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A New View of California’s Decarbonization Plan

Report of the California Grid Project

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July 2024

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Project support provided by the Alex C. Walker Foundation and the Anthropocene Institute

Executive Summary

We have analyzed California's plan for decarbonizing its electric grid using a new modeling tool that allows an hour-by-hour analysis of grid behavior. This model reveals important features of a grid that is dependent on intermittent solar and wind resources, features not disclosed by the computer model currently being used by the state. In particular, it shows clearly and transparently the periods throughout the year when there is a large gap between what these sources can provide and what the grid needs. In 2045, when the state's grid is supposed to be 100% clean, the current plan fails to meet this goal. In spite of a vast expansion of solar, wind, and batteries, and expenditure of nearly a trillion dollars, the grid will continue to rely on burning large quantities of natural gas to fill this gap and keep the lights on.

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

In sum, unless California gets serious about developing a clean, firm, dispatchable source of electricity, it will continue to burn large quantities of natural gas for the foreseeable future.

Outline

1. California’s current plan for decarbonization
2. How we model it
3. What our model shows about gaps in the plan
4. Examples of workable decarbonization plans
5. Conclusions

Appendix A – Datasheets

Appendix B – Grid Model Methodology

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.”

This statement is false.

Introduction

The sun doesn’t shine at night. This simple observation may seem hardly worth saying, but once its implications are recognized, it may force a review of all of California’s climate and energy policies.

The modeling the state has been using makes it difficult to recognize this simple and obvious fact. The electric grid model, from Energy and Environmental Economics (E3), Inc., provides annual total outputs, not daily much less hourly descriptions of output and demand. This project supplies that crucial, missing information.

The absence of sun at night means that, in a solar+wind+battery regime like that now envisioned for California, residents will spend many nights worrying if the limited wind resource will be enough to carry the load. Will the batteries last? Were they sufficiently charged earlier in the day?

Instead, a serious consideration of this obvious fact will lead us to recognize that the dream of a future powered by sun and wind is simply a fiction. Without some clean, reliable source that can generate power at any time and place it is needed, not dependent upon variable weather and time of day, our homes, businesses, data centers, everything will shut down.

That calamity won’t happen under the State’s plan, which continues to burn natural gas to keep the lights on. As this project will show, under the state’s plan your Tesla will most likely be charged by fossil fuel. All the cost and effort of building a solar, wind, and battery-powered grid will have been for nought. Emissions from the grid will be largely unchanged.

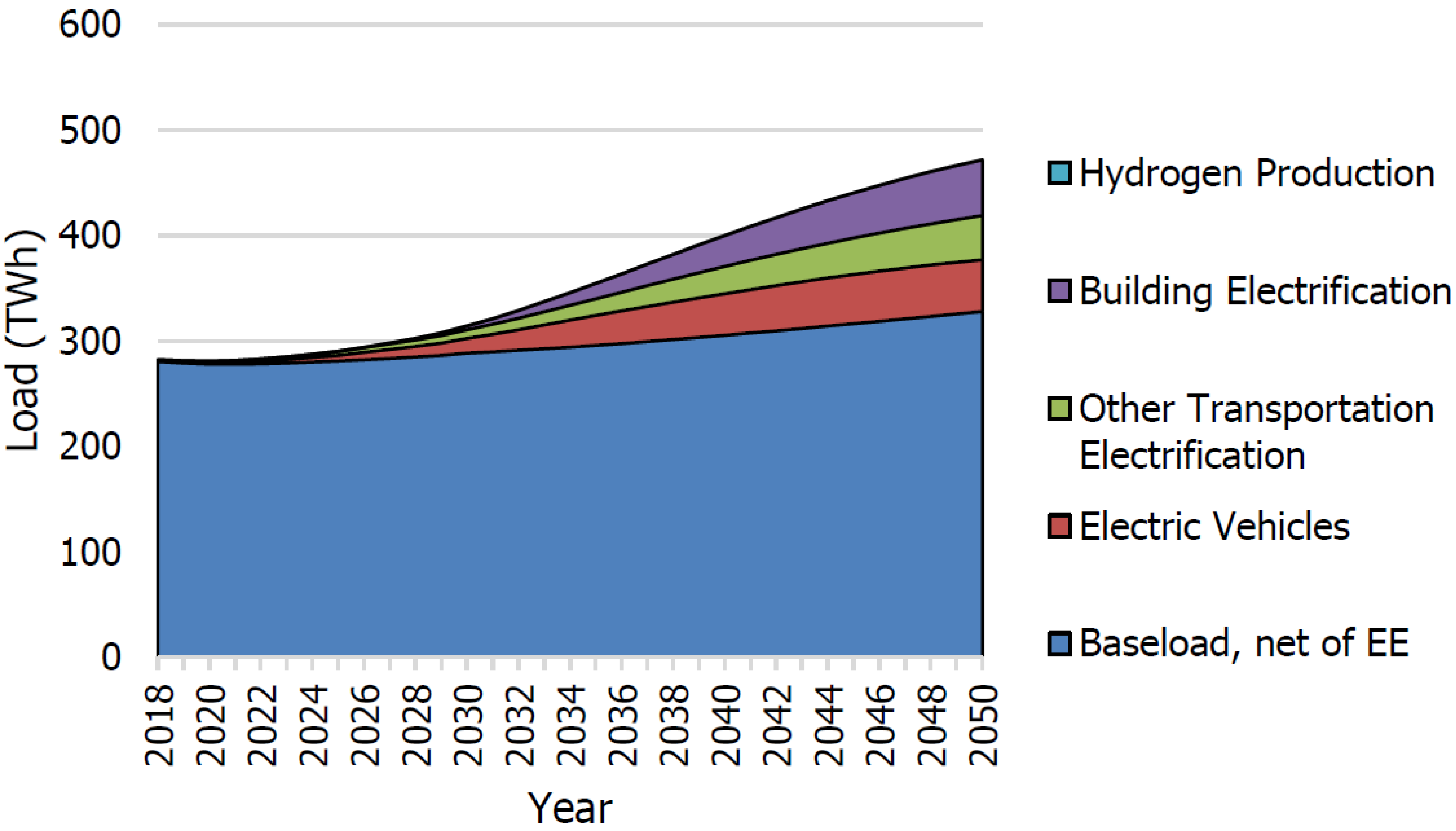
California's Climate Laws

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 Governors' Executive Orders. Current, the 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 will require that 90 percent of generation coming from renewable and zero-carbon resources" in 2045.
- **The California approach** to achieving these goals, like that of most other jurisdiction in the US and internationally, is to attempt to (1**) electrify most applications in which fossil fuels are burned today and (2) generate all electricity with 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.**

The Future of California’s Electricity

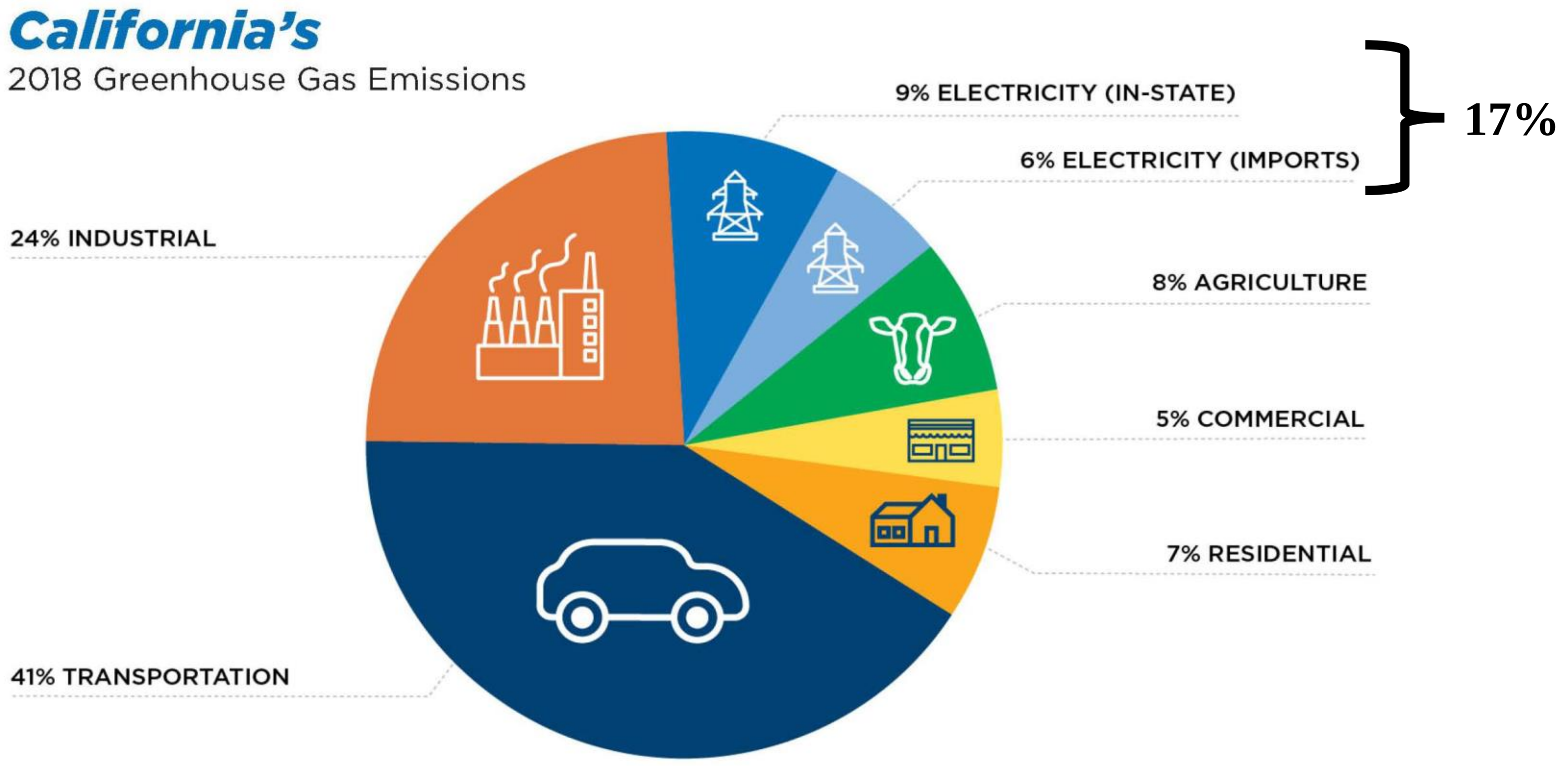
This is the Joint Agencies’ projected annual demand for electricity through 2050. We are using these projections in our analysis.



Source: 2021 SB 100 Joint Agency Report, Figure 22

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 will providing electricity 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 electrical load.

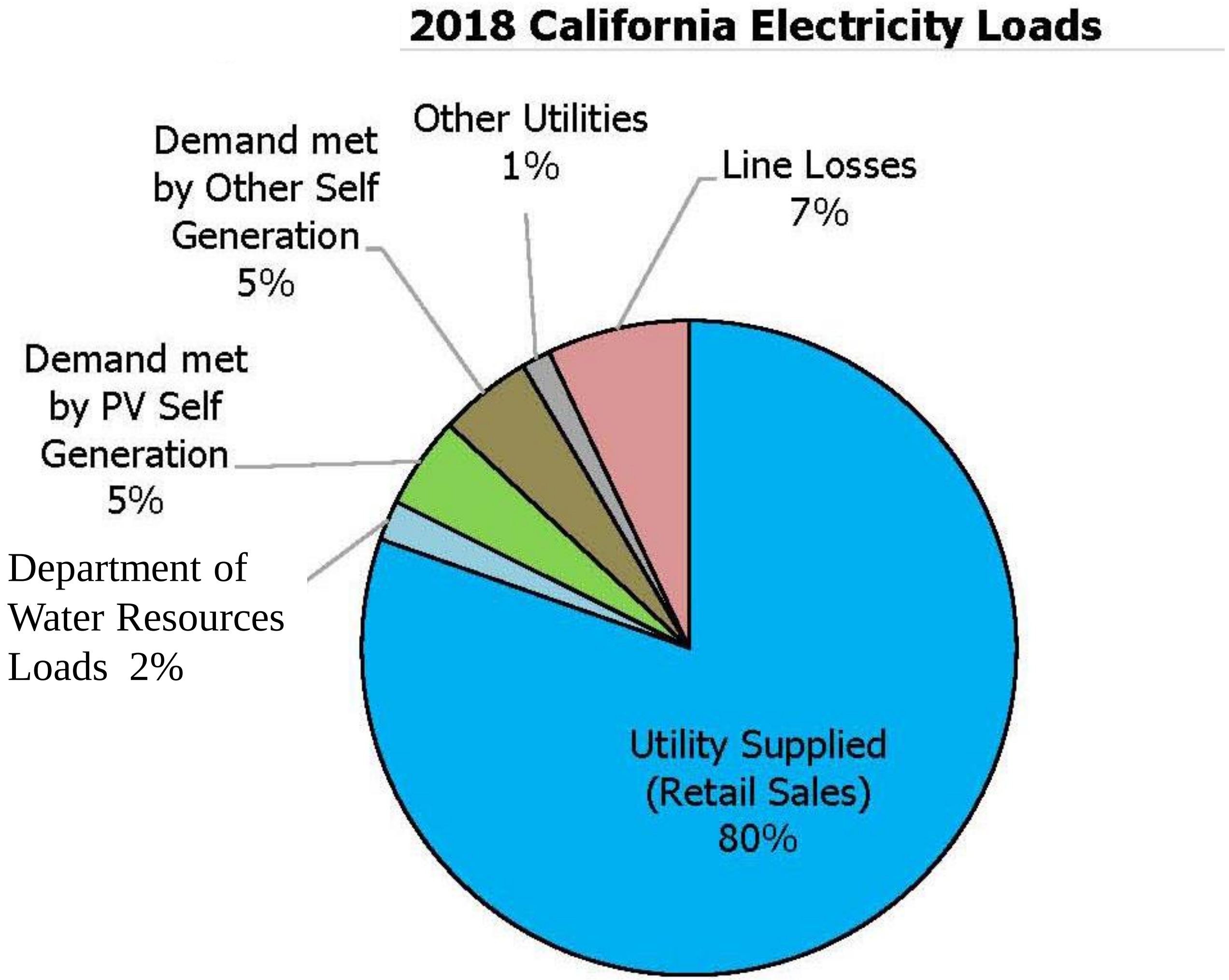


https://efiling.energy.ca.gov/GetDocument.aspx?tn=239588&DocumentContentId=73021

California's SB100 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 (See figure. DWR = Department of Water Resources) and losses due to battery inefficiency (e.g., there is a 15% loss in the charge-discharge of lithium-ion batteries).

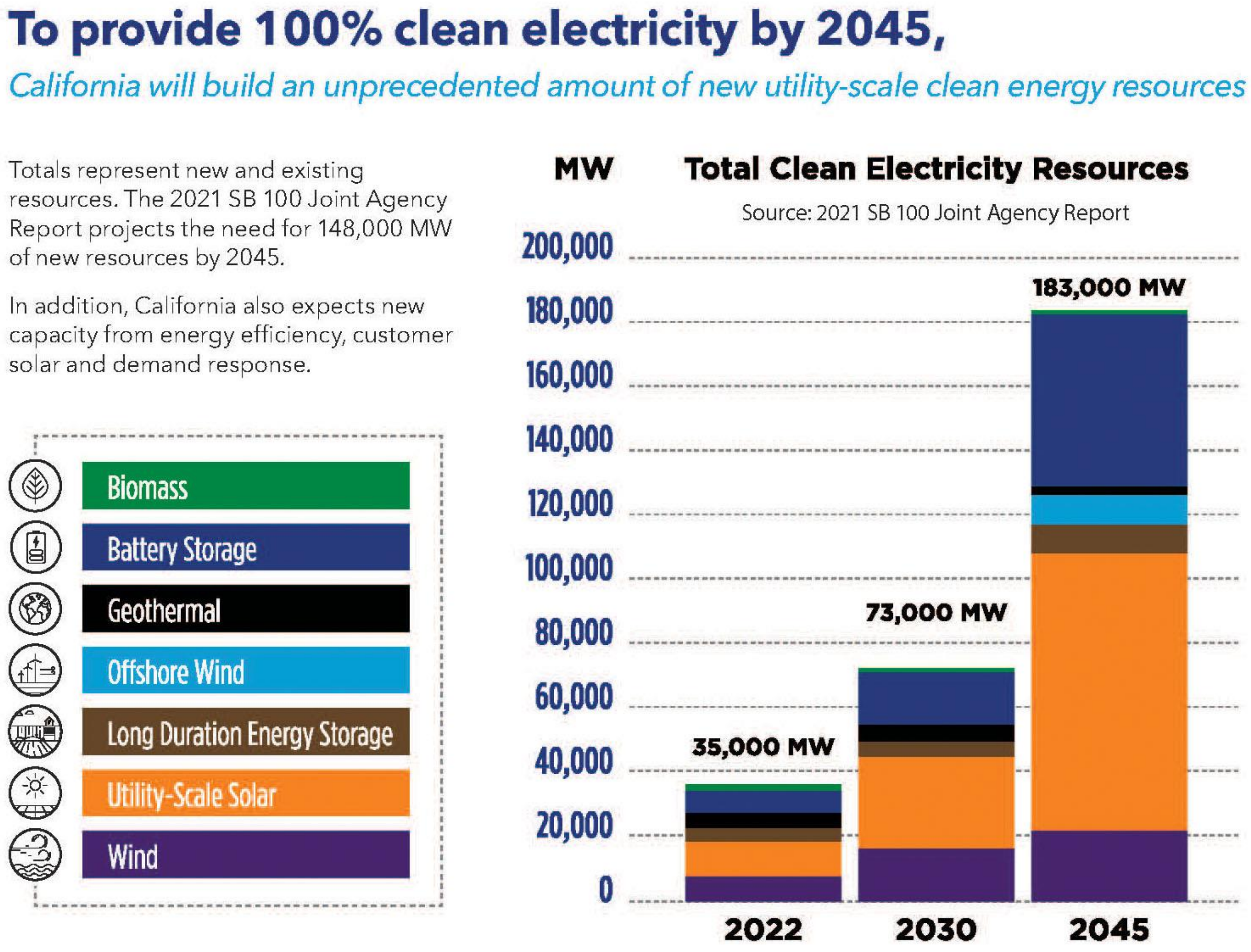
In fact, as we will see, natural gas will actually be used much more than that to keep the grid functioning when the renewable sources are not available.



Source: 2021 SB 100 Joint Agency Report, Figure 19

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 continued burning of gas and claims "100% clean electricity by 2045." This is false. It isn't even close.



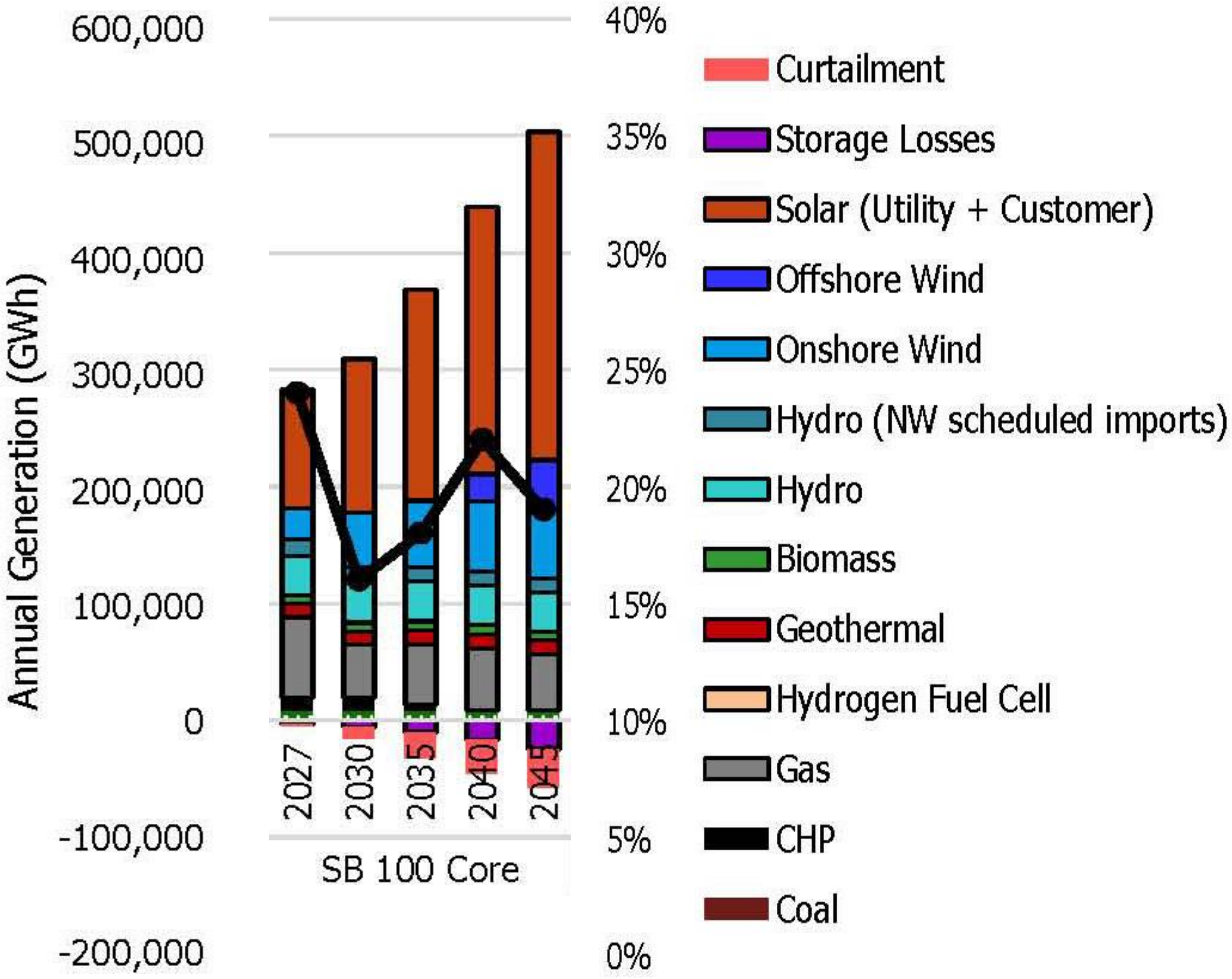
https://www.gov.ca.gov/wp-content/uploads/2023/05/CAEnergyTransitionPlan.pdf

Annual Generation in the SB100 Core Scenario

This shows electric generation 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 found that shows the substantial amount of gas that continues to be burned under the State's plan.

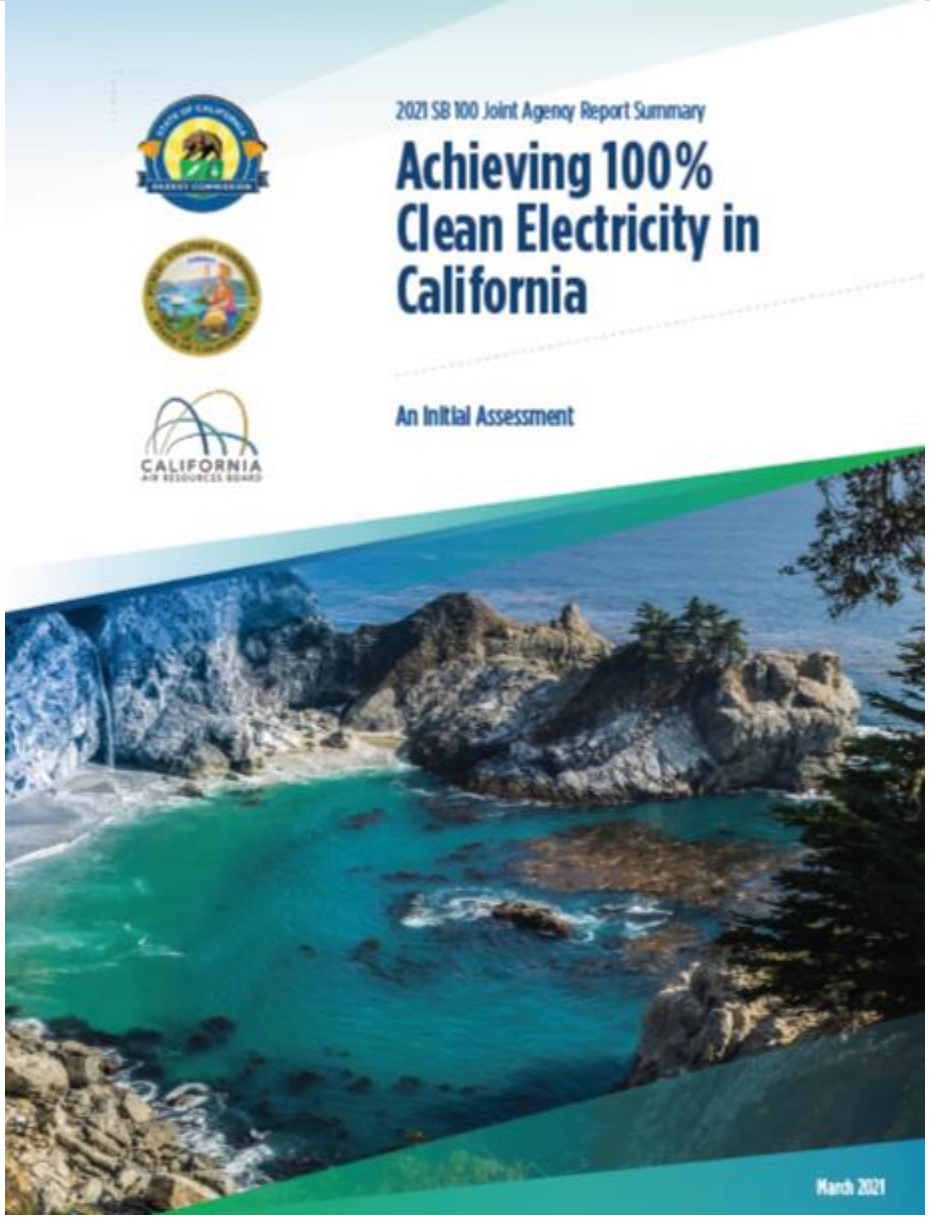
2021 SB 100 Joint Agency Report

Achieving 100 Percent Clean Electricity in California: An Initial Assessment



Source: 2021 SB 100 Joint Agency Report, Figure 29

Projected Resources in 2045



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 the Center for Academic Collaboration Initiatives.[1] We have adapted it for use in analyzing the decarbonization plans of New York[2] and California. We describe it as an hourly dispatch model because, for a particular pre-designed decarbonization scenario and each hour of a selected year, it introduces or "dispatches", sequentially, each of the generating sources, from the fixed (e.g., baseload nuclear) to the most expensive (gas and, potentially, flexible nuclear).

CACI
CENTER FOR ACADEMIC COLLABORATION INITIATIVES

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Programmer, currently at X-Energy LLC

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

Operation of the CACI Grid Model (I)
Comparison with California’s E3 Model

E3 RESOLVE linear programming model (used in California, New York, and many other states)

- Optimizes a multi-year scenario to achieve minimum net present value of investments, given multiple constraints.
- Uses 37 representative days during each year.
- Produces net present value of scenario and annual output of each source during each selected year
- Tells how much energy a source will produce but not when it is produced or whether it is needed at the time it is produced. (When electric power is produced is crucial. It must be produced when it is needed or it must be stored for use at a later time. However, storing electricity is difficult and costly in money and materials.
- Most important, the weather dependence of solar and wind appears only through their assumed capacity factors (ratio of actual output to maximum possible output). **The intermittent, time- and weather-dependent character of solar and wind is ignored in the E3 model**; **solar and wind are treated as if they are always on**, though weaker than they could be.

CACI hourly dispatch model

- Calculates, for every hour of a selected scenario and year, the output of every source needed to meet the projected load.
- **Uses data from a past year to provide actual solar and wind output for each hour of the year.**
- For each hour, 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.
- Charges batteries from excess solar and wind output. Curtails any remaining excess.

Operation of the CACI Grid Model (II)
Calculation Flow

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

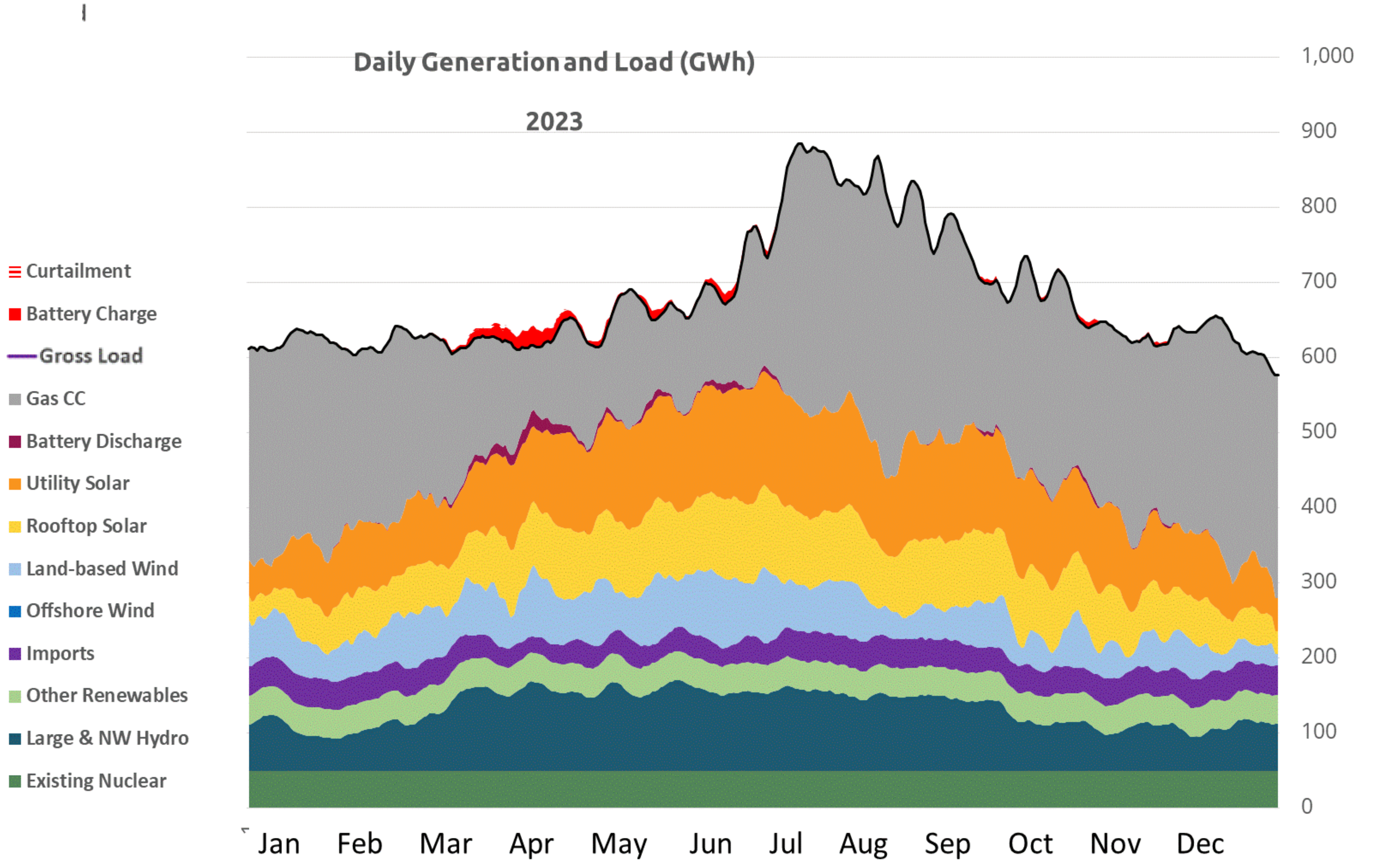
- Daily results for a full year
- Daily and hourly generation, curtailment, and cost by type of generation
- Calculated capacity factors

Visualizations

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

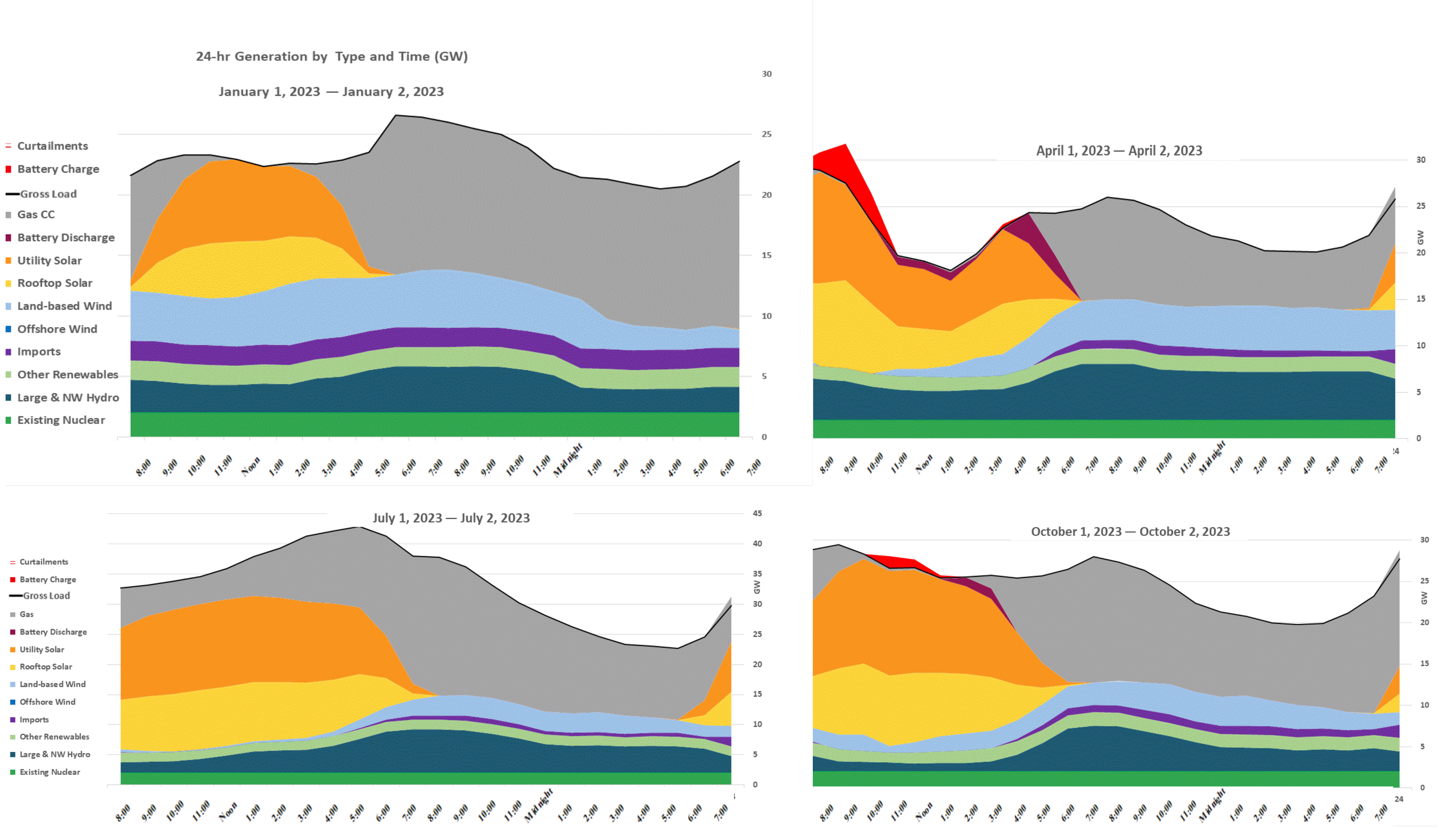
How California's Grid Operates Today

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 small 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 the next page in hourly presentations of a winter, spring, and summer day.



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 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 flowing.



Sources of Electricity in 2023

Both rooftop and utility-scale solar are major contributors to the grid, but the largest source by far is 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, reporteds that most of the curtailment last year was the result of congestion — the inability to transmit the excess power to where it could be used.

Electricity Generation
SB100 Core
2023

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	2,393	17,762	27.8%	7.1%
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%

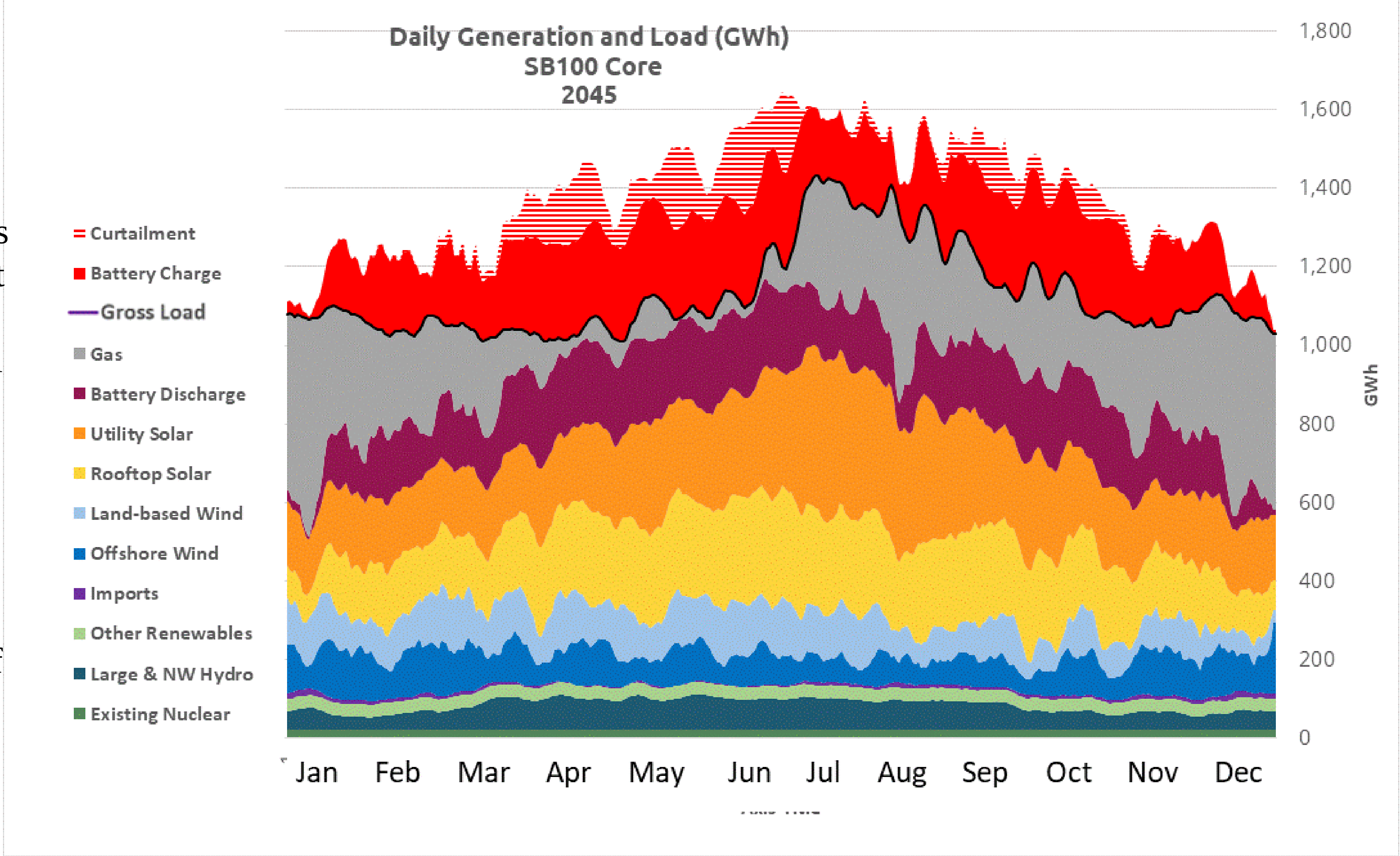
* Battery charging included in solar and wind generation.

Curtailment	50	0.0%

Total Generation Cost ($/MWh) $ 102.41

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 supposed are to be emission-free. Solar output is large, with wind much smaller. SB100 allows the burning of gas to cover transmission losses, but it is needed throughout the year to keep the lights on. Our model assumes no transmission losses, and yet we find that gas must carry nearly 20% of the load, especially at night. Batteries play a large role but cannot fill the gap. Curtailment is extensive; that is, a great deal of excess power can 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 by every evening by the burning of a fossil fuel.

Electricity Generation
SB100 Core
2045

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	1,042	7,734	27.8%	1.8%
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%

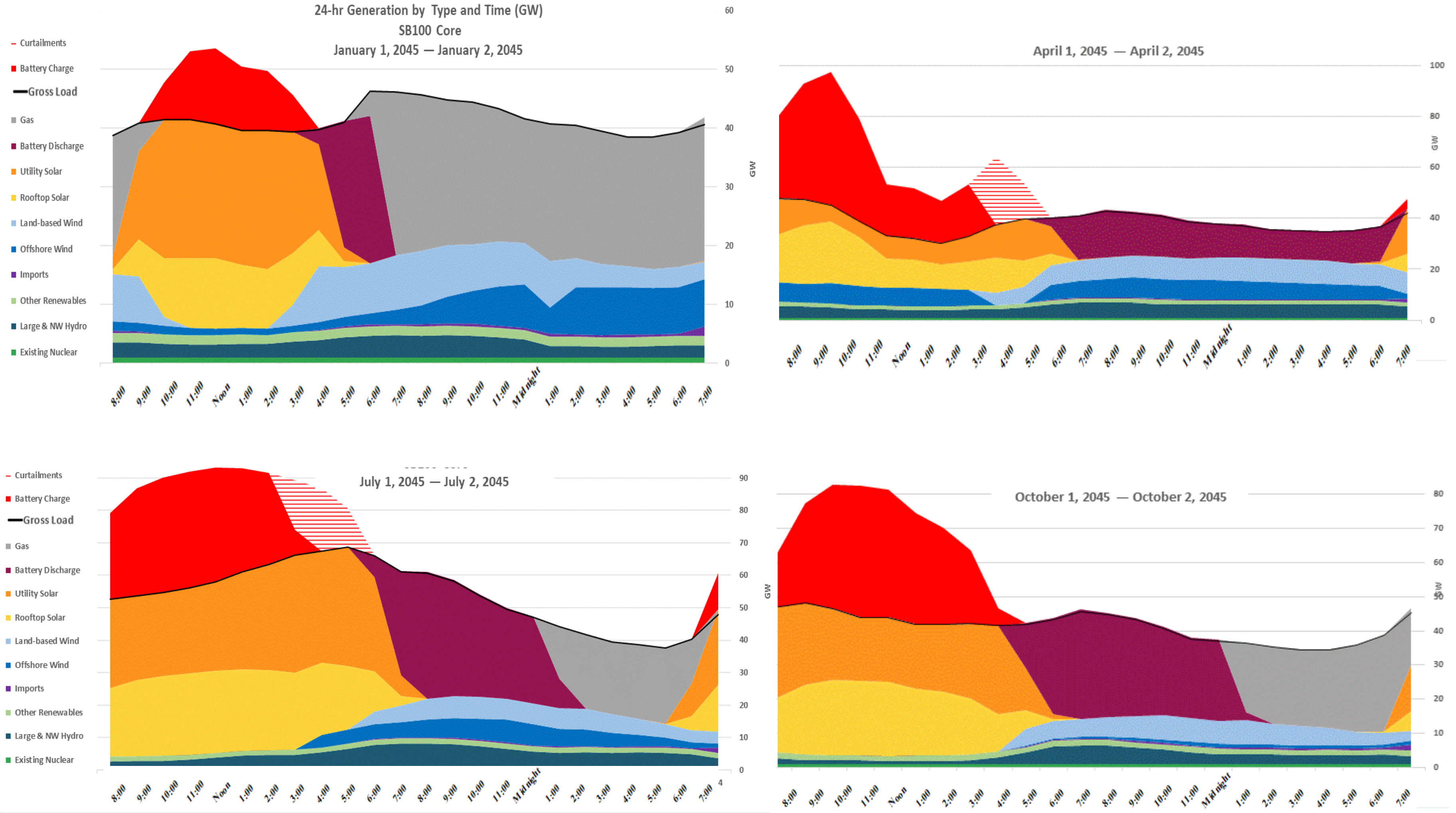
* Battery charging included in solar and wind generation.

Curtailment		21,294		5.0%

Total Generation Cost ($/MWh) $ 101.76

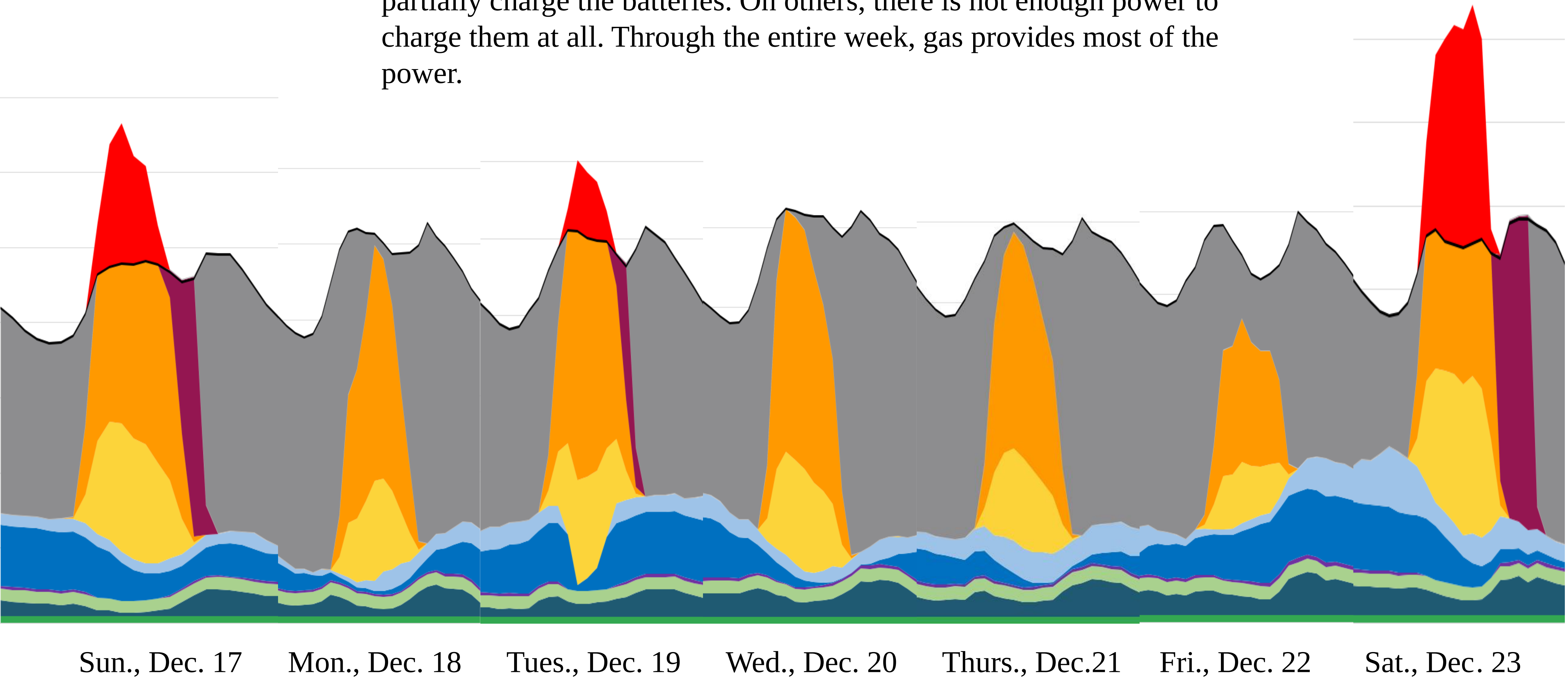
Through the seasons in 2045

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. Wind and other sources, including imports, play only a minor role.



A difficult week in December 2045

On some winter days in California, there is enough sun and wind to partially charge the batteries. On others, there is not enough power to charge them at all. Through the entire week, gas provides most of the power.



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 (to cover gaps in renewable output as demand increases) while consumption of gas declines by less than 20%. The main reason, as we have seen, is that there will be long periods when the only way to keep the 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	+157.1%		27,994	71,984	+157%
Utility Solar	19,887	82,000	+312.3%		41,019	151,363	+269%
Land-based Wind	6,284	12,217	+94.4%		20,825	38,496	+85%
Offshore Wind	0	8,215	-		0	33,525	-
Battery Discharge	7,552	52,329	+592.9%		1,125	61,025	+5324%
Gas	39,689	52,000	+31.0%		92,228	75,015	-19%
Total	87,412	242,761	+177.7%		248,958	414,837	+67%

A Dispatchable Emission-Free Resource (DEFR) is essential

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 when the day is overcast and at night and the wind is not blowing (what the Germans refer to as “Dunkelflaute” – dark doldrums). At that point, a backup is needed which has a capacity nearly as large as the full demand on the system. **Intermittent renewables, in short, require a backup which duplicates the full capacity they can provide.**

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 what is becoming the largest emission-free source, solar power, is absent. In keeping with California’s climate goals, the gap has to be filled by a source that is emission-free. Most important, it has to be firm and reliable – always available when it is needed – and it 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, the continuing fluctuations in demand as lights, computers, and engines turn on and off. To address the state’s climate goals, it has to emit no greenhouse gases. **California needs a firm Dispatchable Emission-Free Resource, a DEFR.**

What can it be?

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

A number of suggestions for DEFRs have been offered:

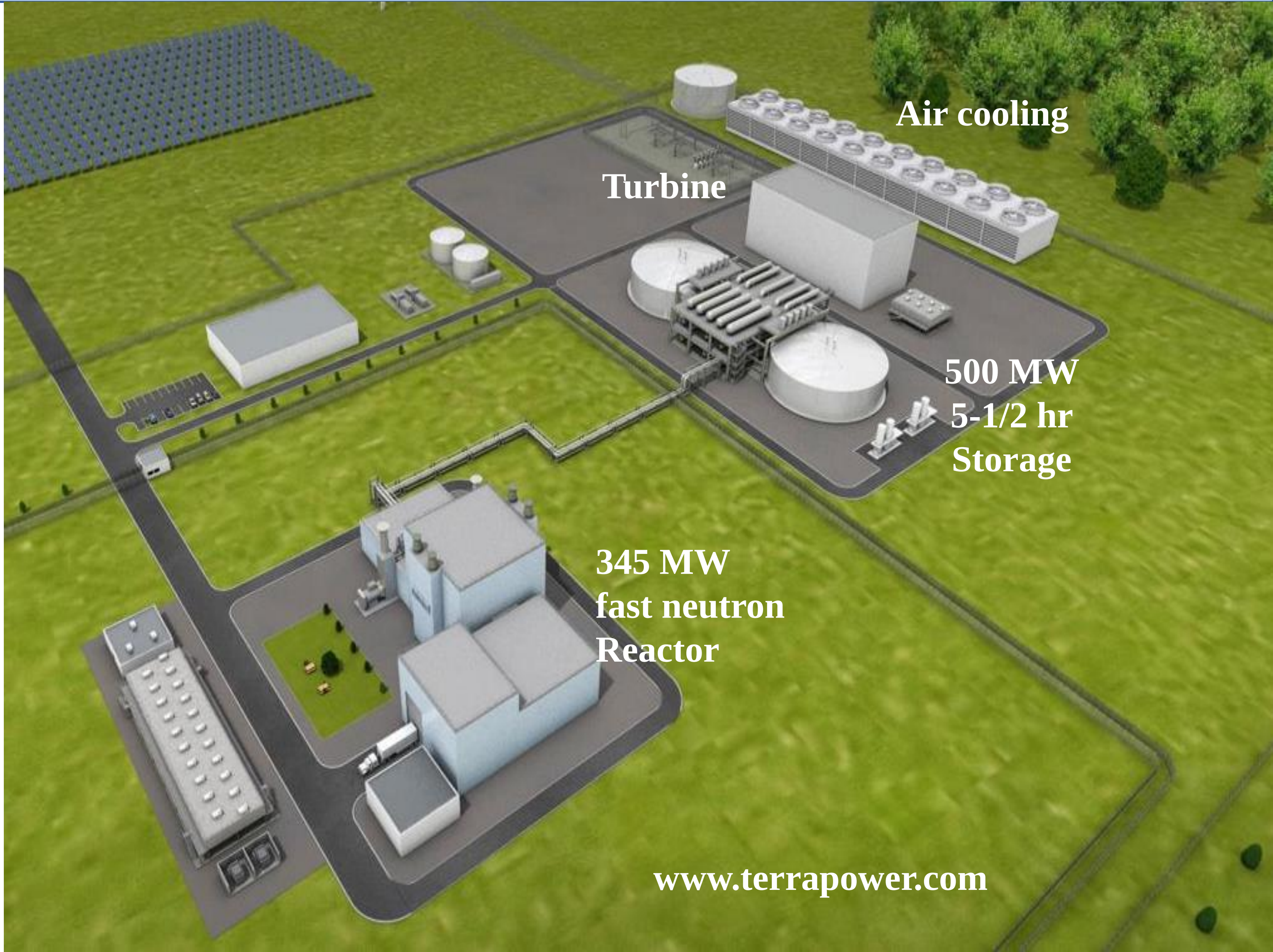
- Long-duration storage: This might help, but currently no realistic scalable form of such storage exists, especially since seasonal storage would be needed. If such storage existed, charging it would require a large expansion of generating capacity, regardless of what storage medium is used.
- Fuel 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 challenged by the fact that the round-trip power-to-gas-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 the DEFR, with a commensurate drain on material resources, land, and societal wealth. However, if nuclear power is used, 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. 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. What should it be? (cont.)

- Nuclear power: This is the DEFR energy source used in each of our scenarios, as well as for additional baseload generation. Only nuclear power has been demonstrated to have the necessary capabilities, not only in gigawatt-scale reactors now operating in California and elsewhere, but in the smaller reactors now under commercial development and operating on submarines and ships for many decades. (California would, of course, have to lift it nearly-fifty-year-old moratorium on the construction of new nuclear plants to follow this path)
- Alternate nuclear options: Alternate ways of using nuclear energy will also deserve consideration. Nuclear reactors, like most energy sources, are most cost-efficient when they run full-time. We found that 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 used in gas turbines or fuel cells. Another option would be to use nuclear power to produce carbon-neutral synthetic fuels which 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.

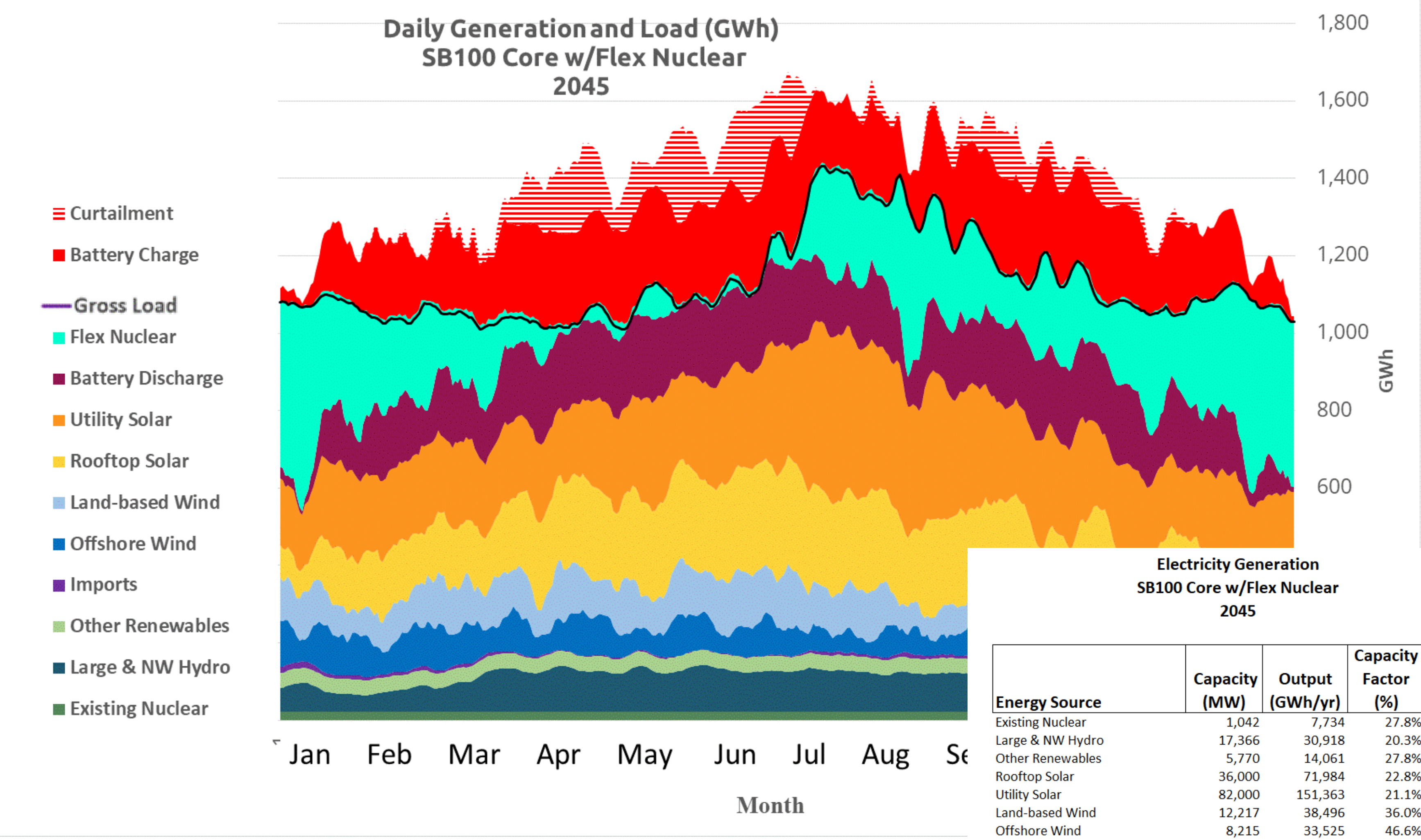
Natrium: an example of a DEFR

Terrapower/GE Hitachi's Natrium system, combining a nuclear reactor with large thermal salt storage 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 by 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 combined with thermal salt 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, it is much more expensive, at current nuclear costs, then when running with existing gas-fired turbines. There are several 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	27.8%	1.8%
Large & NW Hydro	17,366	30,918	20.3%	7.3%
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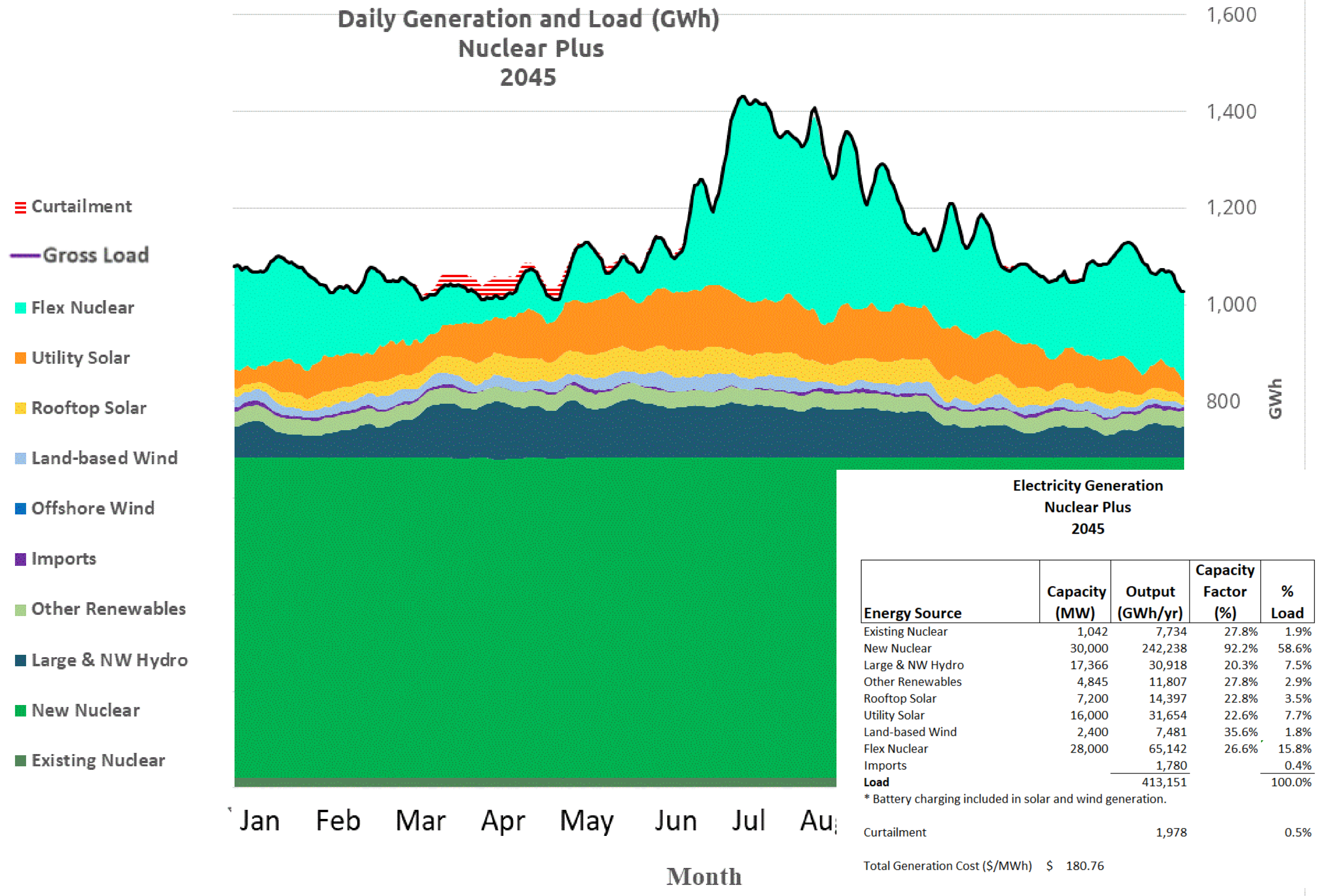
Offshore Wind	8,215	33,525	46.6%	7.9%
Battery Discharge*	52,329	61,025	13.3%	14.4%
Flex Nuclear	37,000	74,956	23.1%	17.6%
Imports		1,736		0.4%
Load		424,774		100.0%

* Battery charging included in solar and wind generation.

Curtailment	21,294	5.0%
Total Generation Cost ($/MWh)	$ 183.85	

Nuclear Plus = Baseload and Flex Nuclear with 20% Planned Renewables - 2045

One option is to replace large amounts 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 a Diablo Canyon. At current prices, this is not likely to save much money, though costs are certain to drop, and it will be far less environmentally-destructive than the vast expansion of solar, wind, and batteries now envisioned.



Electricity Generation
Nuclear Plus
2045

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	1,042	7,734	27.8%	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%
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) $ 180.76

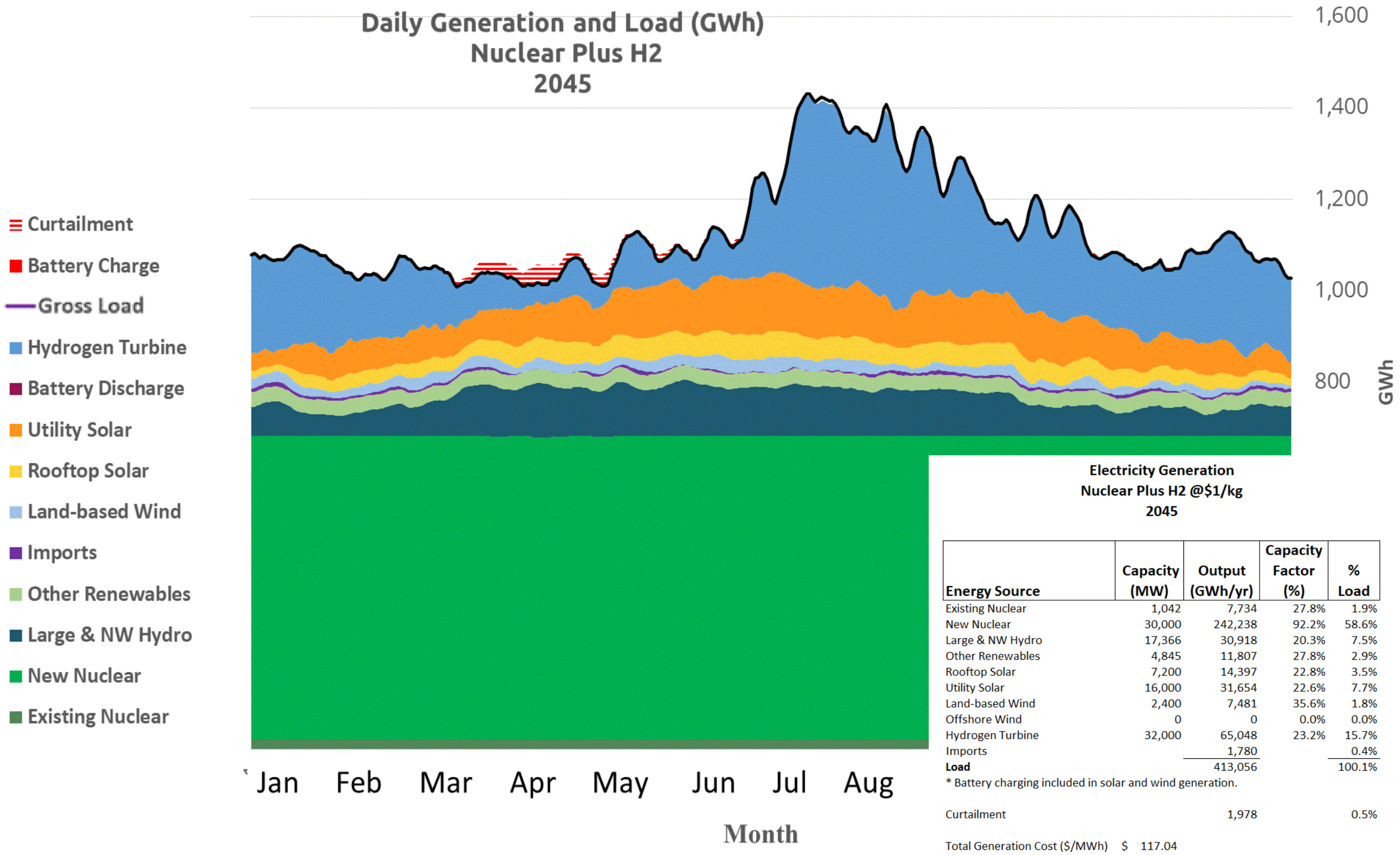
Another example of a DEFR: Hydrogen-powered turbine

Instead of using a nuclear reactor system with a variable output, 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 it with gas, it could be powered with carbon-free hydrogen produced using nuclear power (it could be produced using solar or wind power, but this would require doubling the amounts of both.

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. This could then be burned in a suitably-converted gas turbine. It makes a good alternative to flex nuclear and is likely to be far more cost-effective because the reactors producing the hydrogen could run full-time.

Nuclear H2 = Baseload Nuclear & H2 Turbine with 20% Planned Renewables - 2045

Here's the result using a set of hydrogen-driven gas turbines (many of them could be the same ones now burning natural gas, once the burners and other parts are modified). The turbines would respond to the demand and vary their output as needed, just as they do now. In the case we are looking at, this would require the equivalent of about ten Diablo Canyon plants to produce the hydrogen.



Electricity Generation
Nuclear Plus H2 @$1/kg
2045

Energy Source	Capacity (MW)	Output (GWh/yr)	Capacity Factor (%)	% Load
Existing Nuclear	1,042	7,734	27.8%	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%
Hydrogen Turbine	32,000	65,048	23.2%	15.7%
Imports		1,780		0.4%
Load		413,056		100.1%

* Battery charging included in solar and wind generation.

Curtailment		1,978		0.5%

Total Generation Cost ($/MWh) $ 117.04

Comparative Generation Costs

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

With NREL's projections that there will be a 50% reduction in renewable costs, the SB100 Core (High Electrification) scenario costs has electric generations costs about what they are today. Adding Flex Nuclear as a DEFR increases the cost substantially (with the NREL/EIA estimate of about $5,600/kw for nuclear costs. But if nuclear costs can be brought down near to what South Korea and China are achieving today, there will be little increase from 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	$102.41	
SB100 Core w/Current Costs		$168.45
SB100 Core w/Projected Costs		$101.76
Zero emissions		
SB100 Core w/Flex Nuclear		$183.85
Nuclear Plus (Baseload + Flex Nuclear & 20% of Planned Renewables)		$180.76
Nuclear Plus w/Nuclear cost $3,000/kw		$119.30
Nuclear H2 w/H2 @ $1/kg		$117.04

Major Conclusions

- Today's widely-used grid planning model gives misleading, false results.
- California's planning for a decarbonized grid will not significantly reduce its emission of greenhouse gases.
- Decarbonized electrification requires a large, clean, firm dispatchable source that operates during the entire year.
- Nuclear can provide the needed reliable and affordable power, both directly and by cost-effectively producing clean hydrogen.
- Large-scale building of renewables is wasteful and will make the transition more difficult and costly.

Further Concluding Notes

- California is crippling its ability to address climate change with its outdated moratorium on new nuclear installations.
- Many people seem to forget that the sun only shines during the day. Natural gas takes over at night, perhaps after a few hours when storage batteries have been discharged. 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.

Appendix A

Datasheets

Datasheet: Generation w/Current Costs - 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	$ 31.14	$ 1.22	$ 4.09	$ 1.72	$ 38.16
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%	$ 2,700	$ 7.50	$ -	$ -	$ 243.05	$ 250.55
Utility Solar	19,887	41,019	23.5%	16.5%	$ 1,600	$ 5.33	$ -	$ -	$ 139.63	$ 144.96
Land-based Wind	6,284	20,825	37.8%	8.4%	$ 1,800	$ 10.26	$ -	$ -	$ 97.77	$ 108.03
Offshore Wind	0	0	0.0%	0.0%	$ 3,500	$ 10.84	$ -	$ -	$ 148.49	$ 159.33
Total	65,700	152,579	26.5%	61.4%		$ 17.80	$ 0.91	$ 0.48	$ 95.68	$ 114.85

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%	$ 360	$ 154.38	$ -	$ -	$ 434.96	$ 589.34
Flex Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Gas	39,689	92,228	26.5%	37.1%	$ 644	$4.30	$5.00	$21.00	$44.32	$74.63
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%		$ 6.11	$ 4.94	$ 20.75	$ 49.03	$ 81.82

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%		$ 13.39	$ 2.43	$ 8.11	$ 78.10	$ 102.41

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	$ 31.14	$ 1.22	$ 4.09	$ 1.72	$ 38.16
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%	$ 2,700	$ 7.50	$ -	$ -	$ 243.05	$ 250.55
Utility Solar	82,000	151,363	21.1%	35.6%	$ 1,600	$ 5.96	$ -	$ -	$ 156.02	$ 161.98
Land-based Wind	12,217	38,496	36.0%	9.1%	$ 1,800	$ 10.79	$ -	$ -	$ 102.82	$ 113.61
Offshore Wind	8,215	33,525	46.6%	7.9%	$ 6,500	$ 11.27	$ -	$ -	$ 286.70	$ 297.97
Total	162,610	348,081	24.4%	81.9%		$ 11.48	$ 0.36	$ 0.09	$ 157.13	$ 169.07

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%	$ 360	$ 19.72	$ -	$ -	$ 55.57	$ 75.29
Flex Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Gas	52,000	75,015	16.5%	17.7%	$ 644	$6.93	$5.00	$21.00	$71.40	$104.33
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%		$ 12.67	$ 2.76	$ 11.58	$ 64.30	$ 165.58

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%		$ 11.69	$ 0.79	$ 2.13	$ 140.67	$ 168.45

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/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	$ 31.14	$ 1.22	$ 4.09	$ 1.72	$ 38.16
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%	$ 1,400	$ 7.50	$ -	$ -	$ 126.03	$ 133.53
Utility Solar	82,000	151,363	21.1%	35.6%	$ 700	$ 5.96	$ -	$ -	$ 68.26	$ 74.22
Land-based Wind	12,217	38,496	36.0%	9.1%	$ 1,200	$ 10.79	$ -	$ -	$ 68.55	$ 79.34
Offshore Wind	8,215	33,525	46.6%	7.9%	$ 3,500	$ 11.27	$ -	$ -	$ 154.38	$ 165.65
Total	162,610	348,081	24.4%	81.9%		$ 11.48	$ 0.36	$ 0.09	$ 78.23	$ 90.17

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%	$ 280	$ 19.72	$ -	$ -	$ 43.22	$ 62.94
Flex Nuclear	0	0	0.0%	0.0%	$ -	$ -	$ -	$ -	$ -	$ -
Gas	52,000	75,015	16.5%	17.7%	$ 644	$6.93	$5.00	$21.00	$71.40	$104.33
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%		$ 12.67	$ 2.76	$ 11.58	$ 58.76	$ 155.53

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%		$ 11.69	$ 0.79	$ 2.13	$ 74.78	$ 101.76

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	$ 31.14	$ 1.22	$ 4.09	$ 1.72	$ 38.16
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%	$ 1,400	$ 7.50	$ -	$ -	$ 126.03	$ 133.53
Utility Solar	82,000	151,363	21.1%	35.6%	$ 700	$ 5.96	$ -	$ -	$ 68.26	$ 74.22
Land-based Wind	12,217	38,496	36.0%	9.1%	$ 1,200	$ 10.79	$ -	$ -	$ 68.55	$ 79.34
Offshore Wind	8,215	33,525	46.6%	7.9%	$ 3,500	$ 11.27	$ -	$ -	$ 154.38	$ 165.65
Total	162,610	348,081	24.4%	81.9%		$ 11.48	$ 0.36	$ 0.09	$ 78.23	$ 90.17

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%	$ 280	$ 19.72	$ -	$ -	$ 43.22	$ 62.94
Flex Nuclear	37,000	74,956	23.1%	17.6%	$ 5,480	$ 67.13	$ 2.60	$ 11.00	$ 486.91	$ 567.64
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%		$ 45.86	$ 1.43	$ 6.06	$ 287.79	$ 618.88

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%		$ 17.57	$ 0.55	$ 1.15	$ 115.36	$ 183.85

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: Nuclear Plus: Baseload and Flex Nuclear along with 20% Planned Renewables - 2045

Generation and Cost Summary — Nuclear Plus — 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	$ 31.14	$ 1.22	$ 4.09	$ 1.72	$ 38.16
New Nuclear	30,000	242,238	92.2%	58.6%	$ 5,663	$ 21.67	$ 2.80	$ 10.00	$ 112.21	$ 146.69
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%	$ 1,400	$ 7.50	$ -	$ -	$ 126.03	$ 133.53
Utility Solar	16,000	31,654	22.6%	7.7%	$ 700	$ 5.56	$ -	$ -	$ 63.69	$ 69.25
Land-based Wind	2,400	7,481	35.6%	1.8%	$ 1,200	$ 10.91	$ -	$ -	$ 69.29	$ 80.20
Offshore Wind	-	-	0.0%	0.0%	$ 3,500	$ -	$ -	$ -	$ -	$ -
Total	78,853	346,229	50.1%	83.8%		$ 20.95	$ 2.29	$ 7.09	$ 91.11	$ 121.44

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%	$ 280	$ -	$ -	$ -	$ -	$ -
Flex Nuclear	28,000	65,142	26.6%	15.8%	$ 5,480	$ 58.46	$ 2.60	$ 11.00	$ 423.98	$ 496.04
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	$ 2.60	$ 11.00	$ 423.98	$ 496.04

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%		$ 26.89	$ 2.34	$ 7.71	$ 143.82	$ 180.76

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: Nuclear H2: Baseload & H2 Turbine along with 20% Planned Renewables - 2045

Generation and Cost Summary — Nuclear Plus H2 @$1/kg — 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	$ 31.14	$ 1.22	$ 4.09	$ 1.72	$ 38.16
New Nuclear	30,000	242,238	92.2%	58.6%	$ 5,663	$ 21.67	$ 2.80	$ 10.00	$ 112.21	$ 146.69
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%	$ 1,400	$ 7.50	$ -	$ -	$ 126.03	$ 133.53
Utility Solar	16,000	31,654	22.6%	7.7%	$ 700	$ 5.56	$ -	$ -	$ 63.69	$ 69.25
Land-based Wind	2,400	7,481	35.6%	1.8%	$ 1,200	$ 10.91	$ -	$ -	$ 69.29	$ 80.20
Offshore Wind	-	-	0.0%	0.0%	$ 3,500	$ -	$ -	$ -	$ -	$ -
Total	78,853	346,229	50.1%	83.8%		$ 20.95	$ 2.29	$ 7.09	$ 91.11	$ 121.44

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%	$ 280	$ -	$ -	$ -	$ -	$ -
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%	$ 644	$4.92	$5.00	$33.00	$50.67	$93.59
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%		$ 4.92	$ 5.00	$ 33.00	$ 50.67	$ 93.59

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%		$ 18.42	$ 2.72	$ 11.19	$ 84.71	$ 117.04

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 are included. 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 those developed by E3 for the California Energy Commission.

Grid Model Methodology (cont.)

Hourly generation from solar and onshore and offshore wind is scaled up based on the distribution of 2022 hourly output data for these sources, and offshore wind uses 2021 hourly net capacity factors provided by NYISO. 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 NYISO. Purchases from Canada and PJM-NE are modeled based on 2022 actual hourly data.

The maximum capacity of solar and wind facilities reflects the regional 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 2022 from NYISO. 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 onshore 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 these 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.

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 Canada and PJM/NE 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 data sources. The prices used in the scenarios reported here are shown in Appendix C. The total native 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 capacity and ancillary service auctions operated by NYISO. 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 as well. 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 currently 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.