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Solar Energy and Duck Curve

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Abstract: ***Solar photovoltaic (PV) technology is being deployed to reduce dependence on fossil fuels for electricity use and associated emissions of greenhouse gases and certain pollutants. High solar adoption creates a challenge for utilities to balance supply and demand on the grid. This is due to the increased need for electricity generators to quickly ramp up energy production when the sun sets and the contribution from PV falls. Another challenge with high solar adoption is the potential for PV to produce more energy than can be used at one time, called over-generation. In 2013, the California Independent System Operator published the "duck chart", which shows a significant drop in mid-day net load on a spring day as solar photovoltaics (PV) are added to the system. The chart raises concerns that the conventional power system will be unable to accommodate the ramp rate and range needed to fully utilize solar energy, particularly on days characterized by the duck shape. This could result in over-generation and curtailed renewable energy, increasing its costs and reducing its environmental benefits.***

Keywords: Solar, Renewable Energy, Duck Chart, Demand Curve, Over-generation, Ramp up, CAISO

1. Introduction

1.1 Introduction to PV and Duck Curve

Nowadays the installations of renewable energies have been increasing all over the world. The popular sources of renewable energies are the wind turbine, photovoltaic (PV), concentrated solar power (CSP), biomass, geothermal, hydro and so on. There are various sources of renewable energies, among them PVs are growing dramatically because of a huge price reduction of both PV power plants and residential PVs in recent years. As the PV is a clean source of energy but it has shortcomings too. The output power of PV generators has uncertainty for changing weather conditions. Besides, PV generators can generate power only in the day-time. Therefore, it creates unbalance of a load demand between day and night times. Therefore, power management is a vital issue for PVs generations based smart grid. Given the time-varying output of PV, and the diverse set of electric generators in the power plant fleet, there is considerable uncertainty as to the actual benefits of PV in various regions.

In 2013, the California Independent System Operator (CAISO) published a chart showing the potential for "over-generation" occurring at increased penetration of solar photovoltaics (PV). The "duck chart" shows the potential for PV to provide more energy than can be used by the system, especially considering the host of technical and institutional constraints on power system operation.

In utility-scale electricity generation, the duck curve is a graph of power production over the course of a day that shows the timing imbalance between peak demand and renewable energy production. In many energy markets the peak demand occurs after sunset, when solar power is no longer available. In locations where a substantial amount of solar electric capacity has been installed, the amount of power that must be generated from sources other than solar or wind displays a rapid increase around sunset and peaks in the mid-evening hours, producing a graph that resembles the silhouette of a duck.

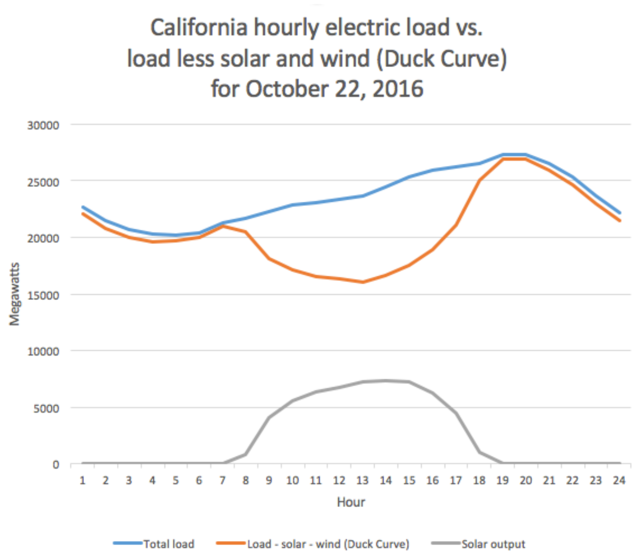

Figure 1: California hourly electric load vs. load less solar and wind (Duck Curve)

Without any form of energy storage, after times of high solar generation generating companies must rapidly increase power output around the time of sunset to compensate for the loss of solar generation, a major concern for grid operators where there is rapid growth of photovoltaics. Storage can fix these issues if it can be implemented.

1.2 Formation of Duck Curve

The curve shows the demand for electricity at any given time of day.

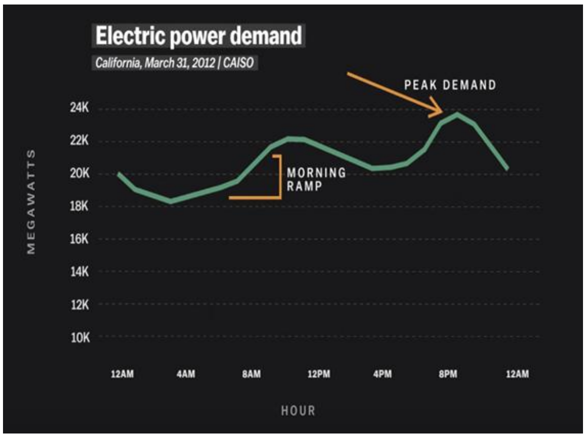

Figure 2: Electric power demand for 24 hours

The power companies supply the least amount of power overnight, then it ramps up in the morning (due to increase in demand), then at sunset, energy demand peaks.

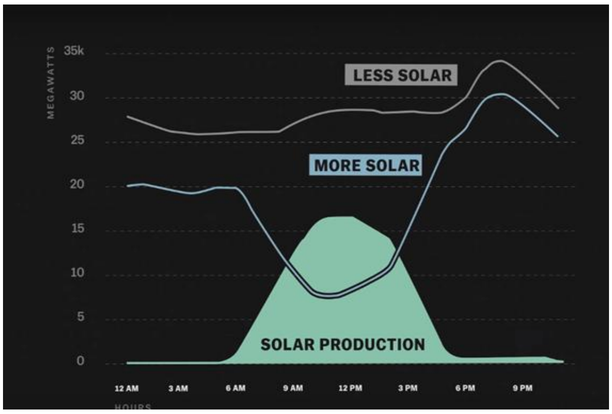

Figure 3: Decrease in demand due to increase in solar production

The graph shows the solar production and the variation of demand curve over the day. The change in demand curve is shown with the increase in solar deployment over years. Maximum solar panel deployment is taking place and it is found that the sun produces most of the energy at the mid-day. Every year meets new solar capacity which makes mid-day demand dip lower and lower. This drop in the mid-day demand explains the formation of the “Belly of the Duck Curve”.

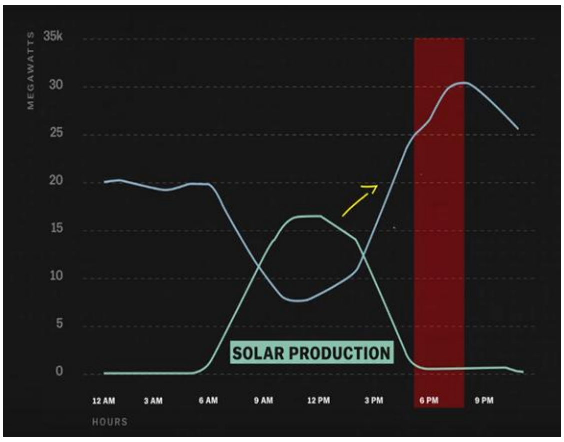

Figure 4: Change in demand curve with increase in solar production

The graph shows the solar production and the variation of demand curve over the day. When the sun is shining, solar floods the market and as the sun sets, solar energy production ends, just as the demand for energy typically peaks in the evening. Power plants than rapidly have to ramp up production to compensate for this increase in demand. This ramping up of demand from the mid- day belly (minimum demand) explains the formation of the “Neck of the Duck Curve”.

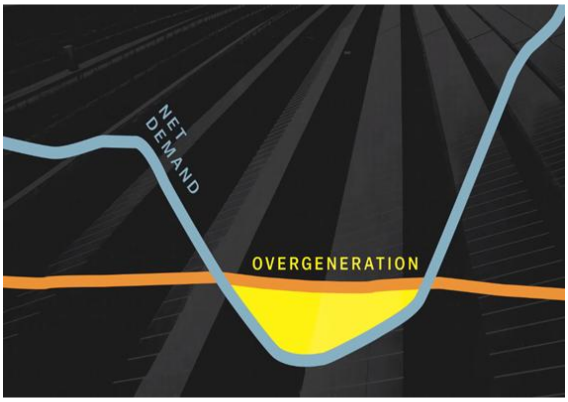

Figure 5: Over-generation due increase in solar production

When the duck gets really fat, its belly starts hanging closer to the bottom of the chart and net load gets closer and closer to zero around midday. That means all the peak and intermediate plants get shut down, and some of the base load plants start to get ramped down too. And then a few hours later, they all get ramped back up. For one thing, that's expensive. For another, grids need a certain amount of reserve power online at all times as a buffer in case of accident or disruption. If so much solar comes online that it starts to eat into those reserves, solar will be "curtailed," i.e., the grid will stop accepting it. Curtailment also happens for economic reasons.

1.3 Duck Curve and Over-generation

The CAISO duck chart itself illustrates the general challenge of accommodating solar energy and the potential for over-generation and solar curtailment. In the chart, each line represents the net load, equal to the normal load minus wind and PV generation. The “belly” of the duck represents the period of lowest net load, where PV generation is at a maximum. The belly grows as PV installations increase between 2012 and 2020. While the amount of PV in 2020 is not shown directly, it can be estimated by comparing the 2012 curve to the 2020 curve. In this case, the normal load (i.e., no PV and adjustments for load growth) at about 1-2 p.m. on March 31, 2020 appears to be about 22,000 megawatts (MW), while PV is generating about 10,000 MW, leaving about 12,000 MW to be met with other resources. In this case, PV provides perhaps 45% of the total demand in this one hour. The duck chart also points to the period of over-generation risk, which could result in curtailed energy.

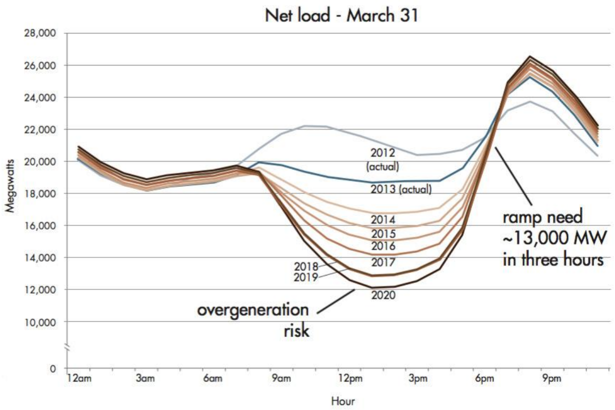

Figure 6: The official "duck chart" first published by CAISO in 2013

The CAISO duck chart document does not explicitly quantify the amount of expected curtailment during this period, but it describes two main causes:

The first occurs as the ISO [independent system operator] prepares to meet the upcoming upward ramps [using conventional generation] that occur in the morning and in the late afternoon. The existing fleet includes many long-start resources that need time to come on line before they can support upcoming ramps. Therefore, they must produce at some minimum power output levels in times when this electricity is not needed.

The second source of over-generation and curtailment occurs when output from any non-dispatchable resource further increases supply in times of low electricity need, typically in the night time hours. Historically, this condition was most likely to occur in the early morning hours when low demand combines with electricity and generation brought on line to prepare for the morning ramp. This second challenge includes the need to accommodate output of all generation resources such as wind and hydro, and plants that produce heat and electricity.

Over-generation can also result from "must-run" plants that are needed for local voltage support and reliability issues, and also from a number of institutional constraints, such as long-term contracts and self-scheduling from certain power plants.

Combined, these issues create an operational challenge which can be described as the "minimum generation" problem which represents the technical and economic limits of thermal and hydro power plants to reduce output or turn off, especially during relatively short periods, such as the few hours of peak solar output. Because of the economic challenges posed by curtailment, it becomes important to examine how much curtailment may occur, as well as methods to reduce curtailment. Examining the relationship between system flexibility and curtailment can help determine the potential contribution of solar to meeting the energy requirements of a region such as California.

2. History of Duck Chart

The duck curve refers to the effect that solar power has on demand for utility electricity. For many decades, demand for electricity followed a fairly predictable daily course, allowing utility grid managers to become experts at predicting and satisfying it. The addition of large amounts of solar to the grid has fundamentally changed the shape of that daily demand profile — in ways that make grid operators nervous about maintaining power and reliability. And in ways that make it look like a duck.

2.1 Variation of demand curves over time from Camel shape to Duck shape curves

Electricity demand used to have a predictable, manageable shape namely a camel. Demand for electricity varies throughout the day, but it does so in predictable ways. It rises in the morning to a little hump before noon, levels out over midday, and then rises to a higher hump in the evening, when everyone gets home from work and turns on their TVs and other electric stuff. Here's a typical "load curve," from the New England region in October 2010:

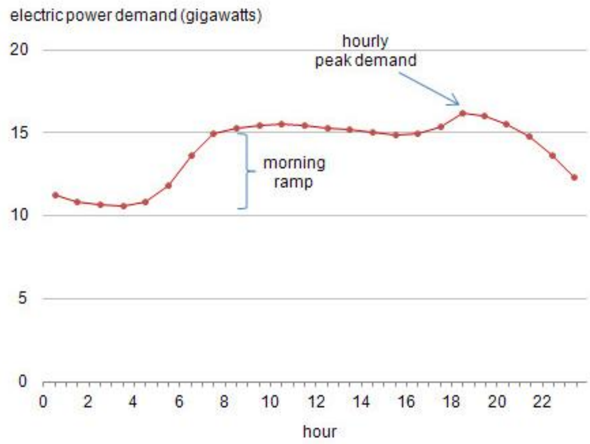

Figure 7: Electric Load Curve: New England, 22/10/2010

If we will closely observe the graph, we can kind of see a camel's back, with its two humps. The exact shape of this curve varies from place to place and season to season. In sometimes and places the humps are more pronounced; in temperate climates, with less heating and cooling demand, they're a little flatter. But in most cases, load curves share a few key characteristics. There are two daily humps. Demand never gets too high or too low, meaning it stays within a reasonably manageable range. And the ramp-ups and ramp-downs of demand are gradual. For almost a century, the utility demands were met, and they got good at it. For that baseline amount of energy that's always needed called as "base load", they run big power plants, usually nuclear and coal, around the clock. These plants are typically slow (and expensive) to start or stop, but cheap once they are running.

In addition to the base load there is "intermediate load," with the next-cheapest tier of power plants, and at the top of that second hump, "peak load," satisfied by (usually natural gas) "peak plants" that are expensive to run but easy to ramp up and down quickly.

It all worked out fine until wind and solar came along. They do different things to the load curve, though, and today we're focusing on solar.

The thing about solar power is that we can't schedule it unlike a power plant. The sun shines when the sun shines, typically from morning to mid-afternoon. When the sun is out and customer's solar panels are generating energy, that customer is using less of the energy put on the grid by the utility.

In other words, from the grid operator's point of view, solar energy doesn't look like a power plant at all (those are controllable, or dispatchable), it looks like a reduction in demand. It's a reduction in demand for the power supplied by the grid operator's power plants — a somewhat predictable reduction, but not a controllable one. So now grid operators no longer have to supply total demand. They have to supply total demand minus solar power. Total load minus solar power is known a "net load." That's the new target utilities have to hit.

With lots of solar, load curves start looking like ducks, which brings us to the duck curve.

A few years ago, the California independent system operator (ISO), or CAISO, put out a short paper on the duck curve that got a lot of attention. California has experienced the highest penetration of solar PV of any state and expects enormous growth in years to come.

In 2012, California's load curve was bopping along like normal, looking like a camel.

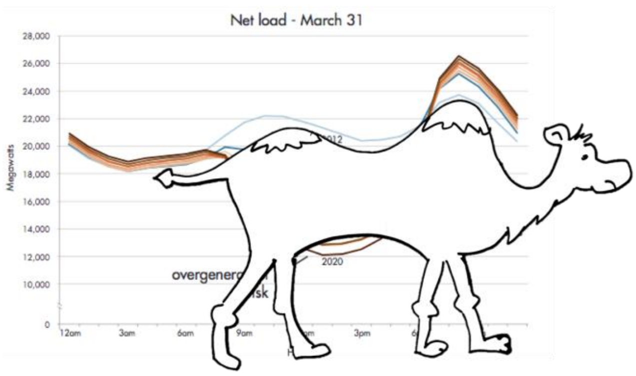

Figure 8: Camel Shaped Demand Curve

That light blue line tracing the camel's humps is the shape of California's actual 2012 load curve. But in 2013, as solar ramped up, things started changing. Demand was suppressed more during the day, when the sun was up. And in coming years, CAISO expects the effect to become more and more pronounced, until the load curve starts looking like a duck:

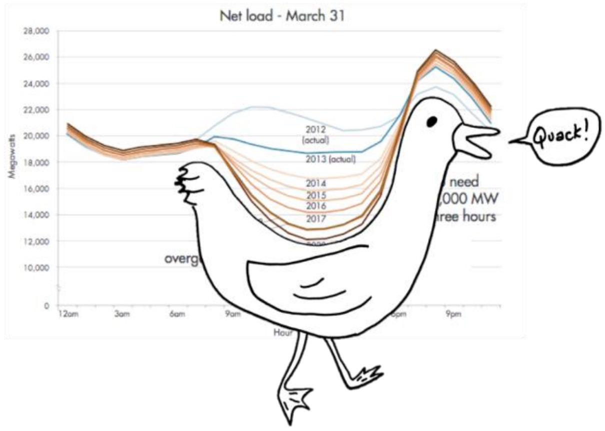

Figure 9: The Duck Curve showing the duck as well

Without symbolising the duck, the curve can be showed as follows:

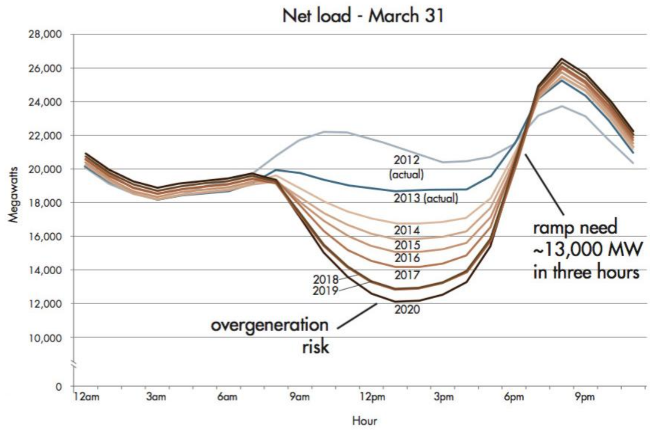

Figure 10: The duck curve shows steep ramping needs and over-generation risk

2.2 List of Events related to Duck curve

a) Early 2000s

In the early 2000s, much of the lab's grid integration analysis work was focused on wind power, as the cost of solar was so high that few utilities considered it a viable option for large-scale deployment. But NREL analysts saw the potential for dramatic solar cost reductions, and believed it was important to examine the implications of achieving such cost reductions on deployment and systems operation.

b) 2008: NREL Releases Foundational Solar Grid Integration Analysis

In February 2008, a team of NREL analysts led by Paul Denholm published a paper that examined how to plan for future large-scale integration of solar photovoltaic (PV) generation on the electric grid. They observed a unique change in the shape of the electric load met by conventional power plants when increasing levels of PV are added to the system—and thus identified the earliest version of what was later named the "duck curve" by the California Independent System Operator (CAISO).

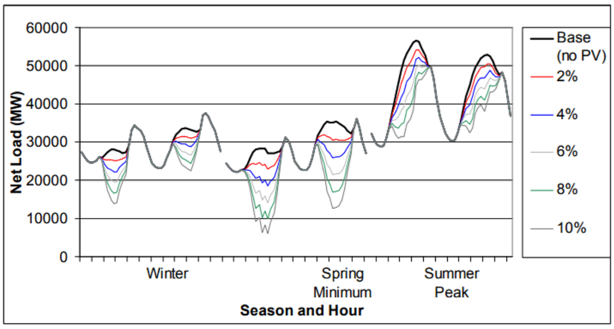

Figure 11: Duck Chart in its early iteration: a figure from a 2008 paper showing the load shapes on California's power system with various PV penetration scenarios

NREL report was one in a series of large-scale renewable integration analyses published by the lab over the last decade.

c) 2010: CAISO began projecting the impacts of increased PV on net load

Projecting significant levels of PV deployment in the late 2010s to early 2020s, the NREL team used a production cost modeling approach to simulate a series of PV penetrations in which up to 10% of the entire U.S. Western Interconnection's annual electrical energy is derived from PV—producing the chart shown above for California's power system. In 2010, CAISO began projecting the impacts of increased PV on net load (or the forecasted electric load minus the expected supply of solar power) on its system through the year 2020.

d) 2013: CAISO Gives the Duck Chart Its Name (and Fame)

Fast forward a few years, and as NREL projected, costs for solar declined rapidly. As a result, PV was deployed more widely, and system operators became increasingly concerned about how solar might impact the grid. In 2013, CAISO produced a chart strikingly similar to NREL's 2008 chart—and noticing its resemblance to the profile of a duck, the term "duck curve" was born.

The moniker quickly gained traction in the industry, especially with emerging energy and environmental policy initiatives pushing for higher levels of solar PV deployment. As a result, CAISO and other system operators began to identify new operating practices that would be able to balance supply and demand with high levels of renewable generation. No longer was utility-scale solar deployment a pipe dream: system operators were now acknowledging the need to plan for increasing amounts of PV in the near future, with California leading the charge.

e) Today: NREL Continues to Find Solutions to the Duck

Today, NREL analysis is continuing to make managing the duck curve easier. To help power system planners and operators across the nation make the most of available renewable resources, NREL analysts are now studying how different combinations of supply- and demand-side options can allow greater system reliability and flexibility with high penetrations of variable generation.

For example, this November 2015 NREL paper explored the duck chart in detail, and suggested two ways to change system planning and operational practices to re-shape the curve and allow more PV on the grid. The first is to "fatten" the duck, growing its belly by increasing the flexibility of the power system—which means changing operational practices to enable more frequent power plant cycling, starts and stops, and so on. The second is to "flatten" the duck, shrinking its belly by shifting supply and demand so solar can meet parts of the load that wouldn't normally be provided in the middle of the day. Flattening the duck typically involves adding energy storage or demand response—both options that are already being deployed in various locations around the United States.

3. Utility Challenges due to Duck Curve

One notable thing about the duck curve is that it wreaks havoc on the revenue of power producers and utilities. That gives them every reason to exaggerate its inevitability and its danger. From the point of view of the grid operator, worries about the duck curve are threefold:

3.1 Steep, tall ramps

The ramps at the time when net load is rising or falling, no longer look like the gentle slope of a camel's hump. They get steep and tall (like a duck's back) and relatively quick. That means grid operators are forced to take a bunch of power plants offline, or put a bunch online, rapidly. What's especially unfortunate is that the sun tends to go down just before the evening peak of demand, which means net load goes from very low to very high, very quickly (13,000 MW in three hours, in the CAISO example), and then down low again. Grid operators don't like steep ramps. It is expensive and highly polluting to turn a bunch of plants down (or off) and then crank them back up again all at once. It also makes voltage and frequency management more difficult. Coal is not good in this role, as it is slow to ramp. Nuclear is proving a little more flexible in some places, but not so much in the US yet. For the most part, for fast-responding power plants, utilities turn to natural gas. So California needs enough natural gas capacity to supply the evening peak, but for most of the midday, it doesn't need any of it. That amounts to a lot of natural gas plants sitting around a lot of the time, with low "capacity factors," but being ramped up and down frequently, increasing operating and maintenance costs. That all makes the grid operators grumpy.

3.2 Over-generation and curtailment

When the duck gets really fat, its belly starts hanging closer to the bottom of the chart — net load gets closer and closer to zero around midday. That means all the peak plants and intermediate plants get shut down, and some of the base load plants start to get ramped down too. And then a few hours later, they all get ramped back up. For one thing, that's expensive. For another, grids need a certain amount of reserve power online at all times as a buffer in case of accident or disruption. If so much solar comes online that it starts to eat into those reserves, solar will be "curtailed," i.e., the grid will stop accepting it. Curtailment also happens for economic reasons.

3.3 Frequency response

For stability, the grid must closely balance supply and demand, second by second. The standard frequency is maintained. In case of a sudden disruption — the unexpected loss of a power plant, transmission line, or large load — the grid needs resources capable of ramping up or down quickly to compensate. This is done by automated frequency response systems, usually on conventional power plants. If solar starts shutting down all those plants in the middle of the day, the grid loses those resources, and with it some stability. Right now, most solar systems do not have automated frequency response, but they are capable of it.

4. Enabling greater solar penetration: Flatten or Fatten the duck

Accommodating greater amounts of PV will likely require multiple approaches to increasing the overall flexibility of the power system. Previous work by the CAISO and other groups suggest many individual approaches, but these can be summarized by two more general approaches, which we illustrate below as fattening the duck and flattening the duck.

4.1 Flattening the duck

Fattening the duck includes growing its belly by increasing the flexibility of the power system—which means changing operational practices to enable more frequent power plant cycling, starts and stops, and so on. Flattening the duck typically involves adding energy storage or demand response.

4.2 Fattening the duck

Flattening the duck, shrinking its belly by shifting supply and demand so solar can meet parts of the load that wouldn't normally be provided in the middle of the day.

5. Survey Data for Duck Curve

The survey data is analysed in the form of net demand trend from California ISO. The graph illustrates how the ISO meets demand while managing the quickly changing ramp rates of variable energy resources, such as solar and wind. These graphs are shown on monthly basis.

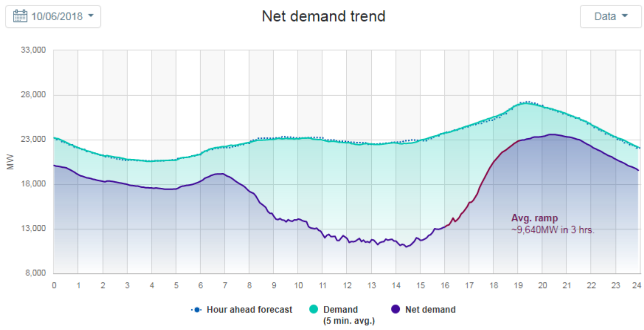

Figure 12: Survey data as on October 6th, 2018

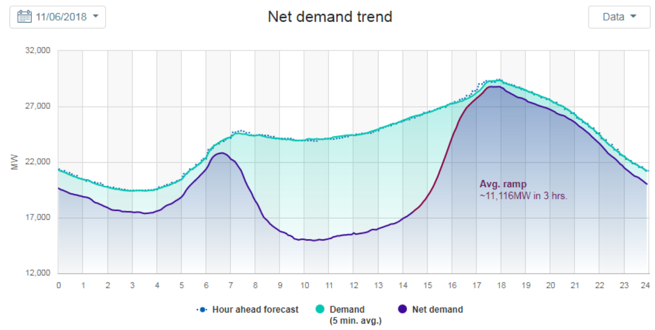

Figure 13: Survey data as on November 6th, 2018

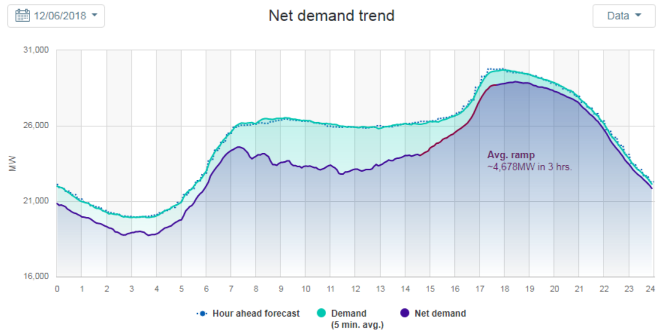

Figure 14: Survey data as on December 6th, 2018

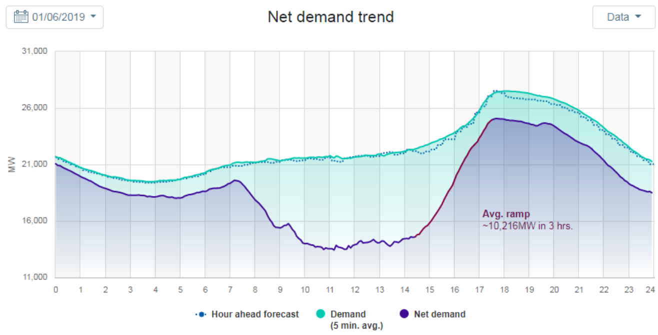

Figure 15: Survey data as on January 6th, 2019

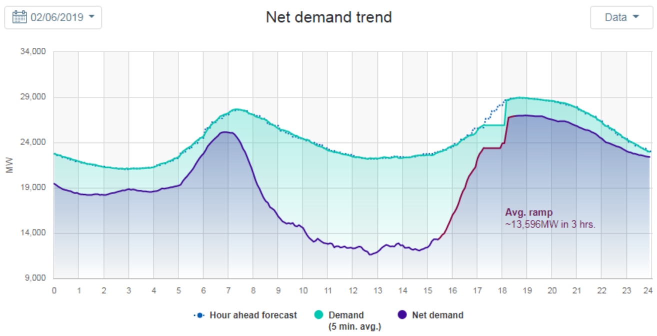

Figure 16: Survey data as on February 6th, 2019

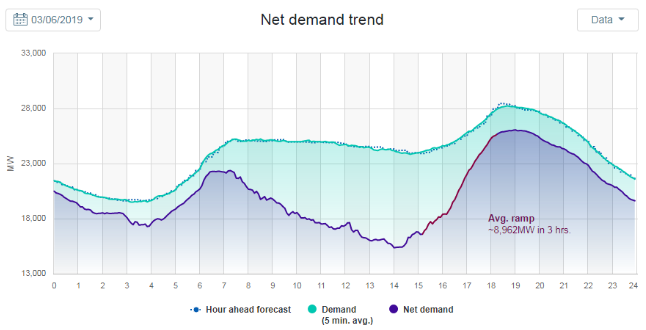

Figure 17: Survey data as on March 6th, 2019

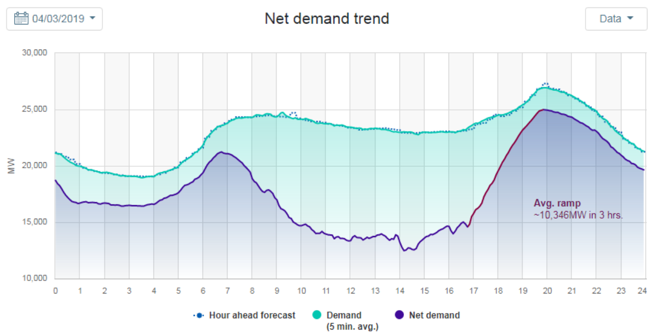

Figure 18: Survey data as on April 3rd , 2019

6. Conclusion and Future Scope

The use of renewable sources of energy like PV solar deployment has proved to be beneficial in many aspects like reducing customer and utility costs, creating jobs, and decreasing environmental impacts. Its role is becoming even more important as we focus on the urgent need to reduce green-house gases emissions and to ensure reliable and affordable grid operations. Although the solar PV market has experienced astronomical levels of growth and cost reductions in recent years, there are many technical challenges and economic realities that need to be reconciled in order for distributed generation resources to be at parity with conventional generation. Energy storage will likely play an important role in future improvements to power systems, as they allow operators to effectively redistribute energy supply and demand to the optimal.

References

[1] David Robert, "Why the duck curve created by solar power is a problem for utilities", Vox Media, Feb 10, 2016.
[2] Becca Jones-Albertus, "Confronting the Duck Curve: How to Address Over-Generation of Solar Energy", Office of Energy Efficiency & Renewable Energy, Oct 12, 2017.
[3] Chris Vlahoplus and Greg Litra, "Revisiting the California Duck Curve: An Exploration of Its Existence, Impact, and Migration Potential",ScottMadden, Oct, 2016.
[4] Paul Denholm, Matthew O'Connell, Gregory Brinkman, and Jennie Jorgenson, "Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart", NREL, Nov 01, 2015.
[5] Ravinder Soin, "Overcoming Duck Curve & Peak Shaving using Energy Storage", All Energy 2016, Melbourne Convention & Exhibition Centre, Oct 05, 2016.
[6] Roger Andrew, "The California Duck Curve isn't confined to California", Enery Matter, Nov 15, 2017.
[7] Jeff St. John, "The California Duck Curve Is Real, and Bigger Than Expected", Green Tech Media, Nov 03, 2016.
[8] Jeff St. John, "EIA Data Reveals California's Real and Growing Duck Curve", Green Tech Media, Jul 25, 2017.
[9] Jordan Wirfs-Brock, "Why Is California Trying To Behead The Duck?", Inside Energy TM, Oct 2, 2014.
[10] "What the duck curve tells us about managing a green grid", Californian Independent System Operator (CASIO), 250 Outcropping Way, Folsom, CA 95630, 2016.
[11] "Ten Years of Analyzing the Duck Chart", NREL, Feb 26, 2018.
[12] Roham Torabi, Alvaro Gomes, and F. Morgado-Dias, "The Duck Curve Characteristic and Storage Requirements for Greening the Island of Porto Santo".