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Alex C. Walker Foundation

Anthropocene Institute

A New View of California's Decarbonization Plan

Report of the California Grid Project

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Project report is available at https://bit.ly/3zhXG2e.

Overview

We have analyzed California's plan for decarbonizing its electric grid using a new modeling tool that allows an hour-by-hour analysis of the grid's behavior. Under Senate Bill 100 (SB 100), by 2045, electricity received by California's consumers is to be free of greenhouse gas emissions. We show here that the current plan fails to meet that goal. The grid will be dependent on intermittent, time- and weather-dependent solar and wind which will continue to need backup from natural gas. Our work shows clearly and transparently that there are numerous periods throughout the year when a large gap appears between what these intermittent sources are able to provide and what the grid actually needs. After a vast expansion of solar, wind, and batteries and expenditure of nearly a trillion dollars, California's grid will be burning nearly as much natural gas as it is now.

To achieve its decarbonization goals, California will have to introduce onto its grid a large firm dispatchable emission-free resource – a DEFR – which will be always available and able to supply whatever additional electricity is needed. To do this, the state has to rescind its moratorium on new nuclear installations, since nuclear power is the only technology capable of meeting this need at the scale required by the 2040s. We present several scenarios in which nuclear can do the job cost-effectively.

In sum, unless California gets serious about developing a large clean, firm, dispatchable source of electricity, it will be emitting large quantities of greenhouse gases for the foreseeable future.

Outline

The Hype

THE NEW YORKER

DAILY COMMENT

California Is Showing How a Big State Can Power Itself Without Fossil Fuels

For part of almost every day this spring, the state produced more electricity than it needed from renewable sources.

By Bill McKibben

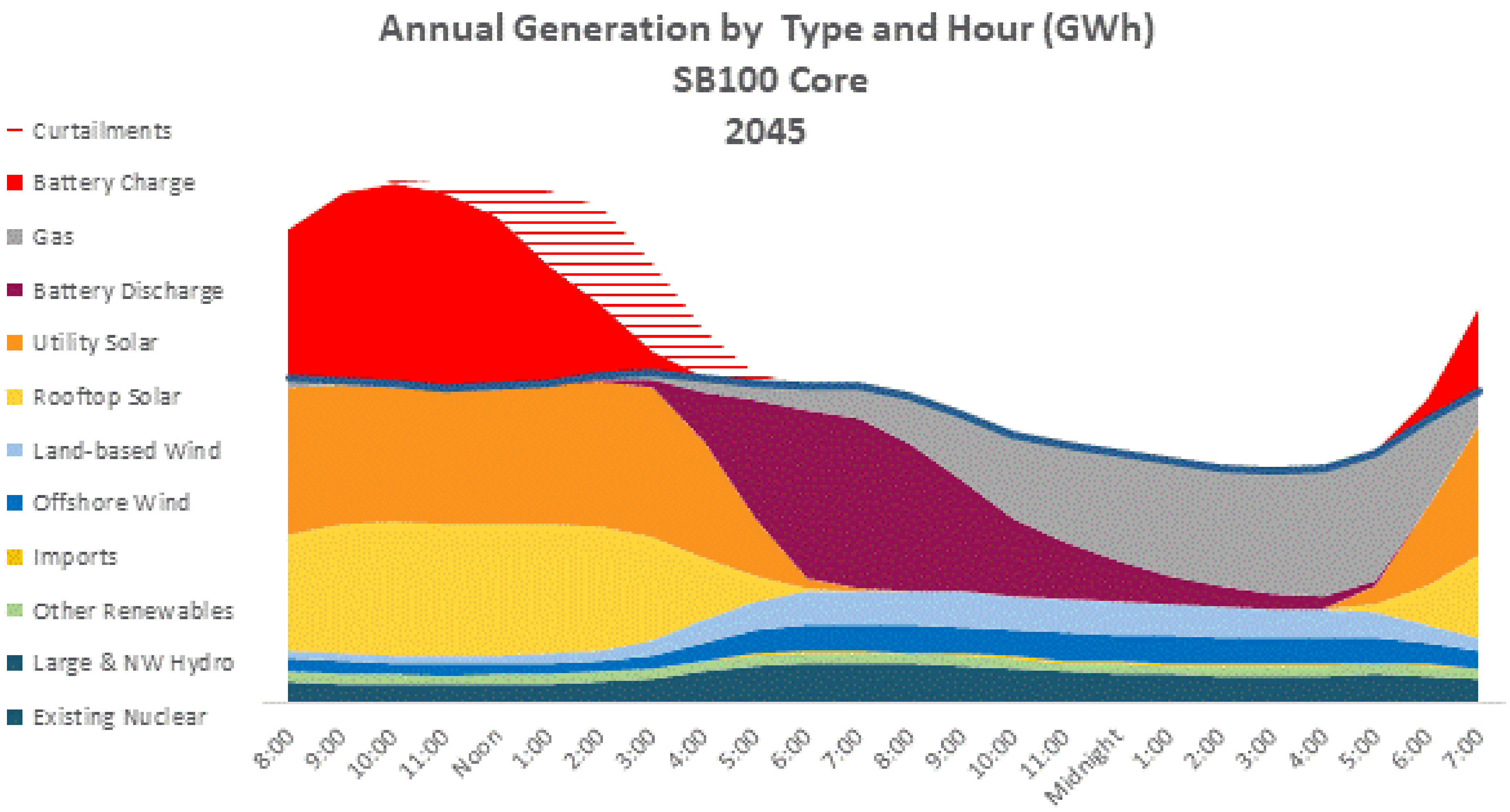
June 27, 2024

“For some portion of almost every day, a combination of solar, wind, geothermal, and hydropower has been producing more than a hundred per cent of the state’s demand for electricity… California has proved that it’s possible to run a thriving modern economy on clean energy.”

The statement is true – the conclusion is false.

The Reality: An Average Day in 2045

This shows the total electric generation for each hour of the day in 2045, averaged over the entire year. Under the State's plan, by that time the grid should be "100% clean". Solar power dominates for a third of the day, but responsibility for keeping the lights on for the rest of the day and night rests with the batteries, and then with natural gas. When the day is overcast or rainy, the batteries won't be charged and only the burning of natural gas will avoid rolling blackouts.



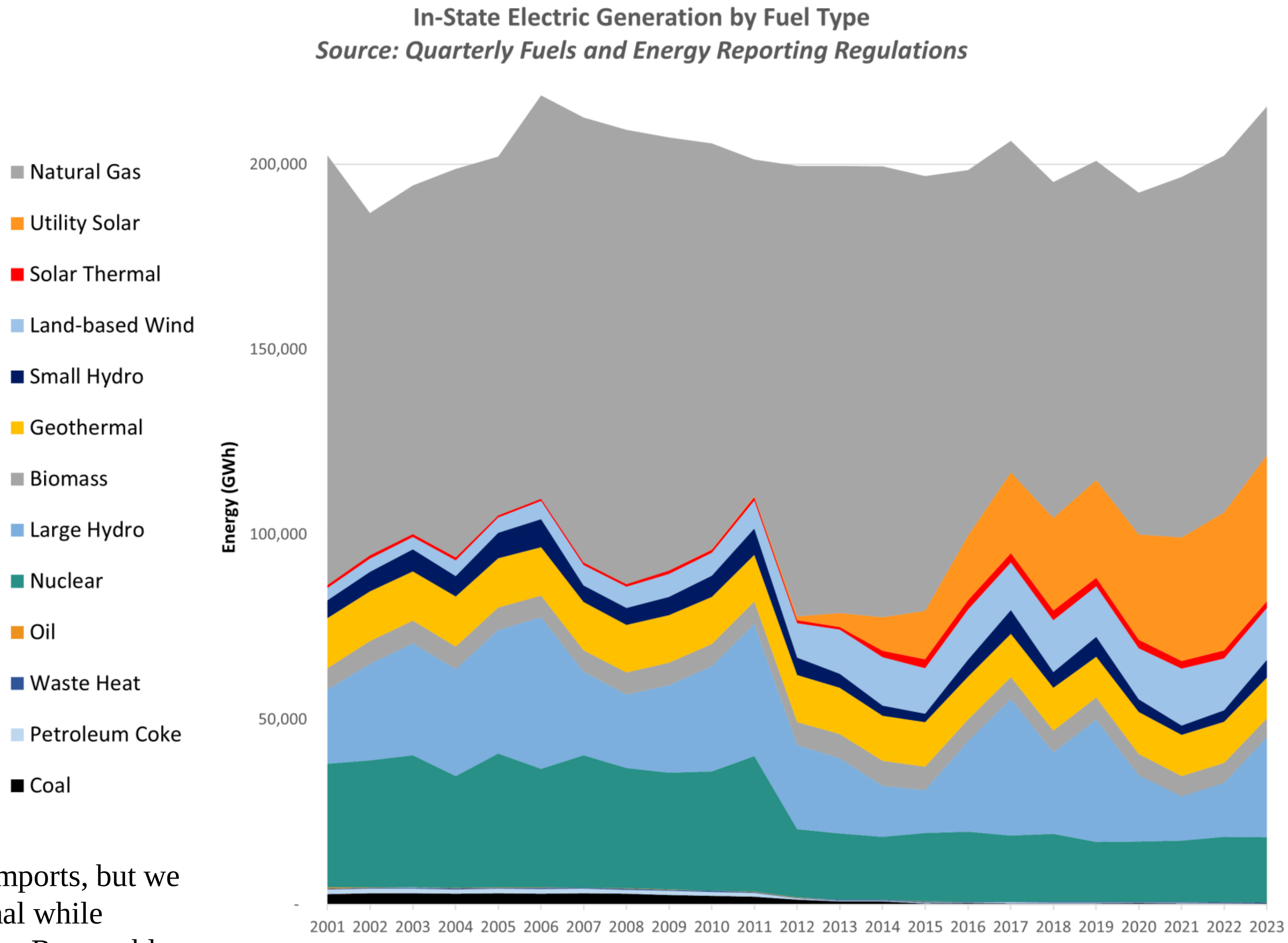
California's Climate Laws

California's climate policy is set principally by laws passed within the last two decades:

- **AB32, the Global Warming Solutions Act of 2006**, set greenhouse gas (GHG) reduction goals which have subsequently been extended by successive Governors' Executive Orders. Currently, the State's goals are to achieve carbon neutrality by 2045 and ensure that by 2045 statewide GHG emissions are reduced at least 85% below 1990 levels.
- **SB100, the 100 Percent Clean Energy Act of 2018** requires that, by 2045, eligible renewable energy resources and zero-carbon resources supply 100% of retail sales of electricity to end-users and 100% of electricity procured by State agencies. The three agencies responsible for implementing California's climate and energy policy – the California Air Resources Board (CARB), the California Public Utilities Commission (CPUC), and the California Energy Commission (CEC) – have concluded that the SB 100 core target requires that 90 percent of electric generation must come from renewable and zero-carbon resources by 2045.
- **The California approach** to achieving these goals, like that of most other jurisdictions in the US and internationally, is to attempt to (1**) electrify most applications in which fossil fuels are burned today and (2) generate nearly all electricity from renewable and zero-carbon sources.**
- In pursuing these goals, California is limited by the **Warren–Alquist Act** which, as amended in 1976, establishes a **moratorium on any new nuclear generating plants** until the federal government has established a means for disposing of high-level nuclear waste. As a result, **no plan for meeting California's goals includes any expansion of its nuclear generating capacity.**

Evolution of California's Grid 2001-2023

This graph, from the California Energy Commission, shows how the grid has evolved over the past twenty years. Most dramatic event has been the shutdown of the San Onofre nuclear plant in 2012 and the four-year increase in gas consumption that followed. The rise in utility-scale solar came in subsequent years, but the net result has been almost no change in gas consumption over this period (gas consumption last year was nearly identical with consumption in 2003). Gas continues to be the largest source of electricity for the state.

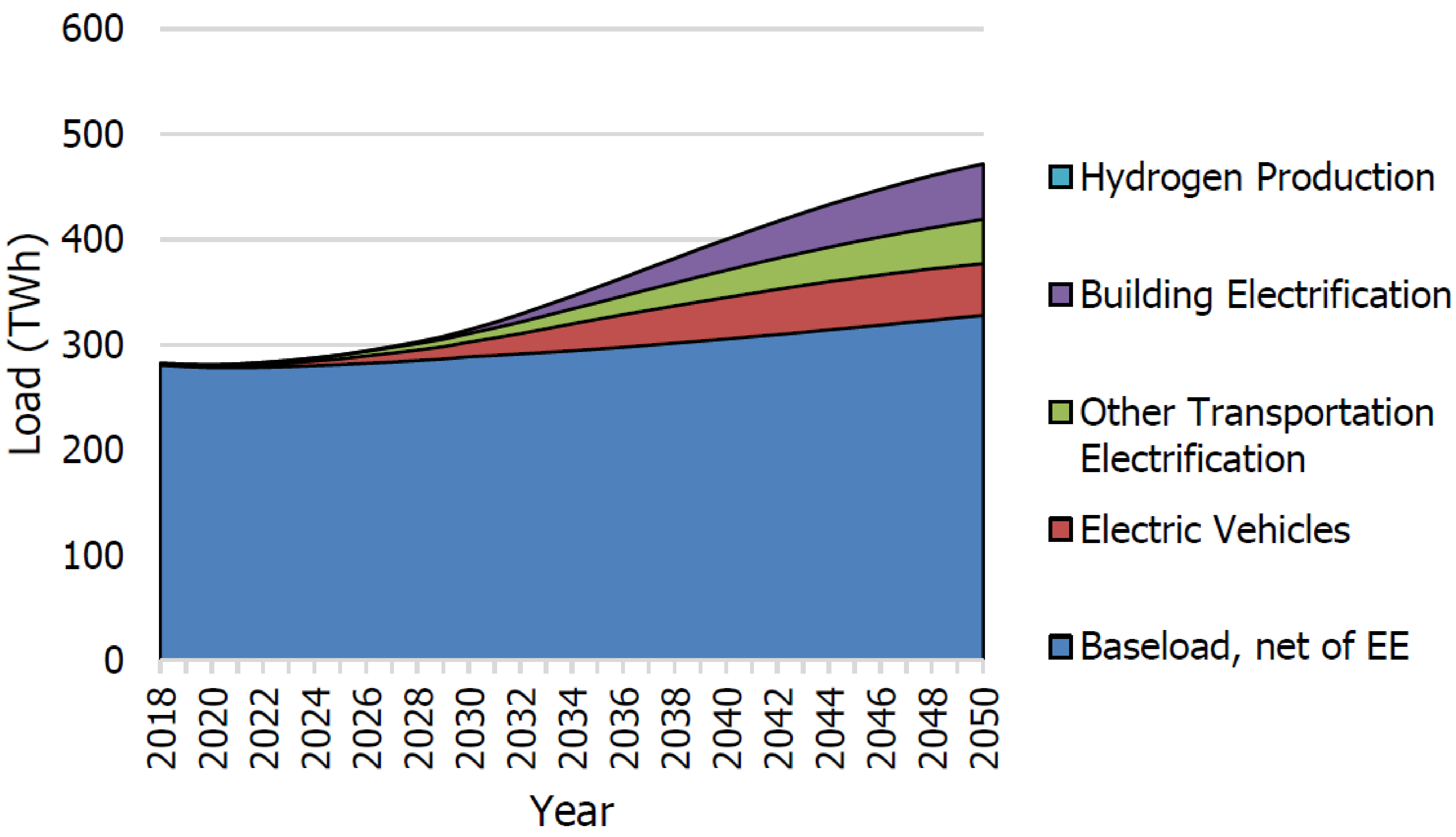


Note: In subsequent graphs, we show Rooftop Solar and Imports, but we omit oil, waste heat, petroleum coke, coal, and solar thermal while combining biomass, geothermal, and small hydro into Other Renewables.

Source: https://www.energy.ca.gov/media/3757

The Future of California’s Electricity

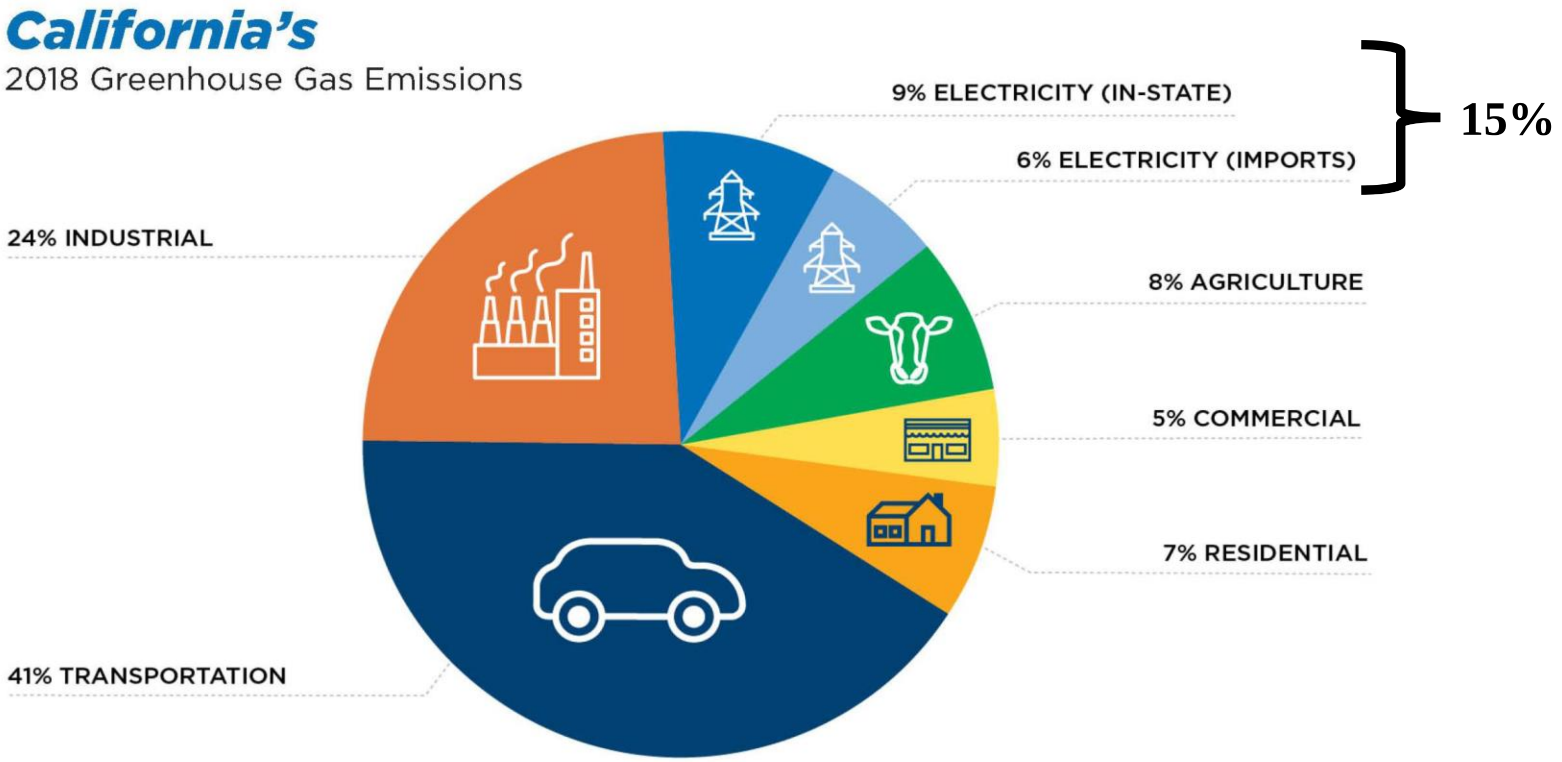
This is the projected annual demand for electricity through 2050, agreed upon by the California Energy Commission, California Public Utility Commission, and California Air Resources Board. We use these projections, as embodied in E3’s RESOLVE calculations, in our analysis.



Source: 2021 SB 100 Joint Agency Report, Figure 22. https://www.energy.ca.gov/sb100

Today electricity accounts for a minor portion of California's Greenhouse Gas Emissions

Electricity currently accounts for just 17% of California's GHG emissions. Legislation, primarily SB 100, aims to reduce that contribution while providing power to replace the burning of fossil fuels in other sectors of the state's economy. After 2030, all new space and water heaters must have zero emissions, and after 2035, all new car and light trucks sold must have zero emissions. The CEC and CARB are examining the potential for electrically-produced hydrogen for decarbonizing industrial processes. All of these will add to the expected electrical load.

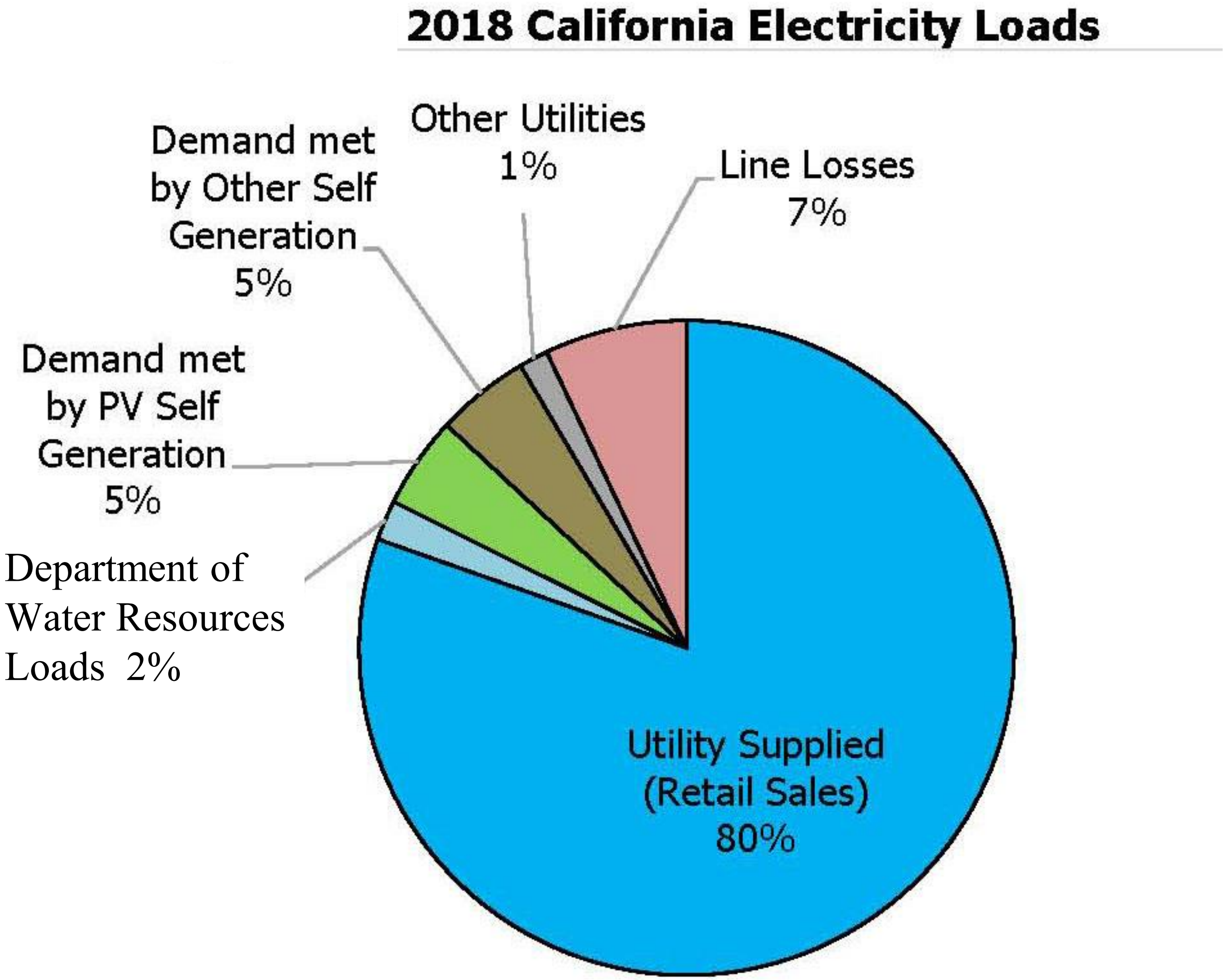


https://efiling.energy.ca.gov/GetDocument.aspx?tn=239588&DocumentContentId=73021

California's SB 100 Sets Zero-carbon Targets for Most Electricity

SB 100 requires that, by 2045, all retail sales of electricity to end-users and to public agencies must be carbon-free. This has been interpreted by State agencies to allow continued burning of natural gas in order to cover transmission line losses and losses due to battery inefficiency (e.g., there is a 15% loss in the charge-discharge of lithium-ion batteries).

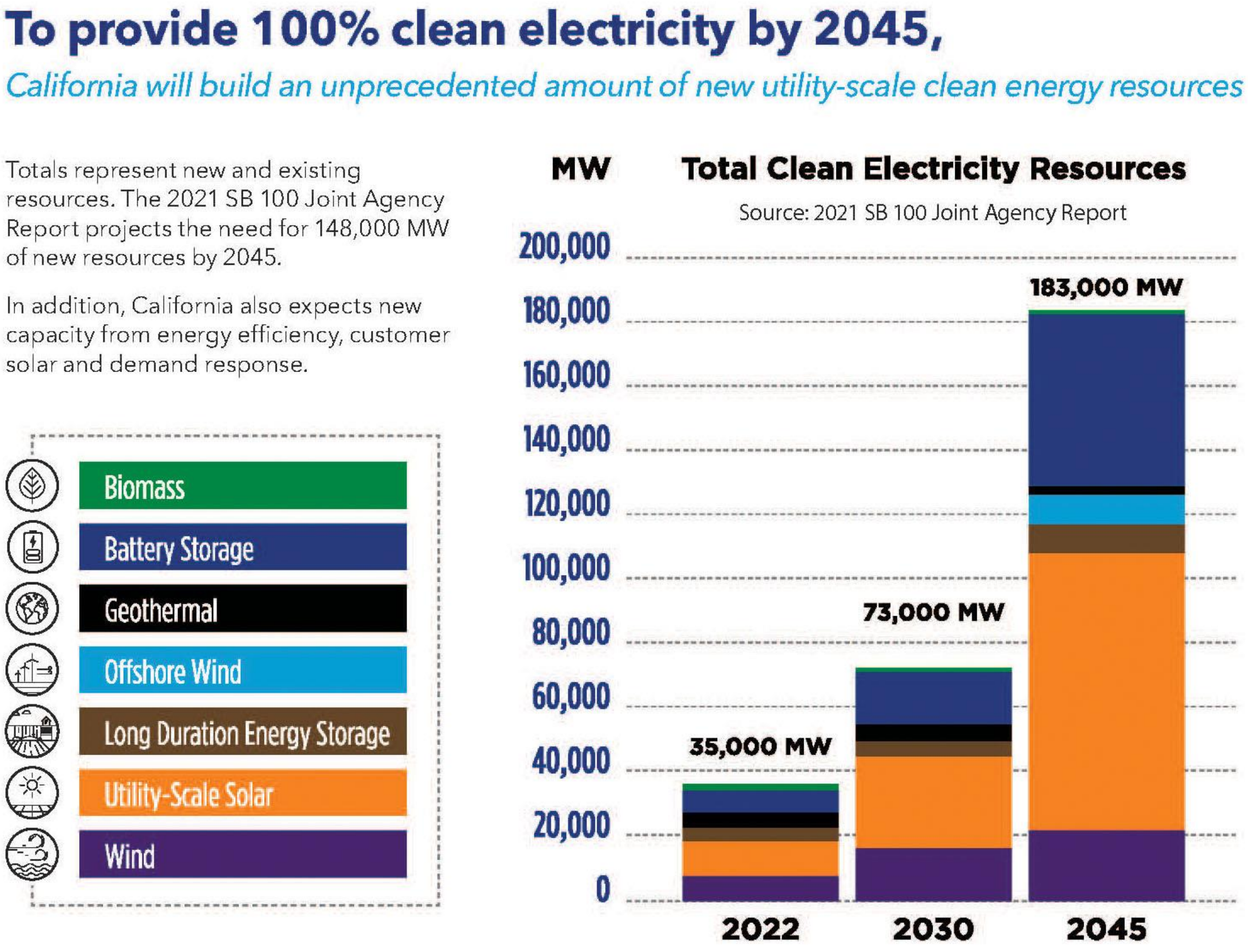
In fact, as we will show, natural gas will be needed far more than that. Gas will be burned simply to keep the grid functioning when the solar and wind are not producing enough power to meet the demand on the grid.



Source: 2021 SB 100 Joint Agency Report, Figure 19. https://www.energy.ca.gov/sb100

California's Current Energy Plan

This is California's current plan, as displayed in a report issued last year by the Governor. It shows each of the renewable sources and battery storage. It features greatly expanded solar, a modestly-expanded wind resource, and much expanded battery storage. It does not show the continued burning of gas and claims 100% clean electricity by 2045. This is false. The reality isn't even close.



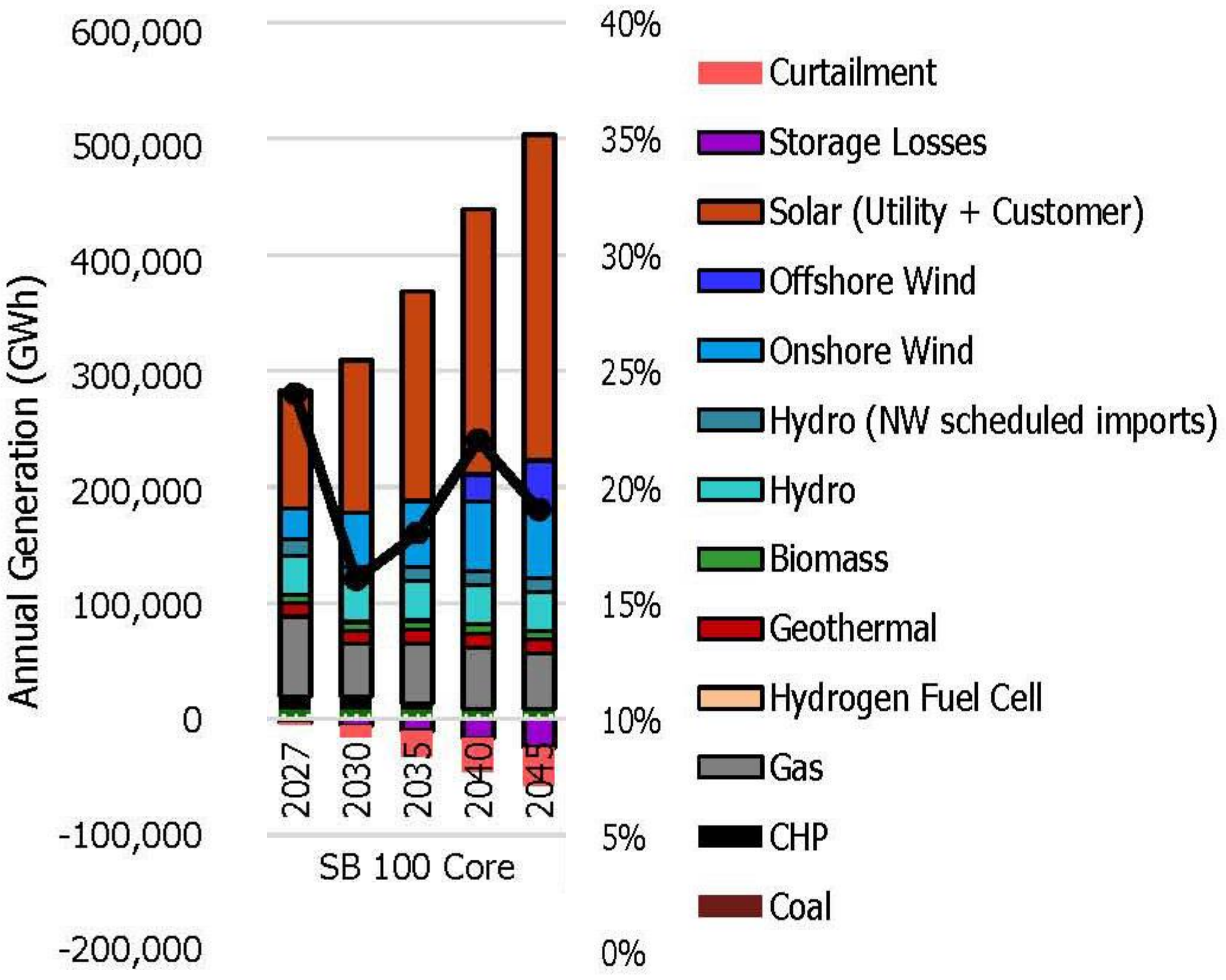
https://www.gov.ca.gov/wp-content/uploads/2023/05/CAEnergyTransitionPlan.pdf

Annual Generation in the SB 100 Core Scenario

This shows electric generation that the State expects under its current plan. (The black line and the percentages show the GHG emissions each year as compared to 1990 levels.) This is the only graph I have found that shows the substantial amount of gas that continues to be burned under the State's plan.

2021 SB 100 Joint Agency Report

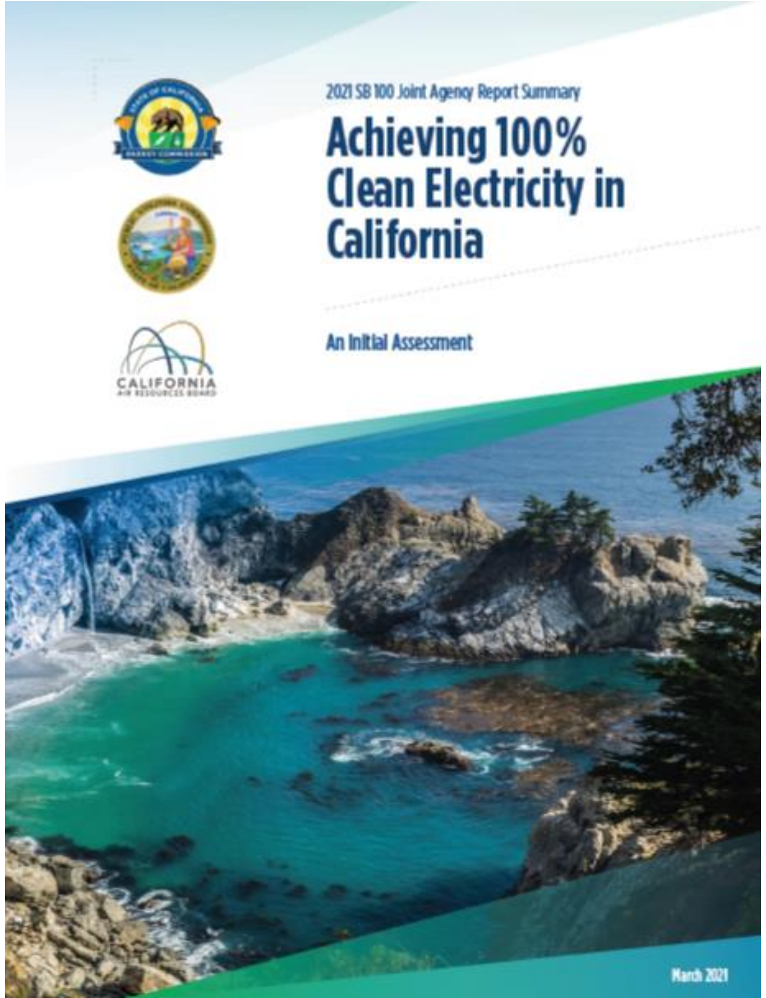
Achieving 100 Percent Clean Electricity in California: An Initial Assessment



Source: 2021 SB 100 Joint Agency Report, Figure 29

Projected Resources in 2045

These are the resources assumed in the 2045 SB 100 Core scenario. This is what is modeled in this study.



California
Clean Electricity Resources

	Existing Resources	Projected New Resources	
	2019*	2030**	2045**
Solar (Utility-Scale)	12.5 GW	16.9 GW	69.4 GW
Solar (Customer)	8.0 GW	12.5 GW	28.2 GW
Storage (Battery)	0.2 GW	9.5 GW	48.8 GW
Storage (Long Duration)	3.7 GW	0.9 GW	4.0 GW
Wind (Onshore)	6.0 GW	8.2 GW	12.6 GW
Wind (Offshore)	0 GW	0 GW	10.0 GW
Geothermal	2.7 GW	0 GW	0.1 GW
Biomass	1.3 GW	0 GW	0 GW
Hydrogen Fuel Cells	0 GW	0 GW	0 GW
Hydro (Large)	12.3 GW	N/A†	N/A†
Hydro (Small)	1.8 GW	N/A†	N/A†
Nuclear	2.4 GW	N/A†	N/A†

https://efiling.energy.ca.gov/GetDocument.aspx?tn=239588&DocumentContentId=73021

A New Model of Electric Grid Behavior

A new computer model of the electric grid has been developed for Massachusetts by an experienced power engineer and a software developer at the Center for Academic Collaboration Initiatives.[1] We have adapted it for use in analyzing the decarbonization plans of New York[2] and California. It as an hourly dispatch model which, for any selected year in a decarbonization scenario, for each hour sequentially introduces (“dispatches”) each of the generating sources from the fixed (e.g., baseload nuclear, solar, wind, other renewables) to the flexible (batteries, natural gas, and potentially, nuclear).

CACI
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1 https://centeraci.com/wp-content/uploads/2022/09/Technical-Economic-Limits-for-Renewable-Power-Integration-in-New-England-Full-Report-Rev-1.pdf

2 https://centeraci.com/wp-content/uploads/2023/11/A_New_View_of_New_York_Electric_Grid_ANofal_LRodberg_RKuhr_Full_Report.pdf

Comparison with California's E3 Model (I)

E3 RESOLVE linear programming model (used in California and New York)

1. **Optimizes** a multi-year scenario to achieve minimum net present value of investments, given multiple constraints including assumed costs for each source.
2. **Output** is annual fraction of each source during each selected year.
3. **Fails to disclose when energy is produced or whether it is needed at the time it is produced.** It does not have the necessary granularity to manage a grid.(When power is produced is crucial. It must be produced when it is needed, or it has to be stored for use at a later time. Storing electricity is difficult and costly.)
4. **Obscures the intermittent, time- and weather-dependence of solar and wind.** This limitation appears only through the use of capacity factors – the ratio of actual to maximum possible output. This shows these sources to be weaker than they appear, but it makes them seem (falsely) to be always available, 24/7.
5. **Uses only 37 representative days during each year, so cannot evaluate how useful batteries will be.** This selected data makes it impossible to see the impact of extreme weather events.

Comparison with California's E3 Model (II)

CACI hourly dispatch model

1. **Calculates**, for every hour of a selected scenario and year, the output of every source needed to meet the projected load.
2. **Uses data from a past year to provide actual solar and wind output for each hour of the year.** It calculates capacity factors from this data.
3. **Introduces** every non-dispatchable source (baseload nuclear, hydro, solar, wind) before introducing ("dispatching") dispatchable sources (batteries, gas, flexible nuclear) until the hourly load is met.
4. **Charges batteries from excess solar and wind output**.
5. **Curtails** (shuts down) any remaining excess from these sources so they don't overload the system.

Operation of the CACI Grid Model (II)
Calculation Flow (see also Appendix B)

Assumptions and Data

- Projected source scenarios through 2045
- Basic hourly load shape from 2023 data
- Energy source capacities and output in 2023
- Hourly solar and wind output in 2023
- Energy source costs

Daily Model Hourly Calculation

- Hourly electric loads
- Non-dispatchable generation and curtailments
- Energy storage charging and discharging
- Dispatchable generation ordered by fuel and variable costs

Annual Analysis

- Daily results for a full year
- Daily and hourly generation, curtailment, and cost by type of generation
- Calculated capacity factors

Visualizations

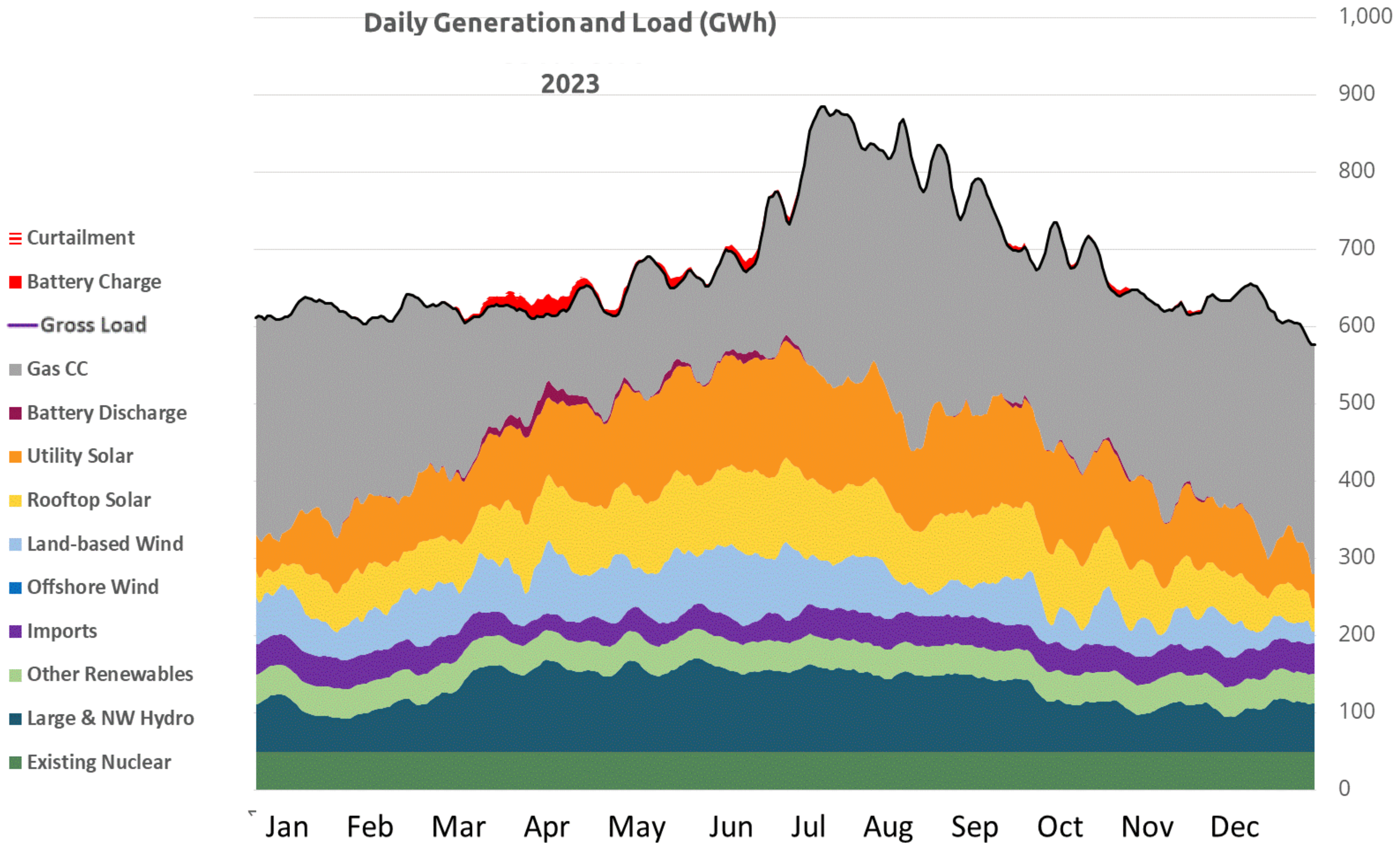
- Hourly and daily graphs
- Loads
- Generation
- Curtailments
- Variations in generation mix by hour and day
- Effect of EVs and building electrification

Inputs and Assumptions in our Model

- Source capacities (GW) and hourly generation (GWh) and system load (GWh) for 2023 are from the California Independent System Operator (CAISO).
- The CAISO service area is treated as a single zone.
- Source capacities and projected load for 2045 are from E3 RESOLVE inputs and 2021 SB 100 Joint Agency Report Summary "Achieving 100% Clean Electricity in California".
- Hourly solar and wind outputs for 2023 are from CAISO. The same weather pattern (solar and wind output per GW of capacity for each hour) is assumed for 2045 with projected capacities at that time.
- Estimated costs are from the 2024 Annual Technology Baseline (ATB) of the National Renewable Energy Laboratory.
- Existing Nuclear, Large Hydro, Other Renewables, and Imports in 2045 are unchanged from 2023.
- Pumped storage (3.7 GW capacity) is omitted. Could be added in later studies.
- Batteries are charged by excess solar and wind output.
- Batteries, Gas, and other flexible sources (if available) provide the needed output when Existing Nuclear, Large Hydro, Other Renewables, Imports, Land-based and Offshore Wind, Rooftop Solar, and Utility Solar are not able to meet the projected load.
- Solar, wind, and any new baseload nuclear are curtailed if they would produce unneeded power.

How California's Grid Operates Today

This graph displays the output of each source contributing to today's grid. From the bottom-up, first come the non-dispatchable sources, then the dispatchable ones, topped by natural gas and a few battery discharges. These fill in the gap left by the non-dispatchables. The batteries are charged by excess solar and wind output. In the Spring, demand is low, and there is excess solar output, so the batteries are charged during the day and discharged in the evening. This is shown in more detail on page 17 in hourly presentations of winter, spring, summer and fall days.



Sources of Electricity in 2023

Rooftop and utility-scale solar were major contributors to the grid last year, but the largest source by far was natural gas. Little curtailment — excess production — is present in our single-zone model. This conflicts with the widely-reported extensive curtailment of solar power over the past year. However, CAISO, the grid operator, has reported that most of the curtailment last year was the result of congestion — the inability to transmit excess power to where it could be used. (Note that the generation cost does not include the substantial federal and state subsidies for solar and wind.)

Electricity Generation
SB100 Core
2023

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	2,393	17,762	84.7%	7.1%
New Nuclear	0	0	0.0%	0.0%
Large & NW Hydro	17,366	30,918	20.3%	12.4%
Other Renewables	5,770	14,061	27.8%	5.7%
Rooftop Solar	14,000	27,994	22.8%	11.3%
Utility Solar	19,887	41,019	23.5%	16.5%
Land-based Wind	6,284	20,825	37.8%	8.4%
Offshore Wind	0	0	0.0%	0.0%
Battery Discharge*	7,552	1,125	1.7%	0.5%
Gas	39,689	92,228	26.5%	37.1%
Imports		3,859		1.6%
Load		248,665		100.0%

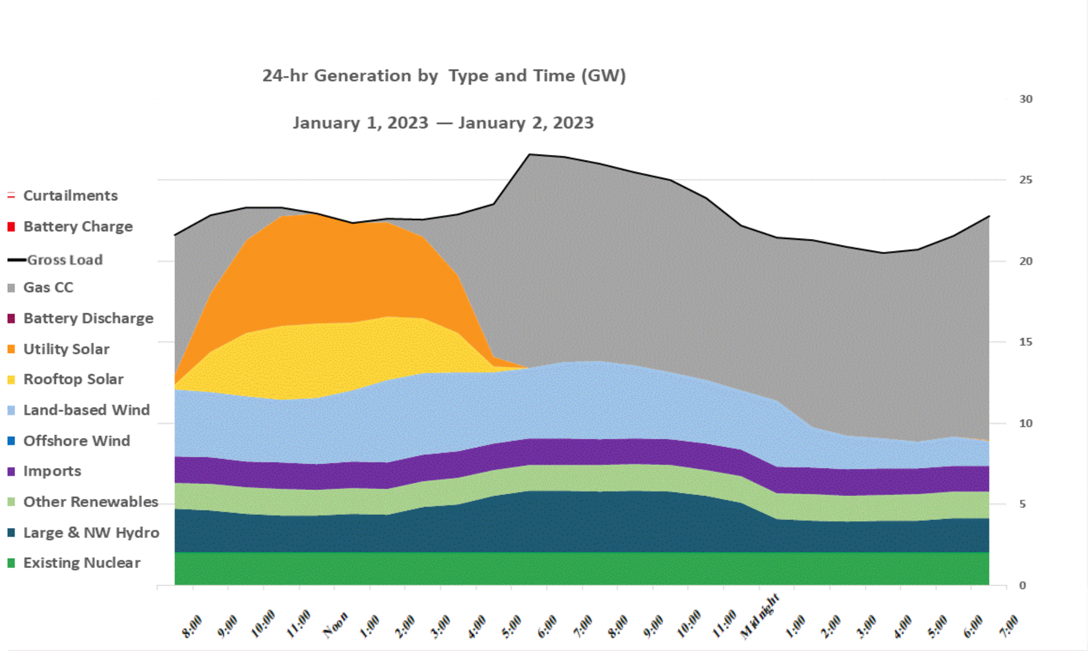
* Battery charging included in solar and wind generation.

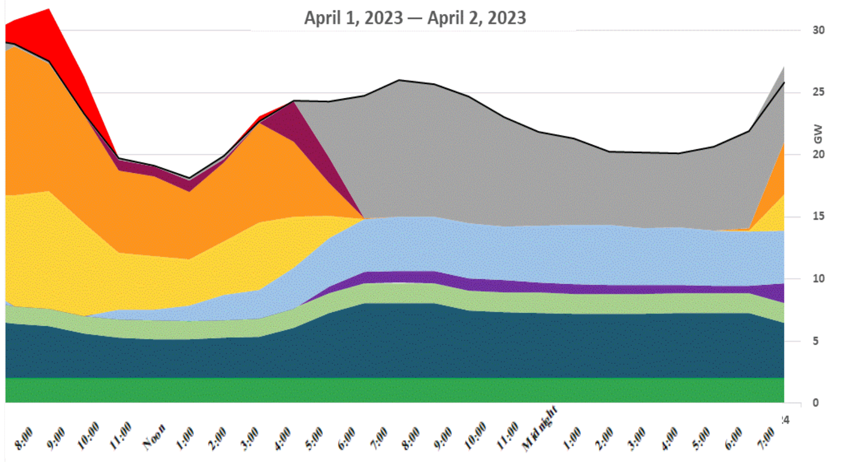
Curtailment		50		0.0%

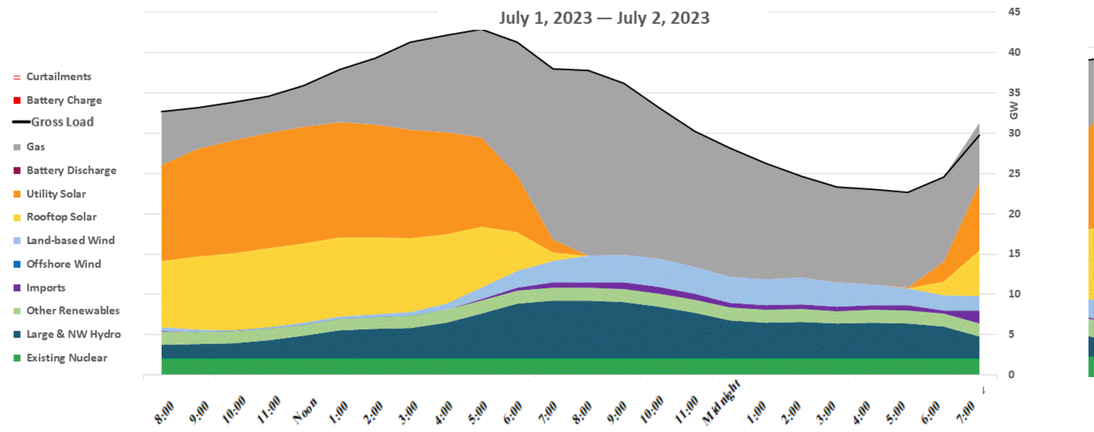
Total Generation Cost ($/MWh) $ 68.95

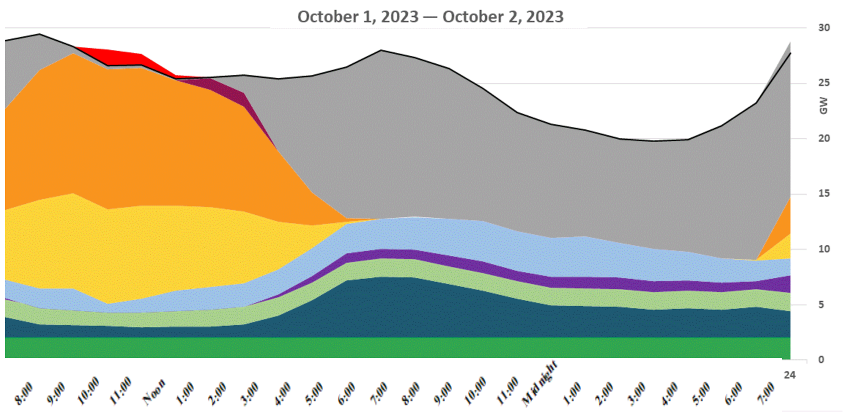
Daily power through the seasons in 2023

Four days illustrate the operation of the grid. As the sun rises, solar power displaces gas, but as the sun sets, gas-driven power returns and keeps the grid running throughout the night. In Spring, with more sun and low demand, solar and wind partially charge the batteries. There is also some curtailment. As the sun sets, the 4-hr batteries discharge, and they are soon depleted, with gas taking over for the rest of the night. In Summer, there is more sun, but also greater demand, so the batteries are often not fully charged. Gas fills the gap. During every season, gas is essential to keep power on.



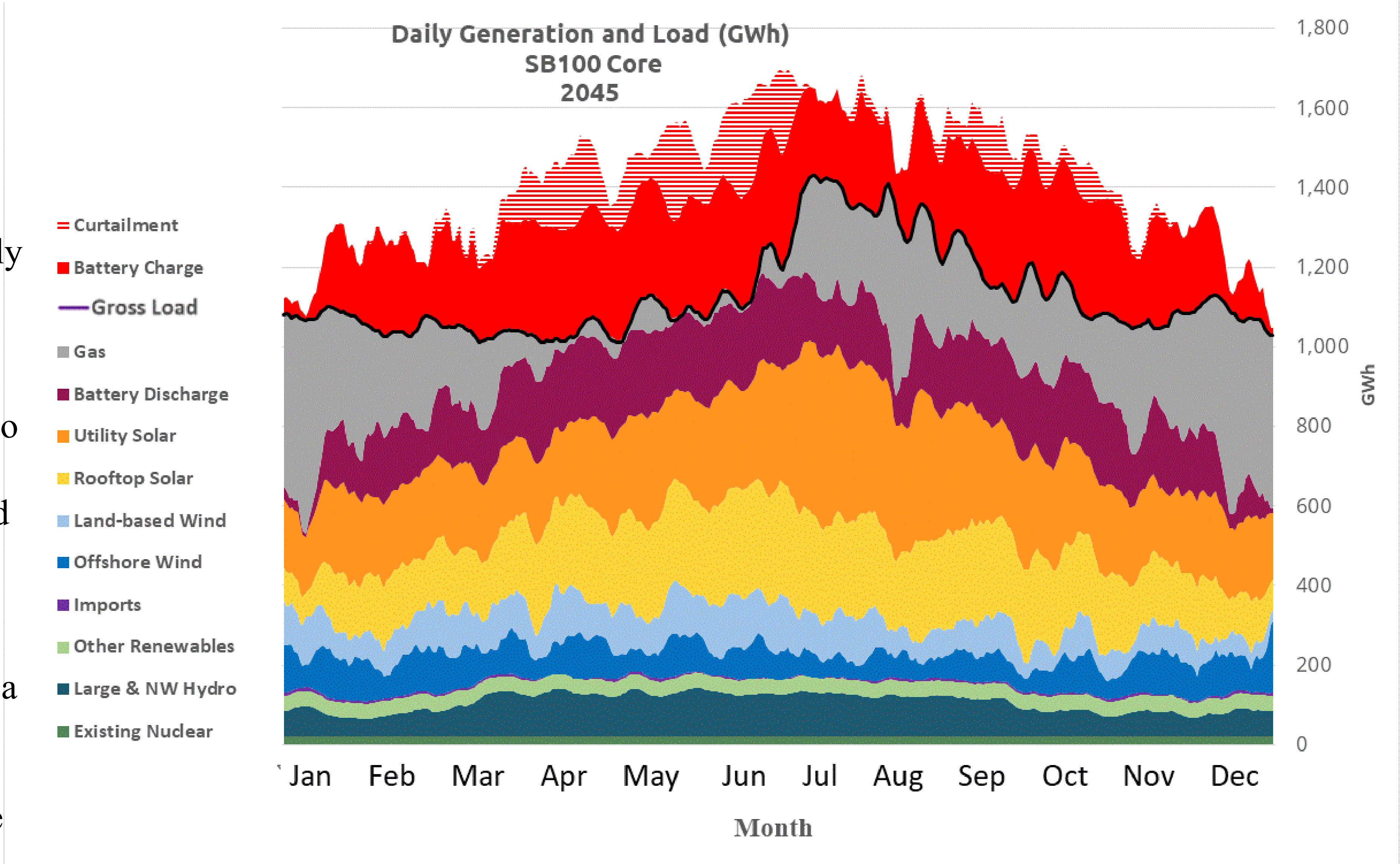






California's goal is 100% clean electricity by 2045. Instead, there is a large gap requiring the use of gas.

By 2045, all retail sales of electricity are supposed to be emission-free. Solar output is large, with wind much smaller. Batteries play a large role but cannot fill the gap between supply and demand. SB100 allows the burning of gas to cover transmission losses, but gas is needed throughout the year just to keep the lights on. Our model excludes transmission losses, and yet we find that, in 2045, California's grid will be burning 81% as much gas as it is now. Curtailment is extensive; that is, a great deal of excess power could be produced, but not at the right times, and only some of it can be stored in the batteries.



Sources of Electricity SB100 Core 2045

By 2045, solar is providing more than one-half the required generation. Wind, even including potential offshore wind, supplies a small share of the state's electric demand. Large battery farms will shift some of the excess solar-generated power to the evening, but overall, nearly as much gas will be burned as is being burned on the grid today.

Society-wide greenhouse gas emissions will be down because fewer gasoline-driven cars will be on the road, and more homes will be electrified, but retail sales of electricity will not be emission-free; the Teslas and other EVs that Californians have purchased will largely be charged every evening by the burning of natural gas

Because solar and wind costs are assumed to drop substantially, generation cost is relatively unchanged from today (at current costs, it would be 50% more). Note that the expected increase in transmissions costs is not included here.

Electricity Generation
SB100 Core
2045

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	1,042	7,734	84.7%	1.8%
New Nuclear	0	0	0.0%	0.0%
Large & NW Hydro	17,366	30,918	20.3%	7.3%
Other Renewables	5,770	14,061	27.8%	3.3%
Rooftop Solar	36,000	71,984	22.8%	16.9%
Utility Solar	82,000	151,363	21.1%	35.6%
Land-based Wind	12,217	38,496	36.0%	9.1%
Offshore Wind	8,215	33,525	46.6%	7.9%
Battery Discharge*	52,329	61,025	13.3%	14.4%
Gas	52,000	75,015	16.5%	17.7%
Imports		1,736		0.4%
Load		424,832		100.0%

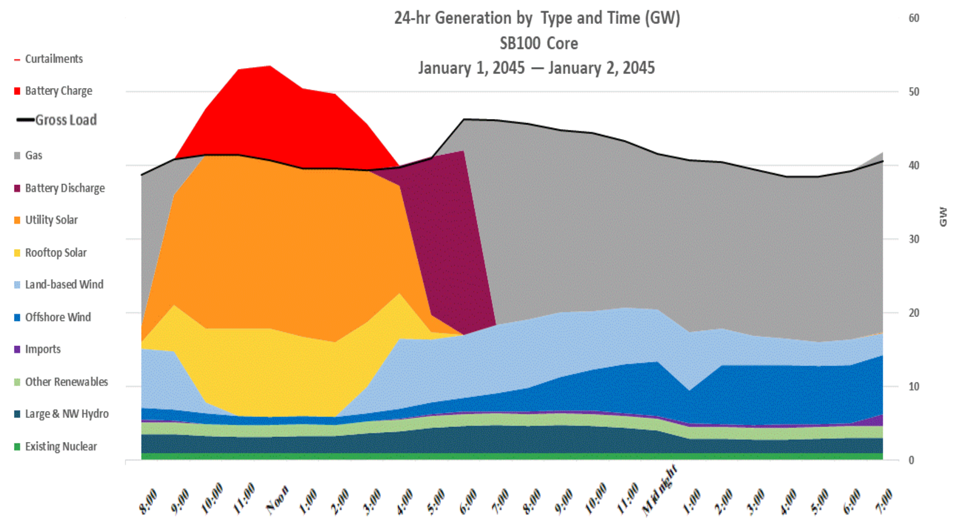
* Battery charging included in solar and wind generation.

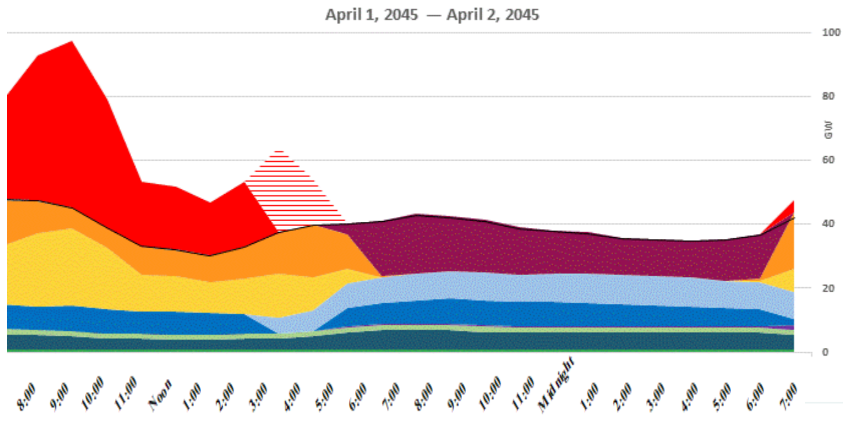
Curtailment		21,294		5.0%

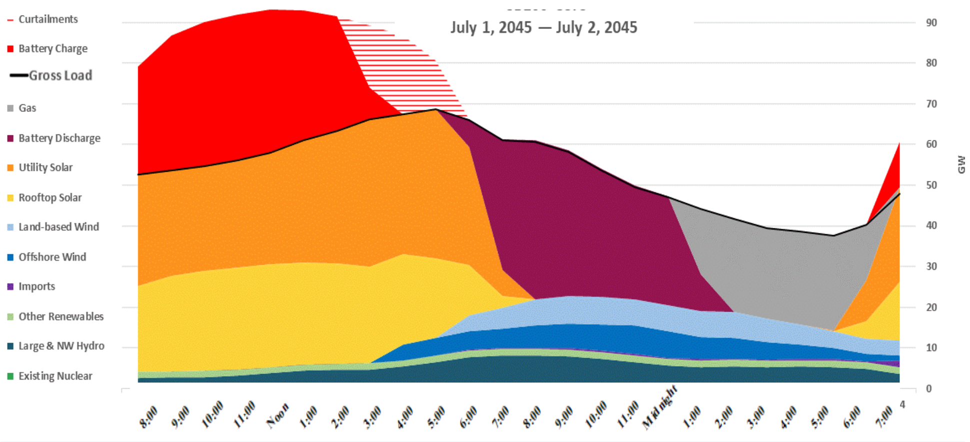
Total Generation Cost ($/MWh) $ 62.86

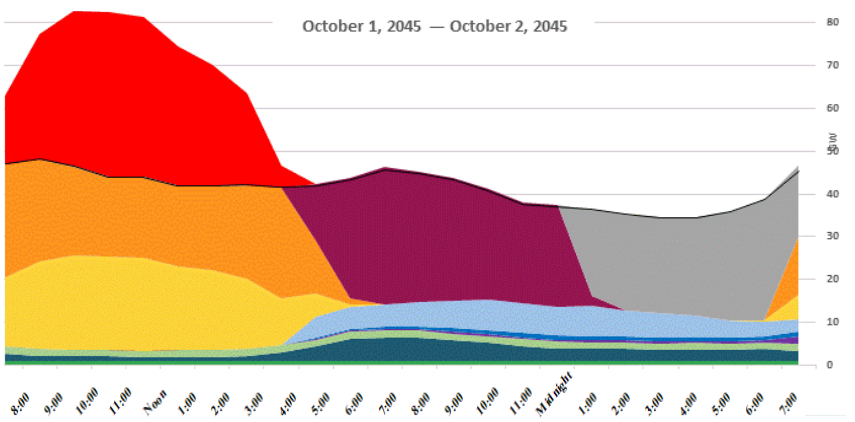
Daily power through the seasons in 2045

In January, the sun is too weak to fully charge the batteries, so they are quickly depleted, and gas takes over for much of the night. By April, the sun is strong enough to charge them fully, and they sometimes last all night. By July, though the batteries are fully charged, the load has increased from the operation of air conditioners, so the batteries are depleted during the night, and gas again has to take over. By October, demand is up and the batteries are not sufficient. Wind and other sources, including imports, play only a minor role.



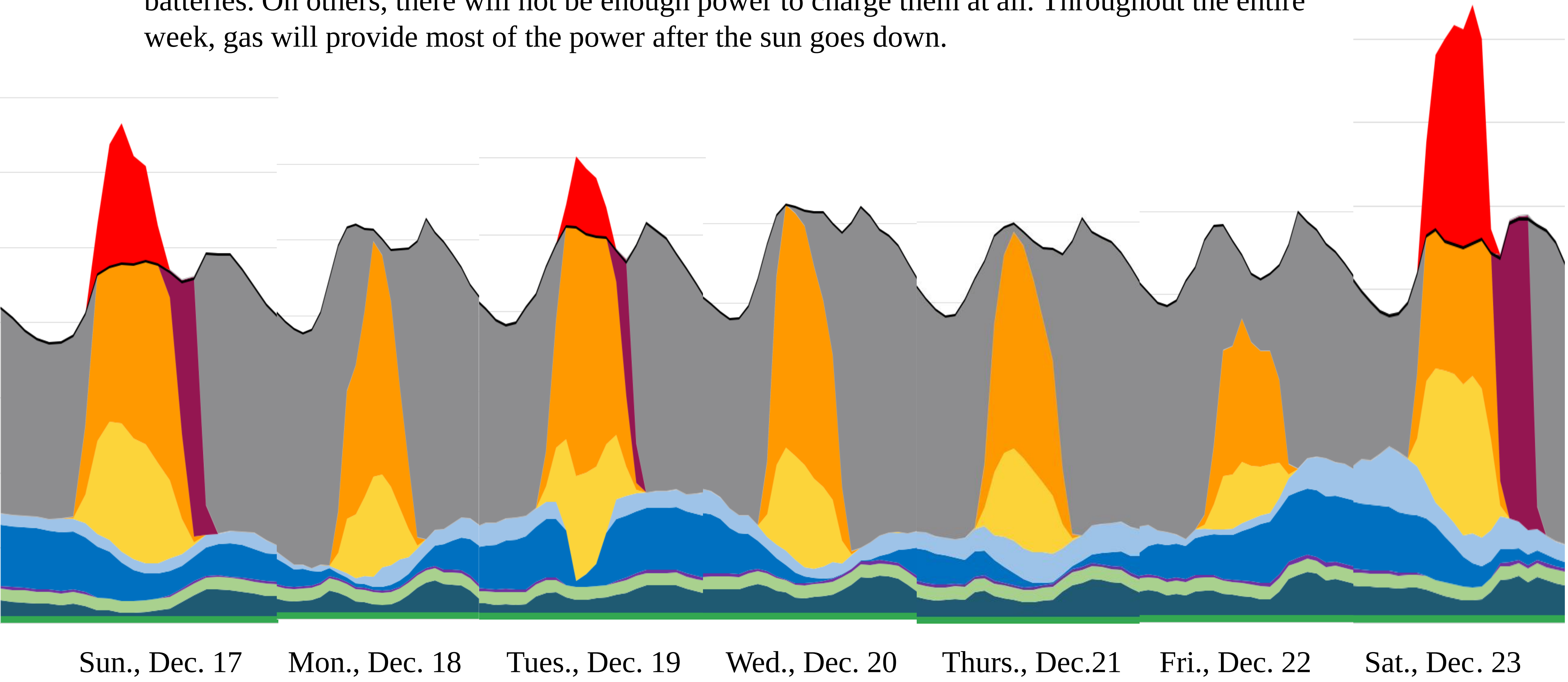






A difficult week in December 2045

On some winter days in California, there will be enough sun and wind to partially charge the batteries. On others, there will not be enough power to charge them at all. Throughout the entire week, gas will provide most of the power after the sun goes down.



Comparing SB100 Core sources 2045 with today

If the state's plan is followed, between now and the target year of 2045, the capacity of utility solar will have quadrupled, land-based wind nearly doubled, and battery output grown almost six-fold, yet gas capacity increases too, to cover gaps in renewable output as demand increases. Consumption of gas declines by less than 20%. The main reason is that there will be long periods, especially at night, when the only way to keep power flowing will be to run the gas plants, so they run nearly as much as they do now. In short, **the grid is not being decarbonized, nor is this plan leading California to the 100% clean future it claims.**

	2023	2045			2023	2045	
Energy Source	Capacity (MW)	Capacity (MW)	Change (2045/2023)		Output (GWh/yr)	Output (GWh/yr)	Change (2045/2023)
Rooftop Solar	14,000	36,000	257%		27,994	71,984	257%
Utility Solar	19,887	82,000	412%		41,019	151,363	369%
Land-based Wind	6,284	12,217	194%		20,825	38,496	185%
Offshore Wind	0	8,215	-		0	33,525	-
Battery Discharge	7,552	52,329	693%		1,125	61,025	5424%
Gas	39,689	52,000	131%		92,228	75,015	81%
Total	87,412	242,761	278%		248,958	414,837	167%

Comparing SB100 Core in 2045 with today

Energy Source	2023 Capacity (MW)	2045 Capacity (MW)	Change (2045/2023)		2023 Output (GWh/yr)	2045 Output (GWh/yr)	Change (2045/2023)
Rooftop Solar	14,000	36,000	257%		27,994	71,984	257%
Utility Solar	19,887	82,000	412%		41,019	151,363	369%
Land-based Wind	6,284	12,217	194%		20,825	38,496	185%
Offshore Wind	0	8,215	-		0	33,525	-
Battery Discharge	7,552	52,329	693%		1,125	61,025	5424%
Gas	39,689	52,000	131%		92,228	75,015	81%
Total	87,412	242,761	278%		248,958	414,837	167%

The grid is not being decarbonized.

This plan is not leading California to a clean future.

A Dispatchable Emission-Free Resource (DEFR) is essential for a clean grid.

We have found a large gap between what the carbon-free renewable sources can provide and what is needed to keep the lights on. That gap can be very large, especially if the day is overcast or at night and the wind is not blowing (what the Germans refer to as “Dunkelflaute” – dark doldrums). At that point, a backup is needed with a capacity nearly as large as the full load on the system. **In short, intermittent renewables require a backup which can duplicate the full output they can provide.** As we show below, this has serious implications for the cost of such a renewable-focused system.

Currently, natural gas, a fossil fuel, plays that role. That is not consistent with California’s climate goals.

One possible solution that naturally comes to mind is to install more renewables. That doesn’t help. Our analysis shows that, even if as much as five times more solar and wind and batteries were to be installed, much of California would still be left with no power for significant periods throughout the year, especially at night. Cloudy days would leave the batteries without adequate charge, and power would drop off during many nights.

The gap is largest at night when California’s largest emission-free source, solar power, is absent. To meet California’s climate goals, the gap has to be filled by a source that can replace natural gas but is emission-free. Most important, it has to be firm and reliable – always available when it is needed – and has to be dispatchable – able to provide whatever power is needed as the demands on the grid change from moment to moment.

Every grid needs such a firm dispatchable resource able to match, moment to moment, continuing fluctuations in demand as lights, computers, and motors turn on and off. To address the state’s climate goals, this source has to emit no greenhouse gases. **California needs a firm Dispatchable Emission-Free Resource, a DEFR.**

What should it be?

A Dispatchable Emission-Free Resource (DEFR) is essential for a clean grid. What should it be?

A number of suggestions for DEFRs have been offered:

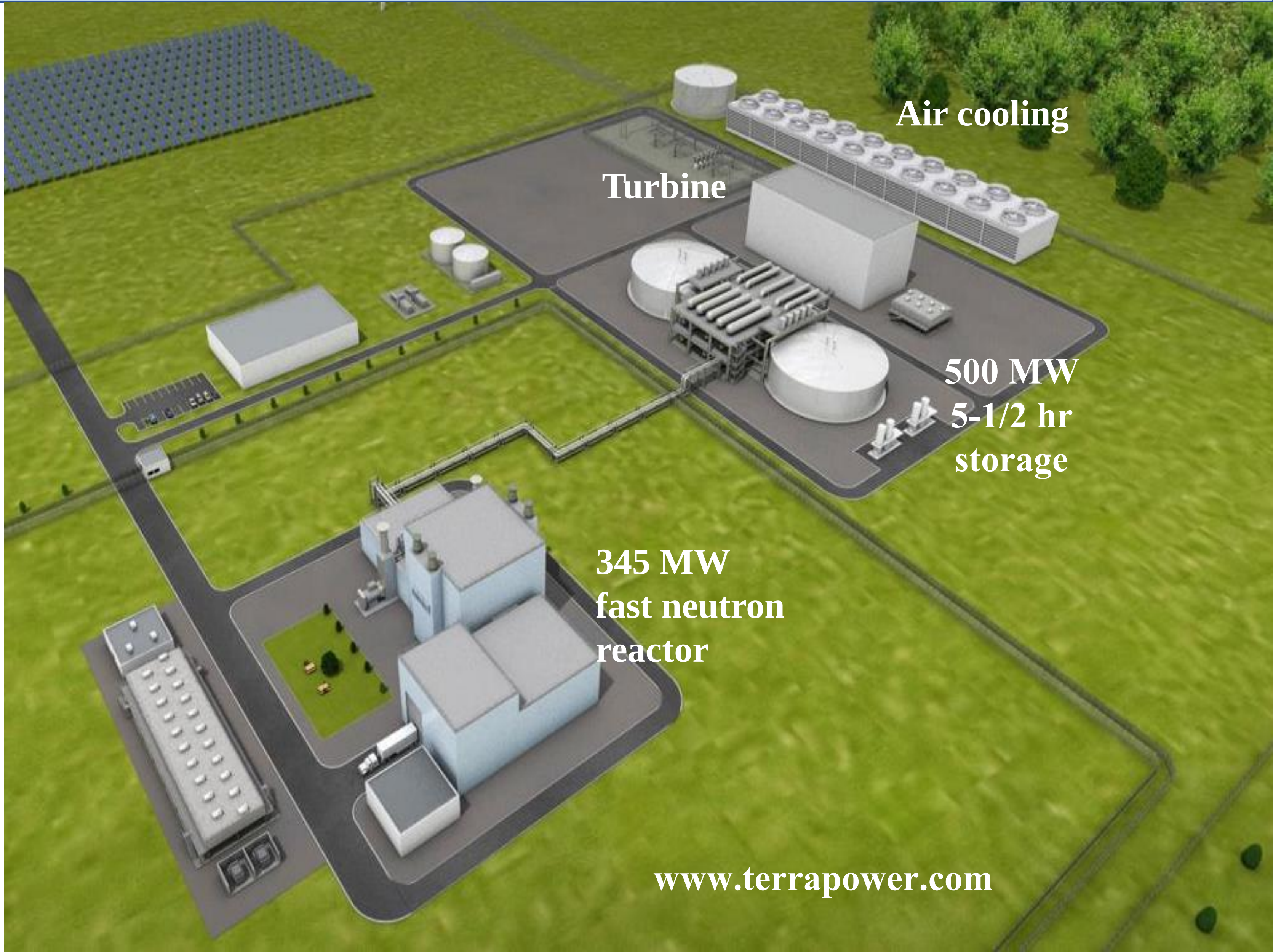
- Long-duration storage: This might help, but currently no realistic scalable form of such storage exists, especially since seasonal storage would be needed. If such storage existed, charging it would require a large expansion of generating capacity, regardless of what storage medium is used.
- Fuel cells or gas turbines powered by "green hydrogen": It is often suggested that hydrogen fuel cells or combustion power plants, similar to those now burning fossil fuels, could run on "green hydrogen" produced in electrolyzers powered by renewable energy. Using hydrogen for energy storage is costly, since the "round-trip" power-to-hydrogen-to-power efficiency of this process is 40% or less. This means that more than twice as much additional energy is needed as will be generated by such a DEFR, with a commensurate drain on material resources, land, and societal wealth. However, if nuclear energy powers the electrolyzers, the economic and environmental case may be much stronger.
- Carbon capture and storage (CCS) attached to gas-fired power plants: This only exists on an experimental basis. It would add substantial cost to the power it was attached to, and there would be leakage of greenhouse gases and other pollutants to the environment, both upstream and at the plants themselves. Further, the captured CO_2 would have to be disposed of, presumably underground, adding additional cost as well as potential environmental damage.

A large dispatchable emission-free resource is essential for a clean grid. What should it be? (cont.)

- Nuclear power: potential carbon-free sources, only nuclear power has been demonstrated to have the necessary reliability, flexibility, and scalability, not only in the gigawatt-scale reactors now operating in California and globally, but in the smaller reactors operating on submarines and ships for many decades and now under commercial development. This is the DEFR used in each of our scenarios, as well as for additional baseload generation. (California would, of course, have to lift its nearly fifty-year-old moratorium on the construction of new nuclear plants to follow this path.)
- Alternate nuclear options: Other ways of using nuclear energy also deserve consideration. Nuclear reactors, like most energy sources, are most cost-efficient when they run full-time. The DEFR would be operating at partial capacity for most of the year. A more cost-effective plan might use a smaller number of reactors running continuously to produce hydrogen which could be power gas turbines or fuel cells. Another option would be to use nuclear power to produce carbon-neutral synthetic fuels that would replace fossil-based hydrocarbons., Full analysis of the cost and suitability of these options is beyond the scope of this paper, but they deserve serious study.

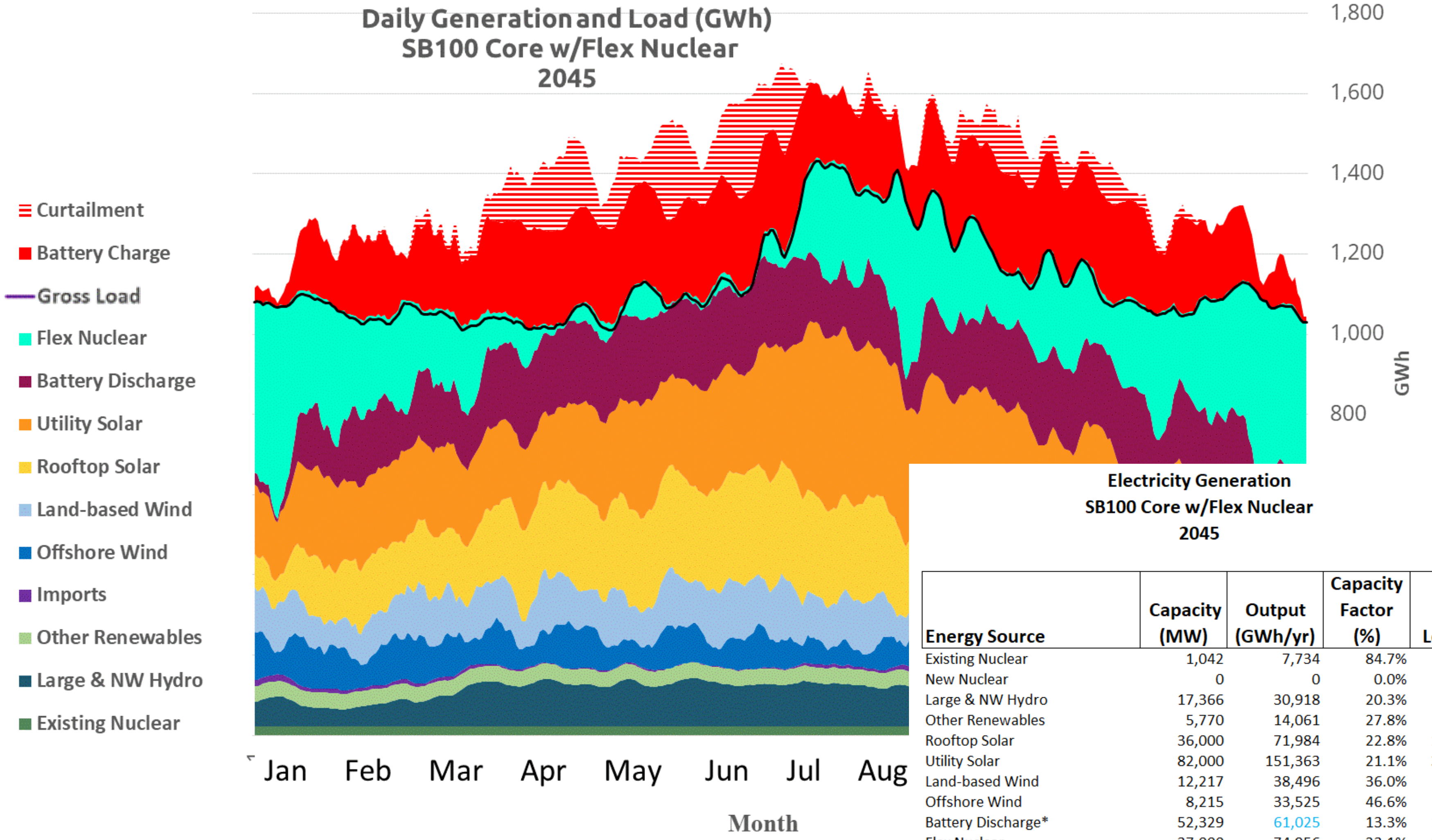
Natrium: an example of a DEFR

The Natrium system, combines a nuclear reactor with thermal energy storage. This is one example of a clean firm dispatchable source of power. It can supply 500 MW for up to 5-1/2 hours and is continuously resupplied with heat by a 345 MW sodium-cooled fast neutron reactor. Using technology first developed in DOE’s EBR-I and II, the first of its kind is now being installed in Wyoming. They are air-cooled and do not have to be located near a source of cooling water, as do most large reactors today.



SB100 Core w/Flex Nuclear

With a Natrium reactor with its thermal storage acting as a firm dispatchable source, we have a clean system which will keep the lights on and the data centers running 24/7. However, added to the cost of the renewables, this is a system that is much more expensive, at current nuclear costs, then when running with existing gas-fired turbines. There are several less-costly alternatives to consider.



Electricity Generation
SB100 Core w/Flex Nuclear
2045

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	1,042	7,734	84.7%	1.8%
New Nuclear	0	0	0.0%	0.0%
Large & NW Hydro	17,366	30,918	20.3%	7.3%
Other Renewables	5,770	14,061	27.8%	3.3%
Rooftop Solar	36,000	71,984	22.8%	16.9%
Utility Solar	82,000	151,363	21.1%	35.6%
Land-based Wind	12,217	38,496	36.0%	9.1%
Offshore Wind	8,215	33,525	46.6%	7.9%
Battery Discharge*	52,329	61,025	13.3%	14.4%
Flex Nuclear	37,000	74,956	23.1%	17.6%
Imports		1,736		0.4%
Load		424,774		100.0%

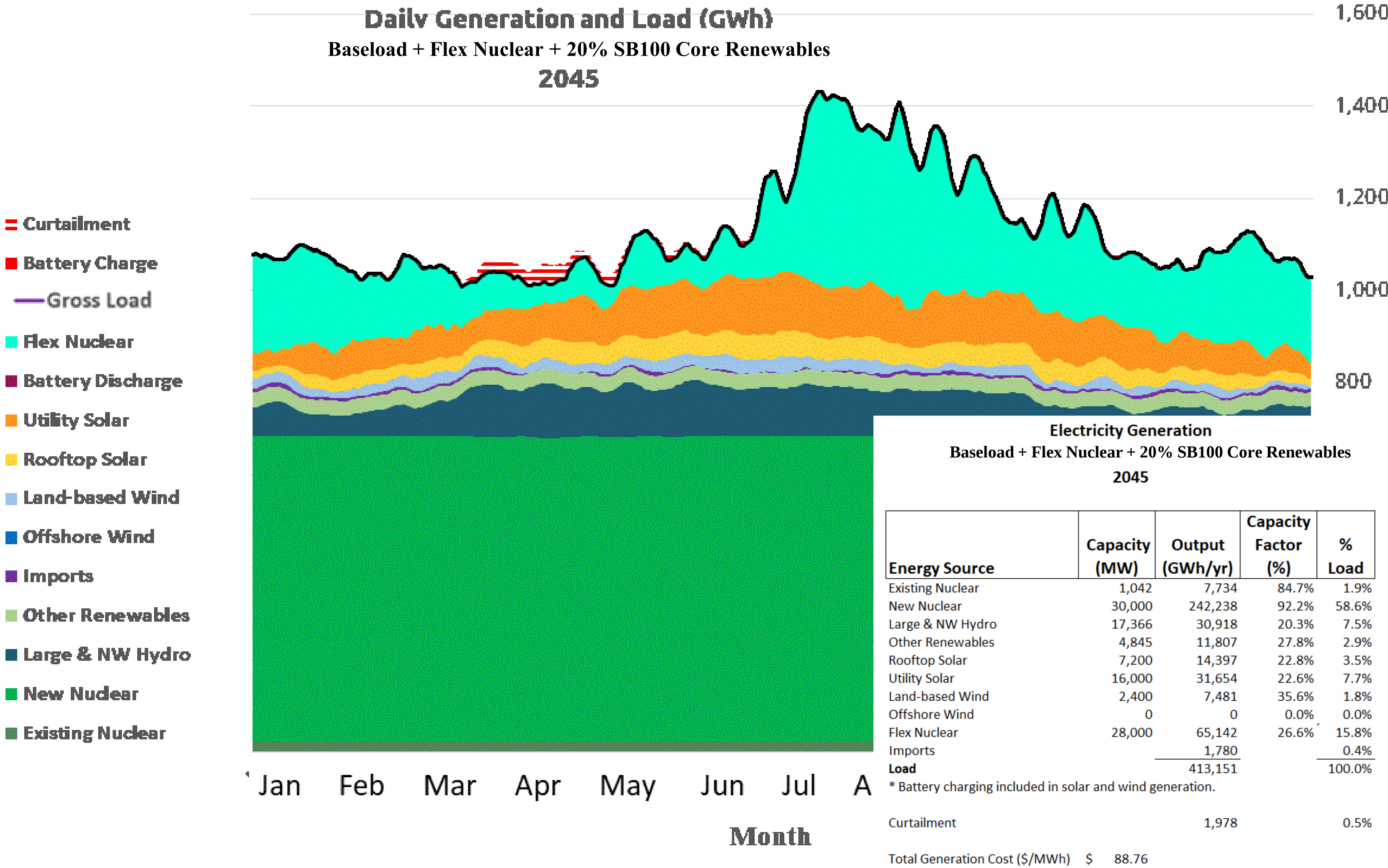
* Battery charging included in solar and wind generation.

Curtailment		21,294		5.0%

Total Generation Cost ($/MWh) $ 91.64

Baseload + Flex Nuclear + 20% SB100 Core Renewables

One option is to replace a large portion of the currently-planned solar, wind, and batteries — much of which will be curtailed anyway — with a set of baseload (always-on) nuclear reactors like that at Diablo Canyon. At current prices for nuclear power, this is not likely to save much money. If nuclear's costs were to decline with more deployments, the cost could become comparable with today's electric prices. Further, this approach will be far less environmentally-destructive than the vast expansion of solar, wind, and batteries now envisioned.



Electricity Generation
Baseload + Flex Nuclear + 20% SB100 Core Renewables
2045

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	1,042	7,734	84.7%	1.9%
New Nuclear	30,000	242,238	92.2%	58.6%
Large & NW Hydro	17,366	30,918	20.3%	7.5%
Other Renewables	4,845	11,807	27.8%	2.9%
Rooftop Solar	7,200	14,397	22.8%	3.5%
Utility Solar	16,000	31,654	22.6%	7.7%
Land-based Wind	2,400	7,481	35.6%	1.8%
Offshore Wind	0	0	0.0%	0.0%
Flex Nuclear	28,000	65,142	26.6%	15.8%
Imports		1,780		0.4%
Load		413,151		100.0%

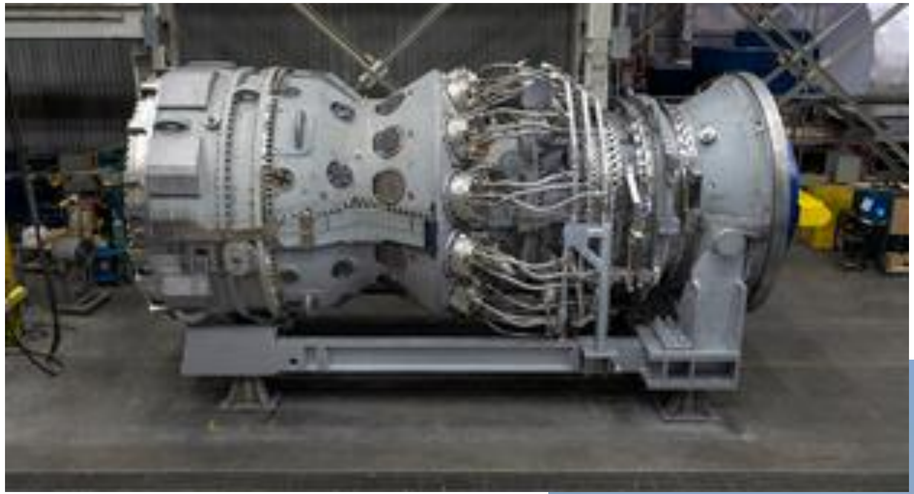
* Battery charging included in solar and wind generation.

Curtailment		1,978		0.5%

Total Generation Cost ($/MWh) $ 88.76

Another example of a DEFR: Hydrogen-powered turbine

Instead of using a nuclear reactor with a variable output as a DEFR, another option is to use gas turbines to meet the varying demand, just as California is now doing with natural gas. However, instead of powering them with gas, they would be powered with hydrogen produced using nuclear power (it could be produced using solar or wind power, but this would require doubling the amounts of both renewable sources.



Nuclear power can be used to produce hydrogen using the heat and electricity of a reactor to split the water molecules and extract the hydrogen. It could then be burned in a suitably-converted gas turbine. This makes an alternative to flex nuclear that is likely to be more cost-effective because the reactors producing the hydrogen could run full-time.

The Hydrogen Earthshot: Hydrogen →$1/kg

The Federal Government is putting substantial funds into an effort to reduce the cost of "green hydrogen" to the point where it is competitive with the price of natural gas.

ENERGY
earthshots
U.S. DEPARTMENT OF ENERGY

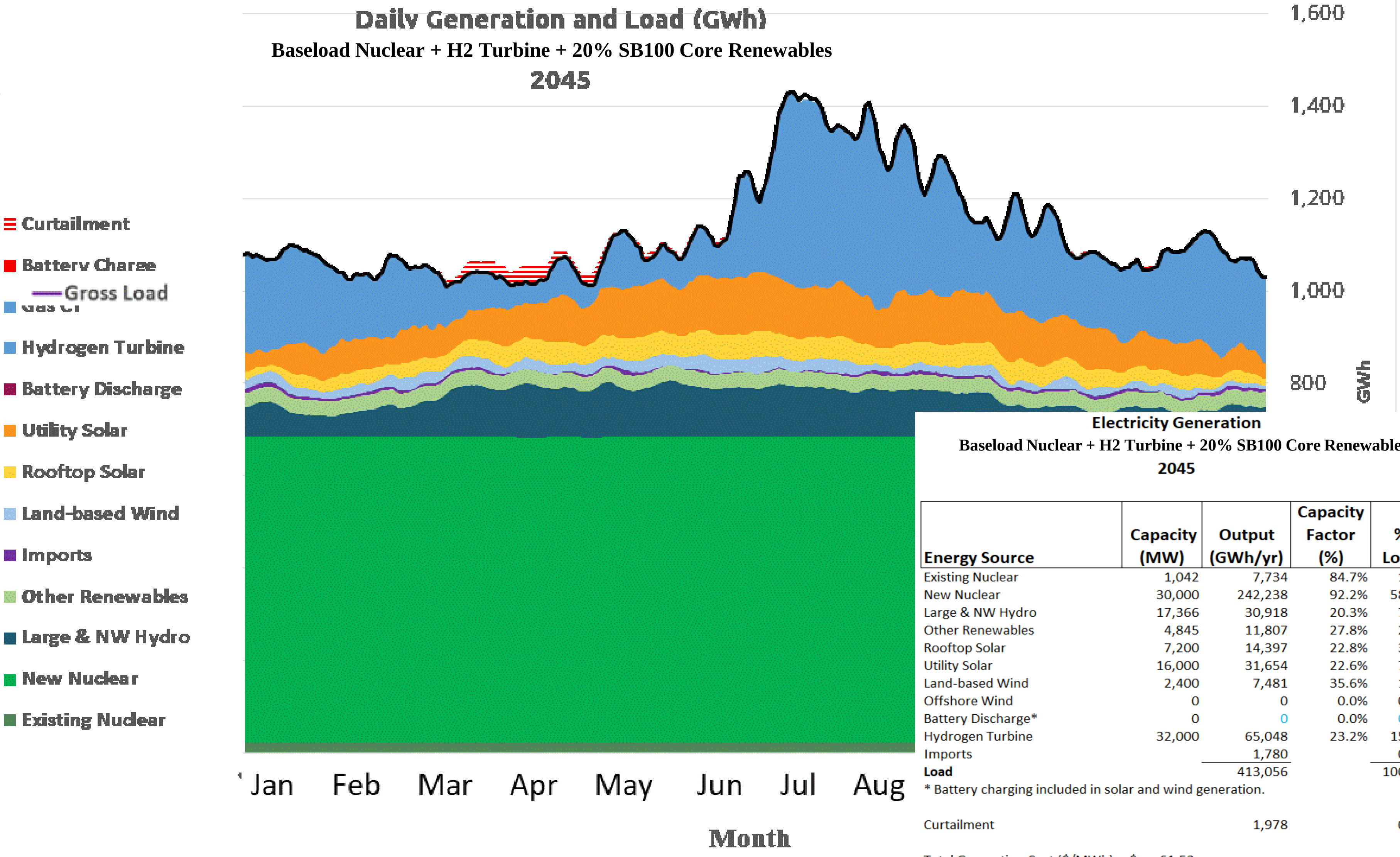
Hydrogen

The first Energy Earthshot, launched June 7, 2021—Hydrogen Shot—seeks to reduce the cost of clean hydrogen by 80% to **$1** per **1 kilogram** in **1 decade** ("1 1 1").

1 Dollar   1 Kilogram   1 Decade

Baseload Nuclear + H2 Turbine + 20% SB100 Core Renewables

Here's the result of using a set of hydrogen-driven gas turbines (they could be the same ones now burning natural gas, once the burners and other parts are modified). The turbines would respond to the varying demand as needed, just as they do now. In the case we are looking at, this would require the equivalent of about ten Diablo Canyon nuclear plants to produce the hydrogen. (Their cost is included in the cost of the hydrogen.) If the Hydrogen Earthshot succeeds, the cost of electricity is estimated to be about what it is today.



Electricity Generation
Baseload Nuclear + H2 Turbine + 20% SB100 Core Renewables
2045

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	1,042	7,734	84.7%	1.9%
New Nuclear	30,000	242,238	92.2%	58.6%
Large & NW Hydro	17,366	30,918	20.3%	7.5%
Other Renewables	4,845	11,807	27.8%	2.9%
Rooftop Solar	7,200	14,397	22.8%	3.5%
Utility Solar	16,000	31,654	22.6%	7.7%
Land-based Wind	2,400	7,481	35.6%	1.8%
Offshore Wind	0	0	0.0%	0.0%
Battery Discharge*	0	0	0.0%	0.0%
Hydrogen Turbine	32,000	65,048	23.2%	15.7%
Imports		1,780		0.4%
Load		413,056		100.0%

* Battery charging included in solar and wind generation.

Curtailment	1,978	0.5%
Total Generation Cost ($/MWh)	$ 61.53	

Comparative Generation Costs

Here are the rough estimated costs in 2045 of the various scenarios. For source cost assumptions, we use the Moderate costs in NREL’s 2024 Annual Technology Baseline).

Using NREL’s projection that there will be 50% reductions in renewable costs, the SB100 Core scenario has electric generation costs about equal to what they are today. Adding flex nuclear as a DEFR increases the cost substantially (with the NREL/EIA estimate of about $5,500/kw for nuclear costs). If nuclear costs can be brought down to what South Korea and China are achieving today, the cost will be less than today’s costs. Alternatively, if efficient nuclear-generated hydrogen is used, the cost can be similarly limited.

Comparative Generation Costs ($/MWh)

	Year	
Scenario	**2023**	**2045**
Continuing CO2 Emissions		
Current costs	$68.95	
SB100 Core w/Current Costs		$91.58
SB100 Core w/NREL Projected Costs		$62.86
Zero Emissions (w/NREL Projected Costs; Nuclear @ $5,500/kw)		
SB100 Core w/Flex Nuclear		$91.64
Baseload + Flex Nuclear + 20% SB100 Core Renewables		$88.76
Baseload + Flex Nuclear + 20% SB100 Core Renewables (Nuclear @ $3,000/kw)		$63.35
Baseload Nuclear + H2 Turbine + 20% SB100 Core Renewables		$61.53

Major Conclusions

- California’s plan for a decarbonized grid will not significantly reduce the consumption of fossil-based natural gas.
- California’s widely-used grid planning model gives misleading results for the operation of intermittent renewables and the consumption of natural gas.
- Decarbonized electrification requires a large, emission-free, dispatchable source that operates throughout the year.
- Nuclear can provide the necessary reliable and affordable power, both directly and by cost-effectively producing clean hydrogen.
- To decarbonize, California will have to remove its outdated moratorium on new nuclear installations.
- Large-scale building of renewables is wasteful and environmentally destructive, doesn’t achieve the decarbonization goal, and will make the transition more difficult and costly.

Further Concluding Notes

- Many people seem to forget that the sun only shines during the day. Even with its climate plan in place, natural gas takes over at night to power the grid, perhaps after a few hours of storage battery discharge. Unless Californians expand their use of nuclear power, they will be charging their Teslas with a fossil fuel.
- California's climate plan keeps gas-fired generators running throughout their clean power program. By 2045, they will have quadrupled the amount of solar, quintupled the amount of storage, and spent nearly a trillion dollars, but they will still need to burn natural gas to sustain their grid. When the sun goes down, they will ramp up the burning of fossil fuels, just as they do now. In fact, they will be burning nearly as much gas as they do today.
- Intermittent, diurnal solar power is not a solution for our energy-hungry society. Only reliable, clean, sustainable nuclear power can keep the lights on and data centers running without driving further global warming.

Acknowledgements

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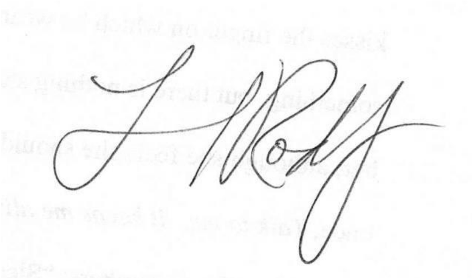
And this work could not have been performed without the original, masterful modeling created by Reiner Kuhr and Ahmad Nofal.

I am grateful for the contributions all of them have made to this work.



Leonard Rodberg

Appendix A

Datasheets

Datasheet: Current Generation - 2023

Generation and Cost Summary | SB100 Core | Year 2023

*Non-dispatchable**	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Existing Nuclear	2,393	17,762	84.7%	7.1%	$ 141	$ 4.20	$ 1.22	$ 4.09	$ 1.31	$ 10.82
New Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Large & NW Hydro	17,366	30,918	20.3%	12.4%		$ 24.59	$ 1.48			$ 26.07
Other Renewables	5,770	14,061	27.8%	5.7%		$ 54.01	$ 5.06	$ -	$ -	$ 59.07
Rooftop Solar	14,000	27,994	22.8%	11.3%	$ 2,682	$ 15.00	$ -	$ -	$ 83.16	$ 98.16
Utility Solar	19,887	41,019	23.5%	16.5%	$ 1,611	$ 10.67	$ -	$ -	$ 45.30	$ 55.97
Land-based Wind	6,284	20,825	37.8%	8.4%	$ 1,786	$ 9.66	$ -	$ -	$ 33.95	$ 43.61
Offshore Wind	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Total	65,700	152,579	26.5%	61.4%		$ 17.39	$ 0.91	$ 0.48	$ 32.22	$ 50.99

Dispatchable	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Battery Discharge	7,552	1,125	1.7%	0.5%	$ 2,080	$ 322.19	$ -	$ -	$ 921.47	$ 1,243.66
Flex Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Gas	39,689	92,228	26.5%	37.1%	$ 1,522	$14.63	$2.00	$21.00	$45.85	$83.48
Hydrogen Turbine	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Gas CT	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Steam Plants	0	0	0.0%	0.0%		$0.00	$0.00	$0.00	$0.00	$0.00
Total	47,241	92,228	22.3%	37.1%		$ 18.34	$ 1.98	$ 20.75	$ 56.40	$ 98.65

Total In-State Generation	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load		Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Total	112,941	244,807	24.7%	98.4%		$ 17.75	$ 1.31	$ 8.11	$ 41.33	$ 68.95

Regional Purchases		Generation (GWh/yr)		% Total Load
Imports		3,859		1.6%

	GWh/yr	% Total Load	% of Grid Renewables
Curtailments	50	0.0%	0.0%
Net Battery Load	199	0.1%	

Total Load (GWh/yr)	248,665

* Battery charging included in solar and wind generation.

Datasheet: SB100 Core w/Current Costs - 2045

Generation and Cost Summary SB100 Core Year 2045

*Non-dispatchable**	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Existing Nuclear	1,042	7,734	84.7%	1.8%	$ 141	$ 4.20	$ 1.22	$ 4.09	$ 1.31	$ 10.82
New Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Large & NW Hydro	17,366	30,918	20.3%	7.3%		$ 24.59	$ 1.48			$ 26.07
Other Renewables	5,770	14,061	27.8%	3.3%		$ 54.01	$ 5.06	$ -	$ -	$ 59.07
Rooftop Solar	36,000	71,984	22.8%	16.9%	$ 2,682	$ 15.00	$ -	$ -	$ 83.16	$ 98.16
Utility Solar	82,000	151,363	21.1%	35.6%	$ 1,611	$ 11.92	$ -	$ -	$ 50.62	$ 62.54
Land-based Wind	12,217	38,496	36.0%	9.1%	$ 1,786	$ 10.16	$ -	$ -	$ 35.71	$ 45.86
Offshore Wind	8,215	33,525	46.6%	7.9%	$ -	$ -	$ -	$ -	$ -	$ -
Total	162,610	348,081	24.4%	81.9%		$ 13.87	$ 0.36	$ 0.09	$ 43.19	$ 57.51

Dispatchable	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Battery Discharge	52,329	61,025	13.3%	14.4%	$ 2,080	$ 41.16	$ -	$ -	$ 117.72	$ 158.88
Flex Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Gas	52,000	75,015	16.5%	17.7%	$ 1,522	$23.57	$2.00	$21.00	$73.85	$120.42
Hydrogen Turbine	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Gas CT	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Steam Plants	0	0	0.0%	0.0%		$0.00	$0.00	$0.00	$0.00	$0.00
Total	104,329	75,015	8.2%	17.7%		$ 31.46	$ 1.10	$ 11.58	$ 93.53	$ 249.67

Total In-State Generation	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load		Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Total	266,939	423,096	18.1%	99.6%		$ 16.99	$ 0.49	$ 2.13	$ 52.11	$ 91.58

Regional Purchases		Generation (GWh/yr)		% Total Load
Imports		1,736		0.4%

	GWh/yr	% Total Load	% of Grid Renewables
Curtailments	21,294	5.0%	5.9%
Net Battery Load	10,791	2.5%	

Total Load (GWh/yr)	424,832

* Battery charging included in solar and wind generation.

Datasheet: SB100 Core w/NREL Projected Costs - 2045

Generation and Cost Summary — SB100 Core — Year 2045

*Non-dispatchable**	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Existing Nuclear	1,042	7,734	84.7%	1.8%	$ 141	$ 4.20	$ 1.22	$ 4.09	$ 1.31	$ 10.82
New Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Large & NW Hydro	17,366	30,918	20.3%	7.3%		$ 24.59	$ 1.48			$ 26.07
Other Renewables	5,770	14,061	27.8%	3.3%		$ 54.01	$ 5.06	$ -	$ -	$ 59.07
Rooftop Solar	36,000	71,984	22.8%	16.9%	$ 1,373	$ 8.50	$ -	$ -	$ 37.77	$ 46.27
Utility Solar	82,000	151,363	21.1%	35.6%	$ 754	$ 7.58	$ -	$ -	$ 26.55	$ 34.14
Land-based Wind	12,217	38,496	36.0%	9.1%	$ 1,188	$ 8.25	$ -	$ -	$ 25.64	$ 33.89
Offshore Wind	8,215	33,525	46.6%	7.9%	$ 4,800	$ 18.13	$ -	$ -	$ 36.51	$ 54.64
Total	162,610	348,081	24.4%	81.9%		$ 12.17	$ 0.36	$ 0.09	$ 25.74	$ 38.37

Dispatchable	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Battery Discharge	52,329	61,025	13.3%	14.4%	$ 1,140	$ 21.44	$ -	$ -	$ 75.27	$ 96.71
Flex Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Gas	52,000	75,015	16.5%	17.7%	$ 1,257	$13.86	$2.00	$21.00	$60.99	$97.86
Hydrogen Turbine	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Gas CT	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Steam Plants	0	0	0.0%	0.0%		$0.00	$0.00	$0.00	$0.00	$0.00
Total	104,329	75,015	8.2%	17.7%		$ 17.26	$ 1.10	$ 11.58	$ 67.40	$ 176.53

Total In-State Generation	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load		Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Total	266,939	423,096	18.1%	99.6%		$ 13.08	$ 0.49	$ 2.13	$ 33.12	$ 62.86

Regional Purchases		Generation (GWh/yr)		% Total Load
Imports		1,736		0.4%

	GWh/yr	% Total Load	% of Grid Renewables
Curtailments	21,294	5.0%	5.9%
Net Battery Load	10,791	2.5%	

Total Load (GWh/yr)	424,832

* Battery charging included in solar and wind generation.

Datasheet: SB100 Core w/Flex Nuclear - 2045

Generation and Cost Summary SB100 Core w/Flex Nuclear Year 2045

*Non-dispatchable**	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Existing Nuclear	1,042	7,734	84.7%	1.8%	$ 141	$ 4.20	$ 1.22	$ 4.09	$ 1.31	$ 10.82
New Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Large & NW Hydro	17,366	30,918	20.3%	7.3%		$ 24.59	$ 1.48			$ 26.07
Other Renewables	5,770	14,061	27.8%	3.3%		$ 54.01	$ 5.06	$ -	$ -	$ 59.07
Rooftop Solar	36,000	71,984	22.8%	16.9%	$ 1,373	$ 8.50	$ -	$ -	$ 37.77	$ 46.27
Utility Solar	82,000	151,363	21.1%	35.6%	$ 754	$ 7.58	$ -	$ -	$ 26.55	$ 34.14
Land-based Wind	12,217	38,496	36.0%	9.1%	$ 1,188	$ 8.25	$ -	$ -	$ 25.64	$ 33.89
Offshore Wind	8,215	33,525	46.6%	7.9%	$ 4,800	$ 18.13	$ -	$ -	$ 36.51	$ 54.64
Total	162,610	348,081	24.4%	81.9%		$ 12.17	$ 0.36	$ 0.09	$ 25.74	$ 38.37

Dispatchable	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Battery Discharge	52,329	61,025	13.3%	14.4%	$ 1,140	$ 21.44	$ -	$ -	$ 75.27	$ 96.71
Flex Nuclear	37,000	74,956	23.1%	17.6%	$ 5,480	$ 67.13	$ 1.20	$ 2.60	$ 189.35	$ 260.29
Gas	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Hydrogen Turbine	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Gas CT	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Steam Plants	0	0	0.0%	0.0%		$0.00	$0.00	$0.00	$0.00	$0.00
Total	89,329	74,956	9.6%	17.6%		$ 46.63	$ 0.66	$ 1.43	$ 138.16	$ 339.02

Total In-State Generation	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load		Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Total	251,939	423,038	19.2%	99.6%		$ 18.28	$ 0.42	$ 0.33	$ 45.66	$ 91.64

Regional Purchases		Generation (GWh/yr)		% Total Load
Imports		1,736		0.4%

	GWh/yr	% Total Load	% of Grid Renewables
Curtailments	21,294	5.0%	5.9%
Net Battery Load	10,791	2.5%	

Total Load (GWh/yr)	424,774

* Battery charging included in solar and wind generation.

Datasheet
Baseload + Flex Nuclear + 20% SB100 Core Renewables

Generation and Cost Summary — Year 2045

*Non-dispatchable**	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Existing Nuclear	1,042	7,734	84.7%	1.9%	$ 141	$ 4.20	$ 1.22	$ 4.09	$ 1.31	$ 10.82
New Nuclear	30,000	242,238	92.2%	58.6%	$ 5,663	$ 21.67	$ 0.97	$ 3.40	$ 49.09	$ 75.14
Large & NW Hydro	17,366	30,918	20.3%	7.5%		$ 24.59	$ 1.48			$ 26.07
Other Renewables	4,845	11,807	27.8%	2.9%		$ 54.01	$ 5.06	$ -	$ -	$ 59.07
Rooftop Solar	7,200	14,397	22.8%	3.5%	$ 1,373	$ 8.50	$ -	$ -	$ 37.77	$ 46.27
Utility Solar	16,000	31,654	22.6%	7.7%	$ 754	$ 7.08	$ -	$ -	$ 24.77	$ 31.85
Land-based Wind	2,400	7,481	35.6%	1.8%	$ 1,188	$ 8.34	$ -	$ -	$ 25.92	$ 34.26
Offshore Wind	-	-	0.0%	0.0%	$ 4,800	$ -	$ -	$ -	$ -	$ -
Total	78,853	346,229	50.1%	83.8%		$ 20.48	$ 1.01	$ 2.47	$ 38.77	$ 62.73

Dispatchable	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Battery Discharge	0	0	0.0%	0.0%	$ 1,140	$ -	$ -	$ -	$ -	$ -
Flex Nuclear	28,000	65,142	26.6%	15.8%	$ 5,480	$ 58.46	$ 1.20	$ 2.60	$ 164.88	$ 227.14
Gas	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Hydrogen Turbine	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Gas CT	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Steam Plants	0	0	0.0%	0.0%		$0.00	$0.00	$0.00	$0.00	$0.00
Total	28,000	65,142	26.6%	15.8%		$ 58.46	$ 1.20	$ 2.60	$ 164.88	$ 227.14

Total In-State Generation	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load		Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Total	106,853	411,371	43.9%	99.6%		$ 26.49	$ 1.04	$ 2.49	$ 58.74	$ 88.76

Regional Purchases		Generation (GWh/yr)		% Total Load
Imports		1,780		0.4%

	GWh/yr	% Total Load	% of Grid Renewables
Curtailments	1,978	0.5%	2.0%
Net Battery Load	0	0.0%	

Total Load (GWh/yr)	413,151

* Battery charging included in solar and wind generation.

Datasheet

Baseload + Flex Nuclear + 20% SB100 Core Renewables

Generation and Cost Summary — Year 2045

*Non-dispatchable**	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Existing Nuclear	1,042	7,734	84.7%	1.9%	$ 141	$ 4.20	$ 1.22	$ 4.09	$ 1.31	$ 10.82
New Nuclear	30,000	242,238	92.2%	58.6%	$ 3,000	$ 21.67	$ 0.97	$ 3.40	$ 26.01	$ 52.05
Large & NW Hydro	17,366	30,918	20.3%	7.5%		$ 24.59	$ 1.48			$ 26.07
Other Renewables	4,845	11,807	27.8%	2.9%		$ 54.01	$ 5.06	$ -	$ -	$ 59.07
Rooftop Solar	7,200	14,397	22.8%	3.5%	$ 1,373	$ 8.50	$ -	$ -	$ 37.77	$ 46.27
Utility Solar	16,000	31,654	22.6%	7.7%	$ 754	$ 7.08	$ -	$ -	$ 24.77	$ 31.85
Land-based Wind	2,400	7,481	35.6%	1.8%	$ 1,188	$ 8.34	$ -	$ -	$ 25.92	$ 34.26
Offshore Wind	-	-	0.0%	0.0%	$ 4,800	$ -	$ -	$ -	$ -	$ -
Total	78,853	346,229	50.1%	83.8%		$ 20.48	$ 1.01	$ 2.47	$ 22.62	$ 46.58

Dispatchable	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Battery Discharge	0	0	0.0%	0.0%	$ 1,140	$ -	$ -	$ -	$ -	$ -
Flex Nuclear	28,000	65,142	26.6%	15.8%	$ 3,000	$ 58.46	$ 1.20	$ 2.60	$ 90.26	$ 152.52
Gas	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Hydrogen Turbine	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Gas CT	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Steam Plants	0	0	0.0%	0.0%		$0.00	$0.00	$0.00	$0.00	$0.00
Total	28,000	65,142	26.6%	15.8%		$ 58.46	$ 1.20	$ 2.60	$ 90.26	$ 152.52

Total In-State Generation	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load		Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Total	106,853	411,371	43.9%	99.6%		$ 26.49	$ 1.04	$ 2.49	$ 33.33	$ 63.35

Regional Purchases		Generation (GWh/yr)		% Total Load
Imports		1,780		0.4%

	GWh/yr	% Total Load	% of Grid Renewables
Curtailments	1,978	0.5%	2.0%
Net Battery Load	0	0.0%	

Total Load (GWh/yr)	413,151

* Battery charging included in solar and wind generation.

Nuclear cost = $3,000/kw

Datasheet

Baseload Nuclear + H2 Turbine + 20% SB100 Core Renewables

Generation and Cost Summary — Year 2045

*Non-dispatchable**	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Existing Nuclear	1,042	7,734	84.7%	1.9%	$ 141	$ 4.20	$ 1.22	$ 4.09	$ 1.31	$ 10.82
New Nuclear	30,000	242,238	92.2%	58.6%	$ 5,663	$ 21.67	$ 0.97	$ 3.40	$ 49.09	$ 75.14
Large & NW Hydro	17,366	30,918	20.3%	7.5%		$ 24.59	$ 1.48			$ 26.07
Other Renewables	4,845	11,807	27.8%	2.9%		$ 54.01	$ 5.06	$ -	$ -	$ 59.07
Rooftop Solar	7,200	14,397	22.8%	3.5%	$ 1,373	$ 8.50	$ -	$ -	$ 37.77	$ 46.27
Utility Solar	16,000	31,654	22.6%	7.7%	$ 754	$ 7.08	$ -	$ -	$ 24.77	$ 31.85
Land-based Wind	2,400	7,481	35.6%	1.8%	$ 1,188	$ 8.34	$ -	$ -	$ 25.92	$ 34.26
Offshore Wind	-	-	0.0%	0.0%	$ 4,800	$ -	$ -	$ -	$ -	$ -
Total	78,853	346,229	50.1%	83.8%		$ 20.48	$ 1.01	$ 2.47	$ 38.77	$ 62.73

Dispatchable	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load	Capital Cost ($/kw)	Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Battery Discharge	0	0	0.0%	0.0%	$ 1,140	$ -	$ -	$ -	$ -	$ -
Flex Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Gas	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Hydrogen Turbine	32,000	65,048	23.2%	15.7%	$ 1,257	$9.84	$2.00	$0.00	$43.29	$55.13
Gas CT	0	0	0.0%	0.0%	$ -	$0.00	$0.00	$0.00	$0.00	$0.00
Steam Plants	0	0	0.0%	0.0%		$0.00	$0.00	$0.00	$0.00	$0.00
Total	32,000	65,048	23.2%	15.7%		$ 9.84	$ 2.00	$ -	$ 43.29	$ 55.13

Total In-State Generation	Capacity (MW)	Generation (GWh/yr)	Capacity Factor (%)	% Total Load		Fixed O&M ($/MWh)	Var O&M ($/MWh)	Fuel Cost ($/MWh)	Capital Recovery ($/MWh)	In-State Generation Cost ($/MWh)
Total	110,853	411,277	42.4%	99.6%		$ 18.79	$ 1.17	$ 2.08	$ 39.49	$ 61.53

Regional Purchases		Generation (GWh/yr)		% Total Load
Imports		1,780		0.4%

	GWh/yr	% Total Load	% of Grid Renewables
Curtailments	1,978	0.5%	1.2%
Net Battery Load	0	0.0%	

Total Load (GWh/yr)	413,056

* Battery charging included in solar and wind generation.

Appendix B

Grid Model Methodology

Limitations of the Current Model

Grid Model Methodology

The California adaptation of the Grid Model works as follows:

In this model, each type of energy source is dispatched hourly to address electric loads, taking account of inter-regional power purchases and sales. CO_2 emissions (if any), energy pricing, and the occurrence of surplus energy each hour from excessive non-dispatchable generation is also calculated.

Model inputs include hourly data for loads, solar generation, wind generation, hydro generation, and power exchange with other regions. The assumptions and methods used in the model are as follows:

Power generation is represented in these simplified categories: behind the meter (rooftop) and grid-connected utility solar, land-based and offshore wind, hydroelectric, nuclear, battery storage, and a series of possible dispatchable sources, especially gas-fired combined-cycle and simple-cycle plants. Existing nameplate capacities are taken from CEC publications, while actual output is based on 2023 CAISO data.

Total system loads are estimated using 2023 data from California Independent System Operator (CAISO), which operates the State's electric grid. Projections of current demand, as well as the new demand from electric vehicles (EVs) and the electrification of buildings, are drawn from forecasts developed by E3 for the California Energy Commission.

Grid Model Methodology (cont.)

Hourly generation from solar and land-based wind is scaled up based on the distribution of 2023 hourly output data for these sources. Hourly load shapes are estimated by reviewing hourly data for weekend/holidays and weekdays. Maximum and minimum daily loads are adjusted weekly based on historic data to account for seasonal variation and adjusted annually based on load growth projected by CAISO. Purchases from other Western states are modeled based on 2023 actual hourly data.

The maximum capacity of solar and wind facilities reflects the distribution of generators and the likelihood that they can operate at the same time. These values are different from nameplate capacity which represents the output of a single unit at a specified point, used to calculate installation cost. Maximum capacity is derived from evaluating actual generating data in 2023 from CAISO. Until actual data is available for offshore wind installations, offshore wind is assumed to have the same relationship of maximum regional output to nameplate capacity as land-based wind,

Capacity factors – the fraction of the potential output of a source that is actually produced during the year – are not assumed but are calculated by the model, based upon the weather and the behavior of the grid.

The Dispatchable Emission-Free Resource – referred to in this paper by the acronym DEFR – is modeled using the characteristics of the TerraPower Natrium small modular reactor (https://www.terrapower.com/our-work/natriumpower/).

Grid Model Methodology (cont.)

Battery storage is modeled by assuming the batteries are charged when there is more inflexible power from hydropower, nuclear, grid-connected solar, and wind than is needed to meet demand. The DEFR is not used to charge batteries. The batteries are discharged when the load on the grid is greater than can be provided by those ongoing inflexible sources.

Hourly loads and source dispatch are determined for each day of the year. Hourly load patterns are modeled based on 2022 data available from NYISO. Hourly load shapes are selected for workdays and for non-work holiday/weekend days and adjusted weekly for seasonal changes. NYISO reports estimated generation from behind-the-meter solar, even though it occurs on the customer side of the grid. Behind-the-meter solar currently represents the majority of solar electric generation capacity, but that will change as State plans proceed.

Each source is dispatched in turn to meet the load, as follows: behind-the-meter solar is introduced first, leaving the remaining load to be served by the various sources connected to the grid. Purchases from the neighboring States and Canada are added. Existing nuclear plant output is added as “must-run” capacity. Hydroelectric generation is added. Output from grid- connected solar plus onshore and offshore wind generation are then added, taking into account their hourly variations as described above.

Three percent of the maximum annual load is set aside for system control by gas combined-cycle plants or battery discharge, representing spinning reserve and other ancillary grid services. This is required even when there are curtailments of solar and wind generation.

Grid Model Methodology (cont.)

When there is unmet load remaining after the non-dispatchable sources have been included, the batteries are called on to discharge up to their ability. If unmet load still remains, then the DEFR is used to supply the remaining load. In the SB 100 Core plan, the DEFR is assumed to be gas-fire turbines.

Curtailments occur when total non-dispatchable generation exceeds the load requirements. When there is insufficient load to use all possible solar and wind generation, purchases from other states are reduced or eliminated. Then curtailments are assigned in random order to offshore wind, onshore wind, and grid-connected solar, but not to BTM solar, which is not controlled by the grid operator.

The model uses current dollars so that the effects of future inflation do not confuse the analysis. Costs of energy sources are estimated from a variety of NREL's ATB. The prices used in the scenarios reported here are shown in the Datasheets in Appendix A. The total in-state generation cost of electricity is the weighted average of annual generation sources. The cost for each generation source includes fixed and variable operation and maintenance (O&M) cost, fuel cost, and capital recovery.

We are not reporting energy generator revenues as we have not analyzed the breakdown between energy market income vs. revenue from resource adequacy and other auctions operated by CAISO. The actual revenue sources depend upon varying arrangements for tax subsidies and other mechanisms for shifting costs from, and among, ratepayers, so this data would be too uncertain to be meaningful.

Limitations of the Current Model

The model we are using, while it shows the principal properties and requirements for the future grid, has significant limitations. Among these are:

- This model treats the state's grid as a single unit without transmission constraints, whereas we know that there are significant barriers to the flow of power between areas of the state. The model also does not reflect transmission upgrade costs that will be required with economy-wide electrification, especially if widely-distributed solar and wind facilities are expanded as envisioned in the State's current plan.

- Our model does not reflect the additional reserve requirements imposed by state and federal law.

- We have not explored the wide range of possible future costs that seem likely for both renewable and nuclear resources, as well as for possible hydrogen options.

- The vast majority of nuclear reactor downtime is for scheduled maintenance and refueling. Routinely, such downtime is placed during periods of predicted low demand, currently in the spring and fall. While our model represents nuclear generation as flat throughout the year at a reduced capacity factor. Full nuclear capacity should be available through the entire winter, the season of peak future demand. Incorporating this into the model would reduce the needed DEFR capacity.

- The chosen nuclear DEFR in our model, the Terrapower Natrium system, drops from 500 MW to 345 MW output capacity when its thermal storage is depleted. Having a DEFR with maximum capacity always available, perhaps accompanied by batteries, might be more cost-effective.