Revisiting the California Duck Curve

An Exploration of Its Existence, Impact, and Migration Potential

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EXECUTIVE SUMMARY

In 2013, the California Independent System Operator (CAISO) conducted an analysis to understand how increasing penetrations of renewable resources would impact grid conditions. The result was the iconic "duck curve" chart, which predicted that as variable generation grows so too will the trough of load served by conventional supply in midday. Some have used the duck curve as the call to arms for finding solutions to better integrate increasing distributed generation resources on our utility systems.

In this report, ScottMadden analyzes average hourly production data from CAISO from January 2011 through June 2016 to understand if actual results align with the original forecast and what implications may tell us about what to do next. Our analysis confirms the duck curve is real and growing faster than expected. In addition, we found some interesting, unexpected, and important nuances. In particular, the duck curve is:

- Producing net loads lower than forecast
- Increasing ramps throughout the year
- Most severe on the weekends
- Occurring in multiple seasons, not just spring months
- Driven by utility-scale solar in California, not distributed resources

If we are to effectively address renewable integration challenges, it is imperative that we understand and address the actual issues that exist. Solutions for a seasonal, weekend, utility-scale solar issue may well be different than solutions for an everyday, distributed resource issue. Additionally, parts of the country without significant distributed resources but instead with significant utility-scale solar, should not feel immune to the risk of these same troughs and ramps. Future duck curve sightings may well occur sooner than we think in states with growing utility scale solar, such as Arizona, Georgia, Nevada, North Carolina, or Texas.

Understanding the root cause and comprehensive impact of the duck curve is essential before developing strategies to address operational impacts.

BACKGROUND

In 2013, the CAISO conducted a detailed analysis of actual and projected electric load for 2012 through 2020 to better understand how increasing penetrations of renewable resources will impact grid conditions.[1] More specifically, the analysis examined "net load" which is the load served by the electric

[1] "What the Duck Curve Tells Us about Managing a Green Grid," California ISO, accessed September 8, 2016, https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf.

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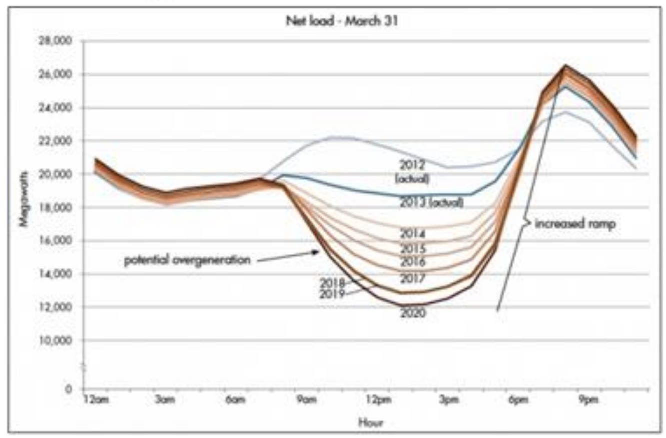
system minus the load served by variable generation (i.e., wind, solar PV, and solar thermal).[2] CAISO is interested in net load because it reflects the load that must be served by traditional dispatchable generation, such as natural gas and nuclear.

The CAISO analysis found that in certain times of the year the net load drops midday and quickly ramps to a late-day peak. More importantly, the forecast finds the drop and ramp of net load becoming more severe each year. This analysis resulted in the iconic “duck curve” chart which shows net load forming the duck’s belly during the midday period and the duck’s neck during the late-day ramp (see Figure 1).

CAISO notes the changes in net load create the following operating challenges:

- **Oversupply Risk:** Occurs when more electricity is supplied than is needed to satisfy real-time electricity requirement. Oversupply risk increases as more renewable resources are added but demand does not increase.
- **Short, Steep Ramps:** Occurs when the system operator must rapidly bring on or shut down generation resources to meet increasing or decreasing electricity demand. In 2020, CAISO forecasts the three-hour afternoon ramp to be approximately 13,000 MW.

Figure 1: California’s Duck Curve Chart



This one duck curve chart has become a foundation of debates on renewable integration and has become the basis of conclusions regarding the solutions to renewable integration. Yet, by itself it represents a snapshot of one spring day. What further or different insights might be gained by reviewing the data behind this iconic chart?

ScottMadden collected and analyzed actual average hourly production data from 2011 to 2016 to better understand if actual results align with the original forecast and what further insights might be gained by looking at all days of the year.[3] Such analysis of the data behind the chart may improve our understanding of the problem, and by extension, impact our conclusions about what to do next. While several studies have modeled operational implications arising from the duck curve chart,[4] this report is unique because it compares the original forecast to detailed, actual operational data.

KEY FINDINGS

Our analysis confirmed the duck is present and maturing quickly in California. More importantly, we found that significant changes in daily daytime minimum net loads (i.e., the duck’s belly) and daily late-day ramps (i.e., the duck’s neck) are primarily driven by utility-scale solar in California.

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[2] Behind-the-meter systems (e.g., rooftop solar PV) do not sell into wholesale markets. Consequently, loads served by behind-the-meter systems are not reflected in CAISO’s system load.

[3] Generation and electricity import data from January 1, 2011 to June 30, 2016 collected from “Renewables Watch,” California ISO, accessed August 23, 2016, http://www.caiso.com/green/renewableswatch.html.

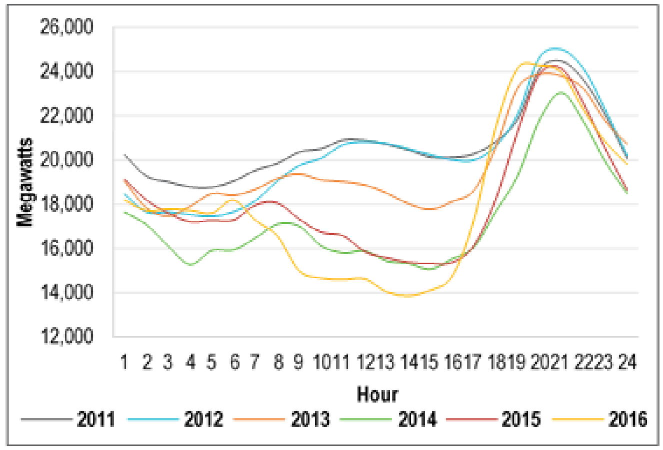
[4] See Denholm et al, *Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart* (NREL/TP-6A20-65023, 2015). Available at http://www.nrel.gov/docs/fy16osti/65023.pdf.

The California Duck Curve Is Real—and Growing Faster than Expected

We analyzed the daytime minimum net load in the month of March to understand: **how does the forecast in the duck curve chart compare to actual data?**

The original duck curve chart shows actual and forecasted net load for a representative spring day (i.e., March 31). To confirm the presence of the duck curve, ScottMadden examined the day in March with the lowest daytime net load from 2011 to 2016. We define daytime minimum net load as the lowest hourly net load between the hours of 8:00 AM and 8:00 PM.

Figure 2: Lowest March Daytime Net Load, 2011–2016



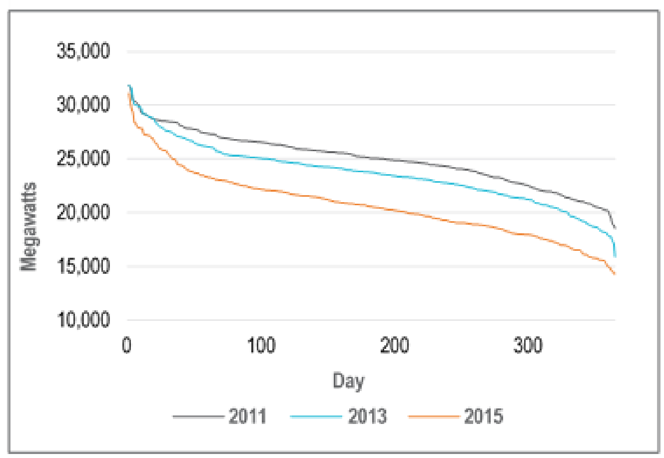
Our analysis shows the lowest March daytime net load declining over time (see Figure 2). From 2011 to 2016, the minimum daytime net load drops 31% from 20,118 MW to 13,854 MW. In addition, the belly of the duck in 2016 is significantly lower than the forecast in the duck curve chart. The results show a minimum daytime net load of 13,854 MW compared to the approximately 15,000 MW found in the forecast. In short, the duck curve is real, growing fast, and impacting system operations.

The Duck Curve Is Producing Net Loads Lower than Forecast

We analyzed the daytime minimum net load over multiple years to understand: **how is the belly of the duck curve changing over time?**

Daytime minimum net load, as defined above, is a useful metric because it represents the lowest point of the duck belly.

Figure 3: Daily Daytime Minimum Net Load, 2011–2015



When daytime minimum net loads are ranked by size, the data shows declines over the majority of each year (see Figure 3). More importantly, there were numerous days in 2015 where the actual minimum net load was below the duck chart forecast. This occurred for a total of three weeks in predominately spring months (i.e., February to May). There were also several days falling below the forecast in November and December.

We also find the lowest daytime net load or deepest belly declining each year. In 2015, the lowest daytime net load was 14,335 MW—a figure roughly equal to the net load in 2017 in the original duck curve chart. Overall, these results indicate a substantial number of individual days are lower—and in some cases substantially lower—than the forecast found in the duck curve chart. Further, oversupply risks attributable to variable generation resources have grown more rapidly than the duck curve chart.

The Duck Curve Is Increasing Ramps throughout the Year

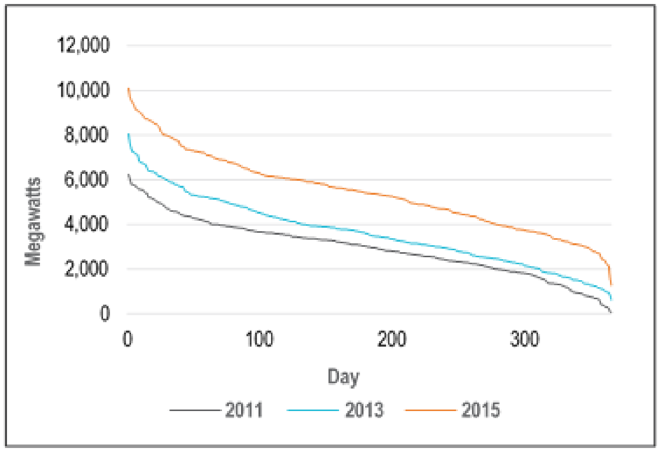
ScottMadden also analyzed the late-day three-hour ramp over multiple years to understand: **how is the neck of the duck curve changing over time?**

We define the late-day three-hour ramp as the steepest three-hour ramp between 2:00 PM and 9:00 PM. The metric is useful because it represents the neck of the duck.

When late-day three-hour ramps are ranked by size, the results show ramps increasing each year (see Figure 4). In 2015, the three-hour ramp exceeded 5,000 MW 58% of the year—up from 6% in 2011. Further, each line is higher than the previous year, indicating changes in system operations are occurring in all parts of the year.

We also find the maximum ramp in each year to be steadily increasing. In 2015, the steepest ramp was 10,091 MW, a 62% increase from the steepest ramp experienced in 2011. At the current rate of change, the 13,000 MW late-day three-hour ramp forecast by CAISO in 2020 may appear well ahead of schedule.

Figure 4: Daily Late-Day Three-Hour Ramp, 2011–2015



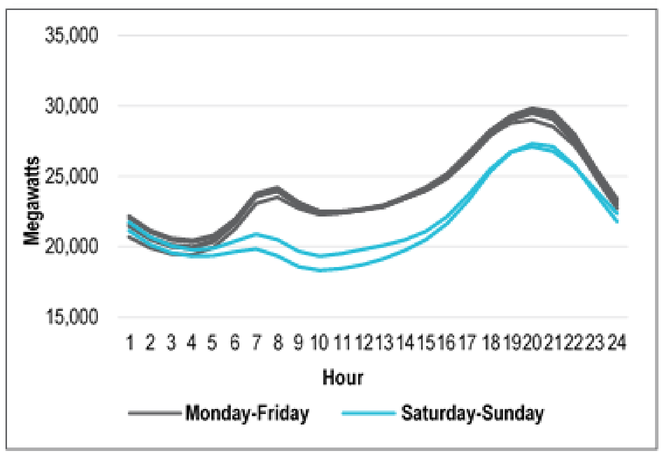
The Duck Curve Is Most Severe on the Weekends

ScottMadden reviewed the average net load in 2015 by day of the week to understand: **how does the duck curve behave depending on the day of the week?**

The analysis demonstrates that the 2015 duck curve was most pronounced on weekends (see Figure 5). On those days, the midday average net load dropped below 20,000 MW before ramping to more than 27,000 MW in the evening. The average three-hour ramp on weekends was 10% steeper than the comparable ramp on weekdays.

These results suggest that weekends are more prone to experience the impacts of the duck curve because of their lower system loads. Conversely, higher system loads on weekdays mitigate the midday decline in net load and the impact of the duck curve.

Figure 5: Average Net Load by Day of the Week, 2015

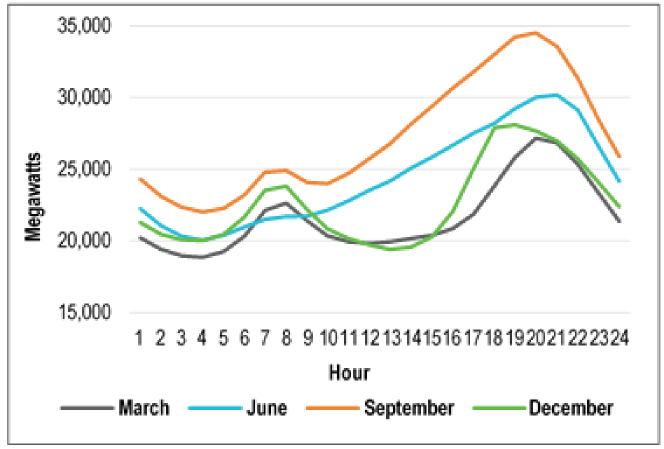


The Duck Curve Is Occurring in Multiple Seasons, Not Just Spring Months

ScottMadden also reviewed the average net load in 2015 by month of the year to understand: **how does the duck curve behave depending on the season?**

Our analysis finds the season has an important impact on the existence and severity of the duck curve. While a "typical spring day" (i.e., March 31) is shown in the duck curve chart, it is not the season experiencing the most prominent impacts (see Figure 6).

Figure 6: Average Net Load by Select Months, 2015



With the average daytime minimum net load (i.e., the belly of the duck) occurring later in the day, the average three-hour ramp in December is 44% steeper than the comparable ramp in March. In particular, the 20 steepest late-day three-hour ramps in 2015 occurred in December (10), November (8), and January (2). As for the summer and early fall, the data indicates the duck curve is not prevalent in these periods due to higher system loads that occur in these months.

The Duck Curve Is Driven by Utility-Scale Solar in California, Not Distributed Resources

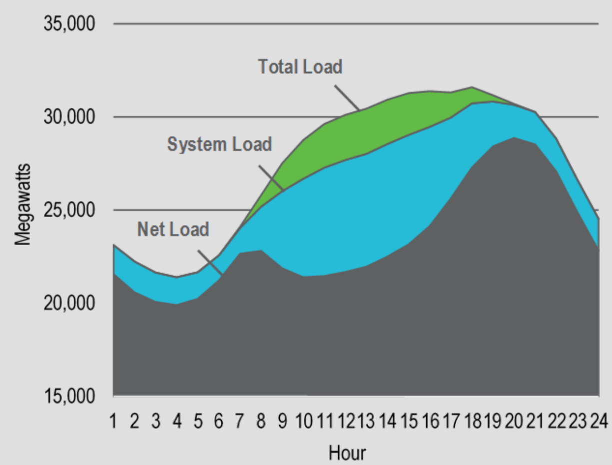
ScottMadden compared system load data from California and Hawaii to understand: **how are utility-scale and distributed resources impacting system operations?**

The duck curve has at times been used to argue the need for better management of distributed energy resources (DERs). But is it always, or even primarily, a phenomenon of DERs? To understand this point, it is important to focus on the difference between system load and net load (see box below). If the belly of the duck is formed by less visible distributed resources, one would see it manifested in both the system load and the net load. This is not the case in the California Duck Curve. Instead, we see a smooth system

Relationship Between Total, System, and Net Load

The key to understanding the duck curve is the distribution among total load, system load, and net load:

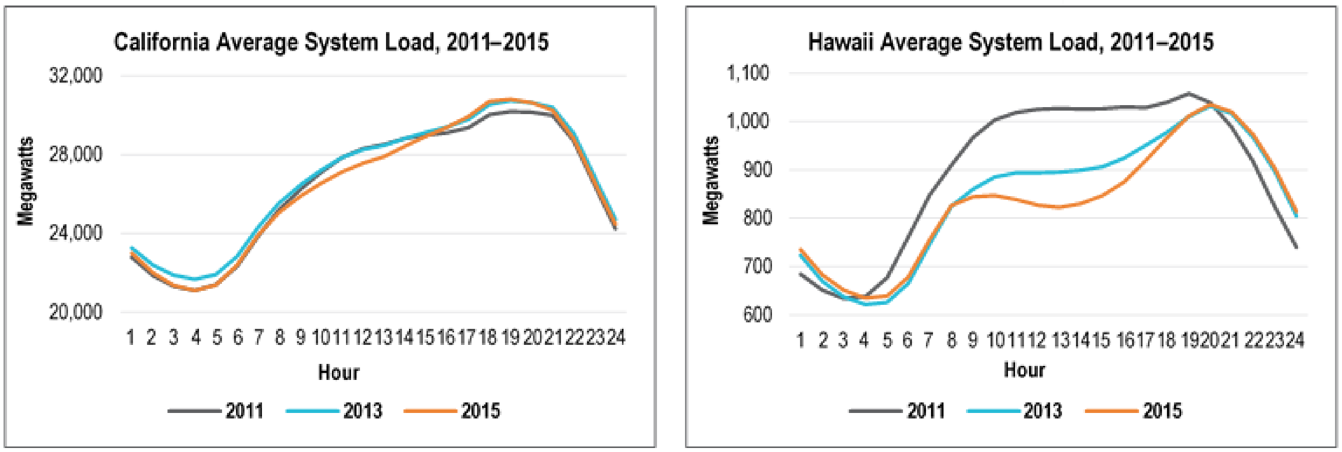
- **Total Load:** Total load regardless of supply source (behind-the-meter systems [e.g., rooftop solar PV] and the electric system [i.e., dispatchable generation, variable generation, and electricity imports])
- **System Load:** Load required to be supplied by the electric system (i.e., total load minus load served by behind-the-meter systems)
- **Net Load:** Load required to be supplied by electric system from dispatchable resources, including imports (i.e., system load minus load served by utility-scale variable generation – wind, solar PV, and solar thermal)



load and a concave net load, which is indicative of the influence of utility-scale solar rather than distributed generation. A comparison of the system load in California and Hawaii further illustrates this point.

In California, the average system load has remained essentially unchanged from 2011 to 2015 (see Figure 7). This trend persists despite the installation of 2,709 MW-dc of residential solar.[5] These distributed resources—which do not participate in CAISO's wholesale markets—remain small compared to overall system, representing just 3% of the participating utility-scale capacity in CAISO markets.[6] These resources, coupled with energy efficiency, appear to be offsetting growth in total load.

Figure 7: California and Hawaii Average System Load, 2011–2015



To contrast, Hawaii's average system load has changed over time due to much higher penetrations of distributed generation, notably residential solar. In 2015, the 305 MW-dc of residential solar operating in the state[7] was equal to 9% of the front-of-meter generation capacity managed by Hawaiian Electric Company.

The comparison of the two states illustrates that understanding the root cause of the duck curve is essential before preparing for and developing strategies to address the operational impacts.

IMPLICATIONS

Our analysis of the underlying data suggests that projections of the duck curve effect in California are real and in some cases occurring sooner than expected. Strategies addressing these challenges should recognize the duck's differing behavior depending on the day of the week and the time of the year. In addition, solutions will need not be totally dependent on complex DER management. Instead, the operational challenge associated with utility-scale solar present the potential for more targeted utility-scale solutions.

While the duck curve was first recognized in California, it may migrate to other regions sooner than expected. Those with little distributed solar should not feel immune to its effects. The duck may prove adaptable to other markets with growth in utility-scale solar. Many parts of the United States are poised for market-driven growth in utility-scale solar. For example, North Carolina is already expecting solar to

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[5] *U.S. Solar Market Insight: Full Report Q3 2016* (GTM Research and Solar Energy Industries Association, 2016).
[6] Residential solar calculation assumes 85% DC-AC conversion.
[7] *U.S. Solar Market Insight: Full Report Q3 2016* (GTM Research and Solar Energy Industries Association, 2016).

inject energy significantly in excess of system needs by 2020.[8] Additional states to watch in the near term include: Arizona, Georgia, Nevada, and Texas. Each of these states, including North Carolina, are forecasted to have more than 3,000 MW of utility-scale solar by the end of 2021.[9] The duck may also appear in less obvious environments, such as small balancing authorities with high penetrations of utility-scale solar.

As the duck curve appears in other states, stakeholders will need to examine their unique system dynamics before developing potential solutions. This is the path being followed by CAISO, which recently proposed time-of-use rate periods designed to match grid conditions.[10] More specifically, the system operator recommended different price periods for weekdays and weekends throughout the year. Not surprisingly, a "super off-peak" period was identified on weekends in most months of the year, which corresponds to the duck curve significant impact on weekends. Ultimately, each utility or state encountering the duck curve will need to develop tailored solutions to address their specific operational situation.

ABOUT THE AUTHORS

Chris Vlahoplus (chrisv@scottmadden.com) is a partner and leads the firm's Clean Tech & Sustainability practice, Greg Litra (glitra@scottmadden.com) is a partner and energy, clean tech, and sustainability research lead, Paul Quinlan (pquinlan@scottmadden.com) is a clean tech specialist, and Chris Becker (cbecker@scottmadden.com) is a research analyst.

[8] "Comments of Duke Energy Corporation to the Federal Energy Regulatory Commission's Technical Conference Concerning Implementation Issues Under the Public Utility Regulatory Policies Act of 1978," FERC Docket Number AD16-16-000, accessed October 4, 2016, http://www.ferc.gov/CalendarFiles/20160617152411-Bowman,%20Duke%20Energy%20-%20Long%20paper.pdf.

[9] *U.S. Solar Market Insight: Full Report Q3 2016 (*GTM Research and Solar Energy Industries Association, 2016).

[10] "California Independent System Operator Corporation Explanation of Data, Assumptions, and Analytic Methods," California Public Utilities Commission Rulemaking 15-12-012, accessed September 20, 2016, https://www.caiso.com/Documents/Jan22_2016ExplanationofDataAssumptionsandAnalyticalMethods-R1512012.pdf.