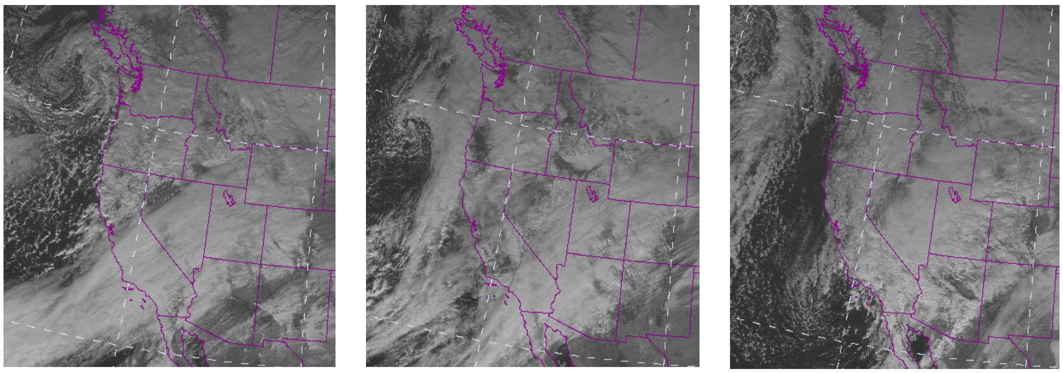


FIGURE 6.

Visible imagery from noon PST on December 20 through 22 (left to right).

Because the airflow was coming from warm sub-tropical waters this pattern produced generally warmer than average temperatures across the region during the event, though the cloud cover led to southern California being around normal. It also produced a lot of rain especially in the southern part of California with daily rainfall totals of 1 to 3” for several days in a row. The dark days may have increased lighting load slightly. In southern California the daytime temperature was below normal while nighttime lows were above, due to the deep cloud cover. Overall, heating loads across the west were presumably normal or below normal with little air conditioning load. As a result, this event is unlikely to be one that is examined by organizations conducting traditional resource adequacy studies. However, the event is likely to cause significant stress to a system with west-wide high VRE penetration. In the generation configuration used in this study, there are eleven contiguous days where the entire of the west VRE generation is unable to meet even California’s load. Significant traditional resources will need to be held in reserve, multiday storage solutions developed, and/or the system planned differently to ensure that wind and solar generators are in regions where resource is high during this type of event with transmission able to move the generation to where it is needed. The first option is not ideal if we hope to decarbonize the electric system, and multiday storage that can cover eleven days or more is currently prohibitively expensive. One option is to strengthen ties to the eastern interconnection, but Figure 4 indicates that resource may be tight there as well. But the situation is not hopeless. While solar generation is poor across the entire west, so that even diverse over building of PV projects won’t solve the issue, the wind generation does have bright spots. In this case, offshore wind capacity factors are good, and so are wind resources in the southwest. In addition, onshore resources in the near coastal areas are good on several days. These are not in zones where wind energy is typically built because the annual capacity factors are low. But as the cost of capacity continues to drop, building in these locations, while not competitive when considered simply on the cost per unit of generation, will become more attractive because the value of the energy they produce will be high due to generating during periods of tight supply. Resource for wind generation in Baja is spectacular during this period, with the modeled values indicating 80%+ capacity factors on all three of the lowest resource days. Along with the other events examined in this paper, it is hoped that this one illustrates why the mindset of how we plan generation and transmission must shift, and how understanding what locations will produce wind and solar power when the "favored" wind and solar areas fail becomes imperative.

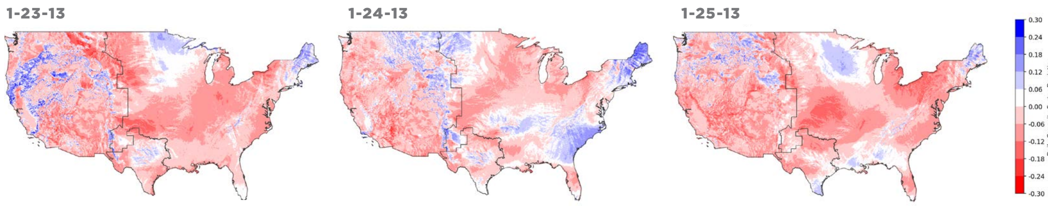
JANUARY 23-25, 2013

TABLE 5.

Modeled resource for different western areas for the period of interest.

	WIND								SOLAR								BULK RESOURCE STATS			
	Cali OSW	CALI	CFE	BC/AB	DSW	IMW	ROCKIES	PNW	Cali BTM	CALI	CFE	CANA	DSW	IMW	ROCKIES	PNW	Cali VRE CF%	Total VRE CF%	CA Load by CA VRE	CA Load by All VRE
Jan 2013 Ave	30%	19%	39%	51%	32%	17%	47%	26%	17%	19%	20%	15%	19%	20%	19%	14%	19%	25%	38%	98%
Overall Jan Ave	34%	20%	36%	46%	36%	25%	47%	28%	15%	18%	20%	14%	19%	19%	18%	13%	18%	25%	36%	97%
22-Jan-13	20%	5%	14%	41%	27%	5%	61%	6%	18%	21%	22%	15%	22%	24%	24%	14%	18%	23%	35%	92%
23-Jan-13	24%	10%	7%	13%	32%	13%	47%	13%	5%	7%	10%	4%	17%	11%	17%	4%	8%	15%	15%	59%
24-Jan-13	16%	8%	11%	59%	46%	13%	57%	15%	6%	6%	8%	16%	5%	5%	16%	14%	7%	18%	14%	70%
25-Jan-13	22%	4%	8%	36%	21%	12%	48%	8%	7%	8%	7%	4%	10%	10%	12%	4%	8%	15%	16%	58%
26-Jan-13	65%	38%	29%	25%	37%	17%	26%	25%	11%	13%	10%	13%	4%	5%	9%	12%	19%	19%	37%	76%
27-Jan-13	74%	55%	63%	50%	59%	43%	31%	57%	16%	20%	18%	18%	14%	19%	23%	17%	27%	32%	52%	124%

Table 5 shows us that both California wind and solar generation is low during the three-day period of January 23 through January 25, 2013. Further, west wide solar is well below average, and west-wide wind is typically below average. However, the DSW, Rocky Mountain and Alberta wind generation numbers are close to or above normal, and offshore wind, while below average, is producing moderate amounts of power. The wind resource deviation plots (Figure 7, top), indicate how generally below normal the wind resource is during this period, with only localized areas of strong resource. Since both the table and the plots use the same resource data source, we can conclude that the modeled capacity indicated to be generating wind energy is located within the Rocky Mountain zones and DSW. This is important to note, since we see that in this pattern the wind resource in the east is also weak so that, even with increased connectivity with the Eastern Interconnection, there is unlikely to be excess generation.



JAN 2013 SOLAR DEVIATIONS

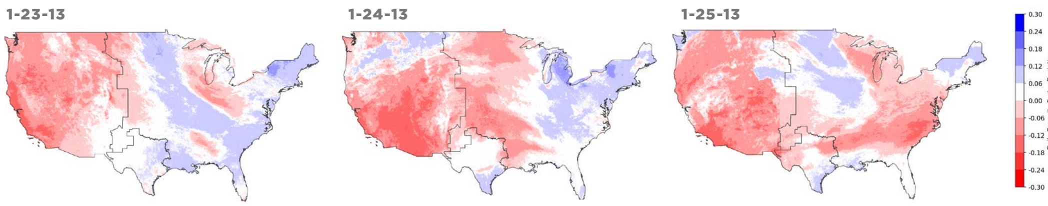


FIGURE 7.

Deviation from mean wind and solar capacity factors based on WIND Toolkit data and standard power curves.

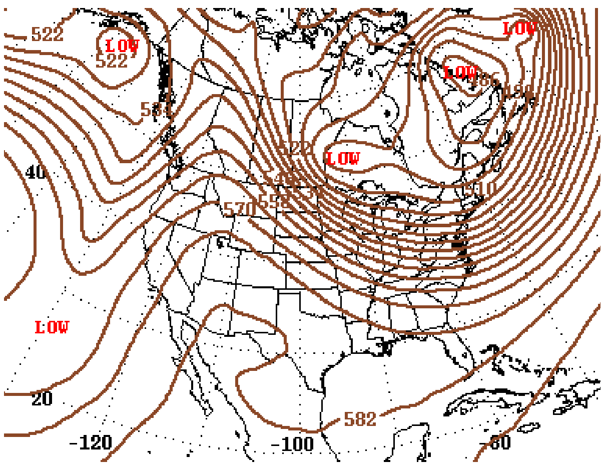


FIGURE 8.

500mb geopotential height and wind field for December 23, 2013, highlighting an upper-level pressure ridge that has slowly moved east for 10-days.

The plots of solar resource deviation (Figure 7, bottom) clearly show that there is broad cloudiness throughout the period resulting in much reduced solar generation, particularly in the most resource rich areas of California and the DSW where most of the solar capacity exists currently and in the model.

This low resource period begins, like the other two considered above, with an amplified ridge of high pressure in the eastern Pacific (Figure 8). However, this event is a little different in that the weather pattern does not become blocked, but rather translates from west to east. The highly amplified pattern was present for over a week with the ridge further west over the Pacific and the jetstream diving south over the west into a high amplitude trough. The entire pattern migrated slowly eastwards and flooded the west with Arctic air from NW Canada resulting

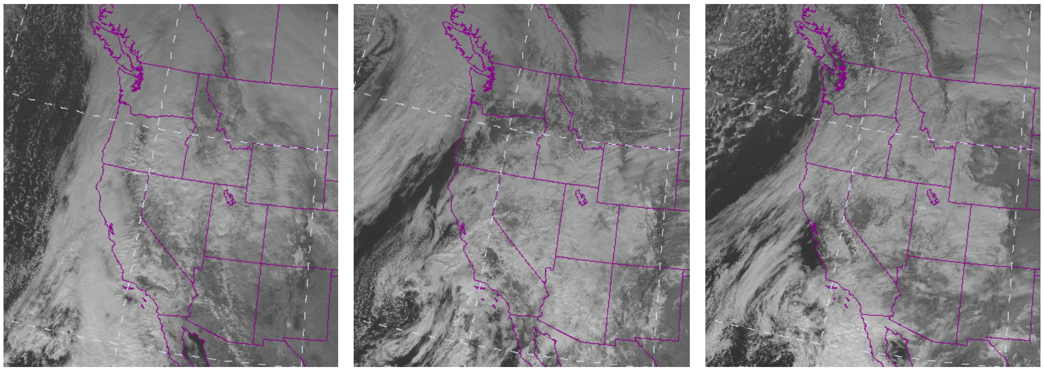


FIGURE 9.

Visible imagery from noon PST on January 23 through 25, 2013 (left to right).

in much below normal temperatures for about 12 days prior to the low resource period. This cold gradually moderated so that temperatures were close to normal by January 23rd when considered across the entire west. However, while the SW had warmed to above normal, parts of the NW, including where a lot of wind generation is located, were still inverted and cold with widespread fog. Aside from the fog in the PNW, the pattern produced clear skies/good solar resource across the west, and strong wind resource in the Rocky Mountain areas and Alberta which compensated for the reduced wind power in California and the PNW. However, as the upper ridge slid slowly inland on January 22, 2013, the west coast came under the influence of three successive storms. The storms were weak and moving slowly as they encountered the strong upper ridge which was still moving slowly east. Clouds began to spread across the entire length of the west coast on the evening of January 22 and by noon on January 23 they were impacting most of the region from Nevada west, along with scattered cloudiness further west (Figure 9, left). By the following day most of the west was completely cloud covered and remains overcast on January 25 (Figure 9, middle and right). For three days, impulses spin inland around a stationary upper-level low off the California coast, before the slow-moving ridge finally weakened and moved off to the east allowing a more progressive pattern to re-establish. These impulses were very weak and didn't produce much in the way of offshore wind. At the same time, persistent offshore gradients, which aren't conducive to generation in California's primary wind energy locations, kept California land-based wind generation low. The model indicated a pickup in Pacific Northwest wind, but here again, like in the other events, this is an over-estimate due to the wind farms there being impacted by a strong inversion. A bright spot is the wind in the DSW which is above normal like for the other events described above. Additional similar events need to be studied to see if this is a typical outcome, and if it is, an evaluation of if it is worth incentivizing more wind capacity in this region to help with regional reliability might be worthwhile.