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Clean Firm Power is the Key to California's Carbon-Free Energy Future

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California's plan to make all of its electricity carbon free by 2045 will double electricity demand. Three groups of analysts optimize its grid to be economically and environmentally sustainable.

California's government has set ambitious goals to eliminate greenhouse gas emissions, starting with electricity. A 2018 law mandated that, by 2045, all retail sales of electricity in the state must derive from carbon-free sources. Jerry Brown, who was then the governor, issued an accompanying executive order requiring the entire state, not just the electric sector, to zero-out net emissions also by 2045. Policymakers have to grapple with achieving these goals. Reducing emissions in the economy as a whole will increase demand for electricity, which will be used to power cars and heat buildings in place of fossil fuels. Energy planners estimate that such electrification will increase California's peak demand for electricity from 50 gigawatts today to 100 gigawatts midcentury.

CAN THIS DEMAND BE MET?

The Environmental Defense Fund and the Clean Air Task Force convened three groups of energy system experts to model California's electricity system in order to figure out how the state might make that much affordable, clean, and reliable electricity. Groups from Princeton University, Stanford University, and Energy and Environmental Economics (E3), a San Francisco-based consulting firm, each ran separate models that sought to estimate not only how much electricity would cost under a variety of scenarios, but also the physical implications of building the decarbonized grid. How much new infrastructure would be needed? How fast would the state have to build it? How much land would that infrastructure require? Although each of these models offered its own depictions of the California electricity system and independently explored the ways it would be optimized, they all used the same data with respect to past conditions and they all used the same estimates for future technology costs. Despite distinct approaches to the calculations, all the models yielded very similar conclusions. The most important of these was that solar and wind can't do the job alone.

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Solar and wind have become mature technologies and enjoy substantial public support. However, they present challenges because they depend on the weather, which varies in predictable and unpredictable ways. Although the costs of solar and wind power are now fully competitive with other sources per kilowatt-hour, their inescapable variability creates reliability problems. Average daily output from today's California solar and wind infrastructure in the winter declines to about a third of the summer peak. Periodic large-scale weather patterns extending over 1,000 kilometers or more, known as *dunkelflaute* (the German word for dark doldrums), can also drive wind and solar output to low levels across the region that can last days, or even several months. Average wind and solar outputs also vary from year to year, particularly for wind power.

Batteries have been improving, and can help make up for fluctuations that last for multiple hours, but they cannot make up for the longer fluctuations. For this reason, having enough capacity for the slack periods would necessitate building an enormous amount of solar and wind power that would exceed the grid's peak demand during more sunny and windy periods. Our modelers sought to figure out just how big the overcapacity would need to be to ensure reliable electricity availability. The models include energy imported from other states when that makes sense economically, but limit imports to a share that does not cause emissions to go up elsewhere. We simulated hundreds of possible scenarios for the weather over the course of a year to estimate how much energy-generating and storage capacity is likely to be necessary.

Solar energy has much more generating potential in California than wind energy, so solar power will dominate the renewable portfolio as a result. Because solar resources provide power only when the sun is shining, we found that reliably generating the electricity needed in 2045 from solar and wind power would require building the system up to nearly 500 gigawatts of power-generating capacity. This is roughly half the capacity of the entire United States electricity generating system today, including nuclear, gas and coal generating stations, hydroelectric dams, and everything else, as shown in Figure 1.

If wind and solar are pushed to do all the heavy lifting themselves, the system requires enormous excess generating capacity and storage (most of which is seldom used) to provide reliable electricity and completely drive out greenhouse emissions. This strategy ends up being much more expensive and much more demanding of land and infrastructure than other possible pathways.

This excess capacity would be expensive. We estimate that wholesale electricity rates would increase by about 65% over today if renewable energy and currently available storage technologies alone were to be used to meet demand in 2045. Furthermore, even if consumers were willing to pay that premium, it may simply not be possible to build renewable facilities at this scale. Getting to nearly 500 gigawatts by 2045 would require expanding solar capacity at a rate 10 times higher than has ever been done before. There may not be enough people, supplies, or land to do this.

This is the great challenge with intermittent energy sources. On a dollar-per-kilowatt-hour basis, they are now cheaper than carbon-intensive sources of electricity such as coal or even gas. They can play a central role in delivering an affordable carbon-free grid. But if wind and solar are pushed to do all the heavy lifting themselves, the system requires enormous excess generating capacity and storage (most of which is seldom used) to provide reliable electricity and completely drive out greenhouse emissions. This strategy ends up being much more expensive and much more demanding of land and infrastructure than other possible pathways.

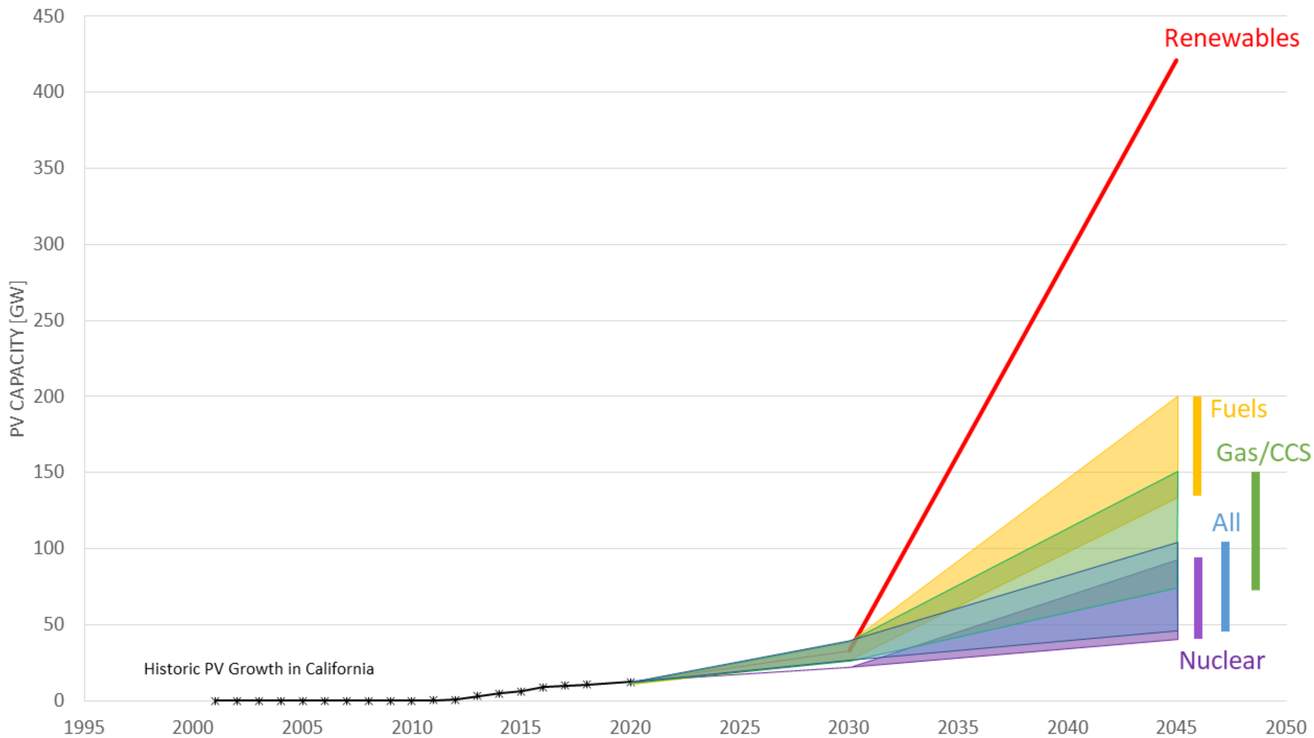

Figure 1. *Scenarios showing different modeled mixes of electricty capacity needed to meet California's needs, and assuming zero emssions by 2045. The red curve is renewables plus batteries only. Other curves show different technological mixes. The bars on the right show the range of results obtained by the different models.*

A CLEAN FIRM SOLUTION

There is a better solution. The state could also develop "clean firm power": carbon-free power sources that can be relied on whenever needed, for as long as they are needed. California could continue to use gas-generated power if the greenhouse gas emissions were captured and safely stored permanently underground. Nuclear power can provide very large amounts of energy steadily in a small footprint. California is currently phasing out the last of its nuclear power stations, but in the future ongoing advances in nuclear technology could allow the deployment of lower-cost reactors with much-diminished accident risk and less waste generation. Geothermal power takes energy from a steady source of heat in the ground. California's geology already provides The Geysers, the largest geothermal plant in the world. Advances in geothermal technology could plausibly expand this resource beyond the special conditions of The Geysers. Hydrogen and other fuels made without life-cycle emissions could also be sources of clean firm power.

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Our modeling finds that almost any combination of these resources (we focused on existing technologies, but new sources of clean firm power may also emerge) could deliver a 100% carbon-free electricity supply with generation and transmission supply costs of about 7–10 cents per kilowatt-hour, which compares well with the current average of 9 cents per kilowatt-hour, and is about one-third less than the cost of an all-wind-and-solar approach, as shown in Figure 2. Renewable energy can inexpensively provide at least half of the carbon-free energy needed by 2045, but clean firm technologies complement renewable energy to ensure reliability while keeping whole system costs low. We also find that having more than one clean firm power option helps reduce costs even further. These results can help decisionmakers planning a decarbonized grid, not just in California but in other parts of the world as well. Opening the portfolio to clean firm power as well as wind, solar, and batteries goes a long way to keeping the total costs and impacts down.

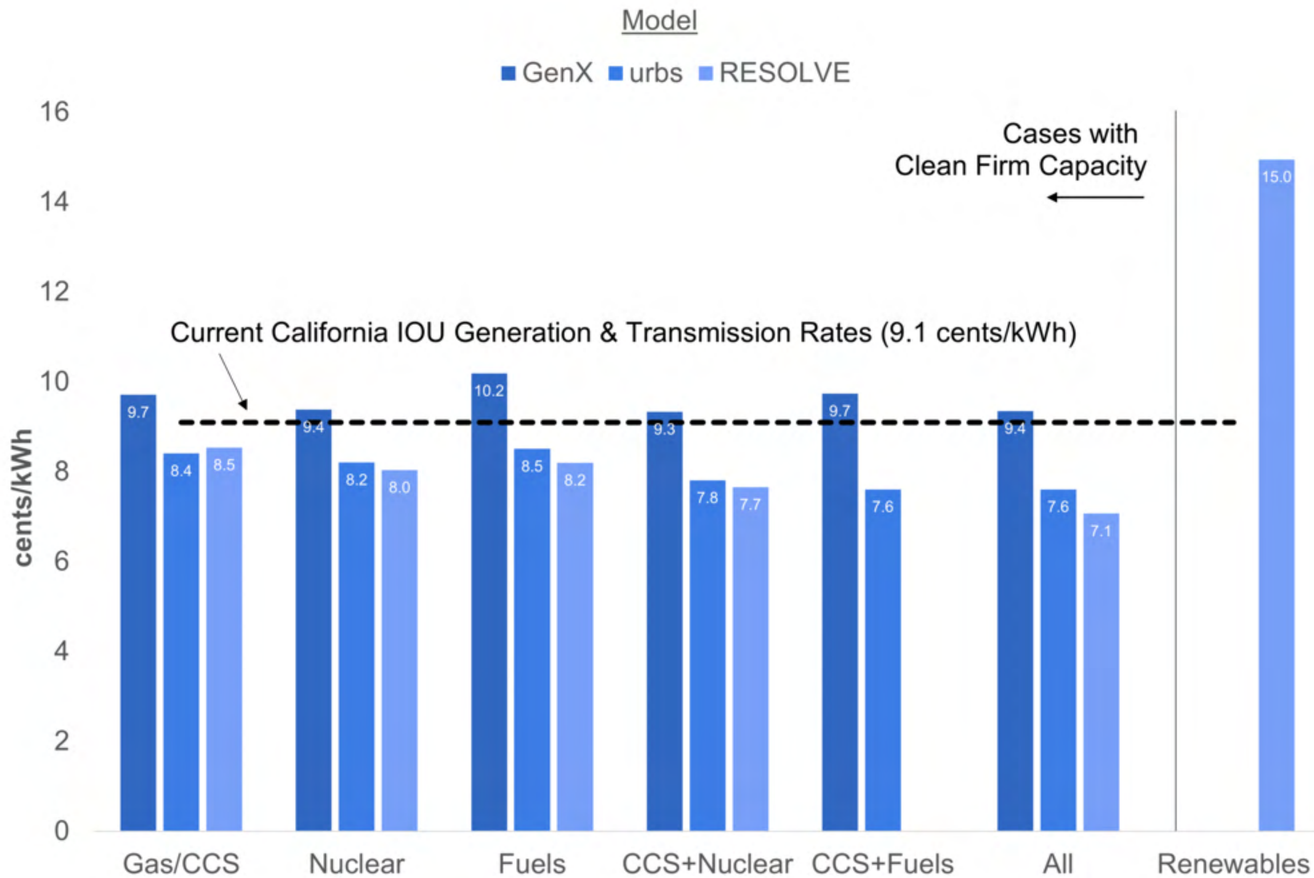

Figure 2. *Modeled estimates of wholesale generation and transmission costs for 100% carbon-free electricity for 2045. The three colored bars indicate results from our three models for several technology sceanrios. The bar on the rigtht is for the all-renewable option. GenX is the Princeton model, URBS is from Standford and Resolve is from E3.*

California today has 48 gigawatts of total firm power capacity, most of which (42 gigawatts) come from natural gas-fired powerplants. The remaining gigawatts come from nuclear power, geothermal, and a small amount from coal. California plans to decommission its last nuclear power plant, at Diablo Canyon, in 2025, which will take 2.2 gigawatts of firm and zero-carbon capacity offline. Our modeling concludes that replacing the gas fleet with 25–40 gigawatts of clean firm power, as an addition to solar or wind, will minimize costs while maintaining reliability. By 2045 the clean firm power portfolio could eliminate the need for some 250–400 gigawatts of additional renewable energy.

Each of these clean firm power resources would play a different role in eliminating overcapacity. For example, nuclear power would act as a "flexible base" power source, generally providing a steady amount of electricity but somewhat reducing output during the height of solar output, enabling nuclear plants to conserve their fuel for longer refueling cycles. Although we did not model geothermal generation explicitly, we would expect it to act quite similarly to nuclear power as it also has large up-front costs and minimal variable expenses. For natural gas plants with carbon dioxide capture and storage (CCS), the models find that it would be economical to vary output as needed, ramping it down at night and up during peak daytime periods, and shutting the plants entirely for longer stretches in the spring. In general, all forms of carbon-free fuels provide expensive electricity. So, power plants using these costly carbon-free fuels would be utilized only occasionally when solar, wind and storage options were unavailable. Any of these resources could adjust to fill the gap during times of *dunkelflaute*.

Decarbonized electricity systems with clean firm power have other key advantages over systems that are solely based on variable renewable energy and batteries (Table 1). Various modeled portfolios that include clean firm power alongside solar and wind in a 100% carbon-free electric system would require between 625 and 2,500 square miles dedicated to utility-scale solar and wind. Without clean firm power, more than 6,250 square miles of land would be required—bigger than the combined size of Connecticut and Rhode Island. Recent assessments of the solar resource in California indicate that 6,250 square miles may actually exceed the amount of land fit for utility-scale solar and not subject to restrictions (such as conservation easements or national park status). Moreover, the estimates of available land for utility-scale solar do not account for other possible restrictions, such as excessive slope, ownership problems, and access to transmission lines. New assessments currently underway will account for these and so will probably decrease estimates of land availability. Should the existing out-of-state supplies of hydro and nuclear power become unavailable, the disparities between all-renewable and renewable-plus-firm power land use demands would be even more extreme.

Issue		With Clean Firm Power	Without Clean Firm Power
Costs for generation and transmission *California transmission and distribution costs are currently about 9 cents/kWh*		~9 cents/kWh	~15 cents/kWh
Solar and Wind Capacity *Entire US electric generating capacity is about 1,100 GW*		25–200 GW	470 GW
New Storage* *Largest battery facility now being built is 0.3 GW /1.2 GWh* *CA expects to have 2 GW battery capacity in 2021*	**New short-term battery capacity**	20–100 GW	160 GW
	New energy storage	100–800 GWh	1,000 GWh
Land Use *CA land area is about 164,000 sq miles*		625–2,500 square miles	6,250 square miles
Transmission *CA currently has about 15 million MW-miles of transmission*		2–3 million MW-miles	~9 million MW miles

*Energy storage beyond existing pumped hydro

Table 1. *Summary of issues related to the need for clean firm power.*

Including clean firm power also reduces the need for millions of megawatt-miles of transmission lines. California currently has approximately 15 million megawatt-miles of transmission lines, carried on about 26,000 circuit miles of power line. All modeled portfolios that include clean firm power add 2 million to 3 million megawatt-miles of new in-state transmission lines to meet the goal of zero emissions by 2045. Some of this might well be built along existing rights-of-way, but even so, getting the necessary permits quickly will present regulatory challenges and face local opposition. Yet an all-renewable portfolio could require 9 million megawatt-miles, hugely increasing challenges of siting, land use, impacts on wildlife, and other considerations.

Better batteries play a key role in a carbon-free grid; they provide flexibility on hourly and diurnal time scales, for instance by saving some solar-generated *electricity from late afternoon into the evening. But economical batteries cannot provide energy for weeks at a time.*

Our models counted on a significant amount of new battery storage in addition to California's existing energy storage facilities, such as pumped water storage. California's energy policies focus strongly on battery development, and some of the world's biggest battery installations have followed. the largest battery storage facility in the world is being built at Morro Bay at the site of a retired power plant and will have a capacity of 0.6 gigawatts and will be able to provide power for 4 hours, or 2.4 gigawatt-hours, enough to power 80,000 homes for about a day. Models with different mixes of clean firm power required between 20 and 100 gigawatts of new battery storage to deliver about 100 to 800 gigawatt-hours of energy storage. This requires dozens of Morro Bay-sized facilities. Without clean firm power, the models require about 160 gigawatts of short-term battery storage to deliver nearly 1,000 gigawatt-hours of energy—the equivalent of more than 400 Morro Bay-sized batteries.

Better batteries play a key role in a carbon-free grid; they provide flexibility on hourly and diurnal time scales, for instance by saving some solar-generated electricity from late afternoon into the evening. But economical batteries cannot provide energy for weeks at a time. We did examine a class of technologies called "long duration storage" to see if these could substitute for clean firm power. Long duration storage technologies, such as electrolysis and underground storage of hydrogen or advances in ultra-cheap metal-air batteries, could potentially provide storage for longer than a few days, but modeling for this study and other recent work indicates these resources are cost-effective only as complements, not substitutes for clean firm power. If long duration storage and clean firm power are available, costs remain low. But if long duration storage is available but not clean firm power, the total energy generation costs increase by about 25%. Long duration storage may provide another useful arrow in the quiver, but systems with clean firm power remain meaningfully less expensive.

DELIVERING A CLEAN, AFFORDABLE AND RELIABLE FUTURE

Weather-dependent renewable resources such as solar and wind will play a starring role in California's low carbon energy future. Even with substantial clean firm power installations, our models show that at least 60% of the electric energy can come from renewable resources. Our models also show that, moving toward 2045, even without clean firm power, California can perhaps abate over 80% of greenhouse gas emissions by building out renewable energy while providing firm, but not clean, power from existing natural gas-fired generators. While carbon emitting, these generators can nevertheless act as firm power in the coming decades, and their use can be decreased to the level essential for accommodating long periods of low sun or wind. But if emissions need to drop to zero by 2045, California will need to replace these carbon-emitting resources with clean firm power or retrofit them with carbon capture and storage or adjustments to burn clean fuels.

Our model results show that squeezing out the last increments of carbon from power generation while maintaining affordability and reliability will require clean firm power. An ambitious but achievable investment in clean firm power with a capacity on the order of California's existing gas fleet could, on the upside, eliminate the need for 10 times that amount of renewable energy. This can help keep generation and transmission costs in line with today's, cut the land area needed for utility-scale solar facilities and energy storage by a factor of 10, and reduce transmission infrastructure needs by a factor of four by 2045. These advantages will help increase the likelihood of achieving climate goals in California by making them more economically and politically feasible.

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California needs to start planning now to obtain clean firm power supplies. The state could initially target deployment of approximately 30 gigawatts of clean firm power by 2045, with interim milestones along the way to avoid high system costs and loss of reliability in the future. These technologies are currently more expensive per kilowatt hour than renewable energy, so deployment will require policy support. Many clean firm power options also face challenges in public acceptance. It takes a long time to develop new technologies and to get regulators to approve them; waiting a decade will put California at risk of failure. Because all these technologies keep costs low in the long run, California can work to scale several of these clean firm options simultaneously and expand whichever ones ultimately prove most feasible and cost-effective.

We don't yet know the best choices and mixes of clean firm power. Consequently, the state should design an adaptive investment strategy—one that deploys and tests a diverse portfolio of clean firm power choices until experience identifies the best and most politically and technologically feasible options. A broad portfolio approach will increase chance of success, help to avoid technological cul-de-sacs, and thus will help ensure affordability and reliability in the long run. California's government could require utilities to build some form of clean firm power now and allow cost recovery for their implementation. Leaving the form of clean firm power up to the utilities themselves—with oversight from California's regulators focused on evaluating what the utilities do on the ground—will allow experimentation and learning.

The federal government can also help, not just California but the entire nation, by making sizeable investments in clean firm power—including investment in innovations needed for the next generations of these sources.

Governments and electric system planners worldwide are pushing hard to deploy vast quantities of renewable power. Our analysis, and many others, show how these power sources can be integrated reliably with clean firm power to meet other goals such as wise land stewardship and improved reliability, accessibility, and affordability. By adopting an approach that combines the best attributes of both renewable and firm, carbon-free energy, California can pave the way for a fundamental change in how energy is made and used.

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