Central Coast Climate Science Education
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Solar Energy and the Duck Curve: If it looks like a duck and quacks like a duck, it must mean…what?

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For whom this essay is intended:

Everyone who wishes to understand some limitations on the deployment of solar and wind energy. Or, for folks to want to know the answer to the question posed in the title.

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Two Caveats

Minor caveat:
Before proceeding it needs to be said that this entire topic is quite complex, both from a technological and an economic standpoint. *I do not have expertise in either of these areas. If readers having such expertise find conceptual or factual errors, I invite them to provide relevant information.*

Major caveat: This essay deals with the production of electricity from solar energy as a means of reducing greenhouse gas emissions. *But currently in California, the emissions resulting from electricity generation are only about 14% of the total*[1]*, the two biggest contributors by far being transportation and industrial processes. Until these two sectors are also electrified, solar energy can make only a limited impact on reduction of greenhouse gases in California.*

What the Duck Curve is and why it is important

Understanding and dealing effectively with the famous "Duck Curve," which is familiar to those who must manage our electrical grids, is crucial in determining how much solar and wind energy can be economically added to our sources of electrical energy and how free of carbon dioxide emissions that energy mix will be.

If you want to know where the duck curve gets its name, here's why:

[1] The 14% refers to the emissions resulting from electricity generation. Emissions resulting from, for example, industrial processes like cement production, are ascribed wholly to the Industrial Sector, regardless of whether electricity is used in the process or not.

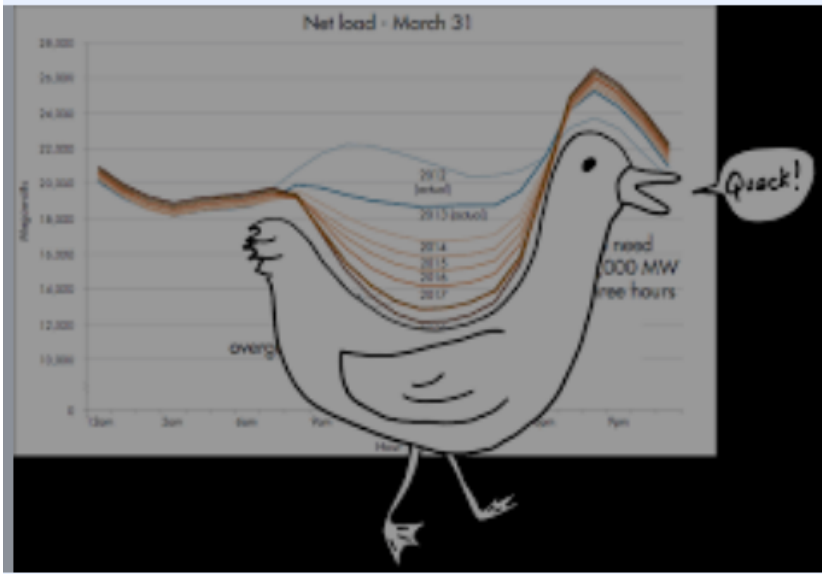

Figure 1: Duck curve with duck!

On the other hand, if you want to understand what the duck curve is representing, it is probably better to look at the curve without the duck!

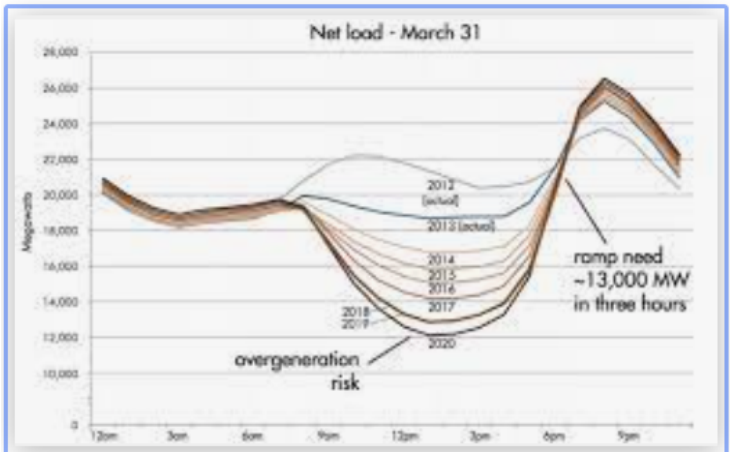

Figure 2: A projection made back in 2012 of how deep the belly of the duck might look like by the year 2020.

As far as figure 2 is concerned, the only things that need pointing out are: The title, which says “Net Load – March 31”, what the vertical axis is measuring (Megawatts of electricity), what the horizontal axis is measuring (time of day, starting from midnight of one day and running through the next 24 hours,) and the notation “overgeneration risk” and “ramp need ~13,000 MW in three hours.”

But what does this all mean and what is meant by these terms?

Section I: The present-day situation in California

To explain these terms, it is useful to look at some real data, rather than projections. The California Independent System Operator (CAISO) is responsible for managing that portion of California's electrical grid that serves about 80% of all of the electricity consumption in California, so we will concentrate on the state of California and use some, but not all, of the data from the power consumed in the area managed by CAISO.

CAISO publishes daily a large amount of data, including the same data included in figure 2. Here are two graphs showing actual data from CAISO for May 14, 2021:

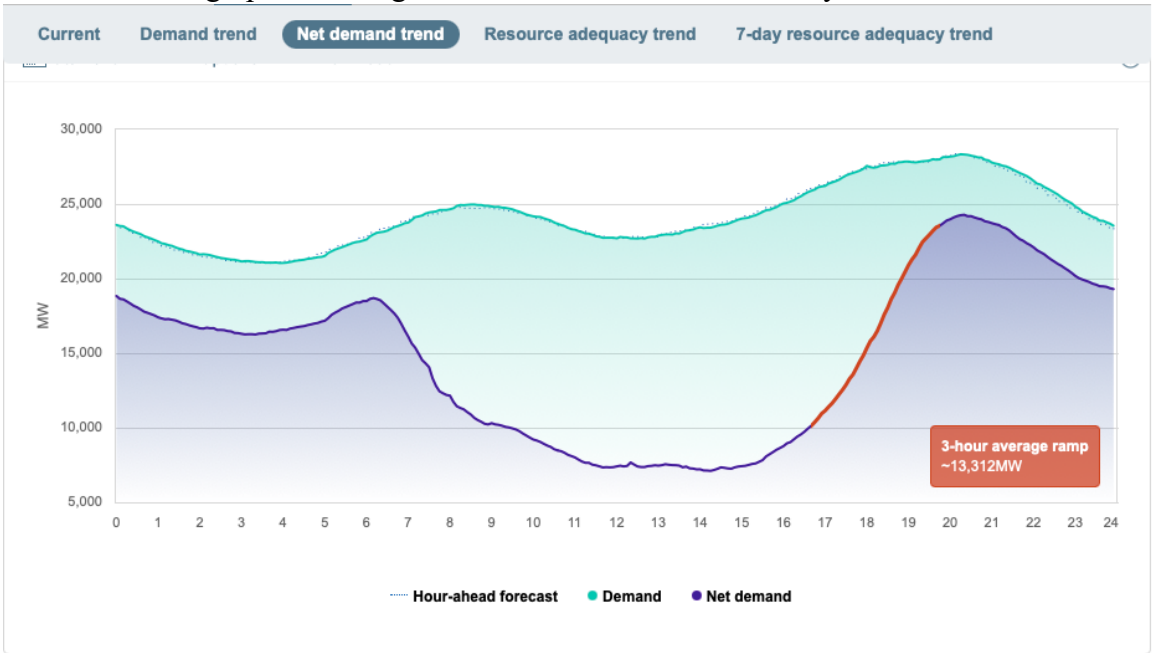

Figure 3: The data showing total demand (in light blue-green) and "net" demand (in dark blue/purple) for May 14, 2021. As in figure 2, the vertical axis is measured in megawatts of electricity and the horizontal axis is the time from midnight at the beginning of May 14, and running for the next 24 hours. See the text for the interpretation of these two curves. The red portion of net demand curve refers to the "ramp need" and the need for "peaker plants" in the text below.

The light blue curve is the *total* "demand" (or "load") for electricity from all the consumers in the CAISO area. (This includes the three largest investor-owned utilities in California: PG&E, Southern California Edison and San Diego Gas and Electric.) The dark blue curve is what is termed the "net demand" (or "net load".) It is the *difference* between the total demand and the energy available from (on-shore)[2] wind and solar. (There are two types of solar energy: **PV**--"photovoltaic"-- usually on flat panels, and the

[2] I have included only on-shore wind, as there are no off-shore wind installations currently in California. If planned offshore wind installations become a reality in California, they have a very different variation with the time of day than onshore wind, and will modify the duck curve. I assume that this contribution will still be included in the definition of "net load".

less common “solar thermal,” which focuses the sun to heat a substance to high temperature.) What this curve represents, therefore, is the amount of energy that must be supplied from energy sources which are *not* subject to the vagaries of times when the sun does or does not shine and when the wind does or doesn’t blow.

As we expect, the total demand is smallest in the very early morning and late evening. It picks up between about 6 AM and 10 AM when people get up, turn on their appliances and go to work. There is a slight decrease in demand in midday, which rises again as people turn on their air conditioners, if it happens to be a hot day, but in any case, it rises as they return home and turn on home appliances.

What about the *net* demand? Since the sun is most intense between about noon and 2 pm, the amount that must be supplied by sources other than solar and wind is at a minimum during these hours and these other sources needed to supply only about 7,500 MW during these hours, as shown by the dark blue curve during these hours. There was certainly enough power from such source available to meet this need, at least on that day, so there should not be any problem, right? Wrong!

Take a look at a complementary CAISO graph which shows the *sources of supply* for the energy during these same 24 hours.

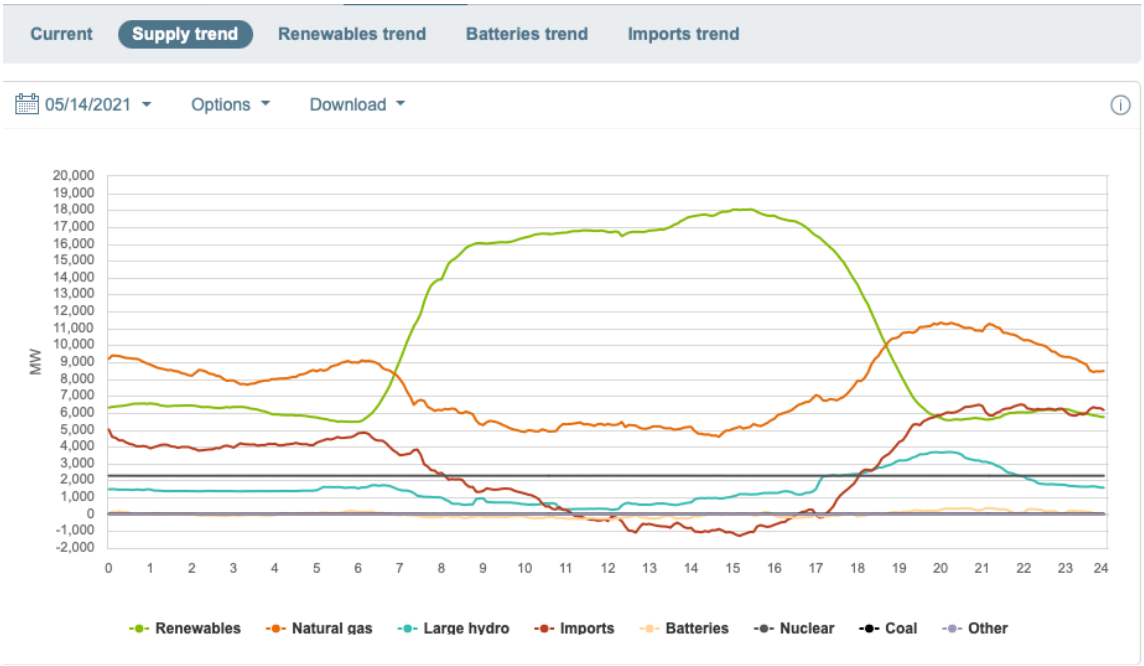

Figure 4. The sources of electrical power during the 24 hour period of May 14, 2021. The green curve is the total of “eligible” renewable energy sources, which is primarily wind and solar but has some contribution from geothermal, biomass and small-scale hydroelectric sources of power. The remaining ones are indicated by the color codes in the legend.

Look at the supply of energy of non-renewables around 6 am. Natural gas contributes around 9000 MW. Out-of-state imported electricity[3], amounted to about 5000 MW, nuclear energy (from Diablo Canyon) amounted to 2000 MW, while large-scale hydroelectric facilities contributed about 1700 MW, for a total of 17,700 MW. Looking back at figure 3, it is clear that if this 17, 700 MW of power were to be continually supplied right through the noon to 2 PM hours, since only 7500MW of non-renewables were required to meet the total demand of about 23,000 MW, there would be an *over-production* of power in the amount of 17,700 – 7,500 = 10,200 MW. This would destroy the grid and the facilities that consume electricity. In fact, the balance between electrical demand and supply must be *very closely in balance*, not just day to day, but over times of just several seconds.

The solution to this dilemma is that during these midday hours, somehow these non-renewable energy sources must be reduced. This was accomplished on this particular day.

But even at present this is not always so easy *and will get increasingly difficult as more wind and solar energy are added to the electricity mix, unless significant investment in research, development and deployment in energy storage and improvements in 'grid flexibility' are made.* This future aspect of the duck curve is discussed in **Section II.**

To examine this a little further, we need to briefly describe some technical terms, because they play a role in various limitations imposed on various energy sources. These limitations are required for reliable functioning of the electrical grid.

The terms are: "*dispatchable*" energy; "*contingency reserves*"; "*spinning*" and *"non-spinning"* reserves.

Dispatchable energy: Strictly speaking, "dispatchable" electrical energy sources[4] are those that can be turned up or down as needed, whereas wind and solar cannot be (but see the discussion in Section II about advanced 'inverter' technology.)

But this simple interpretation is a bit misleading, for it doesn't take into account *how quickly* and by *how much* these sources can be adjusted for either technical or economic reasons.

In principle, while nuclear reactors can be "load-following", that is, adjust how much energy they generate during the day,[5] in practice, at least in the U.S., that has not been utilized. For one thing it is uneconomical to operate them in this way. So, nuclear reactors are considered 'base-line' sources and *not* dispatchable. The same is true, in practice, of geothermal energy and the lesser amounts of other small 'renewable'

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[3] Not all the sources of this imported electricity can be accurately identified; see Appendix 1

[4] See the 1st link below for a very short discussion of dispatchable electricity sources and the 2nd link for a more nuanced discussion:
https://en.wikipedia.org/wiki/Dispatchable_generation
https://www.mackinac.org/25756

[5] https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf

sources.[6] (Since geothermal is part of the renewables curve, in green, its contribution can't be determined simply by looking at figure 4.) Altogether, these base-line non-dispatchable sources contributed about 2400 MW on the day we are examining.

Contingency reserves: Since power generating plants of whatever kind can suddenly fail, as can high capacity transmission lines, CAISO and any grid regulating agencies require that enough extra capacity be kept in reserve for such contingencies, generally about equal to the largest individual generating plant.

Spinning and Non-spinning reserves**:** Not only must just enough power be produced to closely match demand, but the voltage and frequency of the generated AC current must also be kept within narrow limits. The modes of doing this are termed 'ancillary services.' In order to keep the frequency closely within the standard 60-cycles per second frequency, some portion of the reserves are provided by, literally, spinning turbines. These are typically from gas-generating plants, hooked up to the grid, spinning, but not actually providing power, but they must be ready to do so very quickly. This in itself sets a limit on how much gas-fired power can be reduced. The rest of the reserves are provided by non-spinning reserves. In the case of gas-generating plants, there are also limits on how much their power can be reduced. If these plants are totally shut down it takes a long time to bring them up to power-producing mode. Moreover, it is uneconomical to have them operate at much less than their full capacity.

Hydroelectric power is dispatchable, as the flow of water to the turbines can be readily adjusted.

The upshot of this discussion is that gas and hydro are the dispatchable sources located in California which were lowered as solar power rose, as shown in the orange and light blue lines in figure 4.

The red line shows the amount of *imported* energy which evidently was also dispatchable, though as noted in footnote 3, the source of some of this imported energy is not identifiable, but was probably mostly hydro for CAISO on that date.

In fact, between about 12:30 and 5 PM, where the red line falls below zero, a very small amount of energy was *exported* to out-of-state customers. So, while it is true that California sometimes generates so much electricity that it has to send it out-of-state, averaged over a year however, it *imports* far more than it *exports.* In 2020, California had to *import* 30% of its electricity. Please refer to **Appendix 1** where the mix of electrical energy sources that California used in 2020 is discussed.

"Ramp need" and "peaker plants"

As the sun sets, this is also the time when total demand rises. This combination results in the *net* demand curve rising steeply, (see the red portion of the curve in figure 3 and also

[6] Geothermal and other small renewables are lumped in with wind and solar in the green renewables curve of figure 4, and contributed about 1400 MW of effectively base-line, non-dispatchable sources.

figure 2) thus requiring some source of power to provide an additional 13,000 MW of power between about 4:30 and 7:30 PM. Some of this is provided by gas-fired plants called "peaker plants" ready to go but otherwise not providing power the rest of the day. This is uneconomical and so the cost of providing electricity from peaker plants is very expensive (which why, for time-of-use billing, the charge for energy is high.)

Overgeneration and curtailment

Scroll back for a moment to figure 2. When solar power peaks, other sources of power must be lowered to prevent overgeneration, as in figure 4. This was not a problem on May 14, 2021. But as discussed above, there are limits, in practice, to how much dispatchable power can be reduced, which could lead to *overgeneration* and so it has been necessary on occasion to *curtail* the amount of energy solar facilities are allowed to produce. This is also uneconomical for the providers of solar energy.

Curtailment can also result from congestion in transmission lines which can't move solar energy from where it is produced to where it is needed. Even though the total amount of curtailed solar (and to a lesser extent, wind) energy is quite small compared to the total amount energy[7], the focus up till the present has been to try to reduce curtailment to a minimum.

Greenhouse gas emissions

State legislation (not to mention overwhelming scientific evidence) requires that California sharply cut CO_2 and other greenhouse gases. (As must the rest of the world.) As shown in Appendix 1, by far the largest source of greenhouse gas emissions for electricity generation in California comes from natural gas. In addition to the items published daily by CAISO, they also publish the hourly values of greenhouse gas emissions. In addition, month-by-month totals of greenhouse gas emissions are also available, from which yearly totals can be obtained.

Disproving the false claim that increasing solar energy *increases* emissions

Some time ago, I received a communication that falsely asserted that increasing solar energy actually *increases* greenhouse gas emissions. This probably arose from the notion that the number of "peaker plants" may need to be increased, arising from the need for a large "ramp need" as dispatchable energy is lowered during mid-day hours to avoid curtailment. This assertion presumes that this yields a *net* increase in emissions. But, of course, it is non-emitting solar energy which is supplying all that energy during the day. The data shown in the following two figures shows this assertion is false.

The black curve in figure 5 is the yearly amount of greenhouse gas emissions, which are clearly decreasing. The red curve is the variation in hydroelectric power, the yellow curve

[7] See here the discussion of curtailment and the duck curve by UCS Energy policy staff Mark Specht: https://blog.ucsusa.org/mark-specht/renewable-energy-curtailment-101/

is the slow growth in wind power, while the green curve shows the rapid growth in solar power.

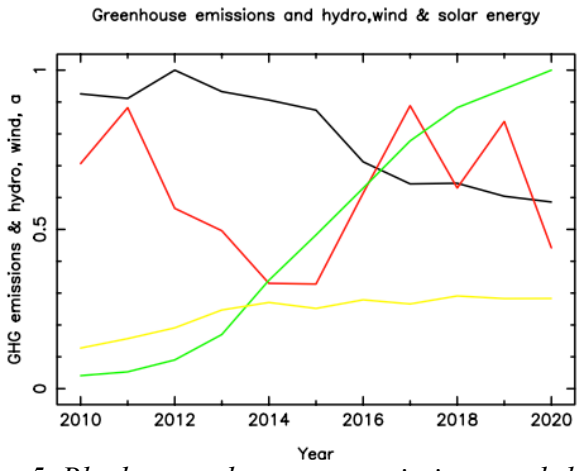

Figure 5. Black: greenhouse gas emissions; red: hydropower; green: solar energy and yellow: wind energy. Note the highly variable amount of hydropower depending on whether there are wet years or drought years. The largest consistent growth of the three energy sources is clearly solar energy.

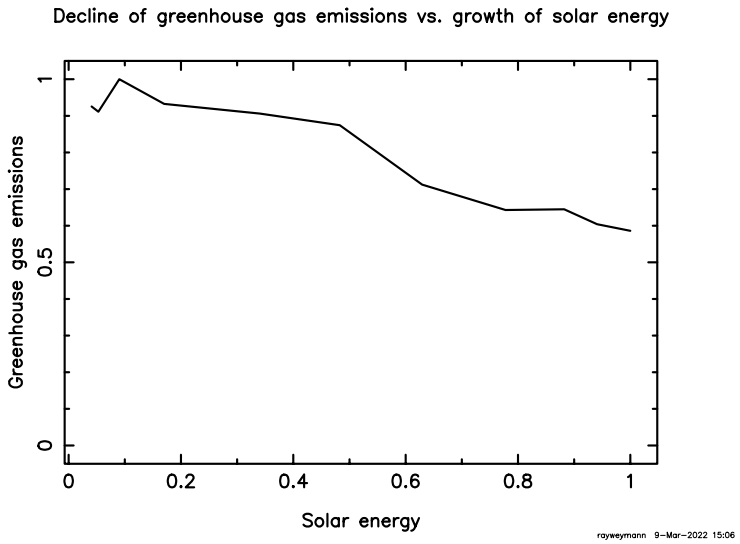

Figure 6 The correlation between the decline of greenhouse gases and the rapid growth of solar energy from 2010 through 2020[8]

[8] Some of this decline in emissions is also attributable to increasing efficiency of gas generating plants, especially as older plants were retired. However, most of these retirements were prior to 2010.

Section II: What will be required to achieve 50% of California's electrical generation from solar by 2030?

As shown in the table of Appendix 1, only about 13% of the energy used for electrical energy delivered to California consumers currently comes from solar energy.[9] In fact the largest contributor is from greenhouse-gas-producing natural gas plants. Solar energy is now very competitive in cost with all other energy sources so it is tempting to simply say "well let's build all the PV plants we can, as quickly as we can." But it is not quite as straightforward as that, since the duck curve quacks really loudly if one wants, say, to have 50% of all electrical energy in California generated by solar, with perhaps an additional 15% or so generated by wind.

The following figure shows this vividly:

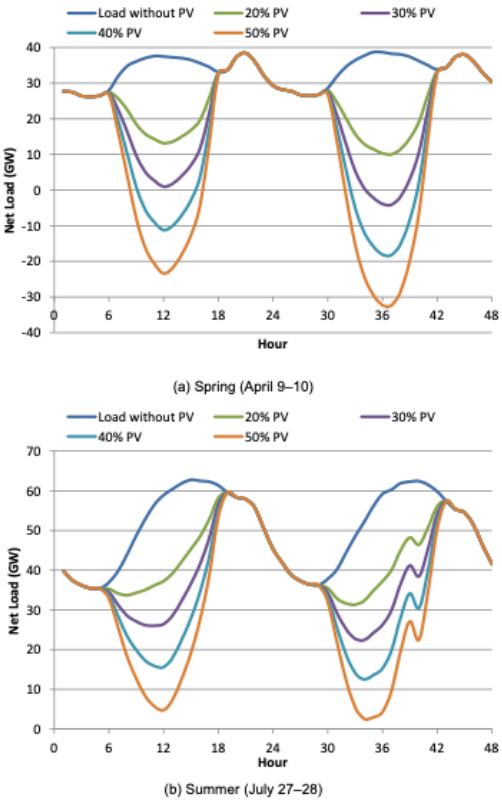

Figure 2. Load and theoretical net load profiles for California during two days in the spring (a) and summer (b) where PV provides up to 50% of annual electricity, assuming no PV curtailment is required

Figure 7. These two graphs are taken directly from the NREL report of footnote 10. The blue curves are the total loads for two 24 hour periods, and the orange curve is for an ***annual*** *average of 50% PV penetration. Note the dramatic difference is the net loads between Spring and*

[9] This is not strictly true, since both the total energy and the solar energy *do not include* a substantial contribution from net-energy-metered (NEM) or 'behind the meter' solar energy which is considerable. See Appendix 2 for a discussion.

Summer, even though Spring and Summer produce comparable amounts of solar energy. See text for discussion.

In figure 7, the amount of solar energy produced in Spring (e.g., May) is about the same as in Summer (e.g., July), but the total demand (essentially the blue curves) is very different for the two seasons: July generally brings much hotter weather with use of air conditioning. This means that there is no over-production in the July curve. But there is very substantial over-production in the Spring curve in the absence of curtailing solar energy or some other way of dealing with this solar energy. Otherwise, a negative net load shown in the Spring curve would cause serious imbalance in the grid.

The following is a summary of an NREL report[10]. This report was written in 2016 and so is somewhat outdated. A more recent NREL report takes a somewhat different approach to the curtailment and grid flexibility issues, partly resulting from improved solar technology and is discussed below.[11]

The basic idea is to find, for "various assumed factors", at what level of solar energy, and what amount of large-scale storage capacity, the cost,[12] or loss of revenue to solar energy suppliers due to curtailment, just leaves them cost-competitive with other energy sources. This is typically combined-cycle gas-fired turbines, which in the analysis of footnote 10 was assumed to be 7 cents/kWh by 2030.

These "various assumed factors" include: 1) The 2030 "base cost" of PV electricity, i.e., before loss of revenue from curtailment. 2) "load shifting"—changing the shape of the total load curve by moving some demand from the evening hours to midday, by, for example, "time of use" price structure." 3) The degree of deployment of electric vehicles, which, if charged during the day, increase the midday demand[13] , or better yet, have the ability to return some of the energy to the grid during evening hours. 4) Flexibility of the electric grid and energy sources such that the practical minimum level of energy produced by hydro, gas, geothermal and nuclear can be lowered more readily than at present.[14] 5) More flexibility in market and transmission facilities so that the ease of exporting or importing out-of-state power is greater than it is currently.

The main body of the paper examines the requirements for energy storage for all of these variables. Because of the complexity of these variables, it is impossible to succinctly

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[10] Nearly all of this material comes from reports from the National Renewable Energy Labs; see especially https://www.nrel.gov/docs/fy16osti/66595.pdf

[11] This is a more recent NREL discussion with a new approach to curtailment and grid flexibility. https://www.nrel.gov/docs/fy21osti/74176.pdf

[12] In such cost analyses a distinction is made between the *average* cost of a certain total PV capacity (say at a facility of 250 MW) and the *marginal* cost and the *marginal* additional capacity (e.g. going from 250 to 251MW). It is the "break-even" point of the marginal cost at which adding more PV capacity is not economical. In the present context the marginal costs exceed the average costs as it gets harder to avoid curtailment.

[13] But see below for additional ways of increasing midday demand which are not discussed in the NREL report.

[14] However, in the study of footnote 10 it was in fact assumed that Diablo Canyon was *not* operating by 2030.

summarize all the results, but in portions of the discussion, items 2-5 are lumped together in three 'flexibility scenarios' : "low", "medium" and "high." In the Executive Summary the plot reproduced in figure 8 shows the storage requirements as a function of the 2030 base price of electricity for each of these three "flexibility" scenarios.

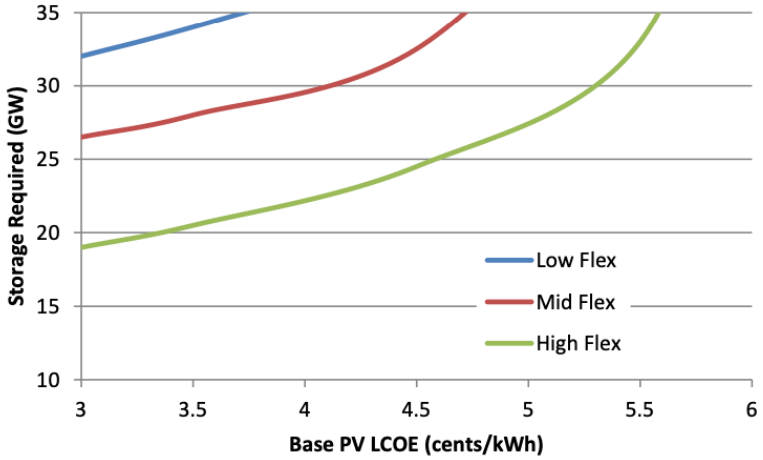

*Figure 8. From the paper in footnote 10: The storage requirements for achieving a "break even" cost for 50% of California's electricity being supplied by PV **vs.** the base cost of PV electricity (LCOE = 'levelized cost of electricity') in 2030. The three curves are for 3 different levels of 'grid flexibility' as enumerated in 'variable factors' 2-5 above.*

From this figure one can see that unless significant improvements are made in the current levels of various aspects of grid flexibility, at least 30 GW of storage capacity would be required for this level of PV to be economical. And only then if the base price of PV electricity is as low as 3 cents per kWh (blue curve.) On the other hand, if very substantial improvements are made in grid flexibility and the base price of PV is, in fact, as low as 3 cents per kWh, then storage requirements could be as low as 20 GW (green curve.)

For several decades the Holmes pumped hydro storage facility (owned by PG&E) has provided about 1200 MW of maximum storage power , but the recent growth in storage has been primarily by Li-I batteries whose capacity is very rapidly accelerating. About 2000 MW of battery storage was added in 2021 alone within the CAISO service area, bringing the total battery storage available to CAISO to 2600 MW. The California Public Utilities Commission (CPUC) "draft preferred system plan" calls for 12,000 MW of installed utility scale batteries by 2025, so reaching 20 GW of storage is not unrealistic.

Moreover, this does not include any private storage in, for example, residences. In fact, even the possibility of the bi-directional ability of electric vehicles to be charged during the day and discharged to the grid during the evening no longer seems 'pie-in-the-sky,' since one EV already has this ability. Namely, the announcement of a partnership

between Ford and Sunrun to provide the ability to use the Ford F150 EV pickup as a bi-directional charging and storage device.[15]

As suggested in footnote 13, however, there are other possible ways of increasing the midday demand which were not discussed in the NREL report. One possibility is to divert some of the baseline electrical energy to produce hydrogen by means of electrolysis, though this is still quite expensive. The hydrogen can be stored for longer periods of time than for Li-I batteries and can be used for various industrial processes,[16] or even turbines for electricity generation.[17] Experiments have shown that a 20% mixture of hydrogen can be mixed with natural gas and used with existing pipes and existing heating and cooking facilities. But full conversion to pure hydrogen for heating and cooking would require very costly infrastructure.

Another application of stored hydrogen is for use in fuel cells which directly convert hydrogen into electricity, either stationary fuel cells or mobile ones for transportation.[18]

An additional load source may be desirable if worsening drought makes fresh water supply an increasingly severe problem: Desalination of ocean water. Nuclear reactors located on the coasts could be used for this, though in principle solar energy could also be diverted for both hydrogen production and desalination. Desalination comes with environmental damage unless water intakes are not with fine mesh to prevent destruction of marine organisms and unless the resulting leftover briny water is adequately diffused into sea water to prevent excess salinity.

Nonetheless, if more than 30 GW of storage are still needed, this is still a formidable task and so there is an evolving philosophy of how one should think of, and even define 'curtailment', particularly in light of new developments in solar panel 'inverters'.

Rethinking curtailment and solar energy flexibility

While curtailment still constituted only about 5% of the total solar PV capacity in the CAISO area in 2020[19] that is not insignificant, and likely exceeded that in 2021. Curtailment has grown rapidly since 2018, and as the discussion above suggests, could become even larger as more and more solar PV is produced.

The following is a brief description of the article referenced in footnote 11. The essence of the report can be seen in these two sentences in their Summary: "*[However,] changing grid and technological contexts warrant new thinking on PV curtailment. In the grid context, as grids integrate more PV and other renewable energy generation, seeking an optimal level of accepted curtailment becomes more efficient than preventing it.*"

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[15] https://media.ford.com/content/fordmedia/fna/us/en/news/2022/02/02/f-150-lightning-power-play.html
[16] https://wha-international.com/hydrogen-in-industry/
[17] https://www.power-eng.com/gas/hydrogen-substitution-for-natural-gas-in-turbines-opportunities-issues-and-challenges/ - gref
[18] https://www.energy.gov/sites/prod/files/2018/01/f46/fcto_fc_stationary_power_apps.pdf
[19] https://www.eia.gov/todayinenergy/detail.php?id=49276 This is a short, readable report and worth reading.

The following figure is Figure 1 report of footnote 11 and shows a real curtailment event for May 24, 2018 in the CAISO area.

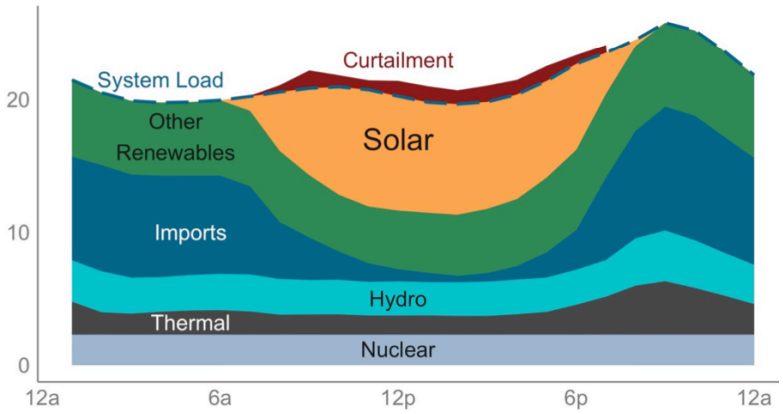

Figure 9. This is figure 1 from the report of footnote 11 and shows the actual curtailment for May 13, 2018 in the CAISO area. Note that curtailment took place while imports were reduced to near zero, but the hydro, thermal (i.e., natural gas) and nuclear generation was not able to be significantly reduced.

Part of the "changing technological context" mentioned above involves advanced PV "inverters." Solar panels produce a steady (DC, or direct current) supply of electricity. Today, however, all consumers of electricity now require AC, or alternating current, in which the voltage and current swing back and forth at a frequency (which must be tightly controlled) at 60 cycles per second. Inverters on solar panels convert the DC to AC. There are new designs for such inverters ("advanced inverters") which provide greater flexibility in how solar panels operate and this can help deal with the curtailment issue.

Without getting into technical details--which I cannot, even if I thought it useful, since I don't understand them myself!--the essential point is this:

With these advanced inverters it is possible that solar panels can provide "ancillary services": While the main purpose of the operators of the electrical grid is to provide power for the myriad services that electricity provides us, they must also ensure that the voltage and frequency of the current they deliver is kept within very narrow limits. The means to do these two things (and others more subtle) are called 'ancillary services'. The spinning generators do some of this and batteries can provide some ancillary services as well. But with the new technology just described, so can PV systems, *even though in so doing they may not always provide their full power.* It is thus argued that they provide an important service to the grid and there should be appropriate economic recognition of this fact.

In more detail, the authors of this paper outline the sense in which PV systems can be considered a 'dispatchable' source of energy. This involves partly the availability of increased battery storage, so that that instead of curtailing solar output more and more will be able to be dispatched to battery storage. But this new inverter technology also allows solar panels to more quickly respond to the need to either increase or decrease power to meet any imbalance in supply and demand of power. See the footnote found inside the following link to this footnote[20], especially the first figure in that link showing the rapidity with which these technical improvement in solar panels can respond to commands for changes in output on times of a few seconds. This same link is also a useful and readable short discussion of the 'ancillary services' as well and also the reduction in curtailment the advanced inverters can provide.

It is not just the technical aspects of increased grid flexibility which affects the economics of temporarily withheld PV power however. The authors advocate new contractual and market reforms for solar energy that recognize these innovations and do not penalize solar energy providers whenever they do not deliver their maximum power.

Additionally, the some of the factors contributing to grid flexibility will help to minimize curtailment, by, for example, allowing gas turbines to reduce their power to lower levels than is currently practicable.

[20] https://www.esig.energy/grid-flexible-solar-and-wind-what-it-means-for-our-future/

Concluding Remarks

If electric vehicles (EVs), which can be charged in the daytime and then discharged in the evening, were to be widely deployed, it could have a large impact on curtailment. It would also significantly reduce the need for inefficient and very costly-to-operate peaker plants.

For this larger deployment to happen though, I believe EV costs will have to drop further, their range must be extended and, just as important, rapid and far more numerous charging stations must be installed.

None of these things are at all impossible. What is needed more than anything is for the members of Congress from both parties to a) realize that this possibility opens up tremendous economic opportunities for American industry and b) to realize what must be done if we are not to cede these opportunities to China.

So, to summarize this entire essay: If it looks like a duck and quacks like a duck, it must mean… that we need a more flexible grid, more energy storage and policies and personnel to deal with the increasing challenge of dealing with more renewable energy!

Appendix 1: California's Electrical Energy Mix for 2020

The figure on the next page comes from the California Department of Energy and shows the sources of electrical energy for 2020. It is pretty complex, so let's break it down.

REALISM NOTE: Before reading further, in both Appendices 1 and 2, the number of significant figures I have reproduced are not to be taken seriously; I have used them simply as a consistency check on some of the calculations!

The right-most column shows the percentage for each type of energy specified for each row, which are listed in the left-most column.

Row 8, **"Total Non-Renewables and Unspecified Energy"** *is the sum of all the energy sources in the rows above it* and totals 66.91%, with the main contributors being natural gas (37.06%) followed by large scale hydroelectric sources (12.21%.) Nuclear energy provided 9.33 % --about 2/3 of which is from Diablo Canyon, which will likely cease to provide energy in 2024/25. "Unspecified" consists of a small portion of imported energy whose source was not identified. Note that there is only a very small amount of energy supplied by coal. This coal-generated electricity is mostly imported by the LA Department of Water and Power, which is outside CAISO's jurisdiction and this source is to be discontinued in 2025.[21]

The next to last row, "Total Renewables" amounted to 33.09%, and the sources for this are give in the 5 rows above that. Solar (13.23%) and wind (11.13%) contribute by far the most, with geothermal (4.89%) contributing most of the rest.

<u>But there is an important caveat</u> regarding both the total energy generated and especially the amount of solar energy generated: Both CAISO and the California Department of Energy have no way of directly measuring the total energy generated by net-energy-metered (NEM), or 'behind the meter' solar energy. This is discussed in Appendix 2.

From the last *row* of the table and the "Total imports" and "Total California power mix" *columns*, dividing the Total Imports by the "Total California power mix," we find that 81,663/272,576, or about 30%, of California's electrical energy had to be **imported** in 2020 to meet its needs.

I *define* 'green' energy as sources producing very little CO_2 compared to fossil fuels. Then, if we want to estimate how "green" California's electrical energy supply was, we must include other sources than those the Department of Energy defines as 'renewables.' Specifically, we need to add nuclear and large hydro. But we can't estimate the total "green energy" exactly because we don't know the nature of the 'unspecified' energy.

To allocate the amount of this 'unspecified' energy between "green" and "dirty", I assumed that the proportion of green and dirty energy from the *unspecified* SW imports

[21] https://www.latimes.com/business/la-fi-utah-coal-los-angeles-climate-20190711-story.html

was the same as for the *identified* portions of the SW imports, and similarly for the NW imports. All of this leads to my estimate of about 60% for green energy in 2020. For those that wish to see the arithmetic details, I have put them in an extended "**endnote**".[i]

These estimates do not take into account the net energy-metered (NEM) or 'behind the meter' solar (mostly residential rooftop) installations. In Appendix 2, I estimated this amount of energy produced in 2020 to be 14,725 GWh. This must be added to the total green energy above as well as to the total energy of all kinds yielding a fraction of green energy consumed by California to be :

Green + NEM : 162,651 + 14,725 = 177,376
Util total + NEM: 272,576 + 14,725 = 287,301
Fraction of green: 177,376/287,301 or about 62%

2020 Total System Electric Generation

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2019 Total System Electric Generation and previous years

Depending on browser width, scrolling of table may be necessary. Scroll bar is at bottom of table.

Fuel Type	California In-State Generation (GWh)	Percent of California In-State Generation	Northwest Imports (GWh)	Southwest Imports (GWh)	Total Imports (GWh)	Percent of Imports	Total California Energy Mix (GWh)	Total California Power Mix
Coal	317	0.17%	194	6,963	7,157	8.76%	7,474	2.74%
Natural Gas	92,298	48.35%	70	8,654	8,724	10.68%	101,022	37.06%
Oil	30	0.02%	-	-	0	0.00%	30	0.01%
Other (Waste Heat / Petroleum Coke)	384	0.20%	125	9	134	0.16%	518	0.19%
Nuclear	16,280	8.53%	672	8,481	9,154	11.21%	25,434	9.33%
Large Hydro	17,938	9.40%	14,078	1,259	15,337	18.78%	33,275	12.21%
Unspecified	-	0.00%	12,870	1,745	14,615	17.90%	14,615	5.36%
Total Non-Renewables and Unspecified Energy	127,248	66.65%	28,009	27,111	55,120	67.50%	182,368	66.91%
Biomass	5,680	2.97%	975	25	1,000	1.22%	6,679	2.45%
Geothermal	11,345	5.94%	166	1,825	1,991	2.44%	13,336	4.89%
Small Hydro	3,476	1.82%	320	2	322	0.39%	3,798	1.39%
Solar	29,456	15.43%	284	6,312	6,596	8.08%	36,052	13.23%
Wind	13,708	7.18%	11,438	5,197	16,635	20.37%	30,343	11.13%
Total Renewables	63,665	33.35%	13,184	13,359	26,543	32.50%	90,208	33.09%
Total System Energy	190,913	100.00%	41,193	40,471	81,663	100.00%	272,576	100.00%

Total System Electric Generation and Methodology

Appendix 2:
Estimating the Amount of NEM (Net Energy Metered) Or "Behind the Meter" Solar Energy

As stated in the main body of the text, neither CAISO nor the California Department of Energy can directly measure the amount of electricity which is generated through net metering ("NEM" or "behind the meter") PV systems. This is the case in the regions served by the three major investor owned utilities serving California (San Diego Gas and Electric, Southern California Edison, and Pacific Gas and Electric.)

While the most familiar example of these NEM PV systems are rooftop solar installations on private residences there are also other installations using NEM. The *net* energy meter measures just the *difference* between the current flowing into your house and the energy flowing out of it from your solar panels back into the grid, not each of them separately. (But there are some utilities which allow installation of 'dual meters' which record each of these current flows separately.) More precisely, net meters measure the *net* amount of *energy* (in kWh) consumed in the facility. If your total monthly consumption of electrical energy was 500 kWh and 200 kWh of this was produced by your solar PV installation, then your monthly bill will be for 300 kWh. But if your solar panels produced 700 kWh monthly then your net energy usage would be -200kWh and you would receive credit for this. (The amount of money this credit is worth is regulated by the California Public Utilities Commission and may be significantly reduced for new NEM users.)

For this reason, no *direct* measure of behind-the-meter production of solar energy is available. What *is* available, however, is the *total installed capacity* of all the NEM solar facilities in each of the three investor-owned areas. That is, the maximum amount of power that the NEM solar installations *can* produce. For 2020 that number was 9,313 MW= 9.313 GW[22]

Obviously, this power varies during the day and is zero at night, as well as during cloudy days. What is needed is an estimate of the average *efficiency factor* for these NEM installations: the *actual* amount of energy produced divided by the *total installed capacity*.

This efficiency factor can be measured for instate *utility scale* PV installations, since *both* the instate installed ("name plate") total capacity and the total energy actually generated annually are known.[23] For instate **PV** installations (thus excluding thermal solar) the 2020 installed capacity was 12,746 MW = 12.746 GW, and the total PV energy generation was 27,169 GWh. Using 8784 hours in 2020 (a leap year), had the nameplate capacity been realized 100% of the time, 12.746 GW* 8784 hours = 111,960 GWh would have been produced. Thus, the efficiency for utility scale PV was 27,169/111,960 or about 24%.

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[22] https://www.californiadgstats.ca.gov/

[23] https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy

But it is almost certainly lower for the NEM installations for several reasons: They are not located in areas where there are minimum clouds, they are likely not as carefully maintained (cleaned or kept free of shading by trees etc.) or for other reasons. In the NEM contribution to total PV energy, I assume an efficiency 75% less, or 18%.

With that assumed number we can estimate the energy, measured in GWh, produced by NEM facilities in 2020. At 100% efficiency and the installed capacity given above of 9.313 GW, we calculate that 8784 hours *9.313 GW = 81,805 GWh would have been produced. But with an efficiency of 18% the total is estimated to be 0.18*81,805 = 14,725 GWh. The estimate for the *total* solar used by California would then be the utility scale value of 36,052 + 14,725 NEM = 50,777 GWh. The 14,725 NEM should also be added to the total energy of 272,576 GWh to get 287,301 GWh, so that one could say that about 50,777/287,301 or about 18% of California's electricity is generated from solar.

The inclusion of NEM therefore makes a moderately significant difference in whether projections of "50%" solar include the NEM contributions or not, since inclusion of NEM solar energy will certainly impact the numbers in the duck curve.

[i] **ENDNOTE: The arithmetic details for estimating how 'green' California's 2020 mix was are as follows:**

There are two *columns* in the table of the 2020 Total system generation that have to do with *imports*: Northwest Imports and Southwest Imports. One of the *rows* for both NW and SW import columns is "unspecified."

NW imports:
NW *identified* imports: The total *identified* NW imports are the *total* NW imports of 41,193 – 12,870 *unspecified* = 28,323 *identified.* Of these, the *dirty identified* are in the first 4 rows, which total 389. The *green identified* are thus 28,323 -389 = 27,934. The ratio of green/total *identified* is thus 27,934/28,323 = 0.9862

NW *unspecified* imports: By assumption, the *green* unspecified = 0.9862**total unspecified*= 0.9862*12870= 12692 *green unspecified*. The remainder are *dirty unspecified*= 178

SW imports
SW *identified* imports: The total *identified* are the total SW imports (bottom row) of 40,471 – unspecified (1,745) = 38,726.
The first 4 (*dirty identified*) rows total 15,626; the remaining are *green identified* 38,726 – 15,626 = 23,100
The ratio of *green* to *total identified* is thus 23,100/38,726 = 0.5965.

SW *unidentified* imports: By assumption the total unspecified (1745) has a clean/dirty ratio which is the same as the identified= 0.5965. The *green unspecified* is thus 0.5965*1745 = 1041, with 704 *dirty unspecified.*

We can now add up the total green of SW and NW i**mports**, both identified and unspecified, from the numbers above.

SW	green	dirty	total	**NW**	green	dirty	total
ID	23,100	15,626	38,726		27,934	389	28,323
UN	1,041	704	1,745		12,692	178	12,870
TOT	24,141	16,330	40,471		40,626	567	41,193

Thus, of the total imports of 40,471 + 41,193 = 81,664, a total of 64,767 are *green,* and 16,897 are *dirty*, with a fraction of green imports being about 79% of the total imports.

Now we can finally add to the imports, the green, dirty and total components of the electrical energy generated *internally* in California:

The *dirty* energy is found from the first 4 rows of the California Instate Generation, which total 93,029. The remainder of the total is *green:* 190,913 – 93,029 = 97,884

Adding in the imports the final totals are

Green: 162,651
Dirty: 109,926
Total. 272,577 (because of rounding errors this differs from the 272,576 of the next to last column of the last row.)

This leads to a **utility scale** fraction of California's green energy fraction being about **60%.**

However, using the results of Appendix 2, if we add the estimated NEM contribution of (green) PV energy then

Green + NEM : 162,651 + 14,725 = 177,376
Util total + NEM: 272,576 + 14,725 = 287,301
Fraction of green: 177,376/287,301 or about 62%