A Weather Analysis for Xcel Energy's 2030 Colorado Preferred Plan

Josh Novacheck, Marty Schwarz, and Grant Buster

Produced under direction of Xcel Energy by the National Renewable Energy Laboratory (NREL) under a Technical Services Agreement.

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List of Acronyms

BA	Balancing Authority
CC	combined cycle
CT	combustion turbine
MW	megawatt
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Resource Database
PCM	production cost model
PSCo	Public Service Company of Colorado
PV	photovoltaic
SAM	System Advisor Model
WACM	Western Area Colorado Missouri
WECC	Western Electricity Coordinating Council
WI	Western Interconnection
WIND	Wind Integration National Dataset

Executive Summary

The Public Service Company of Colorado (PSCo), a subsidiary of Xcel Energy (Xcel), plans to meet its target of an 80% reduction in CO_2 emissions over 2005 levels by 2030 through its Preferred Plan[1,2] that includes increasing the wind and solar energy on its system, reducing coal, and adjusting the operation and dispatch of new and existing thermal generation. The objective of our analysis reported here is to identify how the PSCo generation and transmission of its Preferred Plan might operate in the face of specific weather events. We investigate weather events that currently cause stress to PSCo's system, such as winter storms and extreme heat. In addition, we explore how the future system responds to scenarios that may be considered normal weather conditions today, but that have a large impact on wind and solar generation potential.

In this report we first describe the methods, data, and limitations of the study to assess weather risks to the PSCo Preferred Plan. We then describe the four weather events we modeled and analyzed. The description includes details about the weather during the event, the impact on wind, solar, load and net load, and finally the system dispatch results of the PSCo Preferred Plan generation and transmission system during the event. Finally, we pull together the analysis of the four weather events into two key findings of the analysis.

Note: this study was completed in the Spring of 2021 to provide analysis for PSCo. PSCo referred to this analysis in its public 2030 Preferred Plan. NREL is publishing the study now so that we, along with any members of the public, can cite it. The work is specific to PSCo's system, but we believe the findings can help inform the impact of extreme events on other bulk power systems as well.

Study Approach

Our study leverages high-resolution wind and solar data, technology modeling, and geospatial analysis developed by the National Renewable Energy Laboratory (NREL) to identify and model the generation profiles of 2030 PSCo wind and solar generating resources, along with the rest of the Western Interconnection (WI). The datasets allow for investigation of weather events that occurred between 2007 and 2013. Though 2007–2013 is not a complete sample of all high-impact weather events that could impact PSCo's system, the historical range does allow us to identify case studies to test the ability of the PSCo Preferred Plan to accommodate such events. For details about the wind, solar, and load data sets used, see (Novacheck et al., 2021).

In prior work (Novacheck et al. 2021), we developed future 2030 generation and transmission infrastructure for the WI to be used with a nodal production cost model (PCM). The PCM

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[1] Public Service Company of Colorado. 2021. "Our Energy Future: Destination 2030. 2021 Electric Resource Plan and Clean Energy Plan." https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/Resource%20Plans/Clean%20Energy%20Plan/Vol_1-Plan_Overview.pdf

[2] Public Service Company of Colorado. 2023. "Our Energy Future: Destination 2030. 2021 Electric Resource Plan and Clean Energy Plan." https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/PUBLIC%202021%20ERP%20&%20CEP_120-Day%20Report_FINAL.pdf

database was simulated in PLEXOS by Energy Exemplar[3] to understand the scheduling and dispatch of the system during the selected weather events. For this analysis and working with PSCo, we updated generation and transmission within the PSCo Balancing Authority to better reflect the 2030 PSCo Preferred Plan. Finally, we modeled two infrastructure sensitivities to understand:

1. The resilience value of imports to enable the sharing of the geographic diversity of wind and solar generation from neighbors in the WI, and

2. The operational value of storage versus combustion turbines and combined cycles during the weather events investigated in the PCM.

Key Findings

Based on the analysis of the 2007–2013 weather events within the wind, solar, and load data sets and the PCM analysis of four selected events, there are two key takeaways about the 2030 PSCo Preferred Plan and how its infrastructure interacts with a diversity of weather events.

1. **Peak load period is not necessarily the most concerning period anymore, as wind and solar generation contributions increase. Near peak load periods with low wind generation output in the evening lead to very narrow but high net load peaks.**

The PSCo peak load day in 2007–2013 data set occurs on June 25, 2012. On that day wind and solar generation potential (the generation before any wind or solar curtailment), were at or above the seasonal average. The availability of these resources limits the stress that peak load period may cause to the future system. However, similar periods to peak load quickly become a larger concern. The peak net load hour within our 2007–2013 data set occurs in PSCo on August 22, 2011, with August 23 close behind. On August 22, load peaks 790 MW below the June 25, 2012 peak load hour and on August 23, load tops out at 440 MW below the June 25 peak. High, but not extreme, temperatures drive up demand. However, the heat in this event also comes with stagnant high pressure in the afternoon and overnight, leading to very little wind generation. On August 22 and 23 the daily wind generation potential is in the 9th and 12th percentiles (relative to the seasonal distribution of wind generation), and it falls below 1,000 MW at sunset. More generation capacity from the PSCo Preferred Plan was used during the peak net load period than the peak load period, and therefore the peak net load period presents a greater resource adequacy risk. In our modeling of this period, the PSCo Preferred Plan successfully met all load during the peak net load period, but periods such as these should continue to be a focus for long term planning for PSCo to ensure adequate generation capacity is available.

2. **Winter storms, extreme and moderate cold waves, and periods of seemingly uninteresting weather can lead to infrequent but extended wind and solar resource deficits. NREL's modeling suggests that a generator with high availability for an extended duration that can be called on to respond quickly has unique resilience and**

[3] "PLEXOS Market Simulation Software," Energy Exemplar, https://energyexemplar.com/solutions/plexos/

critical reliability value. Examples of such a generator include combined cycles and combustion turbines paired with a reliable fuel source.

We identified three specific but unique weather events that all lead to extreme deficits to the wind and solar resource output in PSCo and beyond to investigate how PSCo's 2030 system might react to such a weather event. The events include:

- A set of winter storms that impacted the country in December 2013
- The largest wind generation derate due to turbine blade icing in the 2007-2013 data set, which occurred in October 2009
- A cloudy but calm set of days from April 2013.

In all three events, weather causes a decrease in the aggregate wind and solar generation leading to a day or more of elevated net load in PSCo compared to typical conditions for that time of year.

In all three cases, the PSCo system experiences an extended period of high net load due to a combination of factors that lead to low wind and/or solar generation. In each event, PSCo uses its available storage, import capability, and a combination of fast start up and ramping of gas-CCs and gas-CTs to fill the wind and solar resource deficit. Speed of the response is also a critical characteristic to ensure resilience to these weather events. At the height of the December 2013 Winter Storms event, the aggregate gas-CT fleet ramps up at a rate of 600MW in one hour, while in the other two events gas-CTs and storage are called on around the peak net load to provide capacity quickly for a short period.

Geographic diversity of wind and solar enabled by more imports was shown to reduce the modeled impacts of the April 2013 Abnormally High Net Load event. The decreased wind and solar generation mostly impacted Colorado, allowing for imports of wind and solar from other parts of the interconnection to help meet the elevated net load in PSCo. However, the October 2009 Icing and December 2013 Winter Storms events have broad impact beyond PSCo's territory and Colorado's borders, limiting how much imports can replace the role filled by the gas-CTs and gas-CCs in the 2030 PSCo Preferred Plan. 4-hour storage, on the other hand, has limited ability to provide all of the system generation needs in all three events. The results from the sensitivities further highlight the value of combustion turbine and combined cycle generation to provide energy to the system during these events. At times, to ensure system reliability and resilience to the weather events, there is a need for a resource to respond quickly and reliably for an extended period. The 2030 PSCo Preferred Plan contains those characteristics.

Conclusions

In our analysis, we exposed the 2030 PSCo Preferred Plan to a diversity of weather events. Using high spatial and temporal wind and solar data, we identified weather events that caused extremely low generation potential in the aggregate wind and solar resource leading to extended periods of high net load. These events were a mix of heat waves, winter storms, and just calm ——but cloudy or low wind—periods. In all four weather events we modeled using a production cost model of the WI, the 2030 PSCo Preferred Plan was able to reliably accommodate demand in all hours. Further, the events suggest there is unique weather resilience value in the 2030 PSCo Preferred Plan that the sensitivities that added import capability or more storage do not offer.

We did not explicitly investigate how combined cycle or combustion turbine capacity in the 2030 Plan is utilized under average conditions or when there is a surplus of wind and solar. However, with an 80% reduction of CO_2 emissions stated in the PSCo 2030 Preferred Plan and given that the PSCo average net load is only 2,000 MW in our scenarios, the annual capacity factors of these units might be low. However, our analysis suggests that as PSCo's generation fleet becomes increasingly dependent on wind and solar generation, there will continue to be periods that call on the unique resilience value of generating capacity with storable fuels (e.g., combustion turbines and hydrogen fuel cells). These periods are infrequent but can happen any time of year, during stormy conditions or simply during cloudy, calm weather.

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Introduction

The Public Service Company of Colorado's (PSCo), a subsidiary of Xcel Energy (Xcel), 2030 Preferred Plan lays out an ambitious decarbonization pathway over the next few decades. The plan includes an 80% reduction in CO_2 emissions over 2005 levels by 2030, followed by a 100% carbon-free target by 2050. PSCo will likely meet the 2030 target by increasing the wind and solar energy on their system, reducing coal, and adjusting the operation and dispatch of new and existing thermal generation. Though PSCo has many years of experience operating their system with wind, and increasingly with solar, adding wind and solar capacity to the system to achieve these goals will challenge historical operating paradigms, especially during specific weather events.

Weather that stresses grid resilience typically does so by creating peak loads across a broad region while placing constraints and increasing outage potential for transmission and generation (Murphy, Sowell, and Apt 2019; Allen-Dumas, KC, and Cunliff 2019). Two examples of such stresses are cold snap events like the polar vortex of January 2014 (NERC 2014), the recent blackouts in Texas in February of 2021, and extreme heat events like that which the California experienced in August 2020. Also, the increase in wind and solar penetration has exposed the system to new and unforeseen stressors, such as the wind turbine low temperature cutouts that occurred throughout the footprint of the Midcontinent Independent System Operator during an intense cold wave in January 2019 (Rose 2019).

The objective of this analysis is to identify and model specific weather events, and to analyze how the generation and transmission prescribed by PSCo's 2030 Preferred Plan might respond. We investigate weather events that currently cause stress to PSCo's system, such as winter storms and extreme heat. In addition, we explore weather events that operators may not see as concerning today, but which will likely be challenging for a future high variable generation system. These include extended and static high-pressure weather systems, which can lead to depressed wind resource for multiple days.

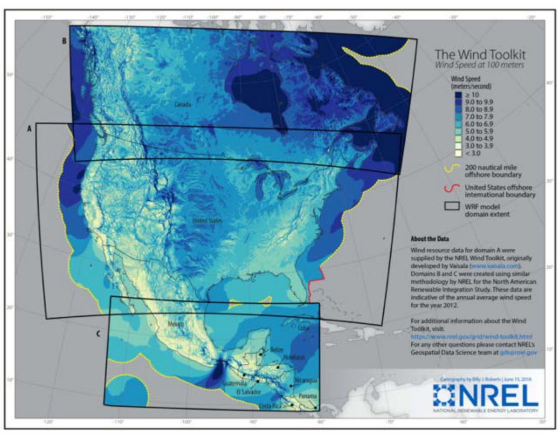
Note: this study was completed in the Spring of 2021 to provide analysis for PSCo. PSCo referred to this analysis in its public 2030 Preferred Plan. NREL is publishing the study now so that we, along with any members of the public, can cite it. The work is specific to PSCo's system, but we believe the findings can help inform the impact of extreme events on other bulk power systems as well.

Methods

Wind, Solar, Load, and Thermal Outages Data

This study leveraged the high-resolution wind and solar data, technology modeling, and geospatial analysis developed by the National Renewable Energy Laboratory (NREL) to identify and model the generation profiles of 2030 PSCo Preferred Plan wind and solar capacity, along with the rest of the Western Interconnection (WI). The data sets allow for investigation of weather events that occurred between 2007 and 2013. Though that period is not a complete sample of all high-impact weather events that could impact PSCo's system, the historical range does allow us to identify case study events to test the resilience of PSCo's Preferred Plan.

The NREL Wind Integration National Dataset (WIND) [4] Toolkit is a wind integration resource data set covering the coterminous United States. This data set models the weather that occurred in 2007–2013 and provides gridded wind resource at 2-km spatial resolution and 5-minute temporal resolution (Figure 1, left). 60-minute temporal resolution data was used for this analysis. The NREL National Solar Resource Database (NSRDB)[5] was used to model the solar resource and it covers 1998–2019. The native resolution is 4 km, and the temporal resolution is 30 minutes (Figure 1, right). The Renewable Potential Model (reV) (Rossol, Buster, and Bannister 2021; Maclaurin et al 2019) and the NREL System Advisor Model (SAM)[6] were used together to create hourly wind and solar generation profiles for 2007–2013. reV chooses the resource pixels from the WIND Toolkit and NSRDB to represent new and existing wind and solar generating facilities, and SAM models the generation profiles based on the weather data at the chosen pixels for the facility technology and configuration. Wind turbine blade icing was modeled within SAM using a range of temperature and relative humidity to identify hours where blade icing might occur. During the hours with such conditions, the generation from affected wind turbines is zero. For this study, we also introduced a 24-hr period during which icing would persist on the blades after the final period of identified icing based on temperature and humidity. This therefore continued to derate potential wind generation at the facility.



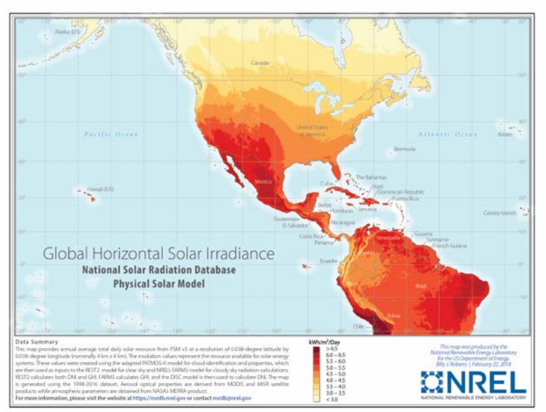


Figure 1. Maps of the WIND Toolkit (left) and NSRDB (right), which were used to create the wind and solar generation profiles

Historical load profiles from 2007 to 2013 for PSCo and the rest of the WI were collected and grown to represent 2030 forecast demand growth. Electrification, urbanization, and technology transformations have altered and will continue to alter the shape of electricity demand profiles. However, in the absence of bottom-up load modeling, it is preferrable to use historical load shape that are based on the same meteorology as the wind and solar generation profiles developed using the WIND Toolkit and NSRDB respectively. Better estimates to the shape of demand while still capturing the simultaneous weather effects that impact wind and solar generation is an area of ongoing research.

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[4] "Wind Integration National Dataset Toolkit," NREL, https://www.nrel.gov/grid/wind-toolkit.html
[5] "NSRDB: National Solar Radiation Database," NREL, https://nsrdb.nrel.gov
[6] "System Advisor Model (SAM)", NREL, https://sam.nrel.gov

Another key aspect of modeling weather event impacts to the power system is capturing the correlation between outrage rates of thermal generating units and temperature. Murphy, Sowell, and Apt (2019) published correlations between temperature and thermal outages by generator type using historical outage data from PJM. Using temperatures from the WIND Toolkit numerical weather modeling, we created outage rates at thermal units throughout the WI and PSCo based on the temperature they would have experienced. The result leads to increased thermal outages during periods of very low and very high temperatures. These outage rates differ depending on the fuel type and unit technology.

Generation and Transmission Infrastructure

In prior work (Novacheck et al. 2021), we developed future 2030 generation and transmission infrastructure for the WI to be used with a nodal production cost model (PCM). The PCM database is simulated in a commercial software produced by Energy Exemplar[7] called PLEXOS to optimize the scheduling and dispatch of the system during the selected weather events. For this analysis, working with PSCo, we updated generation and transmission within the PSCo Balancing Authority (BA) of our WI model to better reflect the 2030 PSCo Preferred Plan. Figure 2 shows the installed generation capacity in PSCo (left) and the WI (right) inclusive of the PSCo generation. The PSCo system includes units previously announced to be retired before 2030, the conversion of the Pawnee coal unit to burn natural gas[8], and the expansion of wind, solar, storage, and gas combustion turbine capacity.

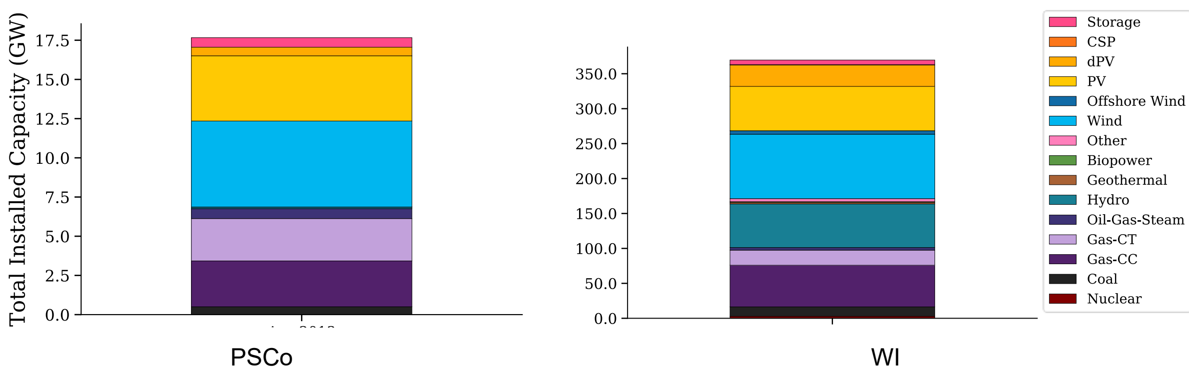


Figure 2. Installed generation capacity in the 2030 model for PSCo (left) and the WI (right)

The original database has a full nodal representation of the WI, including 20,000 transmission buses and transmission lines. To simplify the representation of the WI system, we reduced the transmission representation of regions that are not direct neighbors of the PSCo BA into a basic regional DC pipe-flow model. For those regions, we also allowed their generating units to be committed linearly instead of reflecting the minimum generation levels of thermal and hydro units as we do in the PSCo BA and its direct neighbors.

[7] "PLEXOS Market Simulation Software," Energy Exemplar, https://energyexemplar.com/solutions/plexos/
[8] In this modeling Pawnee was assumed to be a gas combined cycle, while in reality it will be converted to a gas steam turbine.

Within the PSCo BA, we enforce thermal limits of lines with voltages of 230 kV and above. Outside the PSCo BA, we enforce Western Electricity Coordinating Council (WECC) critical paths, which are defined as interfaces (i.e., sets of lines with an aggregate minimum and maximum flow allowed), limiting large interregional power flow beyond the path limits. Additionally, we cap imports into the PSCo BA to be below or equal to 850 MW. This reflects contractual and technical limitations to imports that go beyond the WECC critical path constraints, along with allowing imports to serve non-PSCo load within the PSCo BA.

Finally, we modeled two infrastructure sensitivities to understand the reliability provided by:

1. sharing of the geographically diverse wind and solar generation from neighbors in the WI, and

2. greater deployment of storage instead of combustion turbines located in the PSCo BA.

The first sensitivity removed the 850-MW import limit into the BA, assuming the necessary new transmission is built to accommodate larger transfers of power. We still enforce the interface limits throughout WECC and thermal limits of lines with voltages 230kV and above within the PSCo BA. The second sensitivity added 1,600 MW of battery energy storage and removed an equivalent amount of gas-CT capacity from the PSCo BA. The additional batteries are assumed to have 4-hour duration, which is the same duration assumed for the 350 MW of batteries added in our modeled representation of the 2030 PSCo Preferred Plan. No additional generation capacity was added. These sensitivities are a first-order investigation of the benefit of additional infrastructure to the system during the studied weather events and should not be considered alternatives to the 2030 PSCo Preferred Plan.

Event Identification, Time Series, and Daily Distribution Plots

Several events were identified based on their interesting meteorological characteristics and actual impacts they had on the power system at the time, even before wind and solar become significant contributors to energy production. The methods used, a meteorological description, and an analysis of these events, can be found in (Novacheck et al., 2021). Relevant events to Colorado and PSCo from (Novacheck et al., 2021) were considered for further analysis in this work.

Other events were identified based on their high net loads and wind or solar PV resource deviation from average conditions. The plot shown in Figure 3 demonstrates the criteria for determining the stress an event may cause to the system. Four data types are shown in the hourly and daily plots. All data reflect the 2030 PSCo Preferred Plan. Wind is shown in blue, solar photovoltaics (PV) in gold, the load in green, and net load (load minus available wind and solar) in purple. The solid time series is the actual generation or load profile for the event. The dotted time series is the rolling average generation or load profile using the month around the event for all years in the data set (2007–2013). The vertical distributions on the right side of the figure show the distribution of daily average generation or load. The solid-colored distributions are distributions of the seasonal generation or load, again determined by the month around the event for all seven years in the data set. The dashed grey distribution is daily generation or load for the entire seven-year data set. Finally, the red dashed lines within the distributions are the location of each day of the event within the distribution. Using all of this information, we determined the deviation of an individual event relative to hourly or daily averages and we determined how far into the tails of the distribution the event lies. Working with PSCo, we identified a subset of events to consider for more detailed modeling in the PCM. Additional events that were not model in the PCM are described in the appendix.

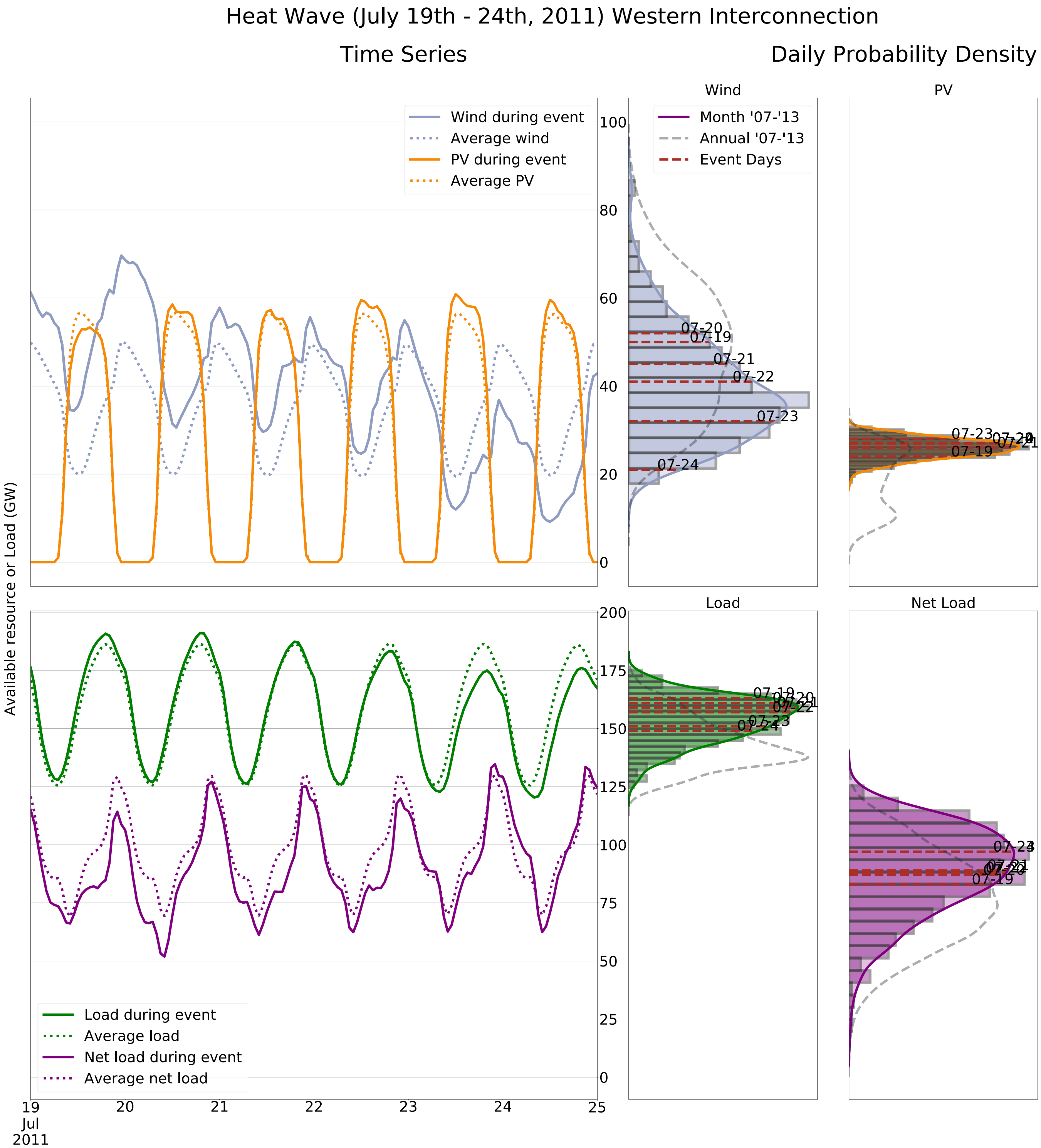


Figure 3. Example of event plot showing the hourly and daily wind, solar PV, load, and net load

All time series plots in this report are shown in Mountain Standard Time.

Production Cost Modeling

This section describes the plots used to understand the results of the production cost modeling (PCM). Figure 4 shows an example of a dispatch stack for the 2030 PSCo Preferred Plan. Each colored area shows the generation of different fuel and generator types over time, each adding to the total, or aggregate, generation within the PSCo BA. The pink area indicates storage generation. The dotted black line is the total demand within the PSCo BA before accounting for battery charging load or pumped storage hydro pumping load. The solid black line is the total demand plus battery charging and pumping loads. Finally, the light grey area on top of the generation stack indicates wind or solar curtailment and is not actual generation.

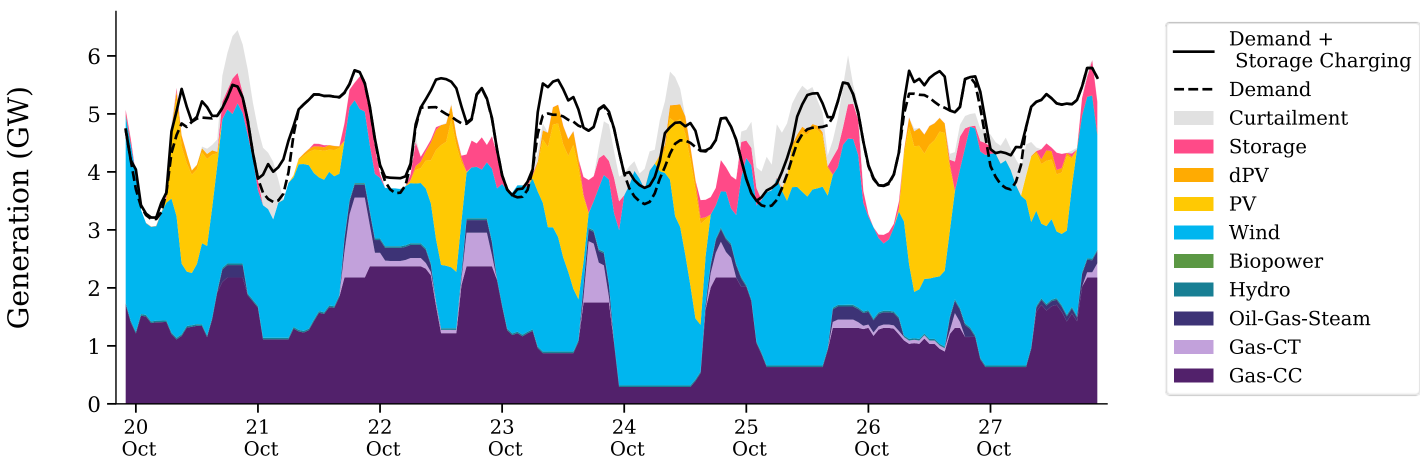


Figure 4. Example of dispatch stack of the PSCo system in October 2019

When the solid line (load plus storage charging) is above the total generation stack, the PSCo BA is importing power from its neighbors. When the stack is above the load line, the PSCo BA is exporting.

Caveats and Limitations

The caveats and limitations for our analysis include the following.

- *Reserve totals:* We do not attempt to capture actual PSCo reserve requirements. Our reserve assumptions aggregate the PSCo BA reserve requirement with the neighboring Western Area Colorado Missouri, or WACM, BA. The total reserve is based on load and the variability and uncertainty of the wind and solar fleet (Ibanez et al. 2013). This may lead to different dispatch decisions in the PCM results, and at times allow for more flexible operations than PSCo deems realistic.

- *Reserves provided by variable renewable energy:* Our modeling allows wind and solar to provide reserves, using curtailed energy to provide upwards reserve and the ability to curtail to provide downward reserve. For both reasons, there are hours in our PCM results where PSCo's system serves it entire obligation load with 100% wind and solar power. These modeling results do not imply PSCo could meet current North American Electric Reliability Corporation (NERC) reliability standards when operating in such a manner.

Like earlier, this may lead to different system dispatch results and more flexible operations.

- *Renewable energy locations:* The new wind and new solar generation capacity in our model are based on assumed locations that meet the anticipated build out in the PSCo Preferred Plan. The generation profiles used in this study reflect the weather experienced at these theoretical locations. They may not coincide perfectly with exact locations of new projects in the 2030 plan.

- *Thermal outage probabilities use a single draw:* As described in Section 1.1, the likelihood of thermal outage is correlated with temperature during these events. The correlation between outages and temperature is based on historical data from PJM (Murphy, Sowell, and Apt 2019), and not on historical performance data from PSCo. Based on the changing likelihood of an outage, the PCM determines the outage pattern for all units based on a single random outage draw. This may overstate or understate the effect of thermal outages on how the event is handled by the model.

- *No transmission outages:* We do not reflect in our modeling any outages of transmission facilities. Flows on major transmission interfaces are derated to reflect security constraints.

- *No forecasting:* We do not consider forecast errors of wind, solar, or load for this study. Adding additional uncertainty to the simulation may lead to increased usage of flexible generators such as combustion turbines or storage.

- *Snow cover on PV panels:* Persistent snow cover on solar PV panels is not well captured in our modeling and is an area of ongoing research.

- *Modeling region:* In our modeling results, PSCo refers to the BA, and not just Xcel's territory. Though much of the BA and its infrastructure is within Xcel's Colorado territory, some of the generation and load belong to other utilities.

- *Historical dataset:* The 2007–2013 data set is not a robust sample of all high-impact weather events that could impact PSCo's system.

Results: Event Analysis

This section steps through four events that were selected for further investigation in the PCM. The events were chosen for their extreme wind and solar resource deviation and for the diversity in the weather that causes the deviation. The four events include:

1. December 2–8, 2013: winter storms
2. August 21–28, 2011: summer heat and peak net load
3. March 31–April 7, 2013: spring cloudy weather and high net load
4. October 20–27, 2009: wind turbine blade icing

We considered each of these four weather events in the PCM with a generation fleet that reflects the 2030 PSCo Preferred Plan but uses the *historical* weather profiles to see the implications of similar events in the theoretical *future* system.

December 2013 Winter Storms Event

Three consecutive named winter storms (Cleon, Dion, and Electra) traversed the country in early December 2013. The storms brought snow, ice, and cold weather and led to above average electricity demand in many regions of the country. The first storm, Cleon, increased load in Colorado and brought precipitation to the region on December 4. Figure 5 shows the 2030 wind and solar generation using the 2013 weather data during the series of winter storms in December 2013, along with the 2030 load and net load.

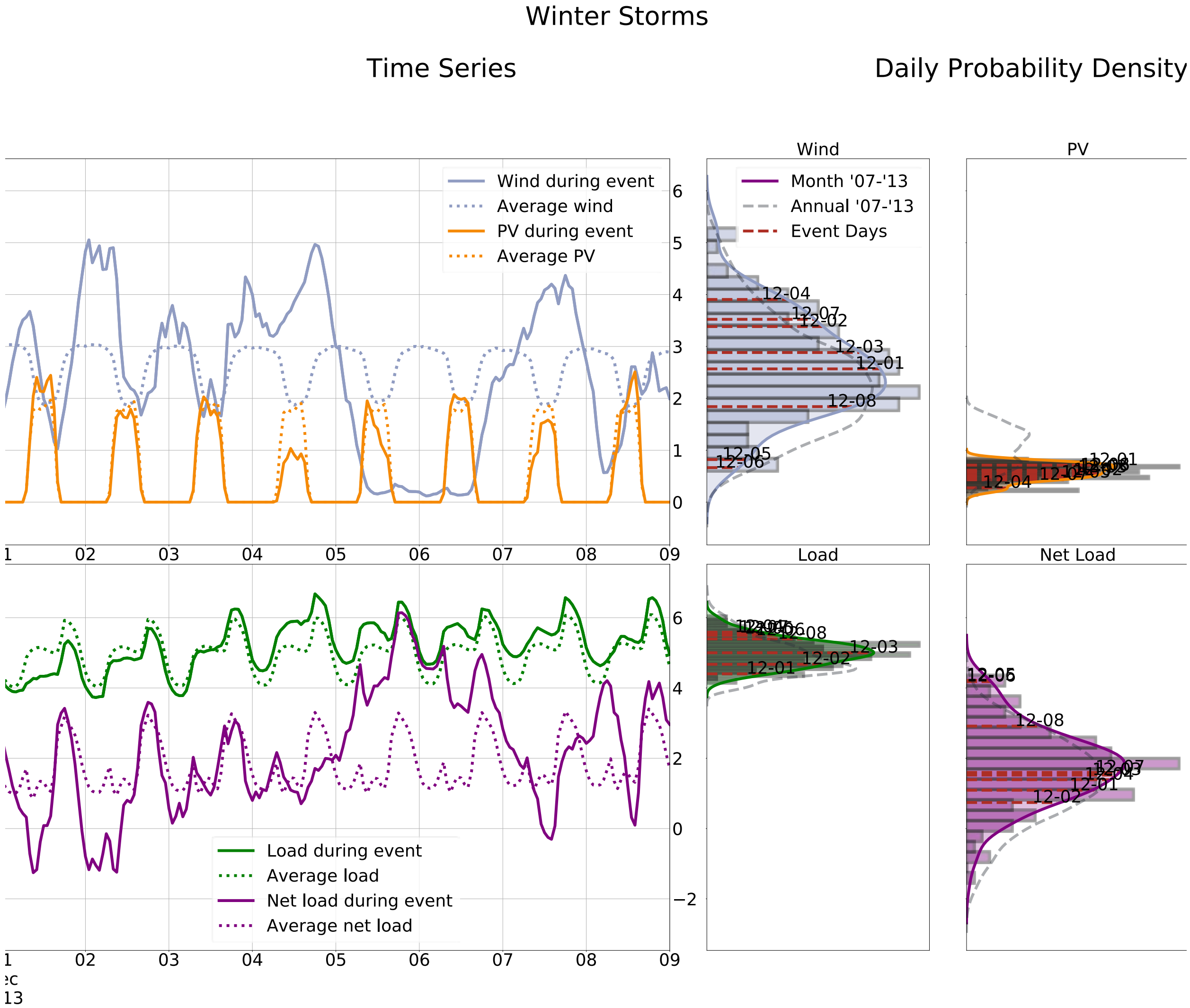


Figure 5. Wind, solar PV, load, and net load in PSCo during the December 2013 Winter Storms event

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

Cleon first affects Colorado and PSCo on December 4. The storm increased load to 10% above average for early December, while clouds and precipitation reduced PV daily generation in PSCo to the 2nd percentile in the entire data set. The storm brought high wind speeds. Without considering icing on the blades, daily wind generation would have been above the 90th percentile day in the full 2007–2013 data set. However, icing conditions reduced wind's generation potential by nearly 1,900 MW at its peak impact on December 4 (Figure 6). By the evening of December 4, wind generation begins a steep decline due to a drop in wind speeds across the Eastern Plains. In less than 18 hours, the aggregate wind fleet dropped from 3,000 MW (nearly 5,000 MW without icing) to near zero output. A clearer day with near average PV generation on December 5 tapered the net load ramp during the daytime hours, but following sunset net load nearly equaled load as wind generation continues to hover near zero. Wind generation finally recovered at sunset on December 6, and PV experienced above average output on December 8.

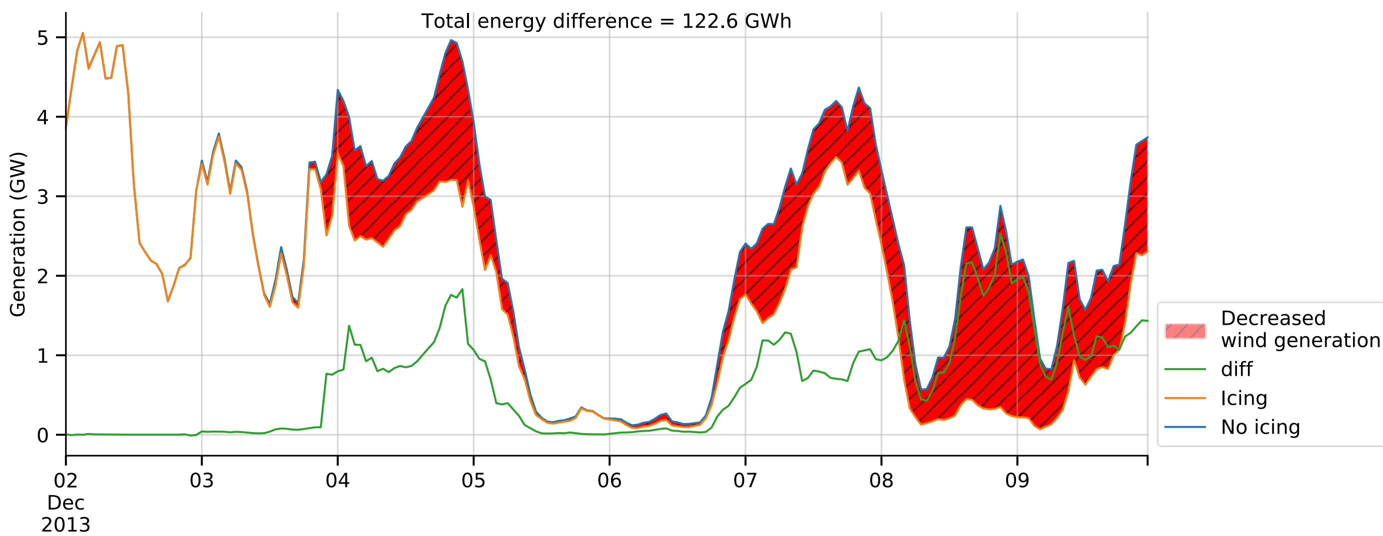


Figure 6. PSCo wind generation derated due to blade icing shutting down turbines during the December 2013 Winter Storms event. The red hatched area shows the wind energy lost due to icing.

Figure 7 shows the 2030 PSCo system dispatch during this event. As the winter storms caused a drop in wind speed and reduction in the wind generation potential on the evening of December 4, gas-CTs came online and stayed online throughout the day on December 5. Offline available generation reserves hit a low on December 5, dipping below 500 MW for the system, as PSCo imported a much as possible and fully dispatched storage. Overnight on December 5 and during the early morning hours on December 6, load decreased enough to turn off many of the gas-CTs, but imports increased. More gas-CCs are available on this day after some of the fleet was impacted by outages the day before. Wind finally recovered on the evening of December 6 as load remained elevated, before icing severely derated wind output in the evening of December 8.

Figure 8 shows how the thermal fleet is impacted by the winter storms. Cold temperatures increase the likelihood of failure for most thermal generators. Initially, net load ramped down on December 4 and 5 due to increased wind output. At this time, much of the gas-CC fleet was forced offline by cold temperatures. So, as wind output decreased on December 5, causing a precipitous increase in net load, fast commitment, and dispatch gas-CTs was the primary resources to respond to the initial net load ramp.

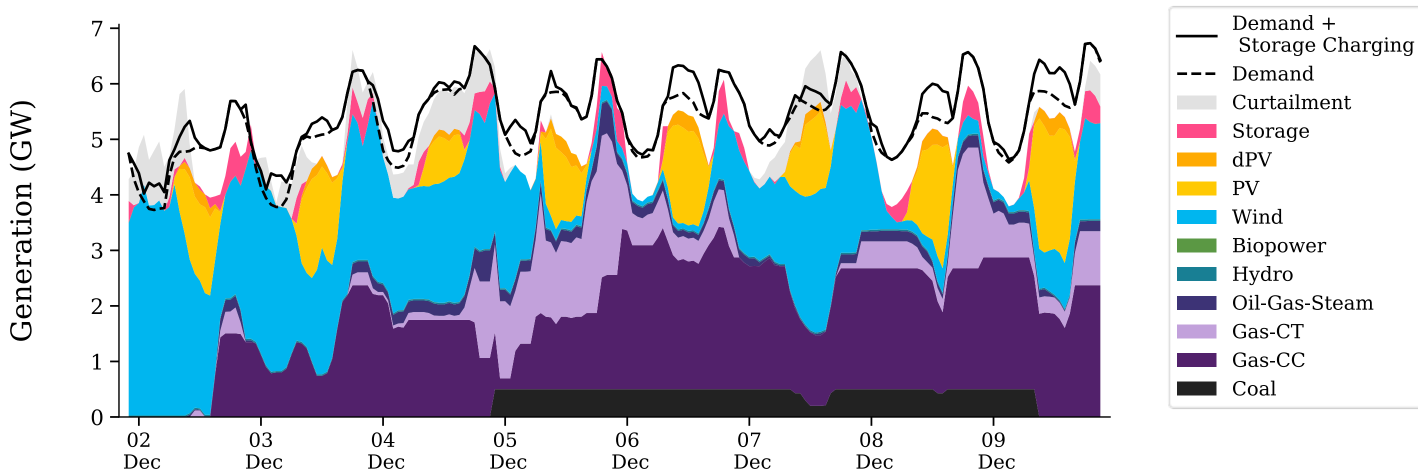


Figure 7. PSCo system dispatch during the December 2013 Winter Storms event

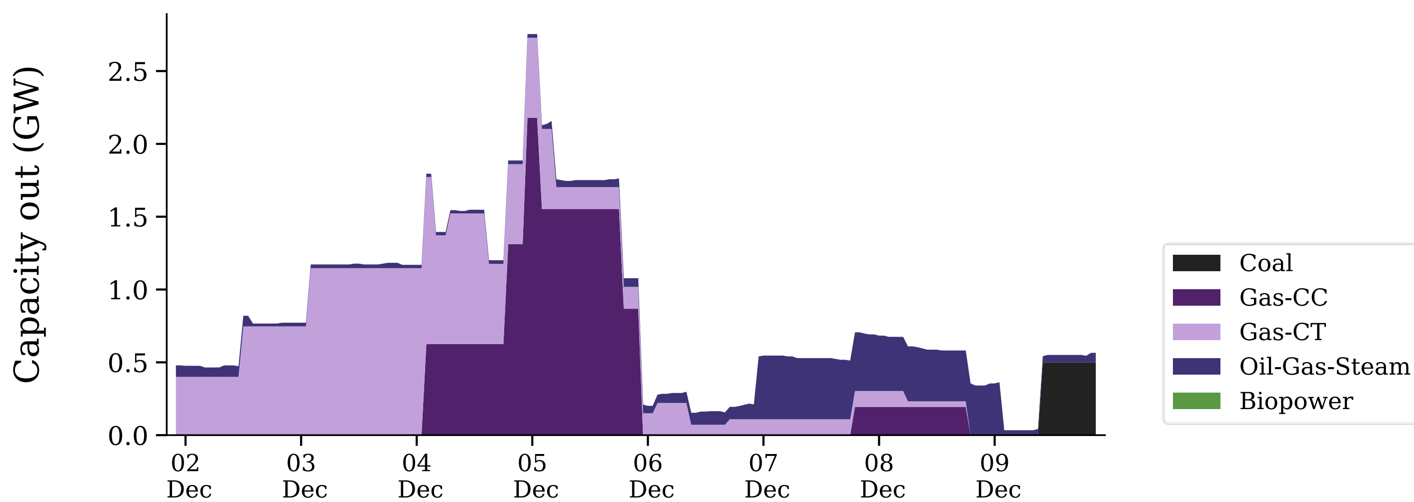


Figure 8. PSCo Thermal Outages during the December 2013 Winter Storms

In the increased import sensitivity, some of the reliance on local gas generation was alleviated by increased imports during the heart of the low wind and solar generation period in PSCo (Figure 9). However, PSCo's gas fleet still filled in the gap as net load increased with the winter storms. Thermal generation peaked at 4,000 MW on the evening on December 5. As seen in Figure 10, wind generation throughout the WI ramped down between December 4 and 6. In fact, all of the imports on December 5, the heart of the event in PSCo, come from increased generation from gas-CCs, gas-CTs, and coal from outside PSCo. Given the simplifications made for generator operations outside PSCo, this result should not be considered a better option than using local gas-CCs and gas-CTs.

In the increased storage capacity scenario, the PSCo system lacks the generation capacity or the import capability to charge the batteries sufficiently to meet all load on the evening of December 5 (Figure 11). This event requires more availability than 4-hour storage can offer. In fact, replacing gas-CT capacity with 4-hour storage results in some unserved energy on the evening of December 5–as shown by the red slivers attached to the solid black line.

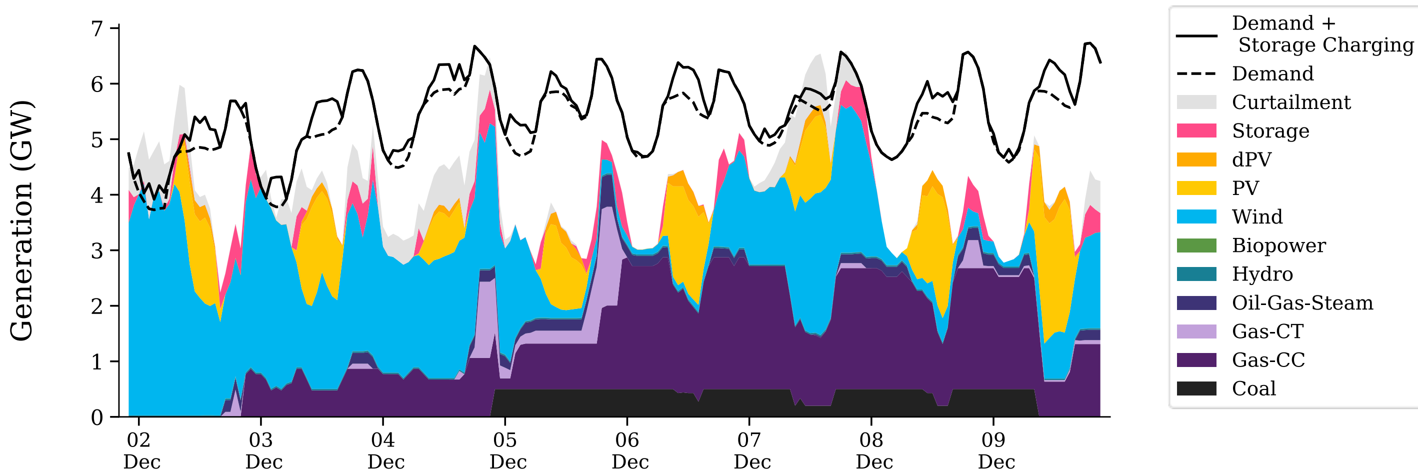


Figure 9. PSCo system dispatch with increased import capability during the December 2013 Winter Storms event

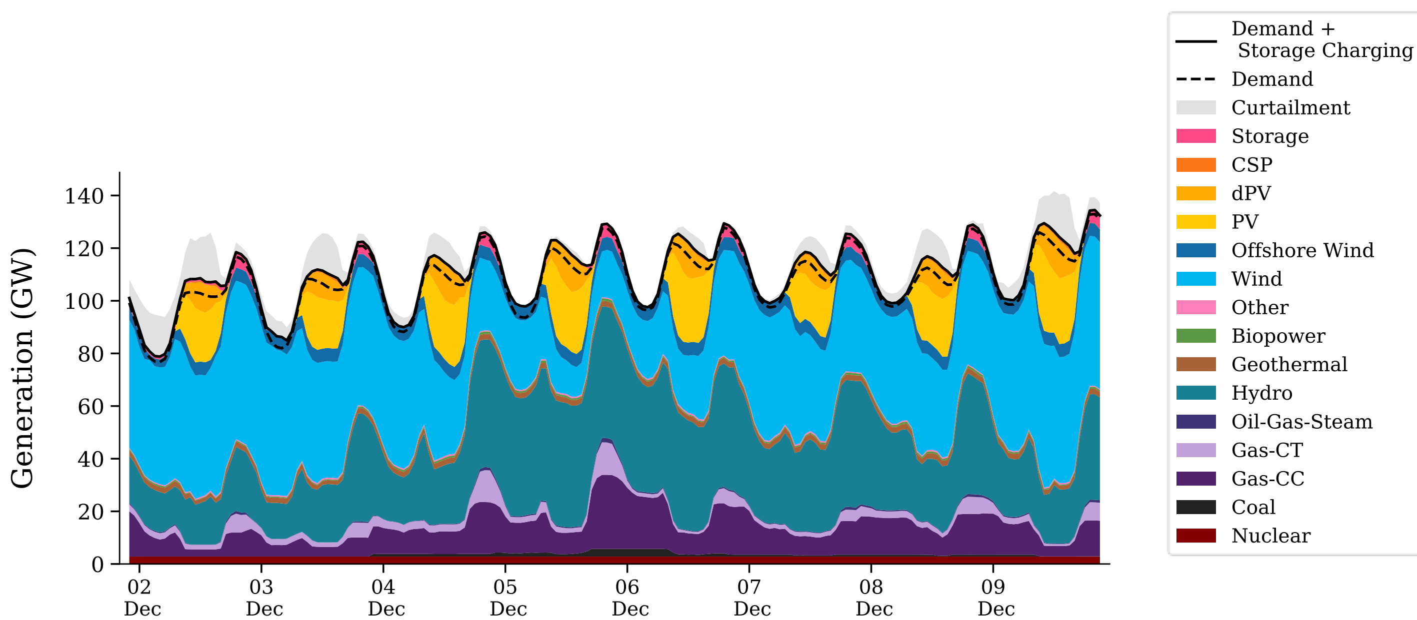


Figure 10. WI dispatch with increased import capability during the December 2013 Winter Storms event

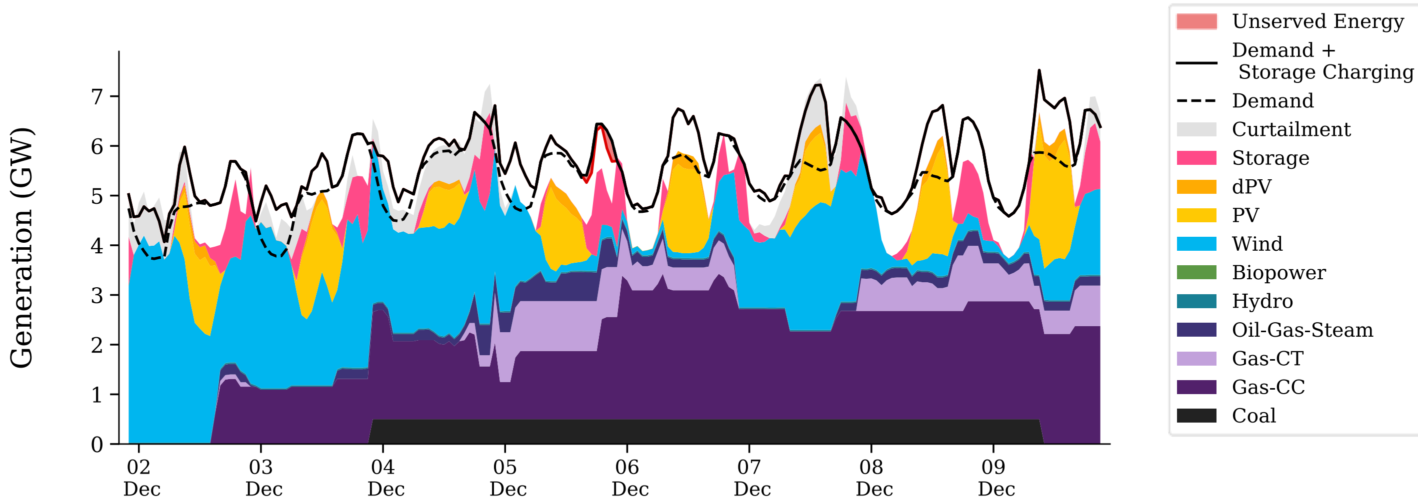


Figure 11. PSCo system dispatch with increased 4-hr storage during the December 2013 Winter Storms event

August 2011 Peak Net Load Event

The week of August 22, 2011 sent temperatures into the upper 90s across Colorado and much of the interior West. In response, load increased across the WI, though not to the highest levels seen in the data set. In PSCo, load tops out 400–700 MW below the dataset's absolute peak load period. As seen in Figure 12, the net load experienced large ramps As solar PV began to generate in the morning, net load hit its daily minimum at 0 MW on August 22 and 23. From there, it ramps up steadily throughout the day, reaching a peak at sunset of 7,400 MW, **the highest in the entire 2007–2013 data set**. Solar PV generates as expected for this time of year as the days are clear, but what makes the net load so high during this event is low wind speeds brought by this heat wave, especially right after sunset. Low wind generation in the evening is not typical of all heat waves (see the appendix for the Peak Load and Heat Wave 1 events), but heat waves with stagnant high pressure, such as this event, are particularly concerning because of the lack of wind in the evenings.

Figure 13 shows the system dispatch for PSCo during this heat wave and peak net load. All days used gas-CT quick start capability to ramp up quickly after sunset, and on August 22 and 23, all available gas-CTs and gas-CCs in PSCo were committed and operating. For four hours on August 22 and three hours on August 23, the gas-CT fleetwide capacity factor was greater than 90%. The gas-CTs ramp down only when load begins to decrease overnight.

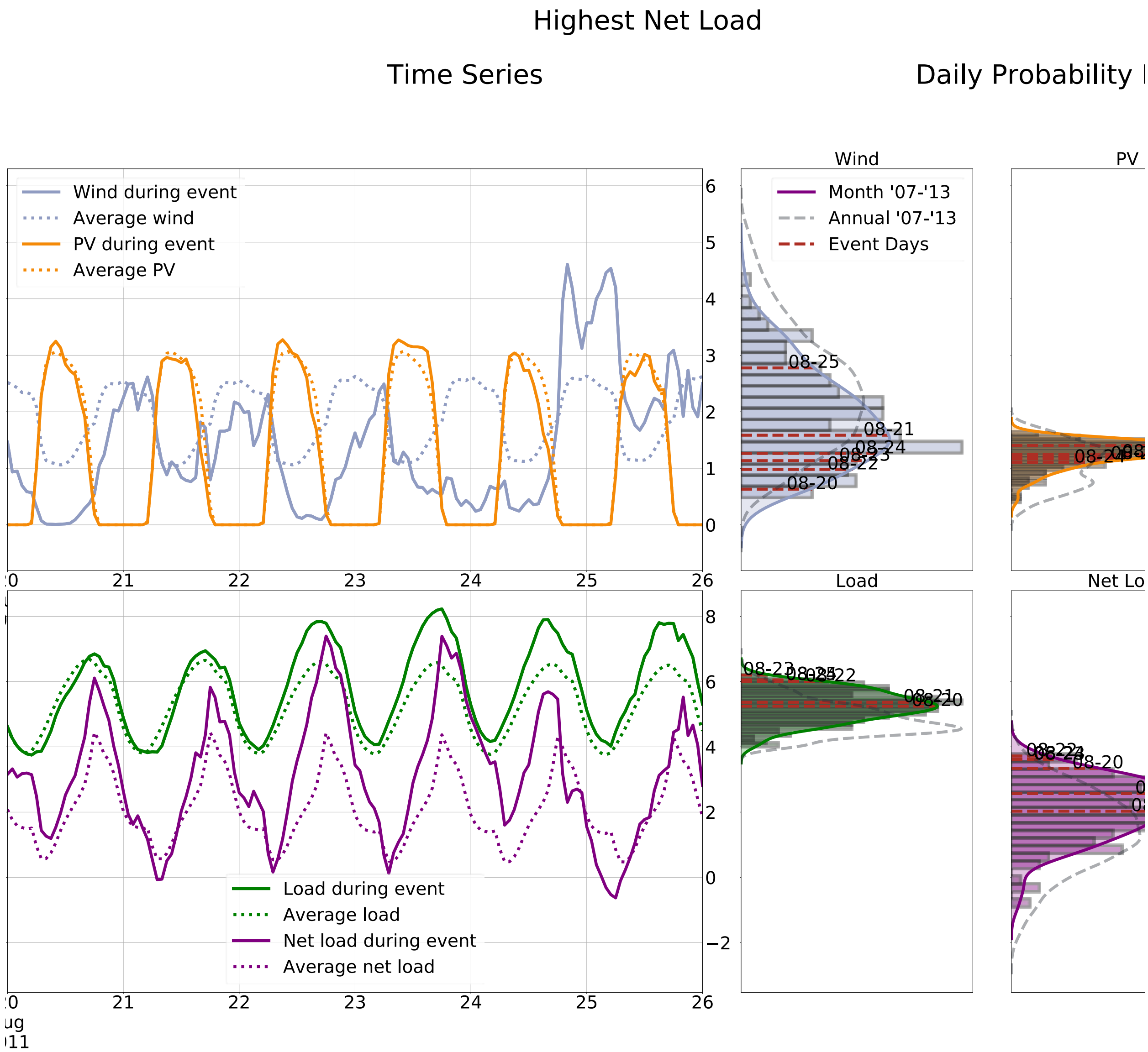


Figure 12. Wind, solar PV, load, and net load in PSCo during the August 2011 Peak Net Load event

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

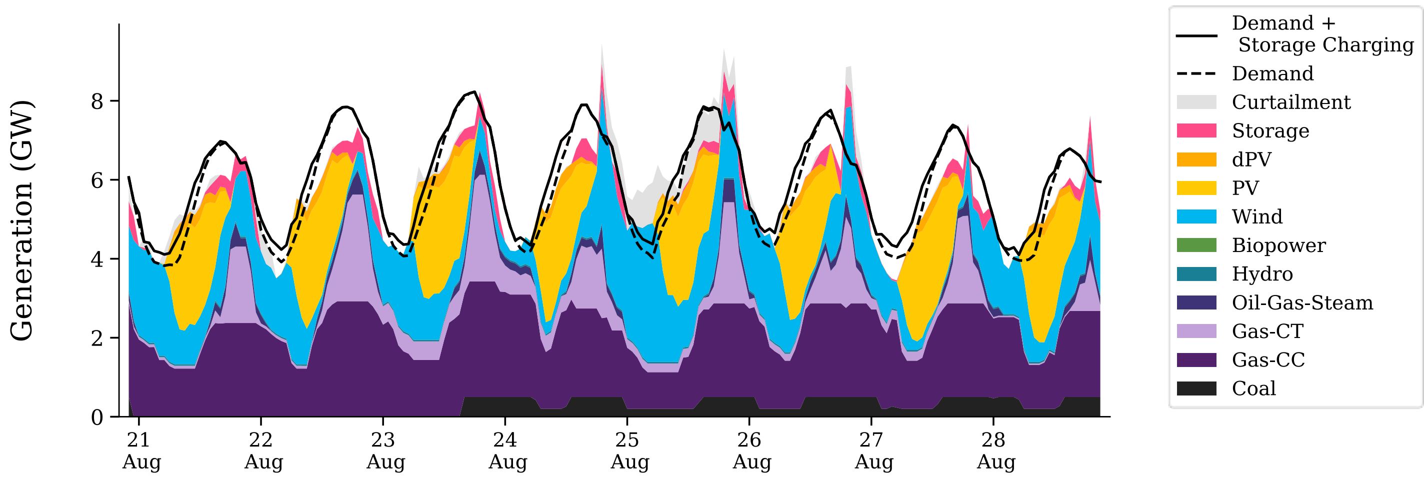


Figure 13. PSCo system dispatch during peak net load for the system in August 2011

In the increased import sensitivity, all available gas-CTs were fully dispatched even with the increased import capability (Figure 14). The time that gas-CTs remained on decreases relative the base Preferred Plan scenario; instead of 2–3 hours of full dispatch on August 22 and 23, the gas-CTs operate at full load for only 1–2 hours in the increased imports sensitivity.

There was some geographic diversity benefit during this event. While PSCo's load was highest during the heat wave on August 23, the rest of the WI load did not peak until after August 23. Also, the high-pressure system had a greater impact on Colorado and New Mexico, which left wind in Wyoming and Montana operating closer to normal for this time of year. But even this fact did not eliminate the local stress PSCo experienced, particularly on August 23, when local thermal output peaked near the amount experienced in the Preferred Plan scenario. During the 1-2 hour gas-CT dispatch peak, PSCo no longer imported electricity from outside its territory.

Swapping gas-CTs for storage predominately led to less cycling of the gas-CC fleet during the day when solar generation was high. Battery charging is represented in Figure 15 by the gap between the solid and dotted black load lines. However, the 4-hour battery storage is insufficient to provide the same level of resource adequacy as the gas-CTs that were removed, as there is dropped load at the peak net load hour on August 22.

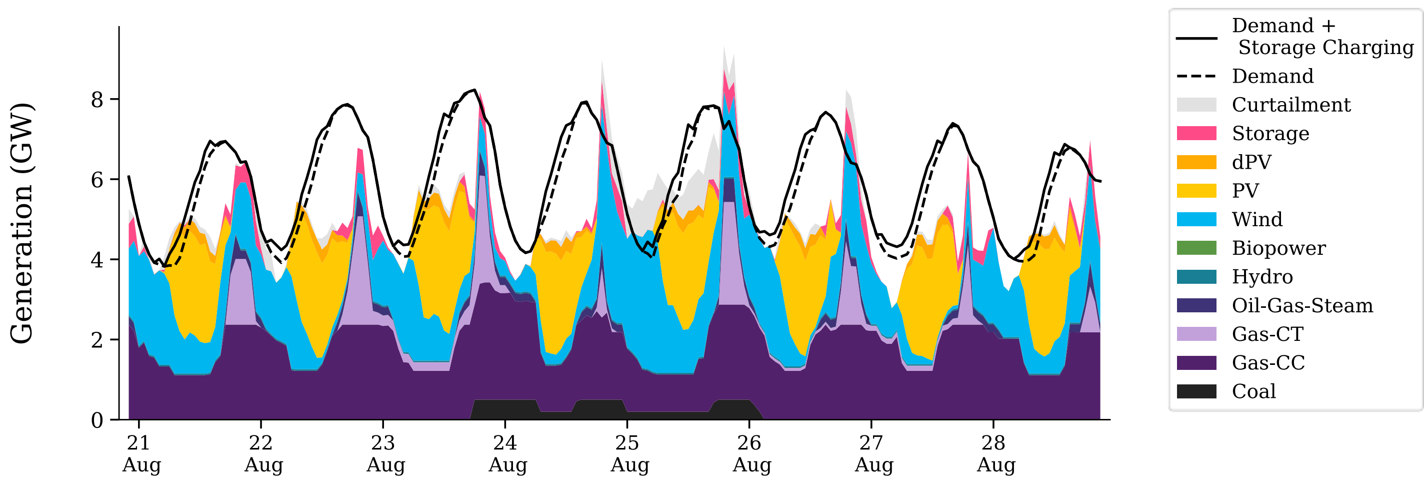


Figure 14. PSCo system dispatch with increased import capability storage during peak net load for the system in August 2011

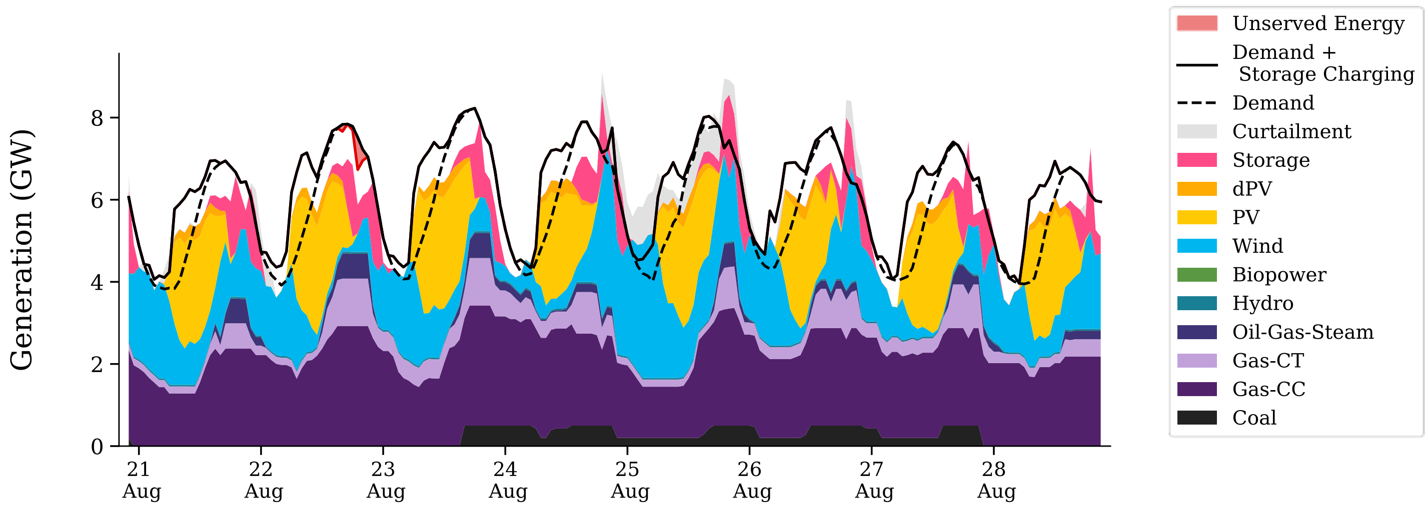


Figure 15. PSCo system dispatch with increased 4-hr storage during peak net load for the system in August 2011

April 2013 Abnormally High Net Load Event

A calm, cloudy, drizzly period in early April led to an extended period of high net load, particularly for that time of year. In April in Colorado, wind plants normally operate above their annual average, oscillating around a daily average of 2,750 MW, while longer days lead to more solar generation than earlier months. Normal conditions for this month have an average net load of only 500 MW in the PSCo Preferred Plan. Given these average conditions and historical trends for maintenance outage scheduling, this would likely be a time operators and planners would take some of the large thermal units down for annual maintenance. However, these normal patterns did not occur in early April 2013. Despite uninteresting weather conditions, abnormally low wind and solar resource resulted in a daily average net load 3,000 MW higher than average (Figure 16).

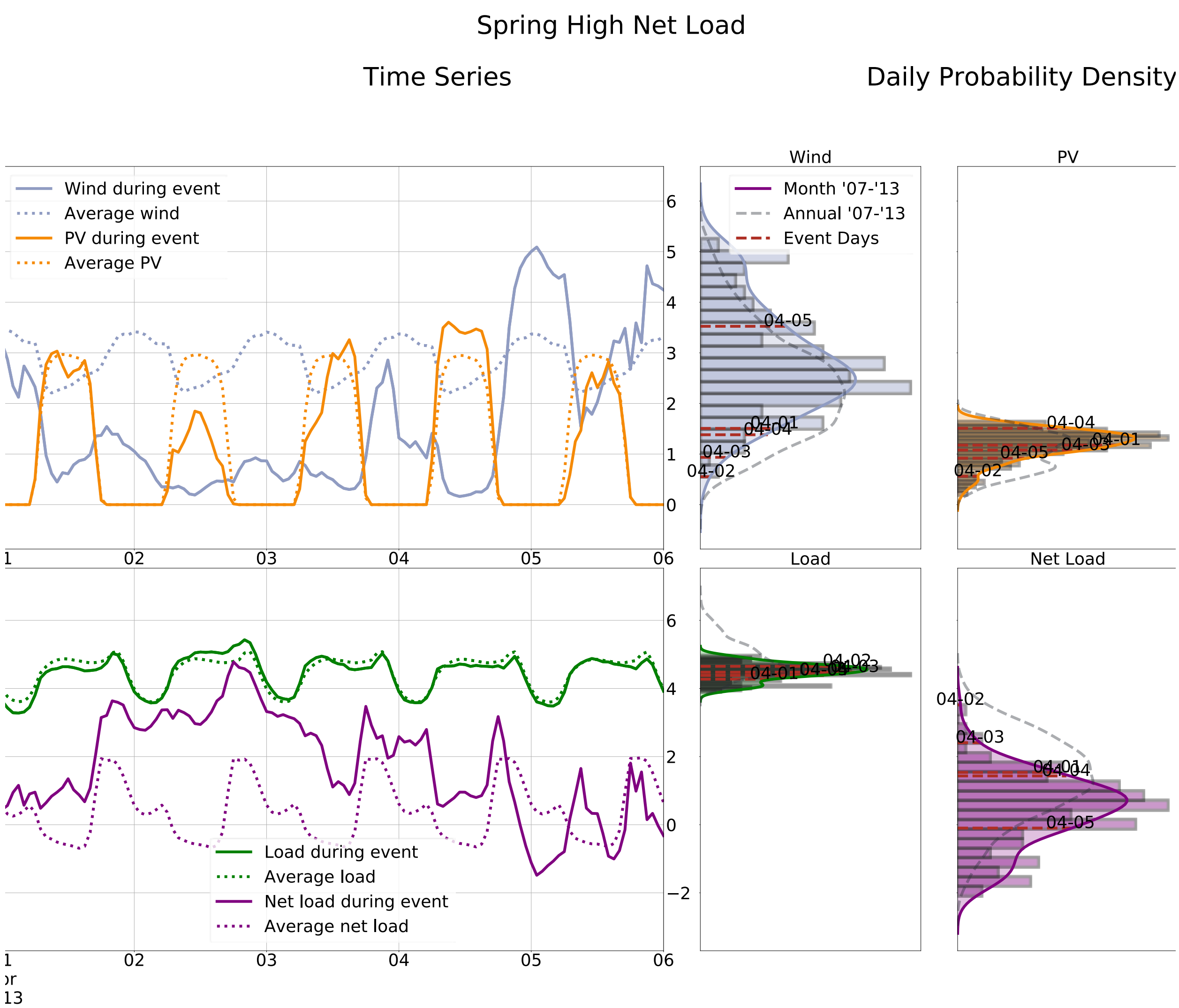


Figure 16. Wind, solar PV, load, and net load in PSCo during the April 2013 Abnormally High Net Load event

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

Figure 17 shows the dispatch stack for the 2030 PSCo Preferred Plan. Gas-CCs, which were largely offline before April 2, responded to the extended net load event, hitting fleetwide capacity factors between 80% and 90% for much of the day. Gas-CTs and storage provided peaking capacity after sunset. Unlike the other events, imports play an important role throughout the event. The weather of the event has a less pronounced impact on wind and solar in the rest of the WI.

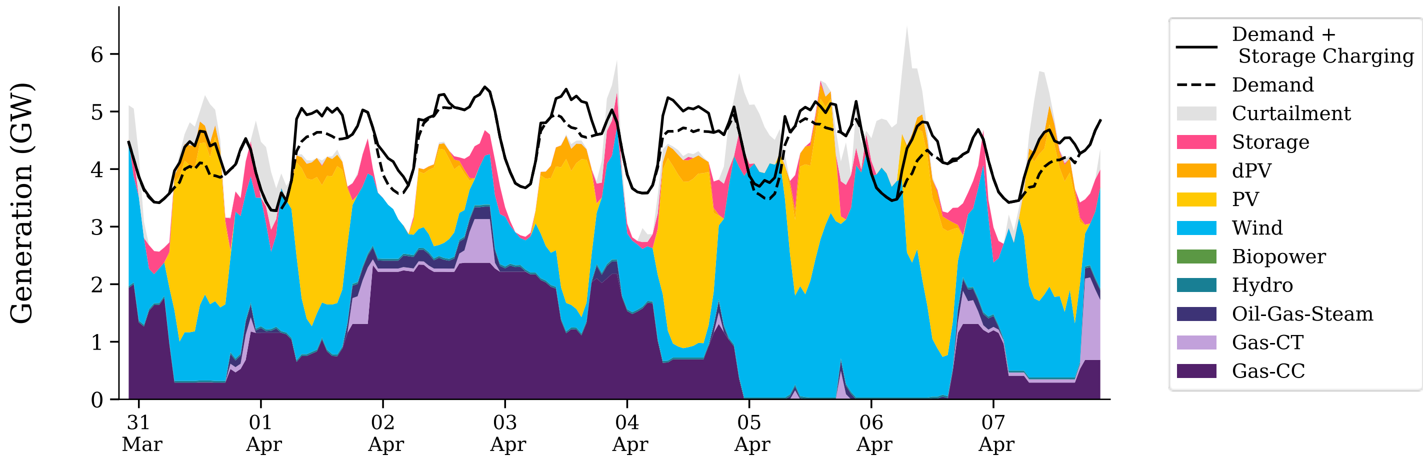


Figure 17. PSCo system dispatch during the April 2013 Abnormally High Net Load event

The role of imports is highlighted during this event by the increased imports sensitivity (Figure 18). Gas-CCs were still committed, but not nearly as many; imports provided much of the power needed to fill the wind and solar deficit throughout the event. This is largely because of the windier and sunnier conditions in Wyoming and throughout the WI during the event, and because transmission enabled geographic diversity to reduce curtailment of the external resources.

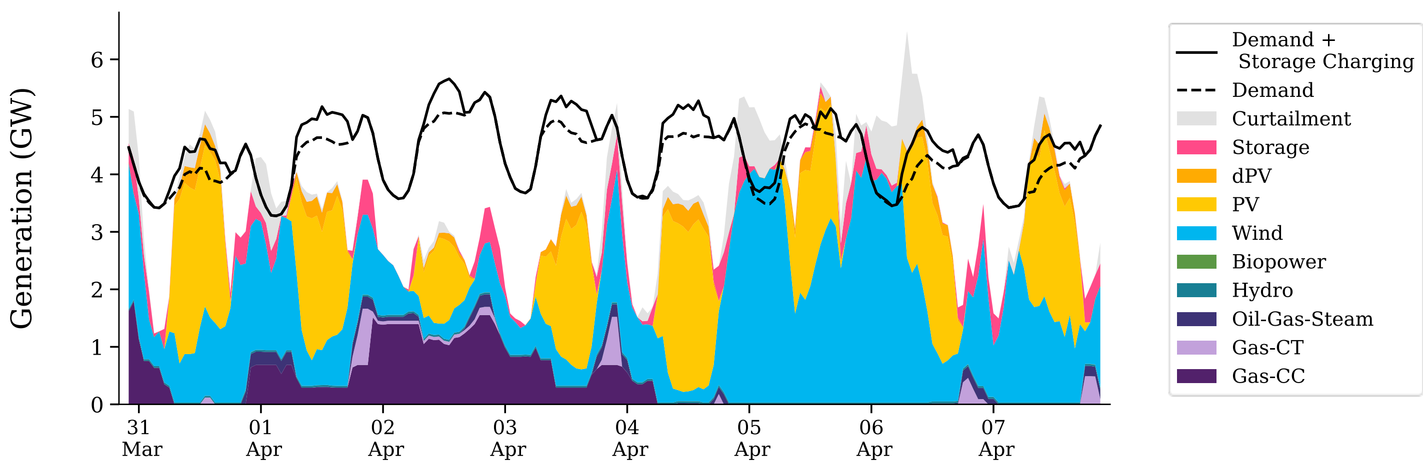


Figure 18. PSCo system dispatch with more import capability during the April 2013 Abnormally High Net Load event

Additional 4-hr storage also reduced the need for gas-CT generation to deal with the peak of the event on the evening of April 2, but the same amount of gas-CC generation was used as in the Preferred Plan scenario (Figure 19). In fact, gas-CCs were turned on earlier in the storage scenario in part to help charge the storage to be ready for the April 2 net load peak.

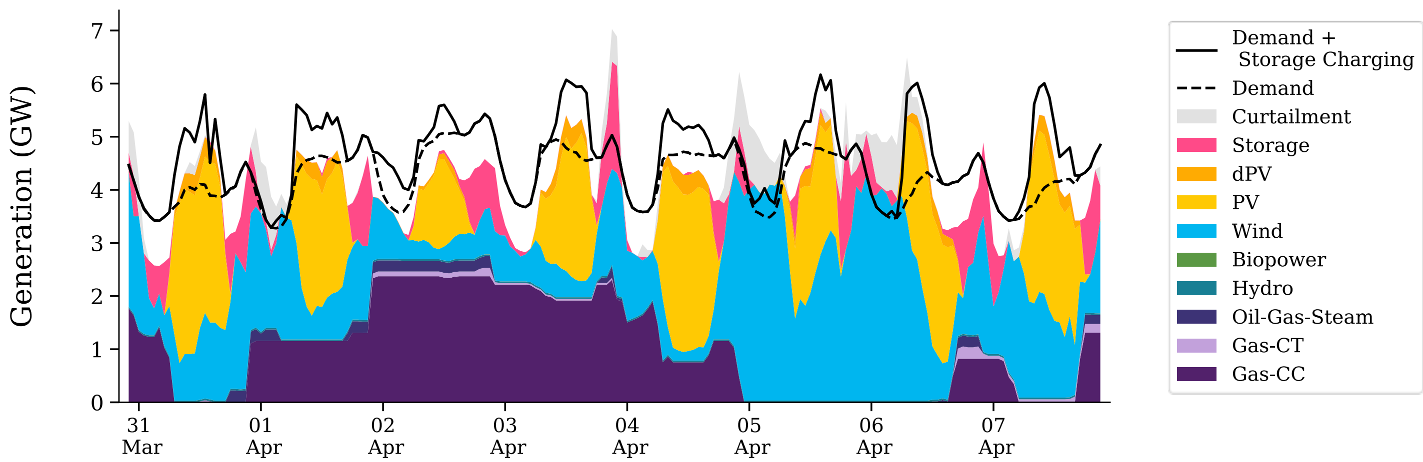


Figure 19. PSCo system dispatch with increased 4-hr storage during the April 2013 Abnormally High Net Load event

October 2009 Wind Turbine Blade Icing Event

October 2009 saw the most impactful icing event in the data set. Turbine blade icing reduced the output of wind generators that otherwise experienced windy conditions. The map in Figure 20 demonstrates the geographic extent of the icing. The impact occurred across the Eastern Plains, but wind farms located near the Wyoming border were mostly spared, allowing for some wind generation even with a significant portion of the fleet shutdown. Though this was the largest icing event in our 2007–2013 data set in the WI, icing could be even more widespread across the Eastern Plains.

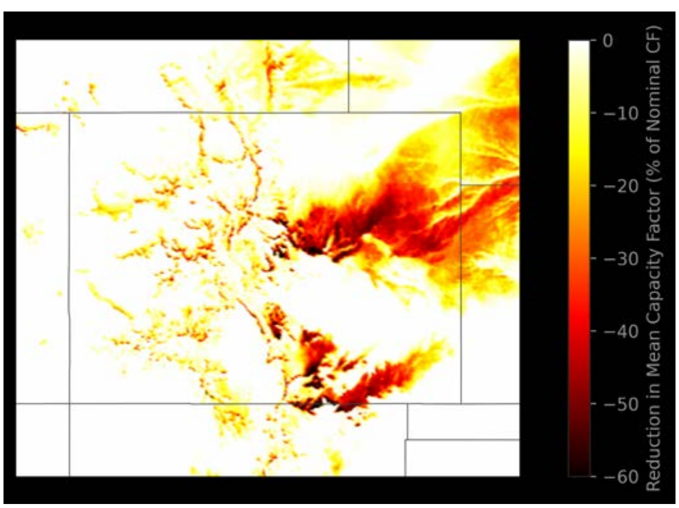


Figure 20. Map of the capacity factor reduction due to wind turbine blade icing over a 3-day icing event in October 2009

Figure 21 shows the time series of the wind generation in PSCo and the impact of icing. On October 21, wind would have operated at about an 80% fleetwide capacity factor all day, but icing cut that capacity factor to near 20% by the end of the day. Despite an otherwise good wind resource on October 22, icing impacts limit wind generation to 1,000 MW. On October 23, more than 2,500 MW of potential wind power is lost due to icing. In all, between October 21 and 27, potential wind energy was reduced by 170 GWh due to icing derates.

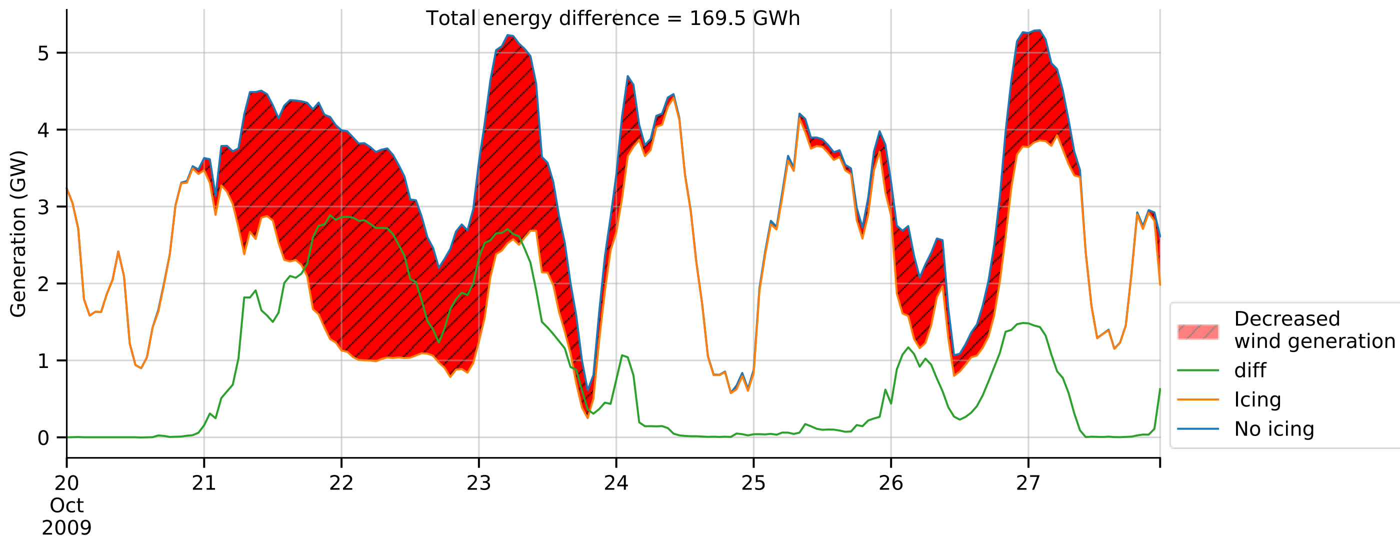


Figure 21. PSCo wind generation derated due to blade icing shutting down turbines. The red hatched area shows the wind energy lost due to icing.

Figure 22 shows the system dispatch during the icing event. Gas-CCs filled most of the gap left by icing, with gas-CTs providing peaking capacity at times for a few hours. After sunset, storage also produced energy and capacity at the same time as gas-CTs

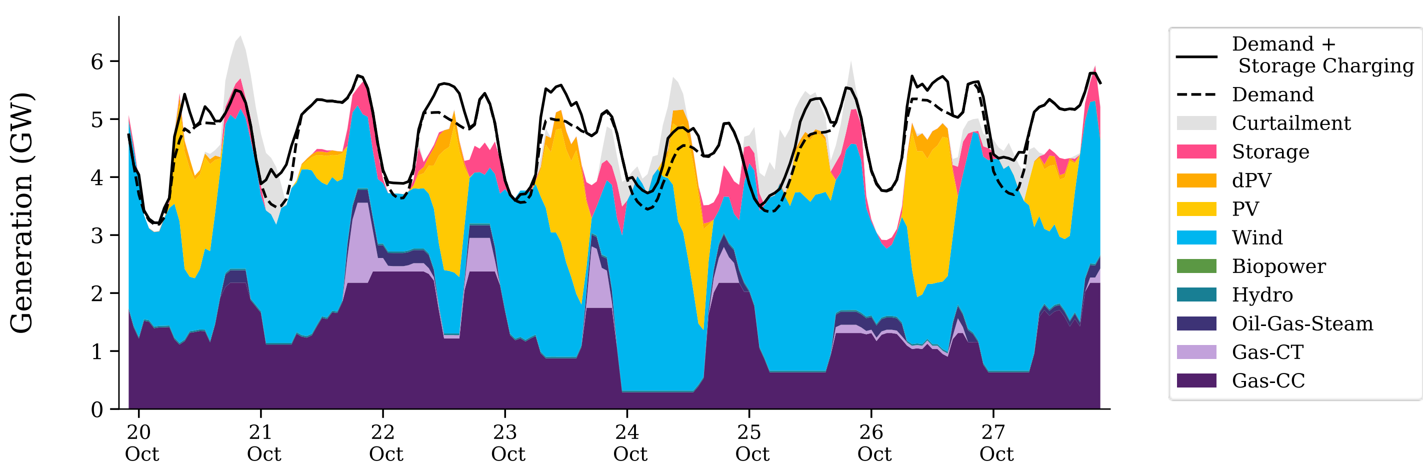


Figure 22. PSCo system dispatch during the October 2009 Wind Turbine Blade Icing event

In the increased import sensitivity, increasing import capability does not provide significant relief to the lost wind on October 22, the day of highest impact. Gas-CCs were still needed to fill much of the gap left by the iced wind turbine blades. Thermal generation peaks at 3,000 MW on the evening of October 21, compared to 3,500 MW in the PSCo Preferred Plan scenario. Much of the increased imports came from gas-CCs elsewhere in the WI, highlighting the limited wind and solar geographic diversity during this event.

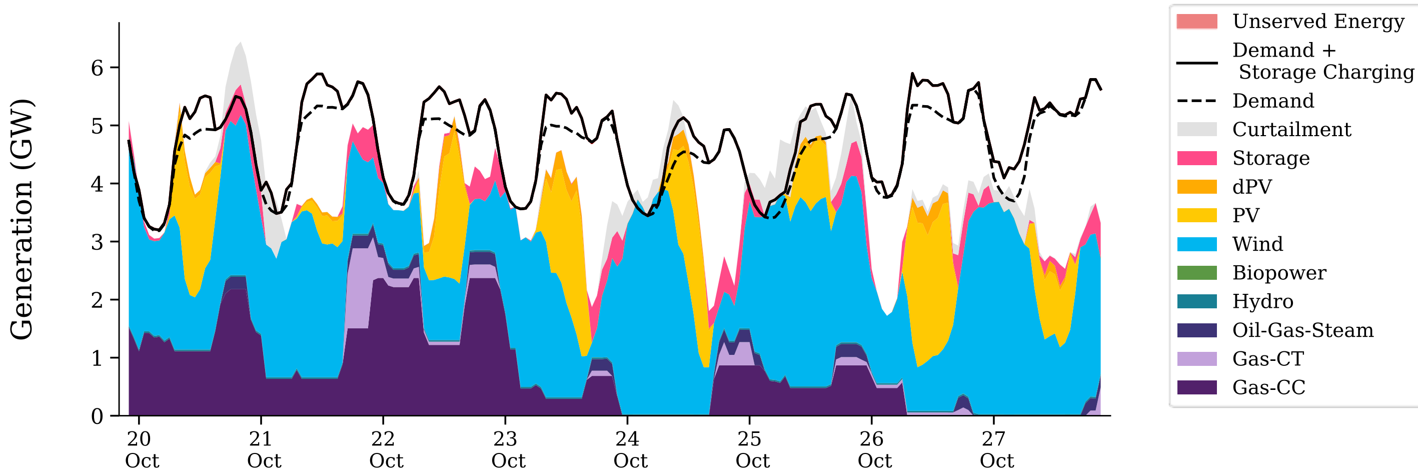


Figure 23. PSCo system dispatch with increased import capability during the October 2009 Wind Turbine Blade Icing event

The story is similar for the increased storage sensitivity. Storage displaced much of the need for gas-CT peaking capacity, but gas-CCs still provided much of the energy lost due to turbine blade icing. Like the April 2013 Abnormally High Net Load event, gas-CC generation increases during the day relative to the Preferred Plan to ensure batteries are sufficiently charged.

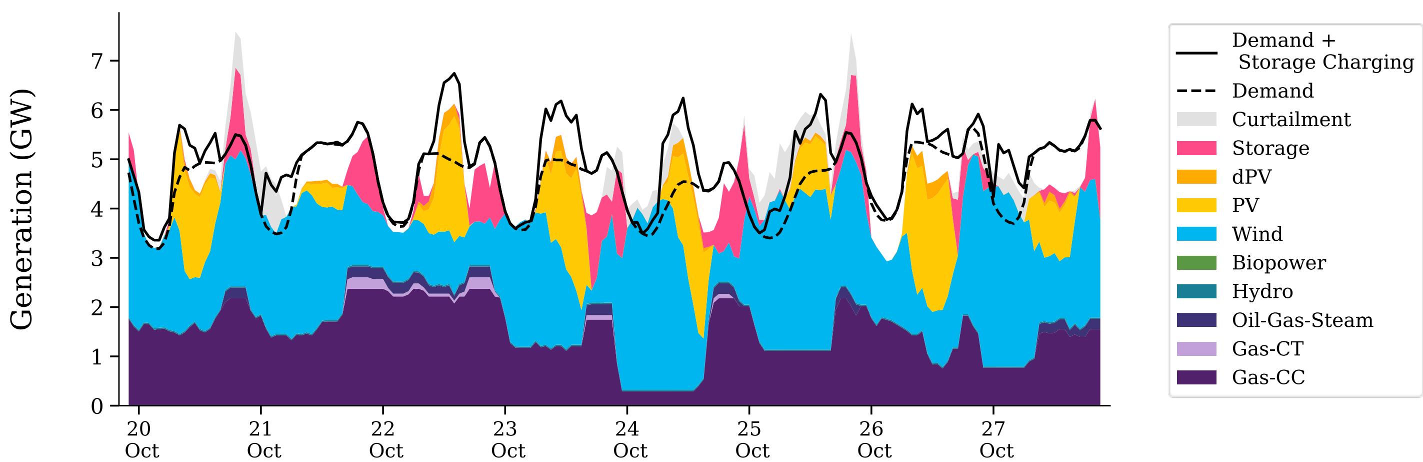


Figure 24. PSCo system dispatch with increased 4-hr storage during the October 2009 Wind Turbine Blade Icing event

Findings

Based on the analysis of the 2007–2013 weather events within the wind, solar, and load data sets and the PCM analysis of four selected events, we identified two key takeaways with regards to how the 2030 PSCo Preferred Plan interacts with a diversity of extreme weather events.

1. **Peak load period is not necessarily the most concerning period anymore, as contribution from wind and solar generation increases. Near-peak load periods with low wind generation output in the evening lead to very narrow but high net load peaks.**

Historically, system planners have been most concerned with ensuring generation capacity can serve peak demand. For Colorado, peak load occurs in the summer months in the afternoon, but the increased penetration of wind and especially solar are changing how the operation of summer days will look in the future. Figure 25 (page 22) shows the wind and solar PV generation potential at the peak load period in our 2007–2013 data set. Peak load tends to occur on extreme hot and clear days, as was the case on June 25, 2012. At the true peak load hour, PV has ample generation potential, shifting the net load peak to after sunset. As was the case in (Novacheck et al., 2021), the peak load day also often has average wind resource for the time of year, meaning the net load peak is high but not extreme. In the case of PSCo, daily wind potential is 47% and 71% above average on June 25 and 26 respectively, pushing the days out of the tails of the net load distribution. June 26 is the peak load day (i.e., the 100th percentile of the load distribution), but it is only in the 52nd percentile of daily net load days. Similarly, while the peak load hour for the entire data set occurs in the afternoon of June 25, net load only peaks at the 91st percentile of net load hours at that time.

Though this offers some relief to the system, periods similar to the peak load day quickly become a larger concern. As described in the results section, the peak net load hour within our 2007–2013 data set occurs in PSCo's territory on August 22, 2011, with August 23, the next day, close behind. On August 22 and 23 load peaked 790 and 440 MW below the June 25, 2012 peak load hour, respectively. High, but not extreme, temperatures drive up demand. However, the heat in this event also came with stagnant high pressure in the afternoon and overnight, leading to very little wind generation--as seen in Figure 26 (page 23). The daily wind generation potential is in the 9th and 12th percentiles on August 22 and 23, and below 1,000 MW at sunset. A higher proportion of available thermal generation capacity from the PSCo Preferred Plan was used during the peak net load period than the peak load period, and therefore presents a greater resource adequacy risk. In our modeling of this period, the PSCo Preferred Plan successfully met all load during the peak net load period, but periods such as these should continue to be a focus for long terming planning for PSCo to ensure adequate generation capacity is available.

As described in the results section, we performed production cost modeling of PSCo's 2030 Preferred Plan to understand what forms of supply it relies on to meet the peak net load demand. Figure 27 (page 24) shows the dispatch results for the 2030 system during the August 2011 Net Load Peak. Gas-CCs cycled throughout all the days of this event, focusing on providing capacity outside of the hours of PV generation in the middle of the day. Gas-CTs were used for peaking capacity, similar to the way they are used today; though on days with less extreme summer loads they tend to be used for a shorter period. However, gas-CTs stay on for hours during the evening of August 23, when peak net load occurred. At the peak of gas-CT usage, PSCo nearly exhausted its available offline thermal capacity.

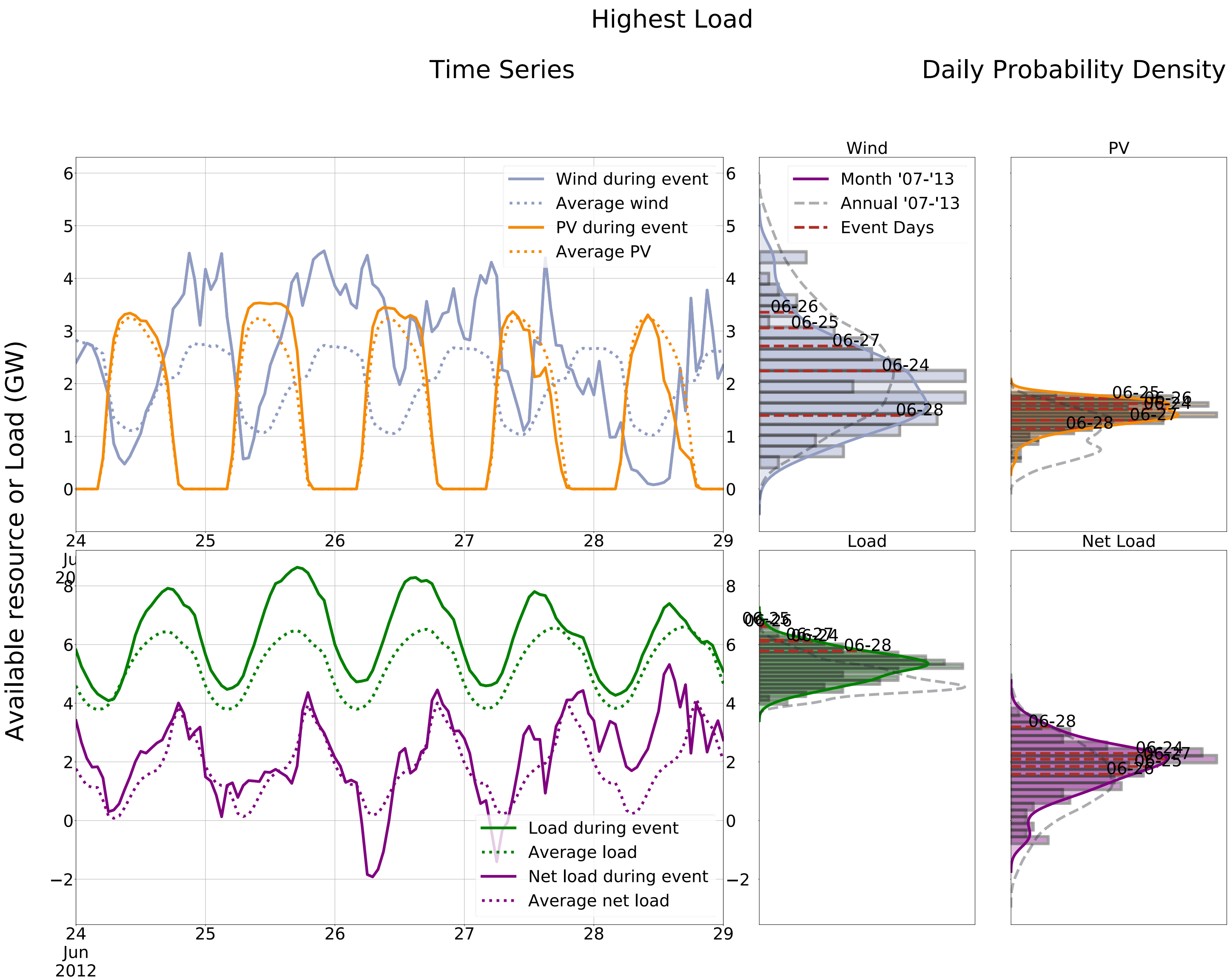


Figure 25. Wind, solar PV, load, and net load in PSCo during the highest load in the record

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

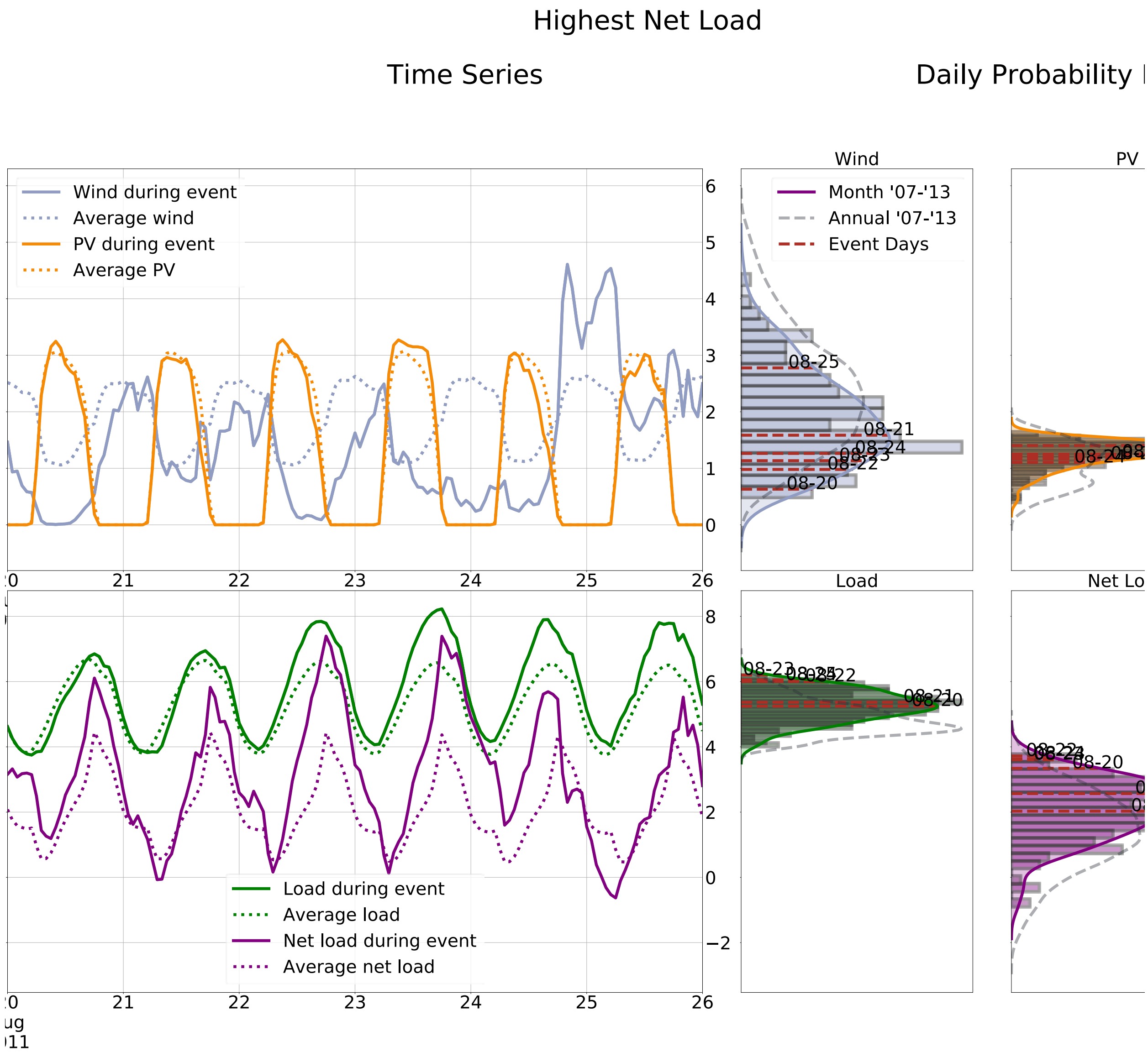


Figure 26. Wind, solar PV, load, and net load in PSCo during the August 2011 Peak Net Load event

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

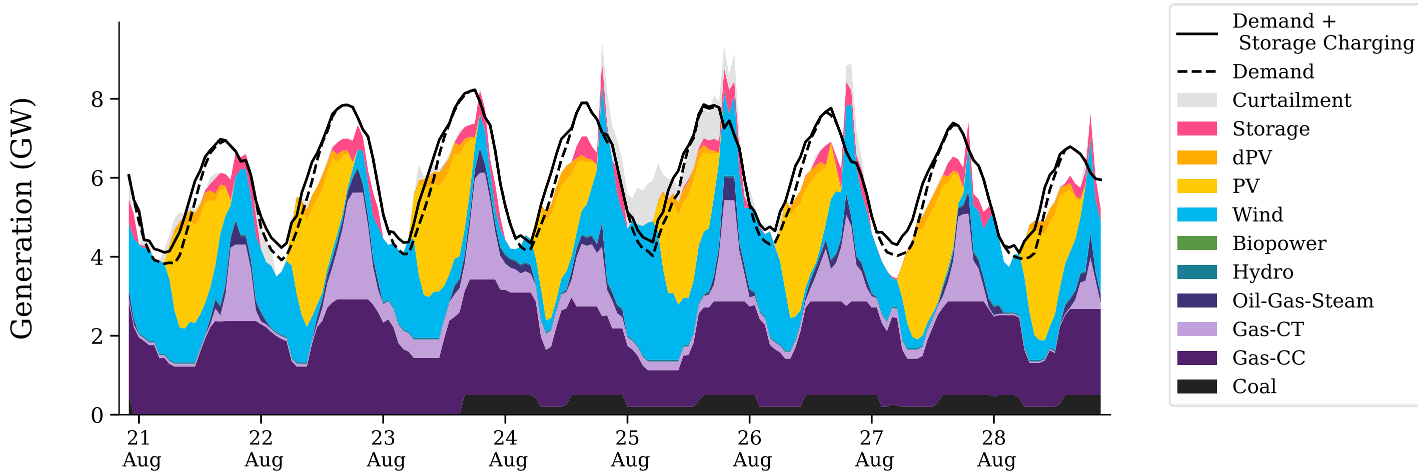


Figure 27. PSCo system dispatch during the peak net load for the system in August 2011

Short to medium duration storage (i.e., 2 to 6 hour) battery energy storage is well suited to contribute to summer net load events, as discussed by (Denholm et al., 2021). In our PCM analysis, we ran a sensitivity where we replaced all new gas-CT capacity in the 2030 PSCo's Preferred Plan with 4-hr battery energy storage and did not add additional generation capacity of any type. The system dispatch for this sensitivity during the August 2011 Peak Net Load event is shown in Figure 28. With this change not all load could be served on the evening of August 22, and the system shed 1,300 MWh over 4 hours with a peak load shed of 790 MW. **The batteries could not to provide the same amount of power for as long as the gas-CTs were able to in the PSCo Preferred Plan scenario.** Also, the increased battery storage led to gas-CCs generating more electricity overnight to ensure the batteries were fully charged. We also considered a second sensitivity which allowed more imports. This change decreases the number of hours during which the gas-CTs need to provide peaking capacity, but at the peak net load hour, much of the gas-CT units still turned on to meet load. On August 22 and 23, all available gas-CTs were used for 2–3 hours in the Preferred PSCo 2030 Plan, compared to being used for 1–2 hours when imports were increased.

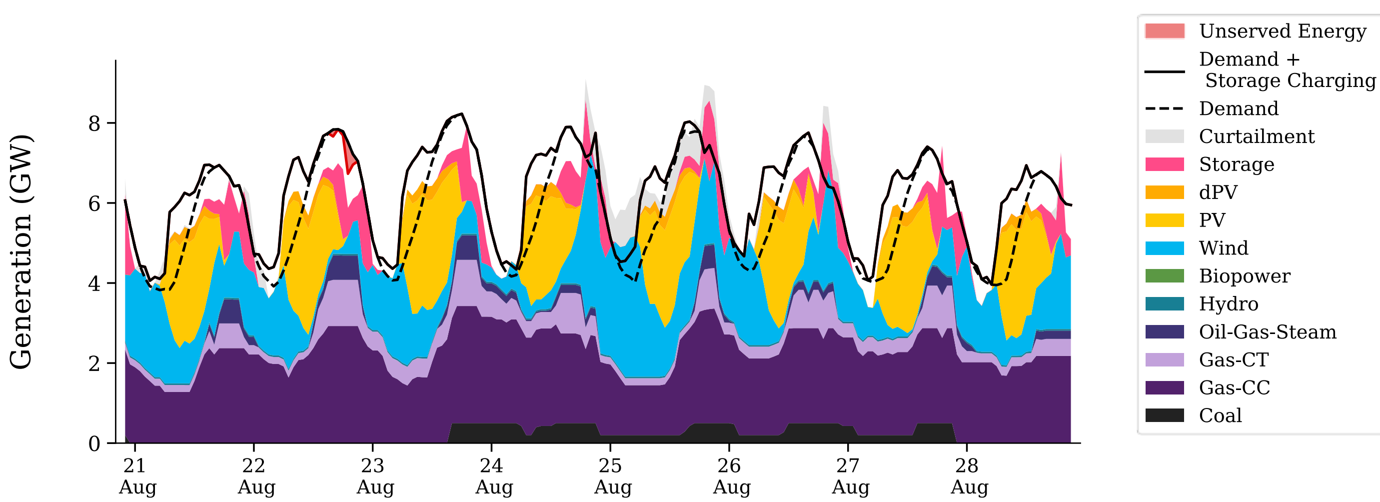


Figure 28. PSCo system dispatch with increased 4-hr storage during the peak net load for the system in August 2011

Wind availability has the largest impact on the peak net load events. This because the highest Colorado loads occur in the summer, during periods of clear skies when solar is generating to its maximum capability. In other words, solar PV generation has little influence on the *day* of the peak net load in Colorado, even though it strongly influences the peak net load *hour*. However, one aspect of solar PV generation in the summer we did not explore is the coincidence of widespread wildfire haze and its effect on solar PV production. Wildfire impacts on PV generation and high loads is the subject of ongoing research.

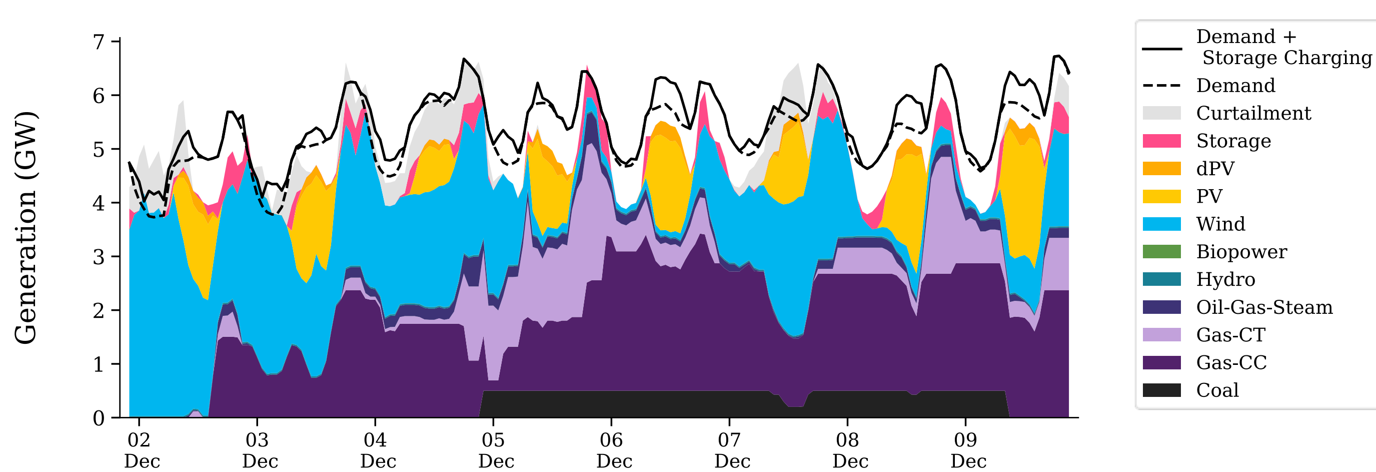
2. **Winter storms, extreme and moderate cold waves, and periods of seemingly uninteresting weather can lead to infrequent but extended wind and solar resource deficits. NREL's modeling suggests the unique resilience and critical reliability value of a generator with high availability for an extended duration that can be called on to respond quickly. Examples of such a generator include combined cycles and combustion turbines paired with a reliable fuel source.**

We identified three specific but unique weather events that all lead to extreme deficits in the wind and solar resource output in PSCo and the broader Western Interconnection to investigate how the resources in the 2030 PSCo Preferred Plan might react to such a weather event. These events included:

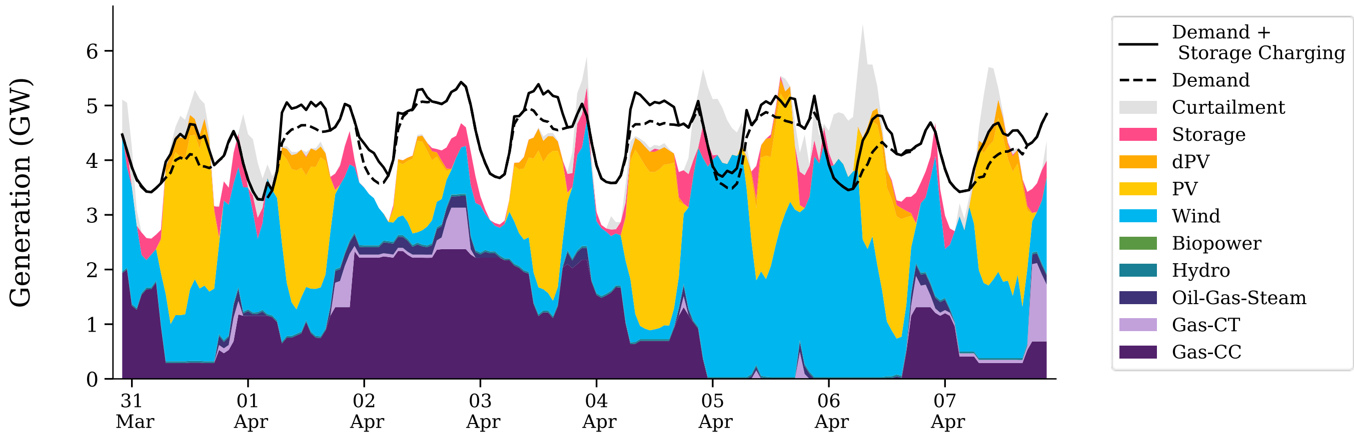
- A set of winter storms that impacted the country in December 2013
- The largest wind generation derate due to turbine blade icing in the 2007-2013 data set, which occurred in October 2009
- A cloudy but calm set of days from April 2013.

In all three cases, weather causes a decrease in the aggregate wind and solar generation leading to a day or more of elevated net load in PSCo compared to typical conditions for that time of year.

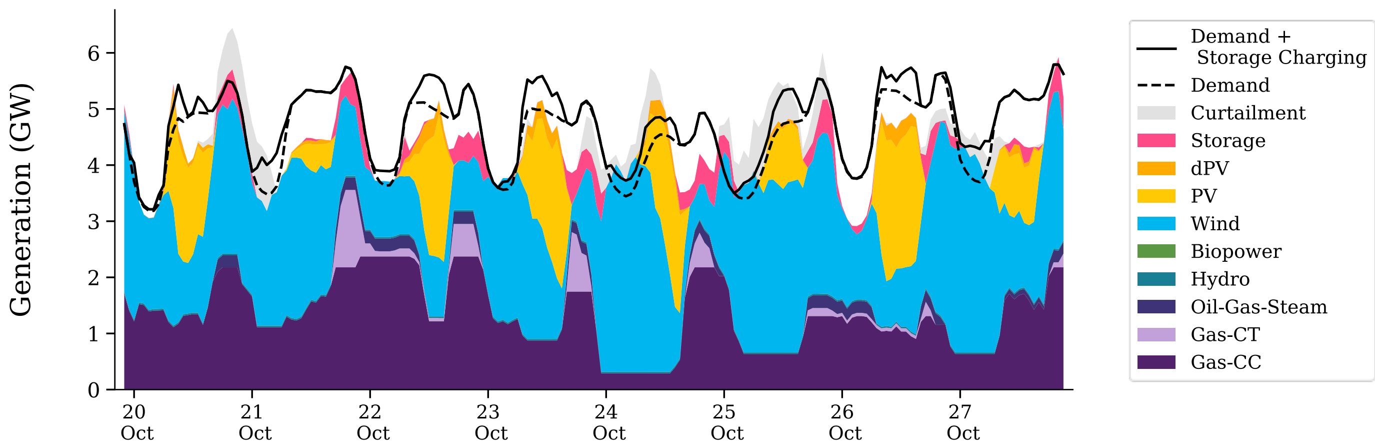
Figure 29 (page 26) shows the system dispatch during all three events using the 2030 PSCo Preferred Plan. In all three events the system response to these compounding impacts comes from the local available gas-CTs and gas-CCs, imports, and local storage to fill the wind and solar resource deficit.



December 2013 – Winter Storms



April 2013 – Abnormally High Net Load



October 2009 – Blade Icing

Figure 29. PSCo system dispatch for the 2030 Preferred Plan during three events with low aggregate wind and solar generation

For the December 2013 Winter Storms event, the gas-CT response began late in the day on December 4 as the wind generation ramped down, while most gas-CC generation remained offline after experiencing cold temperature induced outages earlier in the day. Imports were also highly utilized throughout the day until sufficient gas-CC capacity came back online. This storm had a broad impact and much of the WI also experienced elevated net load due to the storms. In all, thermal output in PSCo peaked at close to 5,600 MW in the evening on December 5, before ramping down as load decreased overnight. Thermal generation peaked again later in the week as the winter storms continued to derate the local wind resource with freezing precipitation. Solar PV generation was also severely impacted by the winter storm: daily PV generation potential reached only the 2nd and 7th percentiles of all PV generation in the 2007–2013 data set on December 4 and 5 respectively (Figure 5). As stated earlier, gas is not immune to the winter weather impact; in our modeling, nearly 2,000 MW of gas-CCs failed as the storm crept into Colorado. Gas-CTs also had outages, but to a lesser extent than the gas-CCs.

The April 2013 Abnormally High Net Load event showcased a similar reduction in available wind and solar resource, but without the freezing precipitation impact. The reduction began in the evening of April 1 and lasts through April 3. The weather causing this phenomenon was largely uninteresting: it is cool but not cold, and cloudy but calm across the state. Load was consequently average for the season, and there was not an increased risk of temperature induced thermal outages. Also, unlike the December 2013 Winter Storms event, the rest of the WI is not strongly impacted by this weather event. Therefore, much of the elevated net load can be met by imports in addition to the local storage and 3,000 MW of gas.

Unlike the other two events, the October 2009 Wind Turbine Icing event involved consistent high wind speeds. Freezing precipitation led to the largest icing related reduction in wind generation potential within our 2007–2013 data set. The frozen precipitation also reduced solar output during this time. However, as shown in the map in Figure 20, icing does not impact the entire Eastern Plains or all of PSCo's wind farms, leading to continued wind contribution throughout the event. Even so, similar to the other events, PSCo relies on imports, storage, and a peak of nearly 3,500 MW of gas on October 21.

Insights from the increased imports and storage sensitivities

The results from the sensitivities further highlight the value of combustion turbine and combined cycle generation to provide energy to the system during these events. Geographic diversity of wind and solar enabled by more imports was shown to reduce the modeled impacts of the April 2013 Abnormally High Net Load event. The decreased wind and solar generation mostly impacted Colorado, allowing for imports of wind and solar from other parts of the interconnection to help meet the elevated net load in PSCo. However, the October 2009 Icing and December 2013 Winter Storms events have broad impact beyond PSCo's territory and Colorado's borders, limiting how much imports can replace the role filled by the gas-CTs and gas-CCs in the 2030 PSCo Preferred Plan. 4-hour storage, on the other hand, has limited ability to provide all of the system generation needs in all three events. At times, to ensure system reliability and resilience to the weather events, there is a need for a resource to respond quickly and reliably for an extended period. The 2030 PSCo Preferred Plan contains those characteristics.

Conclusions

In our analysis, we exposed the 2030 PSCo Preferred Plan to a diversity of extreme weather events using a production cost model of the Western Interconnection. Using high spatial and temporal wind and solar data, we identified weather events that caused extremely low generation potential in the aggregate wind and solar resource and extended periods of high net load. These events were a mix of heat waves, winter storms, and just calm ——but cloudy or low wind—periods. In all four weather events, the 2030 Plan was reliable and resilient, meeting demand in all hours of the events we studied. Further, our analysis of the events suggests that there is unique weather resilience value in the 2030 PSCo Preferred Plan that the increased imports and storage scenarios do not offer. For instance, PSCo experienced dropped load in the storage scenario during the 2013 Winter Storms and 2011 August Peak Net Load events. We did not explicitly investigate how combined cycle or combustion turbine capacity in the 2030 Plan is utilized under average conditions or when there is a surplus of wind and solar. However, with an 80% reduction of CO_2 emissions stated in PSCo's 2030 Preferred Plan, and given that the average net load is only 2,000 MW in our scenarios, the annual capacity factors of these units might be low. Still, our analysis suggests that as PSCo's generation fleet becomes dependent on wind and solar generation, there will continue to be periods that call on the unique resilience value of gas combustion turbines and combined cycles. These periods are infrequent but can happen any time of year, during stormy conditions or simply during cloudy, calm weather. The fast response resources need not utilize natural gas; they could, in the future, use carbon-free fuels like hydrogen.

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Appendix A: Other Weather Events

The Figures in this section summarize other extreme weather events identified in the 2007-2013 dataset. For insights into how the Western, Eastern, and Texas Interconnections respond during these events, see (Novacheck et al., 2021).

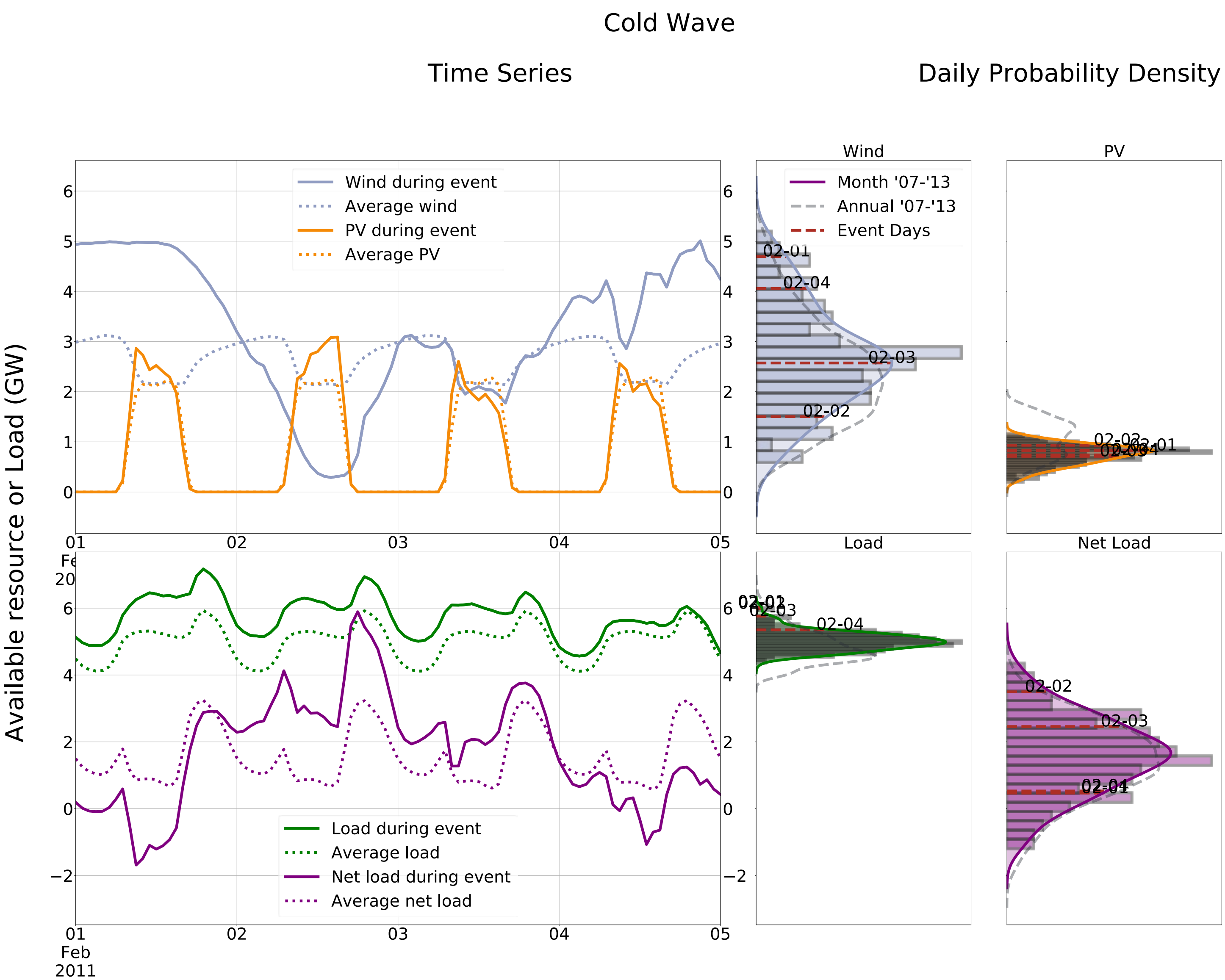

Figure A-1. Wind, solar PV, load, and net load in PSCo during the February 2011 Cold Wave

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

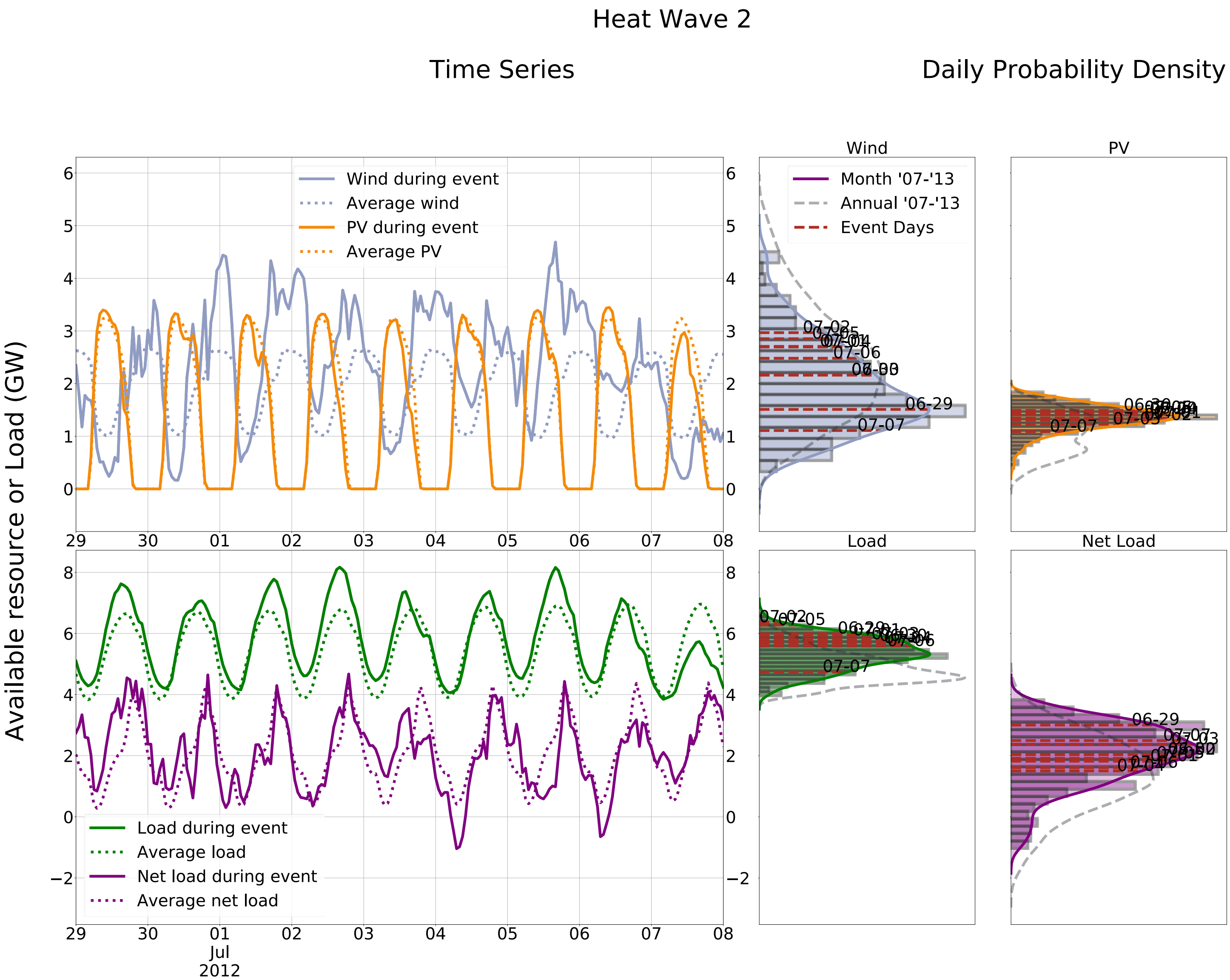

Figure A-2. Wind, solar PV, load, and net load in PSCo during the July 2012 Heat Wave

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

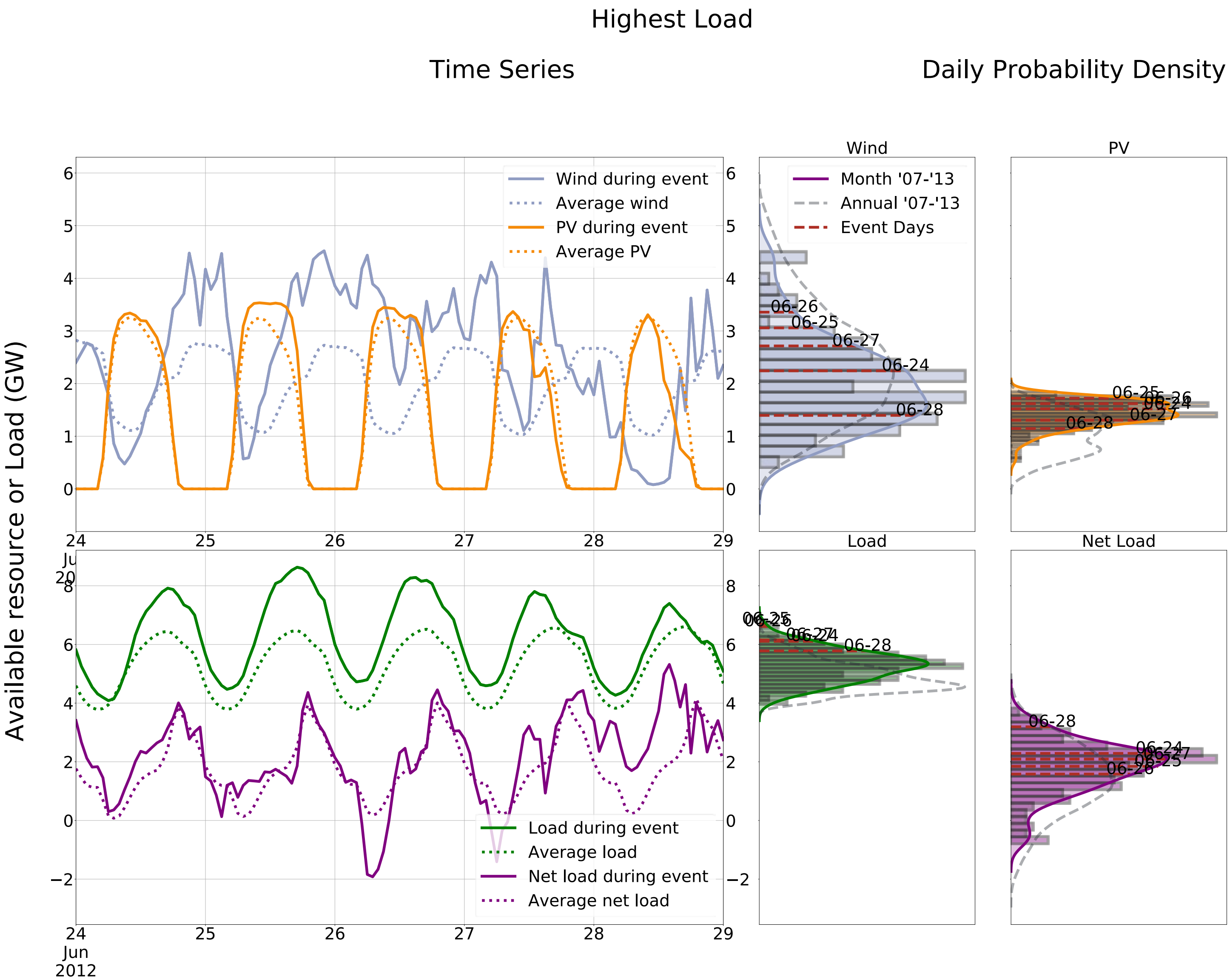

Figure A-3. Wind, solar PV, load, and net load in PSCo during the June 2012 Heat Wave

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.

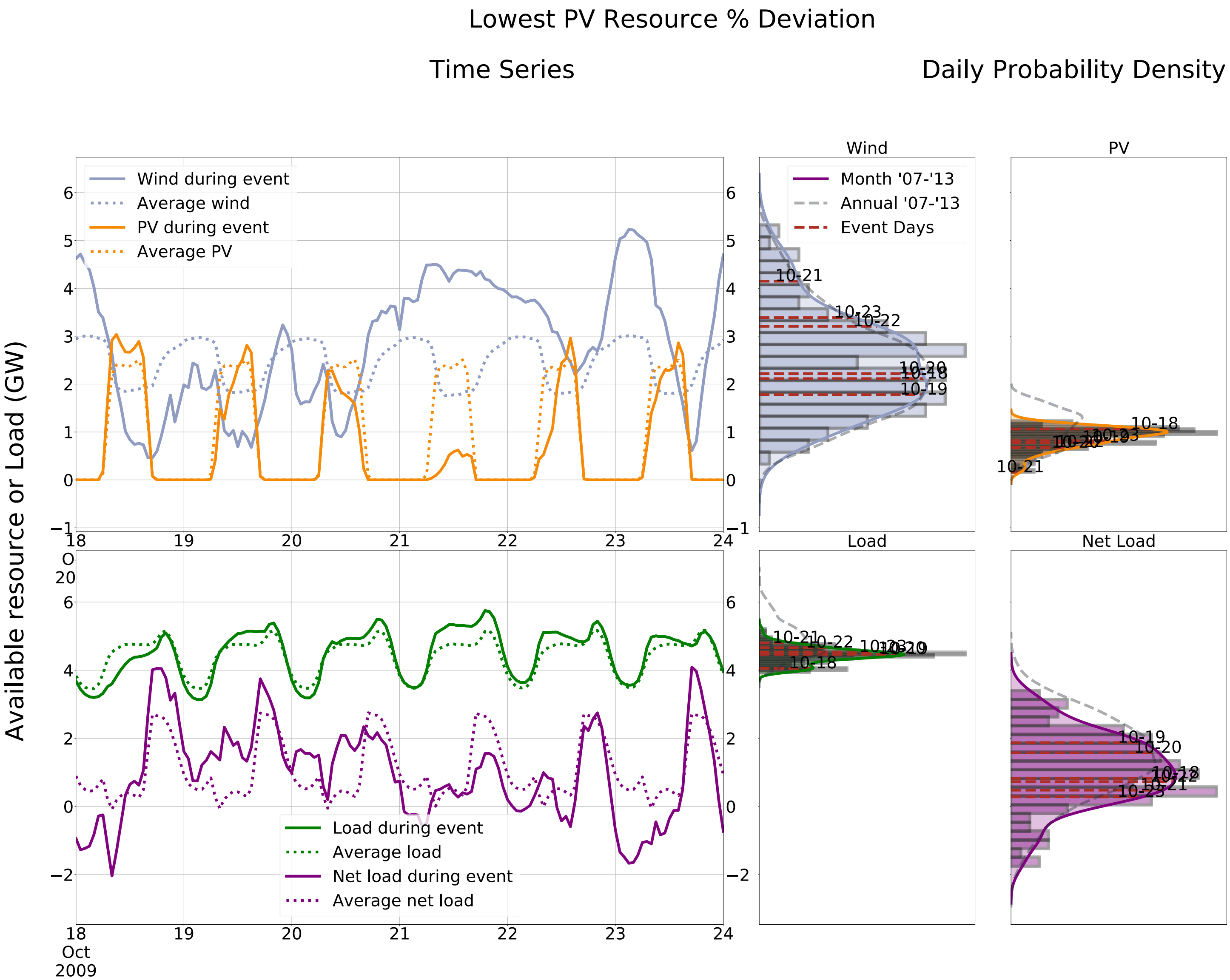

Figure A-4. Wind, solar PV, load, and net load in PSCo during the October 2009 Highest PV Resource Deviation event

Wind (blue-gray), solar (orange), net load (purple), and load (green) time series with average shape for the 29-day period surrounding the center of the event shown as dashed lines. Probability distributions for the same period are shown on the right with the event days marked by dashed lines.