While you might not have been paying attention, California’s electric grid has undergone a radical transformation. Today, more than 25 percent of the electricity used in California comes from renewable energy resources, not including the additional 10-15 percent from large-scale hydropower or all the electricity generated from roof-top solar photovoltaic (PV) panels. Compared to only five years ago, solar energy has grown 20-fold (Figure 1). In the middle of a typical springtime day, solar energy from utility-scale power plants provides an impressive 7 gigawatts (GW) of grid-connected power, accounting for about 20 percent of the electricity used across the state (Figure 2).

Last year, the total electricity from both in-state and out-of-state resources was 296,843 gigawatt-hours (GWh), including out-of-state generation from unspecified sources. An estimated 8 percent of California’s electricity consumption was generated from wind farms and 6 percent from solar power plants connected directly to the California Independent System Operator (CAISO) grid. This rapid growth is great news for the nascent renewable energy industry and can serve as proof-point for the scale-up of renewable energy. In addition to these utility-scale renewable energy power plants, California has an additional 3.5 GW of solar "self-generation" on the customer side of the meter that offsets demand for electricity from the grid when the sun is shining.
And, a growing third source is "community solar," where residents and businesses invest in small, local solar plants.

![Graph showing total electricity generation in California from solar and wind energy directly connected to the CASIO grid.](California Energy Almanac [1])

By law, in 2020 California plans to have 33 percent of its electricity sourced from renewable sources and 50 percent by 2030 under its renewable portfolio standard (RPS) requirements. Many in-state renewable energy projects [3] are in the pipeline, including nearly 9 GW of solar PV and 1.8 GW of new wind projects that have received environmental permits. Power purchase agreements have already been signed for at least 1 GW of new solar projects. If all of these permitted projects were developed, California would have about 16 GW of solar-generating capacity by 2020.

While wind has provided a significant portion of California’s renewables to date, the majority of new additions for meeting the 2020 33-percent RPS requirement is forecast to come from direct grid-connected solar PV. California has an enormous and high-quality solar resource [4], with an estimated technical potential of more than 4,000 GW for utility-scale solar and 76 GW for rooftop solar. Unlike the Midwest, California has a modest technical potential for wind and many of the best sites are already developed. California does have a large offshore-wind resource, some of which is now in permitting, but high costs and technological challenges remain. Importing electricity generated by onshore wind from neighboring states is promising, but some imports will require new high-voltage transmission lines that may take a decade to plan, site, permit, finance and build.
Figure 2. California energy mix on May 29, 2016. Note that renewables provide more than 40% of the power during the middle of the day. Of this, more than 30% is from solar power (CAISO Daily Renewables Watch [2]).

California has a major effort - the **Renewable Energy Transmission Initiative** [5] (RETI) - that has successfully identified and built lines to meet its RPS requirements. This year, California launched a new phase of RETI to develop the additional transmission, both in-state and out-of-state, needed for the 50-percent RPS. A recent study [6] supporting California Senate Bill 350 implementation (which includes the 50-percent RPS) showed from $1 billion to $1.5 billion annual savings by adding major transmission lines that would bring more out-of-state wind energy into California.

If, instead, California continues to rely mostly on solar resource for meeting the 2030 50-percent RPS, the total statewide solar-generating capacity would reach 30 to 40 GW under peak production, according to a report [7] by Energy and Environmental Economics Inc. (E3). Under these conditions, on a sunny day, for most of the year, California would be generating more electric power than it needs during the middle of the day from solar energy alone. E3 calculates that this large amount of overgeneration could be a problem 23 percent of the time, resulting in curtailment of 8.9 percent of available renewable energy, with marginal overgeneration by solar PV of 42-65 percent. In other words, **California could hit the solar wall**. And this does not even consider that midday demand is likely to decrease due to the installation of additional residential and commercial solar PV systems "behind the electricity meter."

**Consequences of hitting the solar wall**
Just a decade ago it would have been nearly unthinkable that during the middle of the day solar energy could provide more electricity than an economy as large as California’s needs. But supportive policies, rapid scale-up and decreasing costs make this possibility a reality today. While from some perspectives this is very encouraging, in reality, there are consequences for hitting the solar wall. For example:

- Reliance on so much solar energy would require rapid ramping capacity for more than 10s of GW of natural gas power plants from 4:00-6:00 p.m., when the sun is going down and electricity demand goes up as people return home.

- Large back-up capacity from natural gas plants or access to other sources of dispatchable electricity would be required for days when the sun isn’t shining.

- Zero marginal-cost solar generation could squeeze out other valuable low-carbon electricity sources that can provide baseload power. For example, natural gas combined cycle plants, geothermal energy and nuclear power that cannot operate during these times at zero marginal cost.

- Large-scale curtailment of solar PV during times of overgeneration, which will reduce the value of solar capacity additions to investors.

- Real-time pricing during times of overgeneration could limit or eliminate the net-metering advantage of PV on residential and commercial-scale installations.

There is no doubt that California’s solar energy potential is invaluable, but we must take steps to avoid the solar wall. Fortunately, these issues are being recognized and addressed at many levels in California.

**Avoiding the solar wall**

Numerous approaches to avoiding the solar wall are available today, and in the future more options will exist as we develop new technologies, policies and markets to take advantage of large solar-energy resources that exist around the world. In the short term, key actions include:

- Develop a renewable energy-generation mix that is well-balanced among solar, wind and other forms of renewable generation. The right generation mix will be region specific, but for California should include increasing wind generation to provide nighttime power.

- Support regional generation markets across wide geographic areas to balance the variability of renewable generation. California has created an energy imbalance market with participants in Nevada, Wyoming and Oregon. Expansion of regional markets is being studied as part of the implementation of Senate Bill 350, California’s 50-percent RPS law.

- Ensure adequate capacity of rapid ramping natural gas plants to provide reliable supply during the morning and evening hours as the sun rises and sets.

- Expand use of load shifting through real-time pricing to incentivize using power during daytime
hours when large amounts of solar power are available.

- Encourage daytime smart charging of electric vehicles to take advantage of abundant and zero marginal-cost solar generation. Achieving this will require workplace charging stations and new business models. With transportation at about 40 percent of the state’s energy use, electrification of the transport sector could have the dual benefits of eliminating tailpipe emissions and providing demand for abundant and low-cost solar energy.

- Increase energy storage to avoid curtailment of solar overgeneration during peak production periods. For now, few financial incentives exist for large-scale pumped-hydropower or compressed air storage projects. **Levelized costs** of small-scale storage in batteries range from about $300 to more than $1,000/megawatt-hour (MWh) depending on the use-case and the technology. These are expensive compared to pumped-hydro storage at $190 to $270/MWh. For comparison, gas peaker plants have a levelized cost of $165 to $218/MWh. The business case for battery storage will be limited until prices come down significantly. Both R&D and scale-up will be needed to reduce costs.

- Use electrolysis to produce hydrogen fuel to augment the natural gas grid, generate heat and power with fuel cells, or power hydrogen vehicles. However, compared to storing electricity in batteries, hydrogen-based storage systems that combine electrolysis and fuel cells are about **three times less efficient**. In addition, today, these technologies are expensive, and significant cost reductions will be required to make them competitive alternatives.

- For the longer term, scientists are developing new methods to produce fuels from renewable energy. The **SUNCAT Center** and the **Joint Center for Artificial Photosynthesis** are developing new materials to produce “zero net carbon fuels” from carbon dioxide, water and renewable energy that can be used for transportation or backing up the electric grid. While we don’t know if and when the needed breakthroughs will occur, the game-changing potential of net zero carbon fuels would unlock the full potential of solar energy and break through the solar wall.

**Taking full advantage of the power from the sun**

The global potential of solar energy is enormous and surely it can play a major role in a deeply decarbonized future energy system. In Thomas Edison’s words, "I’d put my money on the sun and solar energy. What a source of power! I hope we don’t have to wait until oil and coal run out before we tackle that."*
We have work to do, but we are well on the way. Who would have imagined just five years ago that solar energy would provide 6 percent of California’s electricity and is on track to double, triple or go beyond? But we need to be smart – avoiding running into the solar wall by balancing the generation mix, expanding regional markets, creating real-time markets to increase demand during solar peak-generating periods and creating new electricity demand, such as day-time charging for electric vehicles. In the longer term, electricity storage, hydrogen generation and zero net carbon fuels will further unlock the potential of solar energy.

*AS QUOTED IN UNCOMMON FRIENDS : LIFE WITH THOMAS EDISON, HENRY FORD, HARVEY FIRESTONE, ALEXIS CARREL & CHARLES LINDBERGH (1987), BY JAMES NEWTON, P. 31

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