Central Coast Climate Science Education
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Storing Electricity

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The evidence is now overwhelming that the climate is changing and that its cause is fossil fuel consumption and changes in land use. Climate change is becoming increasingly damaging and costly. The nations of the world must take steps to reduce greenhouse gas emissions, even while the demand for more energy grows, especially in the developing nations. Two major contributors to these emissions are the generation of electricity and the use of the internal combustion engine for transportation.

Fortunately, nature has supplied us with huge amounts of non-emitting sources of energy. Among these are wind and solar energy which already can generate electricity at a cost competitive with, or less than, fossil fuels. (Carbon sequestration--removal of CO2 from the atmosphere or from emitting sources, and its permanent storage, may also be essential but is still very costly.)[1] But wind and solar energy suffer from the obvious disadvantage that they are not constant. Thus, to deploy them on a very large scale, the technology for storing and retrieving this energy economically needs to go hand and hand with wind and solar electrical generation.

This is the first in a series of posts in which we survey the present and future status of electrical energy storage with special emphasis on the state of California.

Readers with even a passing knowledge of electricity will not be able to get past the title of this essay without indignantly saying to themselves "don't these authors know you can't store electricity", and of course they are literally correct. But what we can do is to divert the flow of power associated with electrical currents and store the accumulated energy. This stored energy may take many forms. We will describe some of the most promising of these storage technologies in a later post of this series.

All of these energy storage mechanisms can be run in reverse to produce a flow of electrical power which can then be put to use by running electrical motors, heating toasters and myriad other tasks, but of course with the inevitable loss of some of the original energy as 'waste heat'.

The plan of this series is as follows: This first post of the series describes two problems which arise in incorporating wind and solar energy as sources of power and how storage devices can help deal with these problems. In subsequent posts we survey the most important types of electrical energy storage devices, discuss the amount of storage required to successfully incorporate significant solar energy in California[2], and the economics of storage and legislative initiatives to encourage further deployment of storage. Finally, we will consider the overall reduction in greenhouse emissions as electric vehicles displace internal combustion engine vehicles, the growth in green power needed to run the electrical vehicles, and whether the batteries in electric vehicles can be used as viable additional storage technology.

The Electrical Grid and the "Duck Curve"

The transition to the use of renewable energy sources is well under way in California, so California serves as a useful illustration of the issues involved in energy storage.

In California, the procurement and transmission of electricity is dominated by three investor-owned utilities (IOUs), but this procurement and transmission is monitored and managed by the California Independent System Operator (CAISO.)[3] Managing the "grid", the highly complex network of electrical generation facilities and the transmission lines delivering electrical power to users, involves very delicate moment-to-moment balancing between the demand for the power (the 'load') and the amount of power being generated. The load also varies significantly over both a 24-hour period and over the year and each of these three time scales requires some form of storage technology. CAISO is very skilled in predicting what the daily ‘load curve’ looks like a day or so in advance to ensure that just the right amount of power is available. Here is an example of a 24-hour load curve.

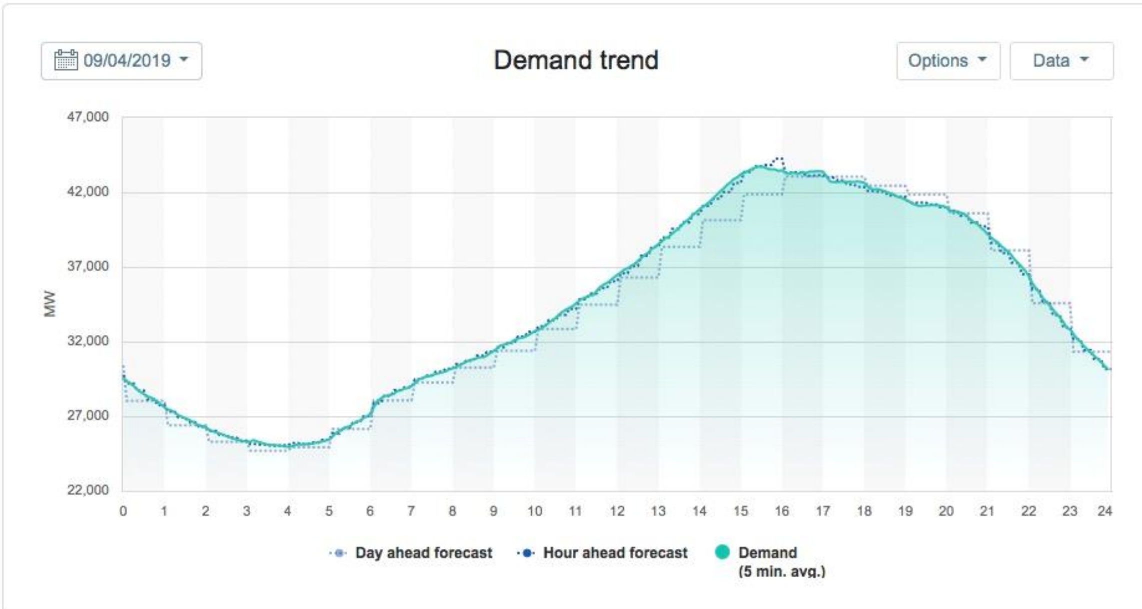

Figure 1: A typical demand curve for California users of electricity during a 24-hour period. The amount of power on the vertical axis is measured in megawatts. (Source: CAISO website)

The shape is typical for late spring through late summer. Most residential and some industrial and commercial users don’t require power in the very early morning hours so there is a minimum, but still substantial, requirement for power around 4 AM. As the day begins the demand ramps up and during warm weather peaks in the late afternoon or early evening as air conditioning units and afternoon and evening appliances turn on.

As of 2018, about 23% of California’s electrical power came from wind and solar.[4] Solar energy especially, is expected to substantially increase. Both of these sources are not distributed uniformly throughout the day of course.

Even in late October the contribution from solar energy produces a strong peak in energy lasting for several hours from mid-morning to late afternoon. Wind power generation tends to be somewhat complementary, stronger in the evenings and dying off during the day.

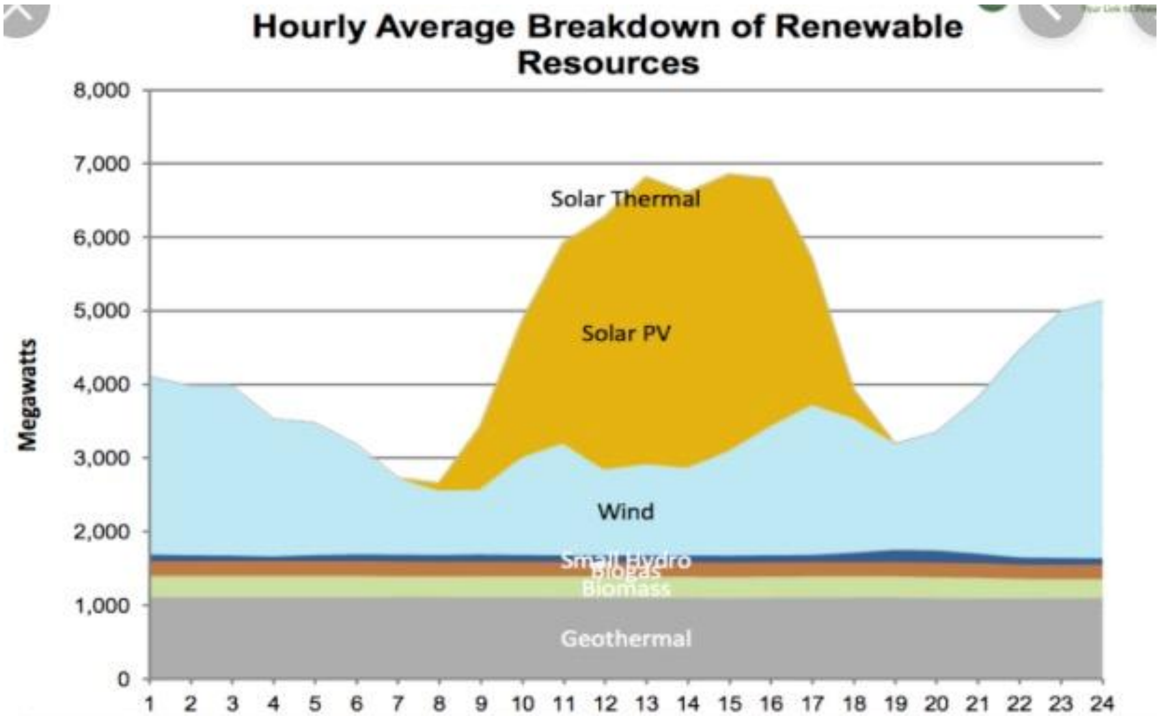

Figure 2: The contribution from renewable energy sources to the CAISO managed grid on October 28, 2015. Solar PV refers to the conventional solar panels we are familiar with while solar thermal involves concentrating sunlight to superheat water to generate steam to drive an electricity generating turbine. Solar PV is the largest contributor. Source: CAISO.

The variable wind and solar sources and the overall demand curve produce the *net* demand curve shown in figure 3: the *difference* between the actual demand of figure 1 and the energy produced by wind and solar.

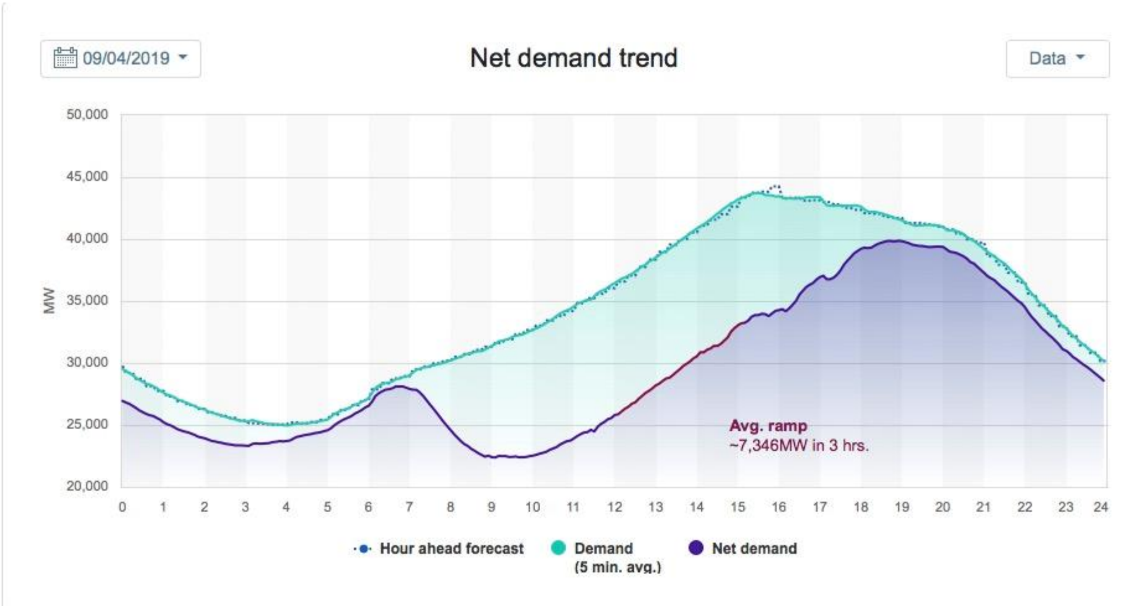

Figure 3: The purple curve shows the *net* demand curve: the difference between the total demand curve (blue) and what is supplied by the variable wind and solar energy. This is for the same date as figure 1. Source: CAISO.

As more and more solar energy is installed, the dip in the *net* demand curve will become more pronounced, since an increasing amount of solar energy is subtracted from the overall demand curve to produce the *net* demand curve. Note that in figure 3 the bottom of the vertical axis is at 20,000 MW (or 20 giga-watts = 20 GW.) If it is replotted so that the bottom of the vertical axis is at 10,000 MW and yearly estimates for solar energy through 2020 are included, then we get a series of *net* demand curves which more and more resemble a duck: the famous “duck curve”, a phrase coined by CAISO.

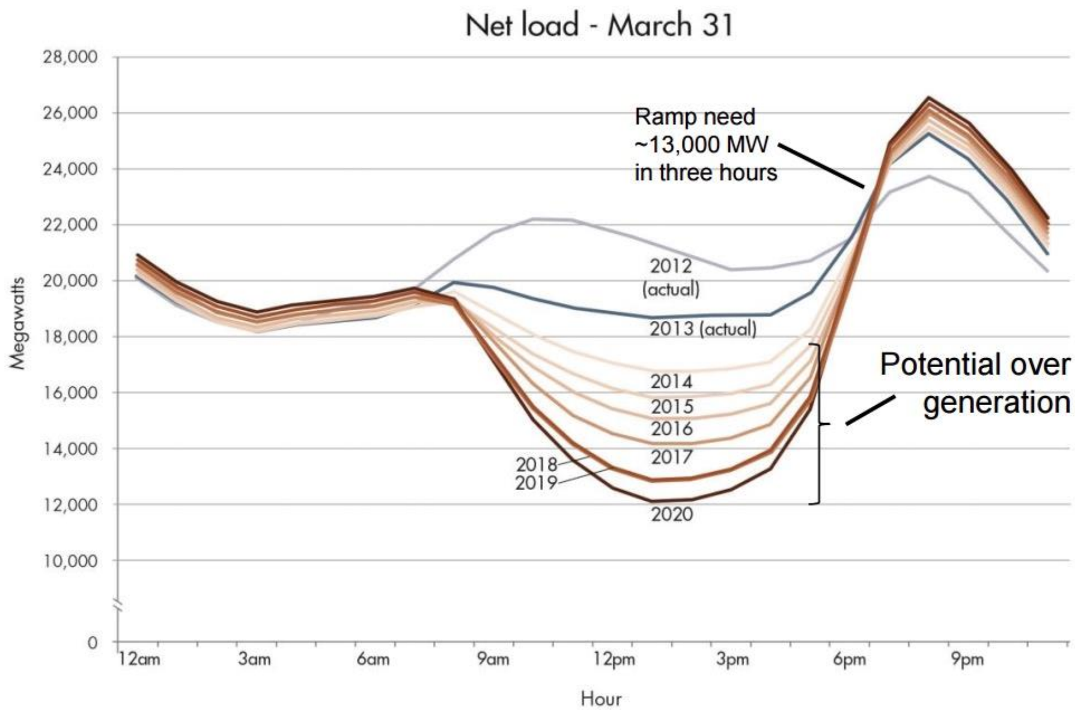

Figure 4: A series of duck curves, with the belly of the duck occurring about 2 PM and the tip of the head at 9 PM for a yearly date of March 31. See the text for a discussion of “ramp need” and “over generation”. Source: CAISO

There are two challenges presented by the duck curve:

First, the *steepest* part of this net demand curve occurs over a period of a few hours from late afternoon to early evening as the sun sets and actual demand increases. This requires that a large *additional* source of power be quickly produced from "somewhere" over this period. This is referred to as the "ramp need" in the figure. (The duration of this ramp need, and the amount of additional power required in figure 4 are only illustrative and will vary with conditions.) But where is "somewhere"? By definition, it is not wind or solar, nor is it any of the steady renewables like geothermal. Nor is it any of the other “baseline” power sources supplying California, including, (until 2025) nuclear energy. Instead, it must currently come from ‘peaker’ gas-powered generating plants, which must be kept ready to go whenever needed. This is an expensive proposition since for much of the time these power plants are idle and to recover their capital costs means that source of power is costly.

The second challenge is the ‘over generation’ problem illustrated here:

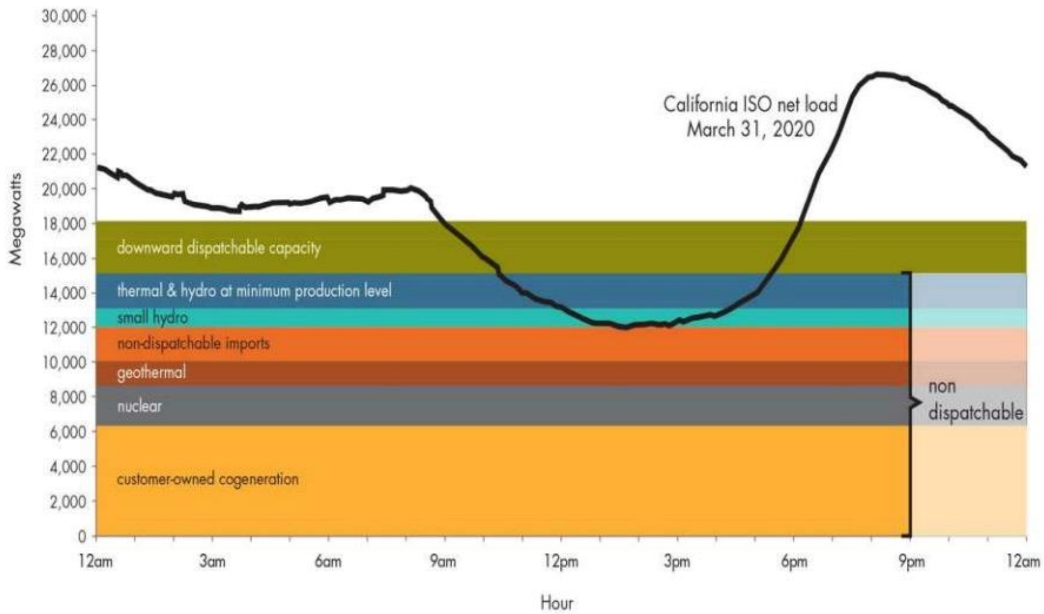

Figure 5: This figure shows the net demand (duck curve) on which is superposed sources of power other than wind and solar. Source: See footnote five.[5]

In figure 5, the steady sources of power that are labeled ‘non-dispatchable’ means that they cannot be turned off in as short a time as the duck curve belly, lasting a few hours. This in turn means during the peak of solar energy production that the net demand curve would dip *below* the approximately 15,000 MW of non-dispatchable power, generating *too much* power. This could severely damage components of both the grid and user facilities. To avoid such overgeneration sources of solar energy, the commercial solar energy producers are required to reduce their production. This ‘*curtailment*’, like the situation with the peaker plants, is obviously ineffective from a cost point of view and is a waste of potential clean energy that should be utilized to the fullest extent possible to help stabilize the climate.

The following figure illustrates how storage technology can help to flatten the duck curve and thus somewhat alleviate both the steep ‘ramp need’ as well as the ‘over-generation’ problem.

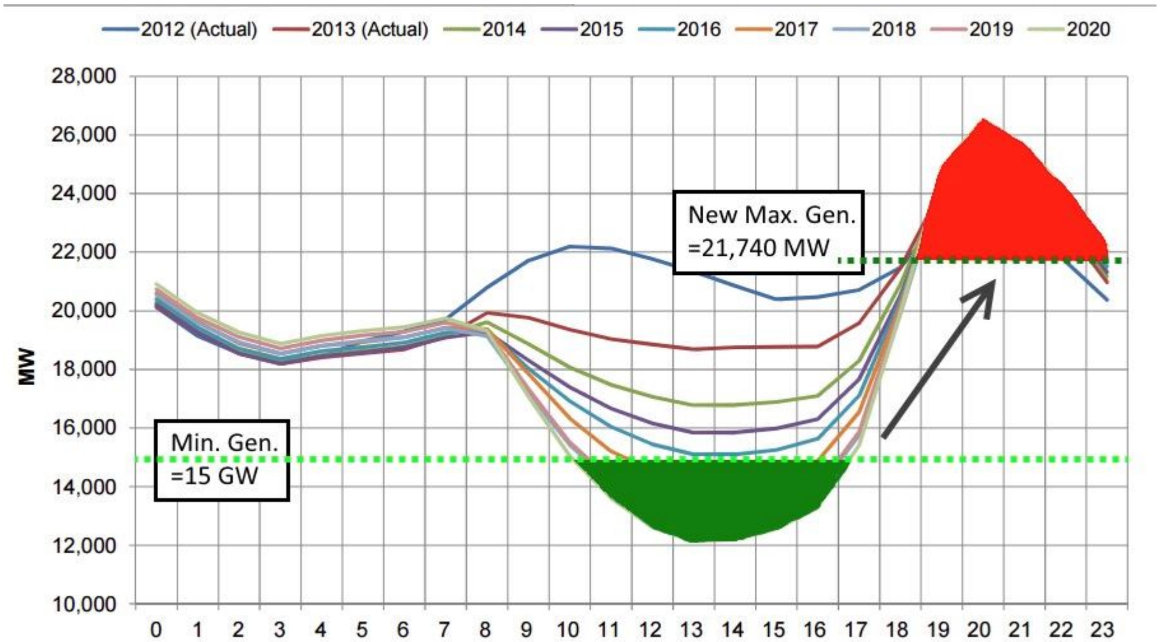

Figure 6: Illustrating how storage can help alleviate the "over-generation" problem and the "ramp need" problem. Source: See footnote six.[6]

The shaded green portion schematically represents the energy (mostly solar) that is stored, while the red shaded portion represents that stored energy returned to the grid. Comparing figure 6 with figure 5 we see that instead of having to curtail solar energy to avoid over-generation, it is stored instead and then returned to the grid in the evening. There will still be a need for ‘peaker’ plants to 'ramp up' however. In this illustrative case, the maximum power needed from these peaker plants is only about 7000 MW, the difference between 21,740 MW (where the stored energy begins to be returned to the grid) and the 15,000 MW of non-dispatchable power.

In this example the maximum rate at which stored energy is returned to the grid at around 8 PM is about 4,500 MW, the difference between 26,500 MW and 22,000 MW in the red area, while the total *energy* required to chop off a good portion of the duck’s head is the area under the red shaded area--about 13 GWh. Since there is always wasted energy in the process of storing and retrieving this energy, the amount of energy required to be stored (represented by the green area) should be about 20% larger, or about 15.6 GWh. Actually, therefore, to allow for this wasted energy, power should have been diverted to storage whenever the net demand dipped below a value that is a little *above* 15,000 MW, say

16,000 MW. The exact value should be chosen to make the green area about 20% higher than the red area. Under 16,000MW assumption, the maximum *rate* at which energy must be stored is about 4,000 MW, the difference between 16,000 MW and the minimum in the duck curve at about 12,000 MW.

To set these two numbers in perspective--the maximum required rate of storage and the required total daily energy storage capacity-- the typical power output from the two reactors at the Diablo Canyon nuclear power plant is a little over 2000 MW, and the total steady, non-dispatchable energy per day is about 48,000 Megawatt hours = 48 GWh.

One final important point: We have noted the importance of storage to flatten the duck curve and reduce the amount of peaker power required. From this, some readers might draw the false conclusion that solar power in some sense encourages the role of gas-fired peaker plants. This is absolutely not the case. Suppose there were no solar or wind energy available. Using the example of figure 1, the difference between the minimum and maximum required power is nearly 20,000 MW which would then have to be supplied by turning on additional costly gas-fired power.

In 2018 wind and solar contributed 22% of California's energy generation.[7] This resulted in a large reduction in both cost due to less reliance on variable gas-powered sources, and of course a tremendous reduction in greenhouse gas emissions.

In part two of this series we will describe the most promising storage technologies for dealing with the moment-to-moment, daily and seasonal energy storage needs.

We thank Simo Nylander for his comments on a draft of this post.

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[1] Today's cost of carbon sequestration is estimated at $130 per ton of carbon dioxide (on the lower end of estimates using stack scrubbers), resulting in a 3-fold and 6-fold increase in cost of electrical generation via natural gas and coal, respectively (https://cleantechnica.com/2016/01/19/carbon-capture-expensive-physics/). But see also soil carbon sequestration, discussed in a forthcoming post.

[2] To meet California's carbon reduction goals for 2030, renewables will need to grow to 60% of the total electrical generation: https://energyfuturesinitiative.org/).

[3] See the essay on this website : A Visit to Cal-ISO:
Where Does California's Electricity Come From and How is it Managed?
http://www.centralcoastclimatescience.org/uploads/5/3/8/1/53812733/ray-weymann-visit-to-california-independent-system-operator-2015.pdf

[4] https://ww2.energy.ca.gov/almanac/electricity_data/total_system_power.html

[5] Prepared Statement of Brad Bouillon on Behalf of the California Independent System Operator Corporation," U.S. Federal Energy Regulatory Commission, 10 Jun 14.

[6] Duck curve from CAISO as modified by Michael Burnnet: Report for Stanford Physics course 240, June 1, 2016.

[7] See the first table in: https://en.wikipedia.org/wiki/Energy_in_California