Retaining Diablo Canyon: Economic, Carbon, and Reliability Implications

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Executive Summary

CONTEXT

California's SB 100 bill has committed the state to decarbonize its power grid with a goal of 60% renewable energy by 2030 and 100% clean electric retail sales by 2045. Plans and resource procurements are falling into place to pursue those goals, including through the California Public Utilities Commission's (CPUC's) recent Mid-Term Reliability Procurement Order and the ongoing Integrated Resource Plan and Long Term Procurement Plan.

Still, fully meeting California's ambitions presents challenges. It will require siting solar and wind power projects and building transmission at unprecedented rates over many years, which poses uncertainties. Further, it will require special measures to maintain reliability in a fleet dominated by intermittent solar and wind energy. Maintaining reliability will require not only batteries for addressing daily variation, but dispatchable or 24x365 capacity for when wind and sun output are low for weeks or seasons, well beyond the duration of existing batteries. If the only goal were reliability, such capacity could be gas-fired, but that emits CO_2 contrary to the state's goals. Novel technologies could include hydrogen-based generators (H_2) or natural gas-fired combined-cycle plants with carbon capture and storage (NGCC with CCS), although these technologies are many years away from being commercially deployed at scale.

STUDY QUESTION

On the eve of when the state and PG&E could still decide to extend beyond the 2024/5 planned retirement date of the Diablo Canyon Power Plant – a 2,256 MW nuclear plant that generates emissions-free energy nearly 24x365 and accounts for 15% of the state's current clean energy production – we ask: **How could retaining Diablo Canyon help meet California's climate and reliability goals? Could it help decarbonize more successfully, quickly, or reliably, and/or at a lower cost than without the plant?**

STUDY APPROACH

The starting point is an assumption that Diablo Canyon could in fact extend its operating license with the Nuclear Regulatory Commission (NRC) and that California would allow the plant to continue to operate without it having to install cooling towers for over $8 billion to address habitat impacts related to its water intake. We adopt assumptions from a study by researchers at Stanford University and MIT* that alternative commercially available intake structures could be deployed at a lower cost. We assume $2 billion, which is conservatively higher than the study's estimate of intake costs. This includes additional capital investment and relicensing costs, which we assume allows Diablo Canyon to operate until 2045.

* Aborn et al, "An Asssement of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production" (2021), https://energy.stanford.edu/publications/assessment-diablo-canyon-nuclear-plant-zero-carbon-electricity-desalination-and

Executive Summary (Continued)

STUDY APPROACH (CONTINUED)

Using Brattle's gridSIM model, we then compare the world with such an investment to one without. gridSIM is a state-of-the-art electricity capacity expansion and operations simulation model comparable to RESOLVE. We start with a base case benchmarked to the 2021 SB 100 Joint Agency Report's "Core Scenario," updated for Mid-Term Reliability Procurement Order and the 2021 Preferred System Plan (PSP). That case shows how California could achieve its goals through 2045 without retaining Diablo, under numerous assumptions of the ability to develop adequate solar, wind, battery, and other resources. We also examine an alternative scenario where clean resources are more limited.

In the scenario in which Diablo's license is extended, we assume that Diablo does not change solar, wind and storage procurement plans through 2032 but can displace gas-fired generation and storage used to meet energy and reliability needs. After 2032, Diablo can substitute for other resource investments otherwise needed to meet clean energy and reliability requirements. We also examine a case where it does not.

Lastly, we examine the impact of Diablo in a scenario in which the SB 100 goal is required to be achieved in 2035 rather than 2045 – ten years earlier than current law. In each scenario, we observe differences in resource development, generation and emissions, reliability (partial analysis), and cost of each scenario.

CONCLUSIONS

Our analysis indicates that Diablo Canyon's unique 24x365 clean energy characteristics would help California decarbonize more quickly (with lower cumulative emissions), more reliably, and at lower total cost. We arrive at five specific insights relevant to policymakers:

1. Even assuming an immediate doubling of the state's recent buildout rate for solar energy and the widespread availability of NGCC with CCS after 2035, California will rely on substantial unabated gas-fired generation and imports. **Retaining Diablo would displace gas-fired generation and emitting imports**, especially during the first 10 years. Initially, the displacement is almost 24x365 (except during spring runoff). Eventually however, this displacement occurs primarily at night, with displacement of solar generation taking place during the day.
2. **Retaining Diablo would massively reduce cumulative emissions by approximately 40 MMT CO_2**, more than an entire year's worth of in-state electricity generation emissions, while also lowering other local air pollution from gas-fired plants. Most of the emissions reduction is in the first 10 years, when Diablo displaces emitting gas-fired and imports; after 2035 it reduces reliance on NGCC with CCS or H_2 or other potential future technologies (and if it does reduce them MWh-for-MWh, emissions in those later years end up the same, but cumulative emissions in the atmosphere are still lower).

Executive Summary (Continued)

3. **Retaining Diablo would provide insurance** for meeting both reliability standards and carbon goals in the event clean energy deployment rates do not double and future dispatchable clean technologies (e.g., NGCC with CCS or H_2) do not materialize at scale. Retaining Diablo would also continue to provide insurance against extreme events such those that caused the August 2020 rolling blackouts.
4. **Retaining Diablo would reduce system costs by more than $4 Billion** by avoiding burning natural gas in California and gas/coal for imported energy, and by reducing capital and fixed costs for other resources otherwise needed to meet clean energy and reliability goals. Savings are positive under all the scenarios analyzed, even accounting for a conservatively higher estimate than MIT's cost of new intake structures, and even if upgrades cost twice as much as that, and assuming no federal assistance. Our estimates also include the ongoing operating and maintenance costs of the plant.
5. **Retaining Diablo could greatly help enable California to achieve a potentially accelerated goal of a carbon free-grid years earlier, by 2035,** by lowering the cost of accelerated compliance by $5 Billion. Retaining Diablo would also make earlier compliance feasible by providing more time for the state to more than quadruple its current annual deployment rate of solar and wind, while delaying the need for carbon capture and sequestration (CCS) on NGCCs, or other novel technologies.

These conclusions and the basis for them are described in the following report sections: (1) a description of our approach and key assumptions; (2) observations about a base case future with California pursuing its goals absent Diablo; (3) an analysis of the impacts of retaining Diablo; and (4) analysis of impacts under alternative scenarios.

It should be noted that this analysis only addresses the value of Diablo Canyon in meeting SB 100 goals, not the more ambitious state goal of complete economy-wide decarbonization by 2045 as embodied in Executive Order B-55-18. Achieving that goal would suggest even more value for zero carbon electricity sources such as Diablo Canyon to decarbonize all sectors.*

* Our analysis assumes the high electrification demand scenario based on CEC's 2018 Deep Decarbonization in a High Renewables Future report, the same demand scenario assumed in the 2021 SB 100 Joint Agency Report's "Core Scenario." This demand scenario is designed to meet the state's goal to reduce economy-wide GHG emissions by 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050.

Study Approach and Key Assumptions

Modeling Approach with gridSIM

This study uses **gridSIM**, Brattle's state-of-the-art model for analyzing deeply decarbonizing electric systems. gridSIM is comparable to RESOLVE and simulates hourly market operations and investment/retirement decisions over a multi-year time horizon, by minimizing total costs subject to policy and reliability constraints. It has a simplified representation of the transmission system and of unit commitment. Further information on gridSIM can be found at **brattle.com/gridSIM**.

To inform the value of retaining Diablo Canyon, this study uses gridSIM to model California as part of the larger Western Electricity Coordinating Council (WECC) system, which encompasses the areas of the US and Canada that are located west of the Rockies. We start with a base case in which California pursues its goals, analyzed in five-year increments from the present through 2045. The licenses for Diablo Canyon Units 1 and 2 are set to expire in November 2024 and August 2025. In gridSIM, the base case assumes that Diablo Canyon fully retires before 2025. We then compare to a change case, with the plant extended to 2045, observing differences in the generation mix, emissions, and costs.

The base case incorporates reasonable, standard assumptions about the current electric system and planned changes to it; expected growth in electricity demand for energy, resource adequacy, and clean energy, per policy requirements; supply options and their investment and ongoing operating costs; and transmission capacities between adjacent areas.

The starting dataset for the WECC was from the US Energy Information Administration's (EIA's) Annual Energy Outlook (AEO), specifically the dataset from EIA's National Energy Modeling System (NEMS). We made numerous refinements to the inputs for California based on the 2021 SB 100 Joint Agency Report's "Core Scenario," and confirmed that the outputs were similar to those in that study. We further updated the inputs to include the CPUC's 2021 Mid-Term Reliability Procurement Order and the 2021 Preferred System Plan (PSP), which achieves 38 MMT annual GHG emissions limit by 2030 and 35 MMT by 2032 in the California's electric sector.

The CEC's 2030 and 2045 planning goals for offshore wind were also included as input assumptions. CEC's Draft Commission Report on Offshore Wind Energy Development off the California Coast specifies 3 GW planning goal for 2030, and a 10-15 GW goal for 2045.

Modeling Approach with gridSIM (continued)

Given the 10 GW offshore wind potential limit imposed in the 2021 SB 100 Joint Agency Report, our analysis used the 10 GW assumption for 2045. We further used the 10 GW assumption in 2040 to be consistent with scenario assumptions used in the CAISO 20-Year Transmission Outlook.* For 2035, we assumed 6.5 GW of offshore wind capacity by linearly interpolating between 3 GW (2030) and 10 GW (2040).

The base case assumes no impediments to the deployment of utility-scale solar (even with deployment proceeding more than 2x faster than historic pace in spite of increasing challenges to siting and accessing transmission) and availability of future dispatchable clean technologies (specifically, NGCC with CCS) starting in 2025. However, we also analyze an alternative scenario with solar development limited to twice the historic pace and with no CCS. This is shown at the end.

All key model assumptions are tabulated on page 8.

The change case, with Diablo Canyon's operation extended to 2045, includes an assumed $2 billion capital cost to address the power plant's once-through cooling (OTC) requirements as well as additional capital expenses such as relicensing costs, which is conservatively high relative to the Stanford/MIT study estimates. We assume the addition of Diablo Canyon does not change the procurement of clean energy and storage resources associated with the 2021 Mid-Term Reliability Procurement Order and the Preferred System Plan.

In the gridSIM simulations, Diablo Canyon runs constantly at full output, contributing to reliability and long-term clean energy goals. The model economically adjusts the rest of the system: the generation dispatch; plant retirements through 2032; and new investments/retirements post-2032 as needed to cost-effectively meet clean energy and reliability requirements.

SOME LIMITATIONS OF THIS STUDY

gridSIM models normal conditions that do not include low hydro conditions, climate-change-induced heat waves or wildfires, or other extremes, such as those California experienced in August 2020. While the system's future vulnerability to such conditions should be moderated by the higher planning reserve margin of 20.7% of peak load, as specified in the Mid-Term Reliability Procurement Order, the study will tend to understate the value of retaining non-weather-dependent resources such as Diablo.

Further, this study does not account for increasing costs of developing solar and wind as the lowest-cost opportunities are used up, which also will tend to understate the value of retaining existing non-emitting resources such as Diablo.

* California Energy Commission, California Public Utilities Commission, and California Independent System Operator. September 2021. SB 100 Starting Point for the CAISO 20-year Transmission Outlook. https://efiling.energy.ca.gov/GetDocument.aspx?tn=239685&DocumentContentId=73101.

WECC-wide System Assumptions

From EIA's AEO Reference Case with California Calibrated to SB 100 Joint Agency Report and CPUC's PSP

DATA ELEMENT	SOURCES
Zones	**AEO 2021:** Electricity Market Module (EMM) Regions in the National Energy Modeling System (NEMS).
Transmission topology and limits	**AEO 2020 Ref. Case:** Interregional Transfer Capability. California statewide export limit of 5GW, as modeled by Joint Agency Report.
Existing and planned generator data	**AEO 2021** (capacity, heat rate, location); **NREL Annual Technology Baseline 2021** (FOM, VOM). **Modifications for CA:** incorporates resource types specified in the Mid-Term Reliability Procurement Order.
Fuel prices	**Nuclear, coal and oil: AEO 2021 Ref Case;** Tables 3 and 54. **Gas: Forward pricing (forwards as of 11/9/2021)** and **AEO 2021 Ref Case**; e.g., average delivered gas price for CANO in 2025 is $4.13/MMBtu.
New generator costs	**NREL Annual Technology Baseline 2021:** Moderate cost case (Capital, FOM, VOM).
Hourly renewable generation shapes	**NREL Renewable Energy Potential Model** scaled to historical capacity factors.
Hourly load shapes	**FERC 714 filing** via S&P Global Market Intelligence (2020 hourly load data).
Load growth	For WECC regions except CANO and CASO : Load and peak demand from **AEO 2021 Ref. Case:** Annual energy and peak demand forecast Modifications for CA: Load, peak demand and BTM-PV assumptions sourced from the **2021 SB 100 Joint Agency Report's "Core Scenario."**
Existing plant retirement age	**NREL ReEDS Model Documentation:** Version 2019 Tables 10 and 11.
Capacity requirements and accreditation	Reserve margin assumptions as standard for each zone in the WECC, with solar and wind accreditation estimated based on the output during top 100 net load hours (which varies with penetration of solar and of wind). **Modifications for CA**: **20.7% planning reserve margin** per the Mid-Term Reliability Order; solar and wind accreditation from the SB 100 Joint Agency Report, adopting the "ELCC surface" RESOLVE relating accreditation to the penetration of solar and wind.
International imports and exports	**EIA Open Data:** US Electric System Operating Data: BA-to-BA interchange (historical hourly interchanges).
Clean energy goals	Outside CA, states meet their own Renewable Portfolio Standard (RPS) and clean energy targets. **Modifications for CA:** (see next page).
Federal tax credits	Tax credits modeled based on current legislation. Solar ITC step down to 10% after 2026 with safe harbor and PTC for wind steps down through 2026 with assumed extension of the PTC at 2026 levels.
Other CA-specific assumptions	• Import-export limits and carbon hurdles, and allowance prices, based on the **2021 SB 100 Joint Agency Report.** • Carbon accounting for imports based on **2021 SB 100 Joint Agency Report** assumptions. • Geothermal and Biomass generators set at max dispatch when online, based on **2021 SB 100 Joint Agency Report's** modeling assumption. • New natural gas-fueled capacity builds prohibited until 2026 based on procurement requirements in Mid-term Reliability Procurement Order. • Offshore wind capacity based on CEC's Offshore Wind Energy Development off the California Coast Report and SB 100 Joint Agency Report.

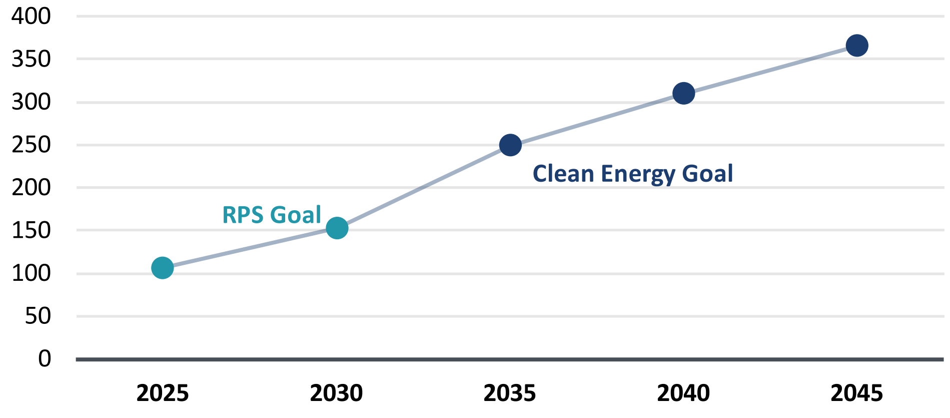
California Demand for Energy, Renewables, and Other “Clean” MWh

Our electricity load forecast is consistent with the 2021 SB 100 Joint Agency Report’s “Core Scenario,” which incorporates high electrification demand based on CEC’s 2018 *Deep Decarbonization in a High Renewables Future* report. The Core Scenario’s “California” forecast is scaled down slightly for gridSIM’s North and South CA zones that encompass only 98% of the state. The resulting forecast is used for the simulated energy dispatch, and as a basis for setting resource adequacy (at 20.7% reserve margin over annual peak loads) and clean energy requirements.

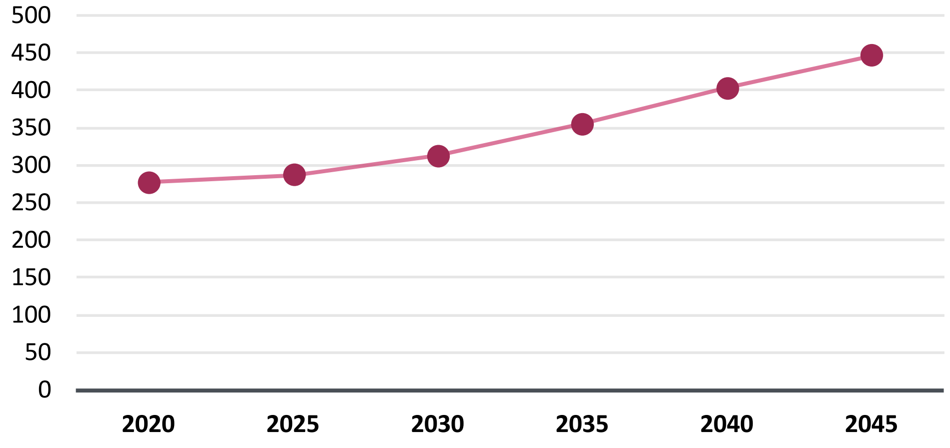
California’s RPS and clean energy goals apply as percentages of the total energy consumed. We assume the version of SB 100 described in the 2021 SB 100 Joint Agency Report’s “Core Scenario”: 60% RPS by 2030, 100% clean by 2045 except losses from transmission and distribution and from charging inefficiencies of storage, which are allowed to be provided by carbon-emitting resources such as unabated natural gas or imports from gas or coal. We update the requirements relative to the “Core Scenario” however, to be consistent with the CPUC’s PSP to meet electric-sector CO_2 emissions limits of 38 MMT by 2030 and 35 MMT by 2032.

Under these assumptions, the state will eventually need over 350 TWh/yr of clean energy as shown in the chart on the upper right. Annual gas-fired generation is limited to the maximum allowable carbon-intensive generation in state, after RPS goals and clean energy goals are met. (This constraint may appear redundant but is necessary to close a loophole that could be used to allow more gas generation at night by exporting over-generated clean energy during the day).

CALIFORNIA DEMAND FOR CLEAN ENERGY GENERATION (TWh)



LOAD FORECAST with T&D Losses (TWh)



Diablo in Relation to RPS and Clean Energy Goals in SB 100

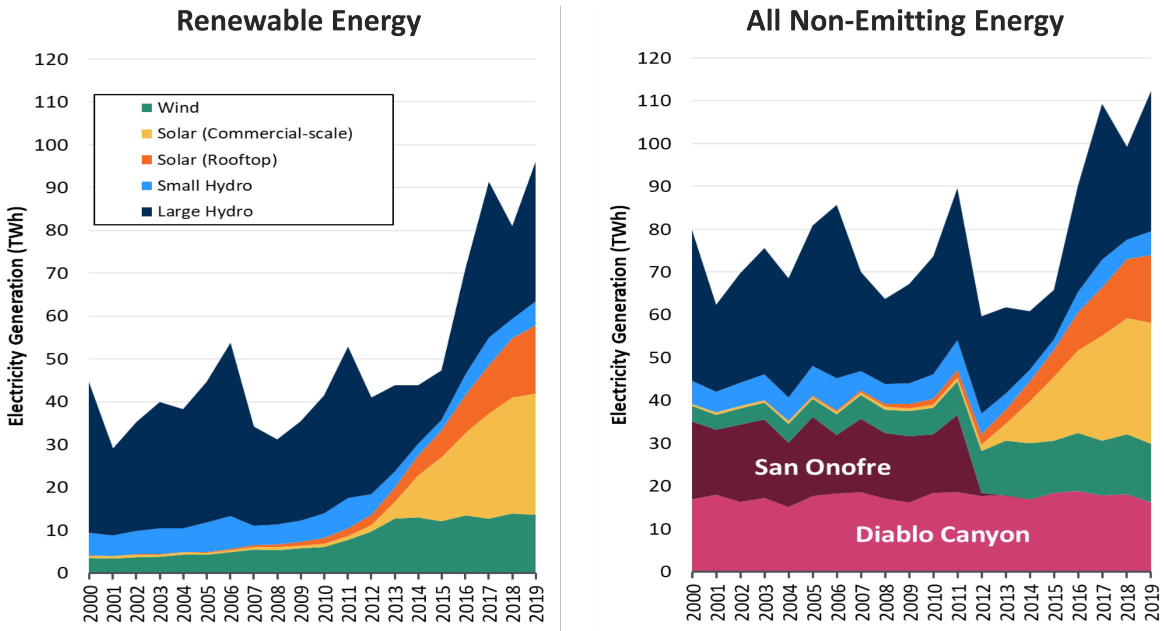
California has been increasing its renewable generation rapidly, for example from 36 TWh per year in 2000–02 to 90 TWh per year in 2017–19, a 146% increase, due mostly to the phenomenal expansion of solar over the past 10 years.

The overall clean energy story, including nuclear, is more mixed: total clean energy started higher (68 TWh in 2000–02) but rose by less (to 106 TWh in 2017–19) due to the retirement of the 2,200 MW San Onofre Nuclear Generating Station (SONGS) in 2012. If Diablo Canyon's 2,250 MW (about 18 TWh/yr) of clean energy had also been lost in this period, the 68 TWh would have risen to 90 TWh, just a 30% increase, not 146%. And 60% of the renewable increase to date would have been offset by lost nuclear output.

The loss of Diablo Canyon, which currently provides almost 15% of California's clean energy supply, would undo the progress made by the last five years of utility-scale solar additions, setting the state back considerably and increasing the future progress needed.* The energy would naturally be replaced by gas-fired generation, all else equal, although California's RPS and procurement plans aim to instead replace it with renewable generation. Much will be needed to do that; even more will be needed to increase total clean energy production and decarbonize the system.

The base case and change case in this study are designed to assess the implications of retiring Diablo Canyon versus not retiring it.

HISTORICAL GENERATION IN CALIFORNIA



SOURCES: Hydro, Solar, and Wind: Adapted from Figure 10 of California Greenhouse Gas Emissions for 2000 to 2019, July 28, 2021, California Air Resources Board.
Nuclear: EIA 906/923 Monthly Utility Power Plant Database.

* California Energy Commission's Electric Generation and Capacity reports that in-state solar generation increased by approximately 14 TWh between 2016-2021. See: https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy.

Observations About the “Base Case” Future without Diablo Canyon

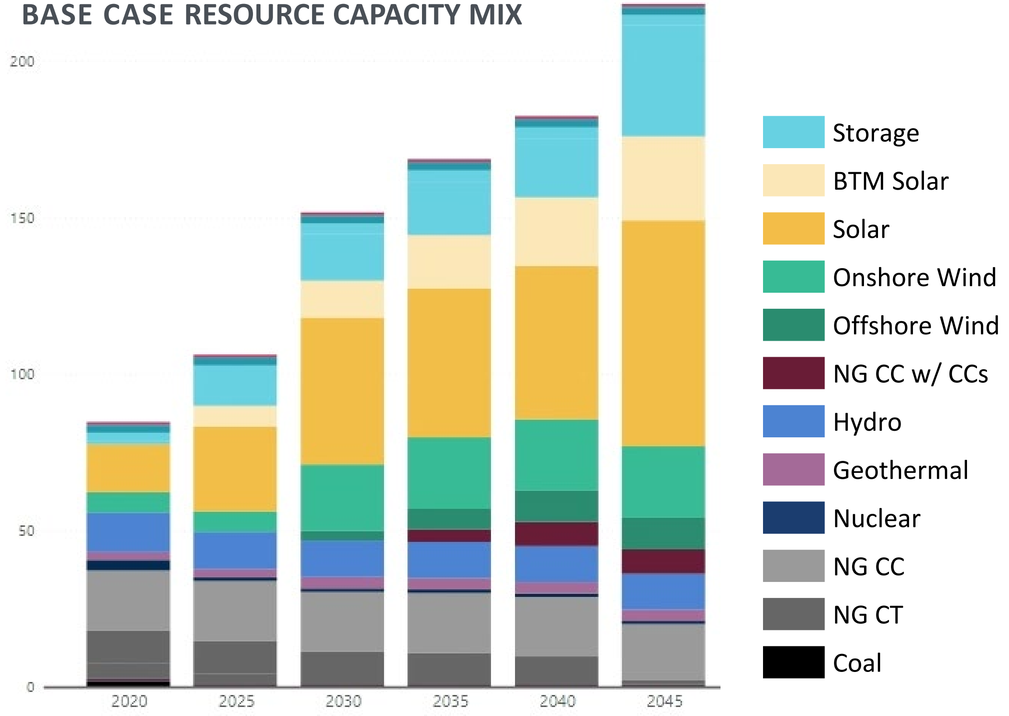
Base Case Resource Development Outlook for California

BENCHMARKING TO THE SB 100 JOINT AGENCY REPORT

To meet future clean energy mandates and maintain reliability, gridSIM projects a resource deployment trajectory similar to that in the SB 100 Joint Agency Report. Notable differences reflect differences in study assumptions. In particular, through 2032, our study includes about 1 GW more new geothermal and 1 GW more new pumped-storage, consistent with the Mid-Term Reliability Procurement Order since the 2021 SB 100 Joint Agency Report was published and more solar capacity to meet the 38 and 35 MMT CO_2 limits from the Preferred System Plan. In 2035 and beyond, our study assumes NGCC with CCS is available as a dispatchable clean energy source (as a stand-in for one of several possible such technologies), and this displaces a portion of renewables and storage appearing in the SB100 Joint Agency Report. Finally, the scale of our study is slightly smaller, since gridSIM's North and South CA zones encompass only 98% of the CA-wide zone in the SB 100 Joint Agency Report.

This buildout would meet SB 100 goals and maintain reliability, but hinges on some key assumptions. First, it assumes a pace of solar development of more than 2 GW per year, more than twice the historical rate of less than 1 GW per year, as shown on page 23. This may be optimistic given the siting, transmission, and supply chain challenges with deploying greater amounts of solar. Second, it assumes gas-fired capacity can be retained to help with resource adequacy when wind, sun, and hydro are low for days and seasons, beyond battery durations. This is technically feasible, but policymakers must be aware of its necessity. Third, it assumes NGCC with CCS or other new clean dispatchable technologies can fill in for extended periods of low sun and wind starting in 2035. This is perhaps the most optimistic assumption about the future since such resources are not yet commercially available at scale and *provides a conservative basis for estimating Diablo's value*. We consider alternative assumptions at the end of this report.

BASE CASE RESOURCE CAPACITY MIX



Nameplate Capacity (GW)

Base Case Generation Patterns

BENCHMARKING TO THE JOINT STUDY (AND DIFFERENCES)

Generation patterns are similar, corresponding to the similar load and capacity mix as discussed on the prior page. For example, the dispatch of unabated gas-fired generation (without CCS) is very similar, with both studies allowing it to meet losses even in 2045. Notable differences reflect the capacity differences described on the prior page, including this study's addition of new geothermal generation by 2025.

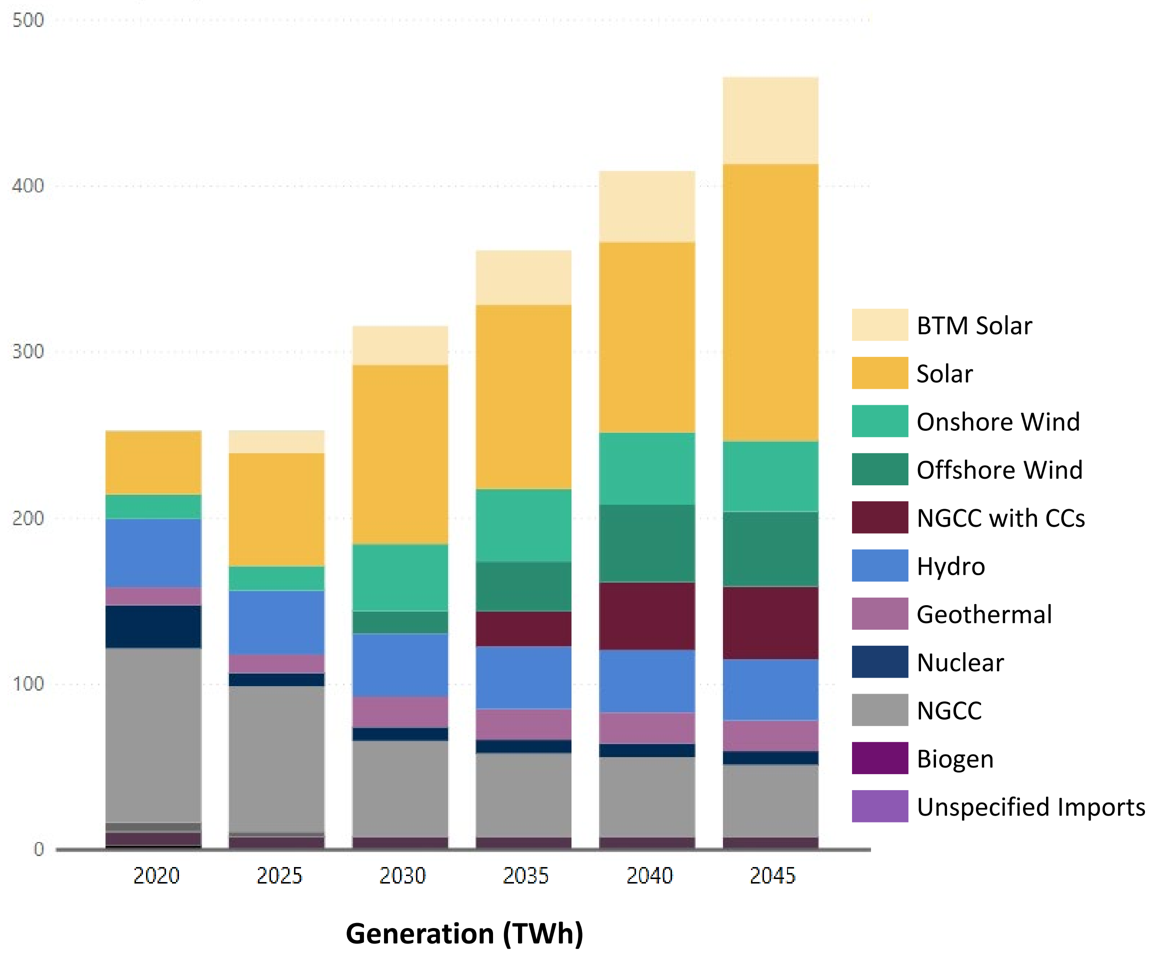
OBSERVATIONS RELEVANT TO ESTIMATING THE VALUE OF DIABLO

Renewable generation tracks renewable capacity, with the greatest growth in solar, but eventually wind and offshore wind. Substantial natural gas-fired generation is still needed to reliably meet energy needs, especially in 2025–2030.

Gas-fired generation is often on the margin at night and sometimes during the day, as shown on the following two pages. Unspecified imports serve a similar role to gas, with a deemed emissions rate similar to that of NGCC.

In the long-term, total clean energy meets the "100%" requirement but a substantial quantity of unabated natural gas-fired generation is still used to meet annual energy lost to transmission and distribution (T&D) and storage inefficiencies under the state's current interpretation of SB 100.

BASE CASE RESOURCE GENERATION MIX



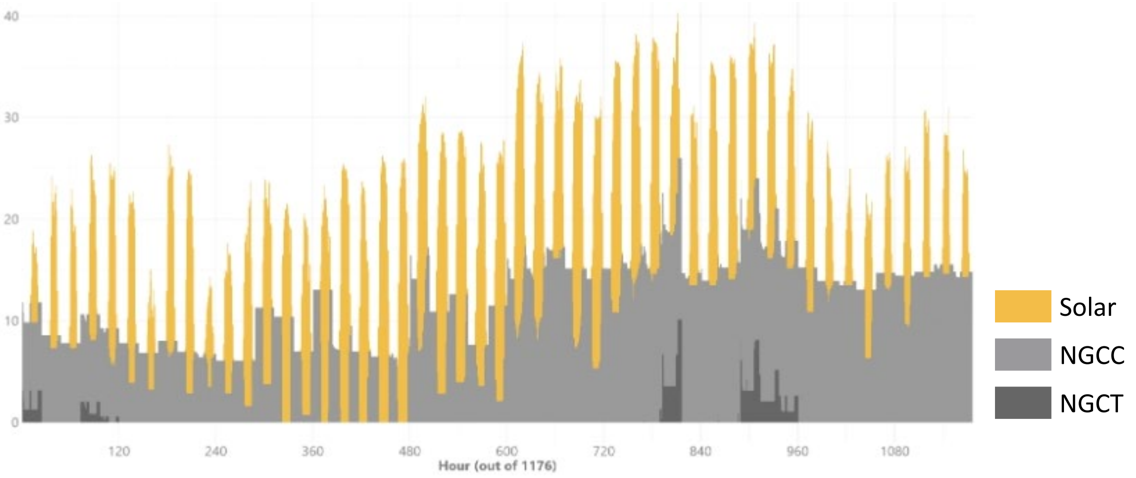
Hourly Generation Patterns

The charts at the right show the chronological hourly generation for the 49 representative days modeled per run year, with 2025 on the top and 2030 on the bottom.

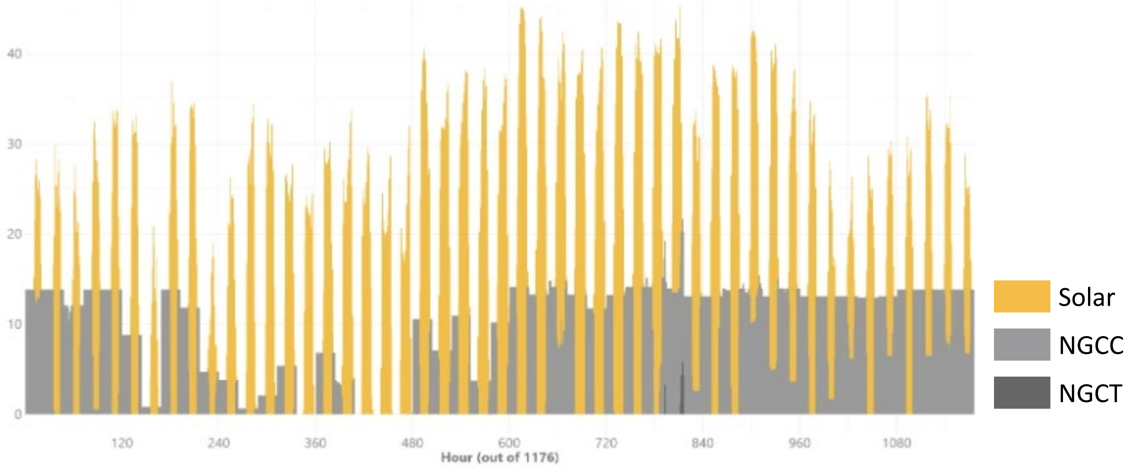
2025 has natural gas-fired generation running all night throughout the year and throughout the day, as well, except on spring days when load is low and solar and hydro are high. In 2030, natural gas-fired generation also runs at night, but usually not during the day. At these times, when NGCCs or simple-cycle natural gas-fired combustion turbines (NGCTs) are running, retaining Diablo will usually displace gas.

Note that this study only partially captures the effect of ramping: It does account for the most important aspect, that gas-fired and other dispatchable resources must pick up when solar declines. It just does not model the need to turn on gas-fired generation earlier due to its ramp rate limits. The next section will discuss why this should have a limited effect on the estimated value of Diablo.

2025 HOURLY GENERATION OF SOLAR AND NATURAL GAS (2025)



HOURLY GENERATION OF SOLAR AND NATURAL GAS (2030)

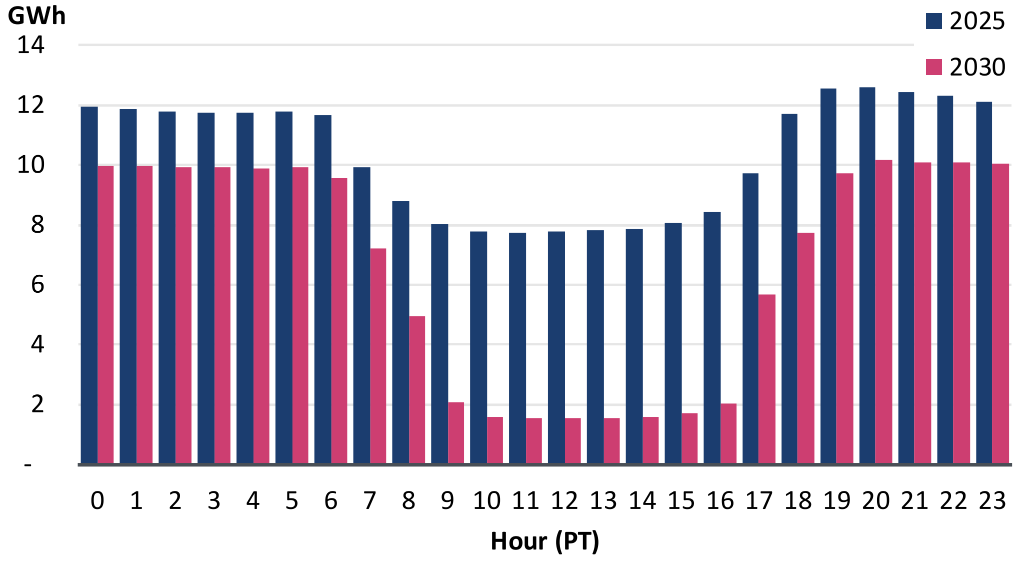


Hourly Generation Patterns (continued)

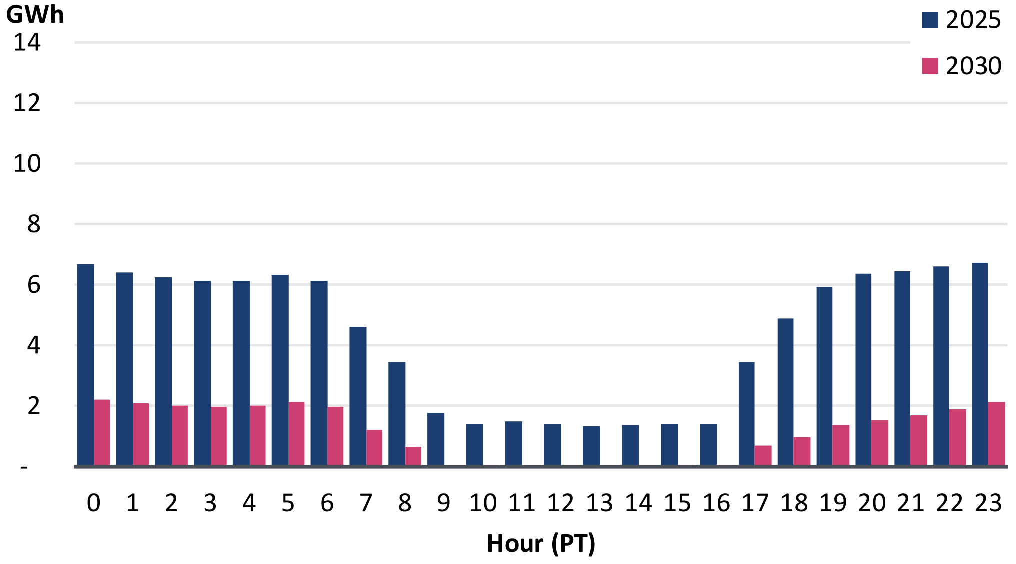
The patterns of natural **gas-fired generation** are displayed differently in the left chart, which shows – for each hour of the day – the average across all days. Again, natural gas runs more at night, but in the day as well. By 2030, the addition of large amounts of solar PV obviate the need for natural gas during the day (except as needed to prepare for ramping to meet the rising need in the evening).

Unspecified imports, as shown in the right chart, follow a similar pattern to natural gas, and these imports, with an average emission rate roughly the same as unabated natural gas generation, also could be displaced by retaining Diablo Canyon.

AVERAGE GAS-FIRED GENERATION, BY HOUR OF THE DAY AND YEAR



AVERAGE UNSPECIFIED IMPORTS, BY HOUR OF THE DAY AND YEAR



Balancing Load and Generation: Managing Short-term Imbalances

Load and generation balancing must occur across multiple timeframes. Short-term imbalances are readily managed.

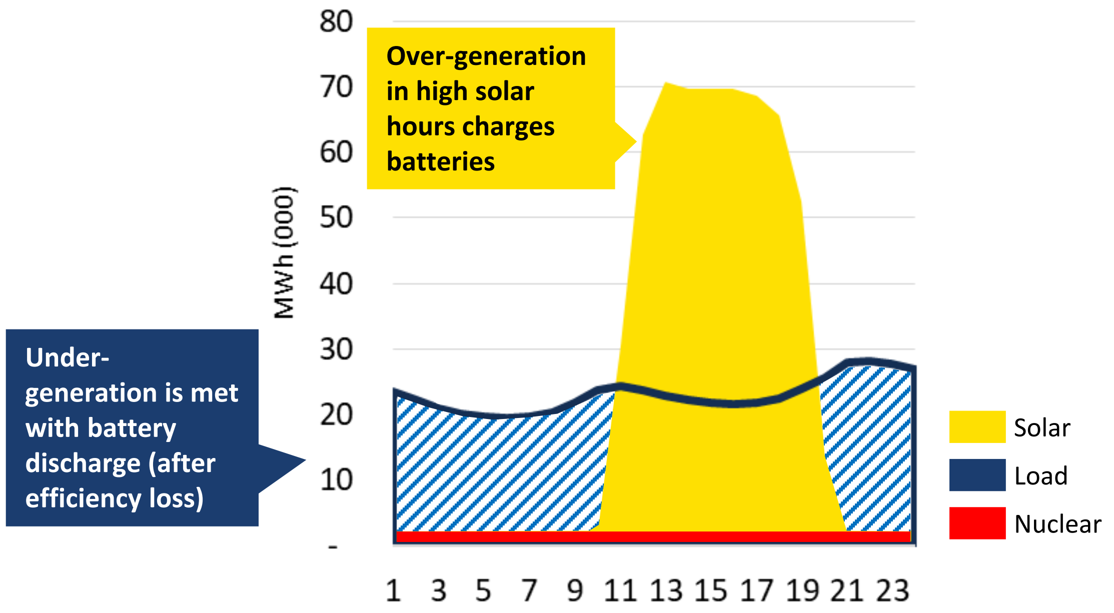
For illustrative purposes, the figure shows a simplified hypothetical solar-dependent system like California’s. It shows a surplus of solar generation relative to the load during the day, and not enough generation at night. To balance the supply across the day, batteries (along with hydro and load flexibility, and some resource diversity between solar and wind) can manage the hour-to-hour mismatch between time-varying load and intermittent generation. Daytime over-generation is shifted to the evening and night.

The amount of energy that must be shifted is relatively limited because of the short duration, and the cost of short-duration storage resources can be spread across many charge-discharge cycles within a year.

Batteries also have good ramping capabilities (as does some hydro), so with sufficient storage capacity, shorter-term imbalances are likely to be manageable, both operationally and economically.

This illustrates the relative easy part of managing a high-renewable system.

SHORT-TERM DAILY BALANCING



SOURCES: Hourly load and solar generation for California ISO, Nov 9, 2020. Hourly CAISO load is shown. A hypothetical solar-dependent system is illustrated. After accounting for Diablo Canyon nuclear generation, hourly CAISO solar output is scaled to provide energy equal to total daily load, plus 15% efficiency loss on stored energy.

Balancing Load and Generation: Challenges of Longer-Term Imbalances

Long periods of low solar and wind will become the biggest challenge.

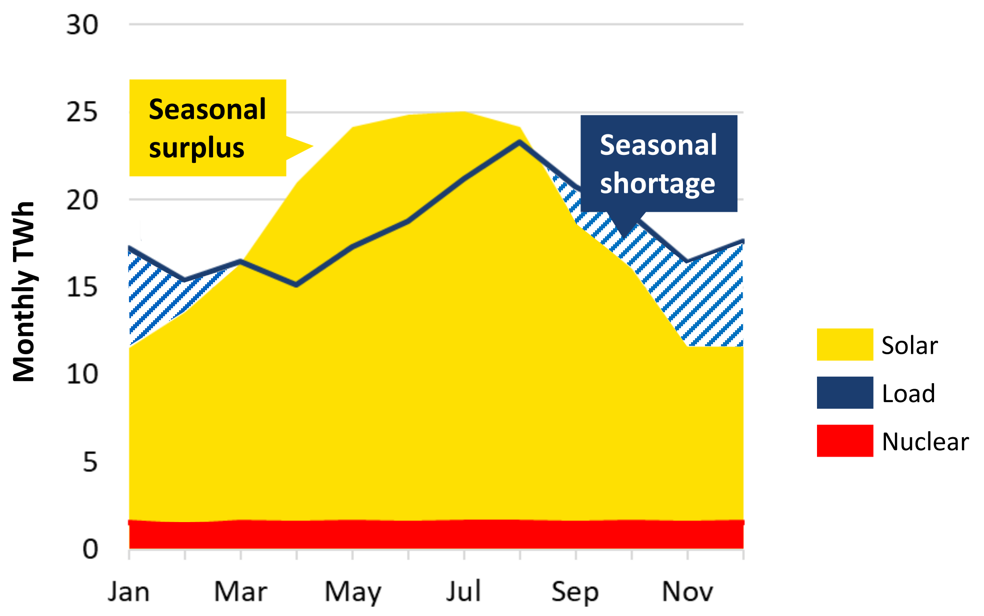
Now consider mismatches that can occur over longer timeframes from multiple days to seasons, using another simplified example of a hypothetical system like California's. As in California, there is a significant mismatch between solar generation and load across seasons. Summer has a solar surplus (despite higher load), but there is a shortage in October through February, when days are shorter, the sun is lower in the sky, and extended cloudy periods are more prevalent. California wind generation is also lower in winter, which does not help with seasonal balancing.

One way to solve this problem would be with a vast solar overbuild with massive seasonal storage of some kind. But current batteries are not suited to managing seasonal variations with their merely few-hours-worth of storage (or even a few days for emerging technologies).

Instead, some form of dispatchable clean energy is likely needed, such as NGCCs that use CCS, renewable natural gas (RNG) or green hydrogen. But these technologies are not yet commercially available at reasonable cost at scale. In addition, their efficiency losses tend to be high. The round-trip efficiency of green hydrogen utilized in NGCC is likely about 30%.

In this context, nuclear generation's non-weather-dependent output could help the system considerably, primarily by limiting the exposure to winter energy shortages.

LONGER-TERM SEASONAL BALANCING



SOURCES: Hourly load and solar generation patterns from California ISO, 2020. Monthly 2020 CAISO load is shown in TWh. After accounting for Diablo Canyon nuclear, monthly CAISO solar output is scaled to provide energy equal to annual load, for illustrative purposes.

Effects of Retaining Diablo

Capacity and Generation Impacts of Retaining Diablo

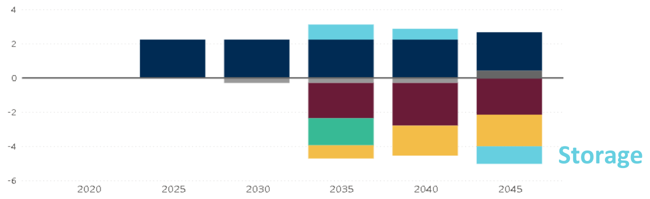
In 2025, when natural gas-fired generation is almost always needed to help meet demand, **Diablo reduces the necessary online capacity and output of gas-fired generators, resulting in emissions reductions. Unspecified imports, with an assumed emissions rate similar to NGCCs, similarly back off**.* It does not displace renewable capacity due to RPS goals and planned procurements that we assume remains unchanged. In turn, renewable generation of clean energy is unaffected.

In 2030, Diablo still displaces some gas-fired generation and imports, especially at night. During the day, Diablo forces some solar and wind curtailment (but not enough to threaten meeting RPS requirements). **From 2035 onward**, Diablo displaces primarily NGCC with CCS (and some solar and wind projects) that are otherwise needed to meet the 35 MMT limit and clean energy goals.

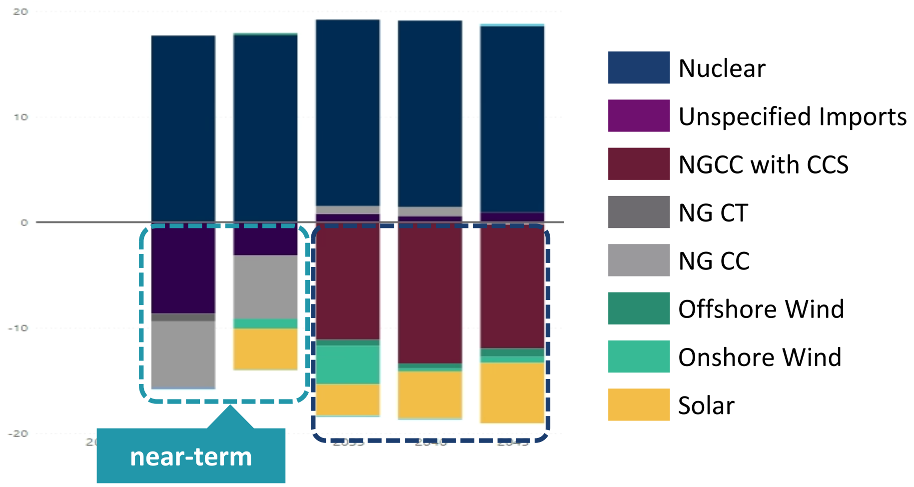
As noted earlier, gridSIM captures the primary effect of ramping needs, where dispatchable resources must pick up as solar output declines. It does not, however, capture secondary effects associated with resources' ramping limits that work in offsetting directions. On the one hand, it does not capture that gas-fired generation that must be turned on and generating the minimum amount they can in order to be stable and to get ahead of ramping needs (particularly before enough battery storage is installed to meet all of the ramping need). The model may thus slightly overstate the amount of gas-fired generation that can be displaced in the afternoons in 2025-30. On the other hand, it also misses the reduction in gas-fired generation that must be committed in 2030 and beyond, when Diablo would force some solar curtailment and thus reduce the ramping need. Since these two missing effects are secondary and would occur in offsetting directions, this study should provide a reasonable indicator of the amount of gas-fired generation that can be displaced.

* Emissions rate for unspecified imports is based on the California Air Resources Board's Mandatory Greenhouse Gas Reporting Regulation, available at: https://ww2.arb.ca.gov/mrr-regulation

CHANGE IN NAMEPLATE CAPACITY (GW)



CHANGE IN GENERATION (TWH)



CO_2 Emissions Savings from Retaining Diablo

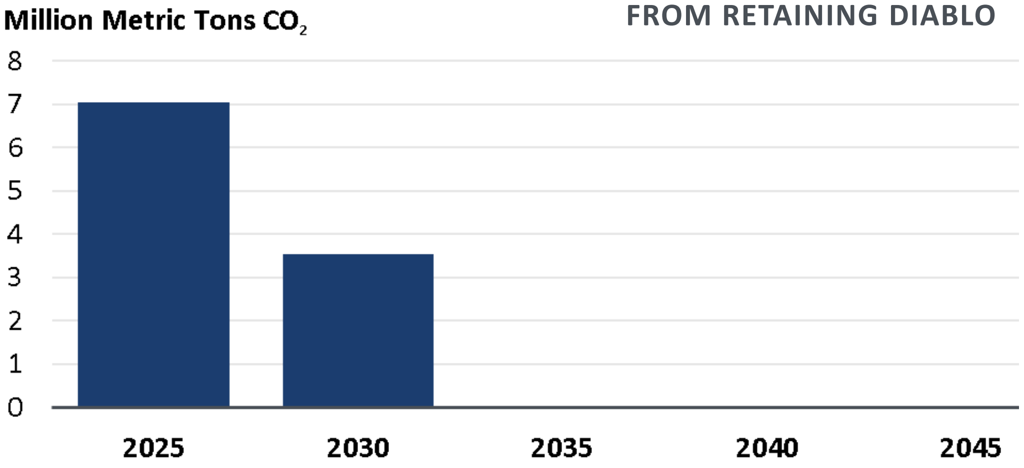
Since we assume Diablo is retained *in addition* to the clean energy and storage procurements already contemplated through 2032, total non-emitting generation increases (as shown on prior pages), displacing gas-fired generation and non-specified imports. This in turn reduces emissions.

Retaining Diablo would thus avoid approximately 7 million metric tons of CO_2 in 2025 and 3.5 million metric tons in 2030. The effect is highest in 2025 when gas-fired generation is more often producing and subject to displacement. Displacement diminishes in 2030 as the fleet decarbonizes further, with the 38 MMT emissions limit and the 60% RPS goal at that time. After 2032, the annual emissions savings impact disappears due to the stringent 35 MMT emissions limit that binds with or without Diablo operating. The binding limit means Diablo displaces other clean energy investment and dispatch (and saves money) while keeping emissions the same. Again, this reflects the study design that allowed clean energy procurements to adjust to Diablo's presence after 2032 but not before, due to RPS goals and already-contemplated procurements until then.

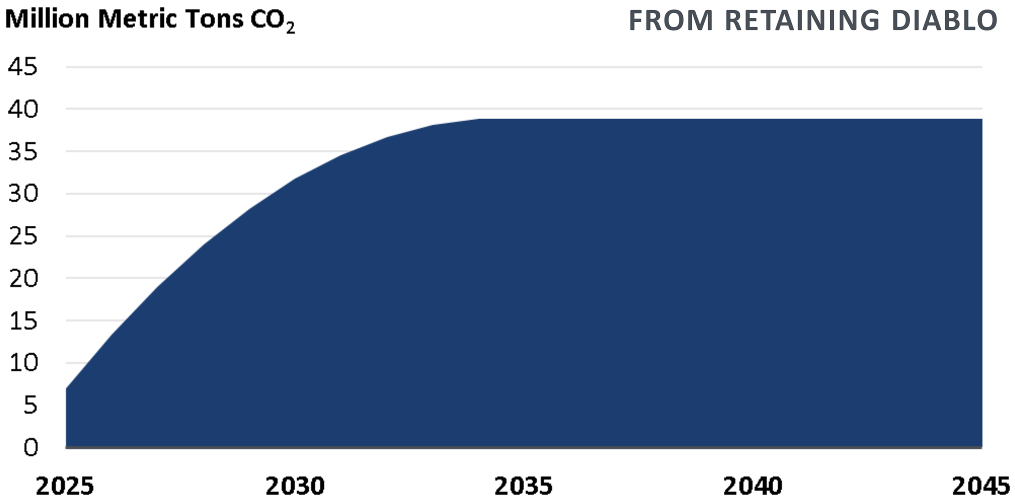
Over its extended lifetime, Diablo leaves a lasting impact of cumulatively reducing emissions by almost 40 MMT. This is comparable to an entire year of California's electric system emissions.

** The cumulative emissions savings chart uses annual emissions savings information that results from interpolating between the annual emissions savings data points displayed in the top chart.*

STATEWIDE ANNUAL EMISSIONS SAVINGS FROM RETAINING DIABLO



STATEWIDE CUMULATIVE EMISSIONS SAVINGS FROM RETAINING DIABLO



Systemwide Cost Savings Impact of Retaining Diablo

Our analysis shows that retaining Diablo Canyon would also save money. Despite an assumed $2 billion assumed capital investment, the future savings would be much greater, resulting in a **$4 billion net present value (NPV) in 2025–45**. This implies that retaining Diablo Canyon would save money even if capital costs were twice the $2 billion assumed.

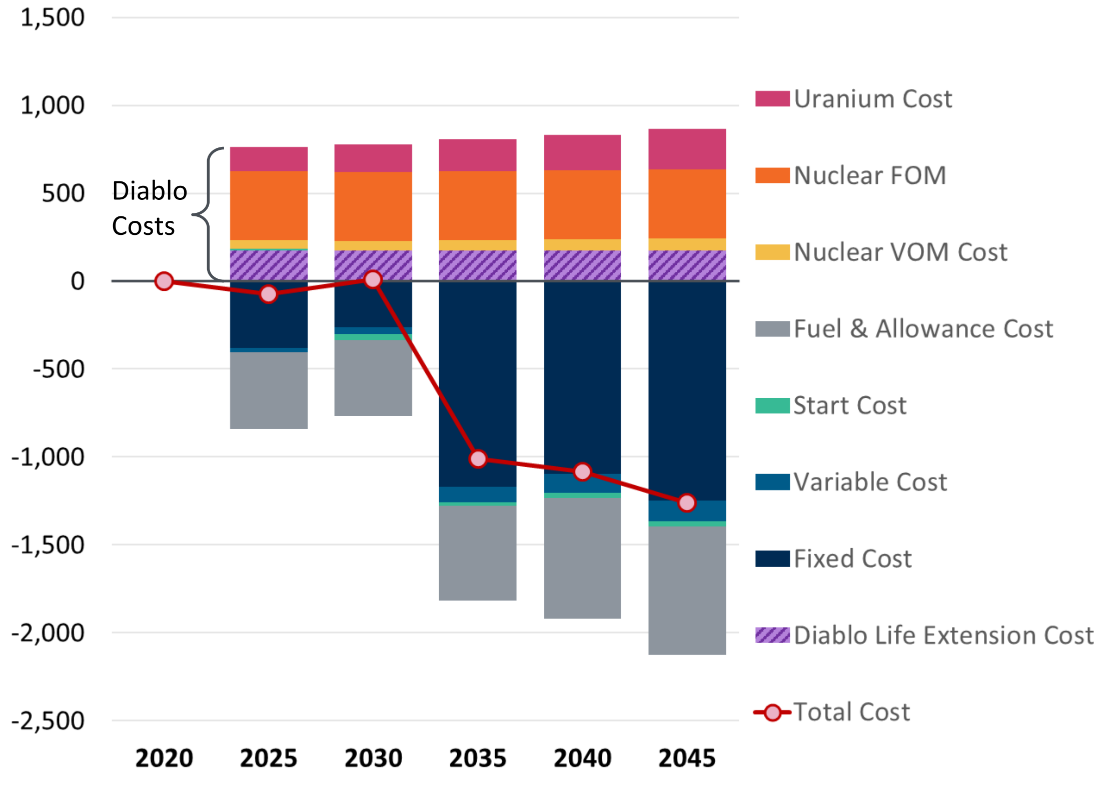
In 2025, the savings derive from burning less natural gas in California and less fuel associated with unspecified imports. Fixed costs also decline, with less investment in other resources (only outside CA due to the assumption that CA procurements are set through 2032). In 2035–2045, savings derive mostly from avoided investment and operating costs for NGCC with CCS.

Note that these calculations do not reflect the details of how customer bills are determined. The presumption is that reductions in variable costs and fixed costs (even if outside California) could be translated to customer value in the long-run through transactions.

These calculations include savings from buying fewer emissions allowances (at assumed prices that grow from \$20/tCO_2 in 2025 to \$70/tCO_2 based on the 2021 SB 100 Joint Agency Report). Savings would be greater if counting a “social cost of carbon” greater than these allowance prices.

** The data in the NPV of cost savings table uses annual cost savings information that results from interpolating between the annual cost savings data points displayed in the top chart.*

ANNUAL DIABLO SYSTEM COST IMPACT



	2023–2035	2023–2045
NPV of Cost Savings ($ millions)*	1,381	4,110

Limited Deployment Scenario

Potential Limitations to Future Clean Energy Deployment

We also assess an alternative scenario in which renewable energy deployment is limited by siting and transmission challenges, and where future dispatchable technologies, such as carbon capture and storage (CCS) and hydrogen-based resources, do not materialize at scale as assumed optimistically in the primary scenario presented on pages [12]-[21].

2GW ANNUAL LIMIT ON SOLAR BUILDS

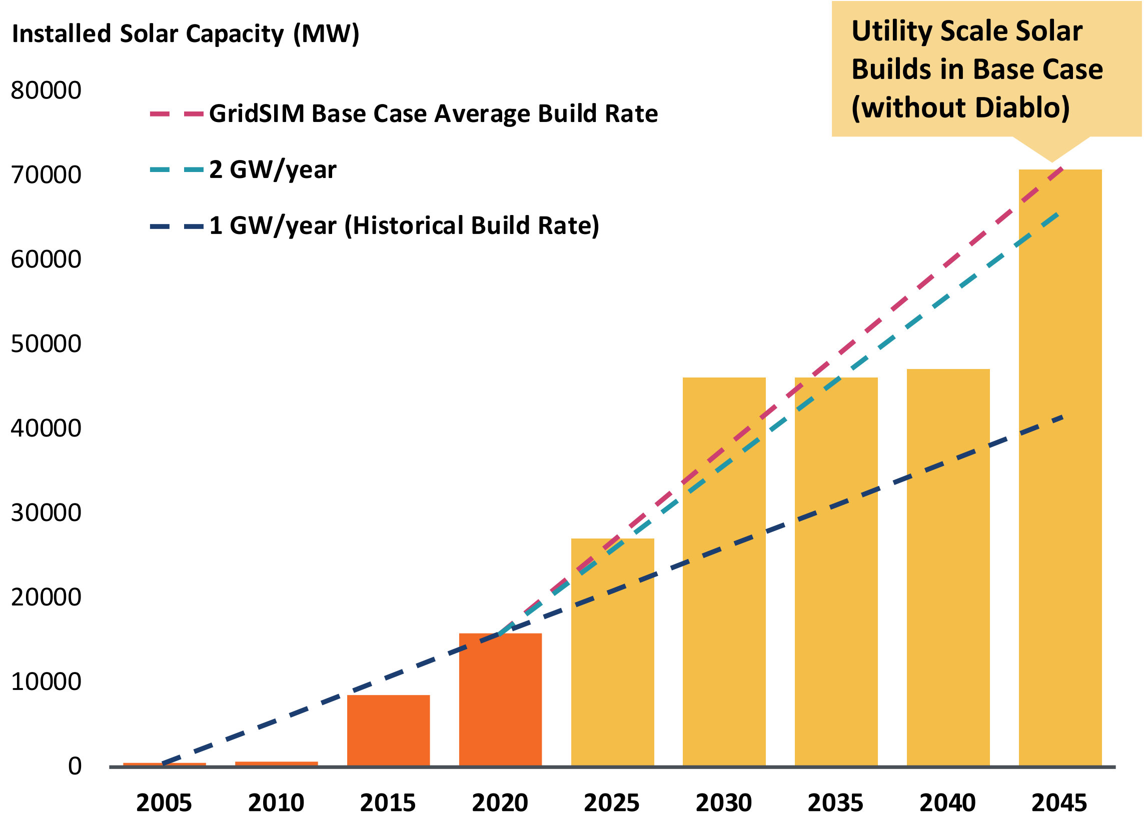
The optimized average annual build rate of solar resources in our base case without Diablo exceeds 2 GW on average. Especially in years in which the emissions limit (2030) and clean energy goal (2045) incentivize aggressive solar deployment, simulated solar capacity growth exceeds 4 GW per year.

This is far greater than the annual historical average rate of solar deployment between 2005–2020 of only 1 GW. In an alternative scenario, we limit solar to be built to twice the average annual historical build rate (2 GW per year). Even this may be optimistic given siting and transmission challenges and current supply chain bottlenecks, including the recent US Department of Commerce's investigation of alleged circumvention of American import tariffs by solar manufacturers. A recent GridLab study highlights the relevance of these concerns and the corresponding value of diverse clean resources.

LIMITED CLEAN TECHNOLOGY DEPLOYMENT

We also assume natural gas CCS and hydrogen-based technologies are unavailable to be deployed as in the Base Case in 2035 and beyond. The implications of this scenario are shown on the next page.

SOLAR DEPLOYMENT IN CA EXPECTED TO GROW AT FASTER RATE THAN AVERAGE HISTORICAL BUILD RATE

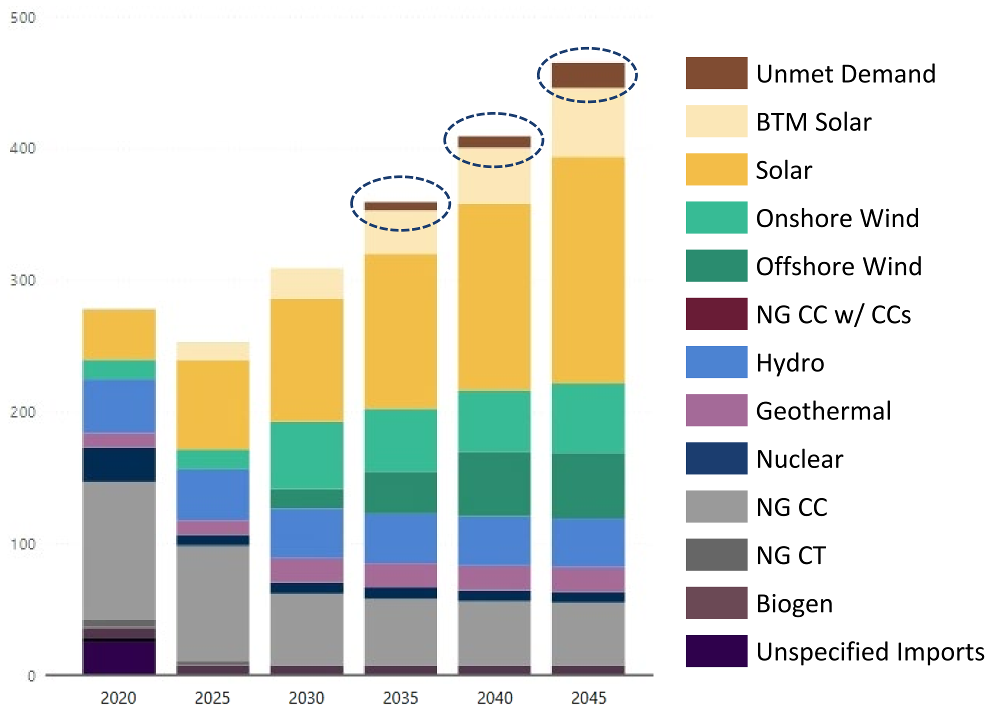


SOURCES: Historical Data from Solar PV and Solar Thermal Electricity Production (Annual Totals; Includes Imports), California Energy Commission

LIMITED DEPLOYMENT SCENARIO

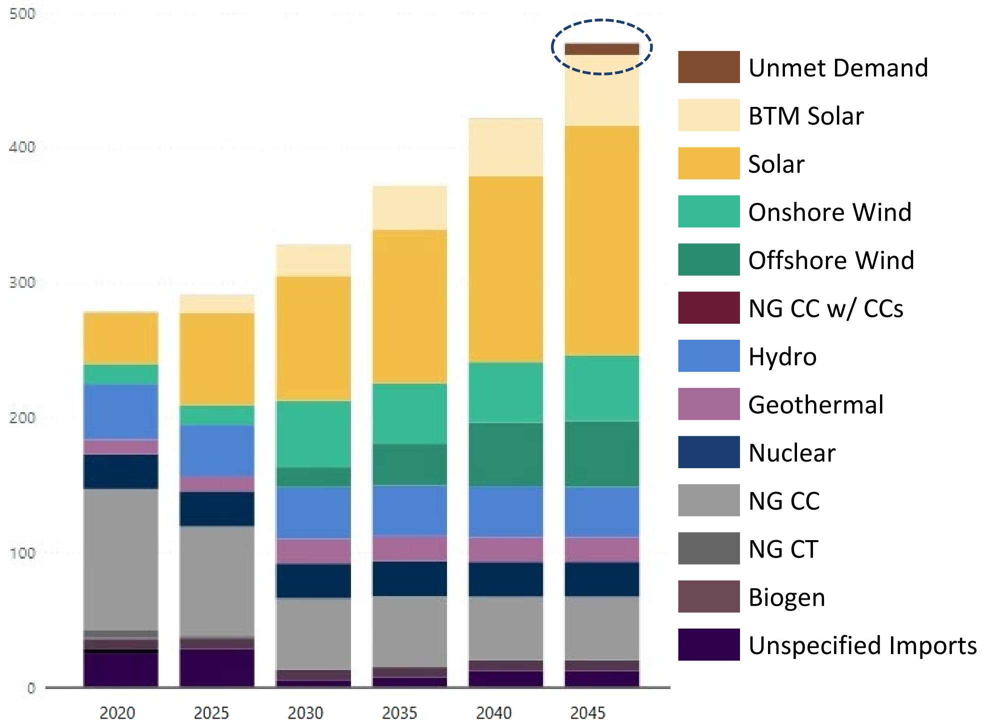
Diablo Canyon's Insurance Value

DIABLO RETIRED



With limited renewable deployment and the absence of CCS and H_2-based technologies—and with Diablo retired—the state would fail to consistently meet both reliability and SB 100 goals starting in **2035**. We note that the chart above contemplates prioritizing SB 100 goals and not serving load, but we could have modeled the opposite scenario, where load is served but clean energy goals are not met because of the need to run additional fossil energy units to maintain reliability.

DIABLO ONLINE



In the Limited Deployment scenario, California would fail to meet its SB 100 goal in 2045 even with Diablo retained. Diablo however helps California **stay on track through 2040** given its capacity to provide 17.7 TWh/yr of firm, clean power. **Diablo helps avoid the uncomfortable choice between shedding load and shedding SB 100 goals in the event that renewables and new technologies do not fully materialize as optimistically assumed.**

Accelerated Clean Grid Scenario

Diablo Could Help Accelerate Achievement of State Clean Grid Goals by 2035

We also assessed the impact of Diablo Canyon in an alternative scenario in which California decides to accelerate achievement of SB 100 goals in 2035 rather than 2045 – ten years earlier than current law.

SCENARIO ASSUMPTIONS

The base case used for this scenario was the same as for the previous analysis – including unconstrained deployment of onshore wind (and assumed aggressive offshore wind deployment), solar, and other zero carbon technologies, and Diablo offline – but with a requirement that the SB 100 target be achieved by 2035. We then examined the impact of allowing Diablo to remain online (*we do not fix procurement plans through 2032 as they would have to flex to meet the more ambitious goals*).

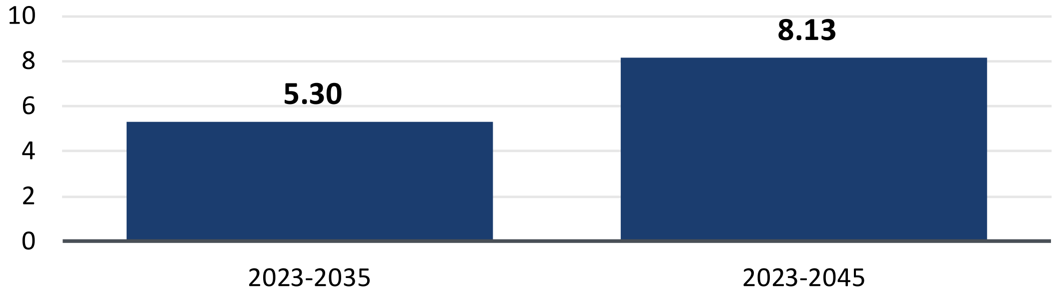
COST SAVINGS

As shown in the upper figure at right, **leaving Diablo Canyon available would reduce the net-present cost of achieving the zero carbon target in 2035 by $5 Billion**, with a further NPV savings of $3 Billion from 2035-2045. This is largely due to the faster displacement of more expensive unabated gas, the avoidance of gas CCS, and of more expensive solar and onshore wind.

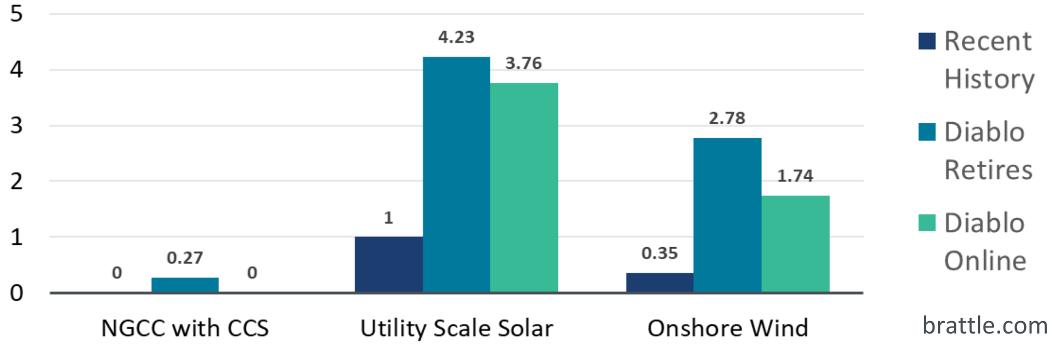
INCREASING FEASIBILITY OF ACHIEVING THE GOAL

With Diablo offline, meeting a 2035 zero emissions target would require the deployment of NGCC with CCS in 2035 as well as a challenging level of annual deployment of solar (at more than four times current annual levels) and onshore wind (at more than five times current annual deployment levels). Keeping Diablo online, however, lowers the challenge by eliminating the need for NGCC with CCS by 2035, and lowering the maximum annual build rate of solar by 11% and onshore wind by nearly 40%. This would give California more time to ramp up from its current low deployment rates to much faster ones, making a successful outcome more likely.

CUMULATIVE SAVINGS FROM RETAINING DIABLO IN THE 2035 ATTAINMENT SCENARIO ($BILLION NPV)



MAXIMUM BUILD RATES FOR VARIOUS TECHNOLOGIES 2023-35, FOR A 2035 SB 100 GOAL ATTAINMENT VERSUS RECENT AVERAGE BUILD RATES (GW/YR)



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