DOCKETED	
Docket Number:	22-IEPR-01
Project Title:	2022 Integrated Energy Policy Report Update
TN #:	242820
Document Title:	Ryan Pickering Comments - Publication - Assessment of the Diablo Canyon Nuclear Plant - Stanford University
Description:	N/A
Filer:	System
Organization:	Ryan Pickering
Submitter Role:	Public
Submission Date:	4/26/2022 12:57:41 PM
Docketed Date:	4/26/2022

Comment Received From: Ryan Pickering
Submitted On: 4/26/2022
Docket Number: 22-IEPR-01

Publication - Assessment of the Diablo Canyon Nuclear Plant - Stanford University

Hello EIPR 01 Team,

My name is Ryan Pickering. I am an energy policy researcher living in Berkeley, CA. The crux of my research is related to Diablo Canyon Power Plant.

Attached is a November 2021 report published by Stanford University entitled "An Assessment of Diablo Canyon Nuclear Power Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production.

The file size was too large (113 pages), so I have reduced the report to the introduction and Chapter 1. The entire document can be found at free online: https://energy.stanford.edu/sites/g/files/sbiybj9971/f/diablocanyonnuclearplant_report_11.19.21.pdf

I have reviewed this document over the past few months. Through my own research, I concur that the plant is economically viable today, and the matter merits further investigation by the CEC.

Chapter 1 is the most compelling (pages 13-31). Later chapters introduce auxiliary ideas that are not necessary to the continued operation.

This is the first of a few documents that I am planning to upload over the next few weeks. I apologize I have not written sooner.

I heard rumors that the Governor plans to change his mind about Diablo Canyon Power Plant. As a citizen, I want to make sure we have a public paper trail so that Californians may stay informed.

I have observed indicators of the necessary public support required for the continued operation of this plant at the local, state and federal level.

Thank you for your public service,

Ryan Pickering

P.S. The "Subject(s)" link on your webform does not appear to be functioning. The link to "select one or more" does not compute.

In the spirit of transparency, I will be sharing this document with IEPR 1-3.

Additional submitted attachment is included below.

An Assessment of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production

Justin Aborn, LucidCatalyst, LLC

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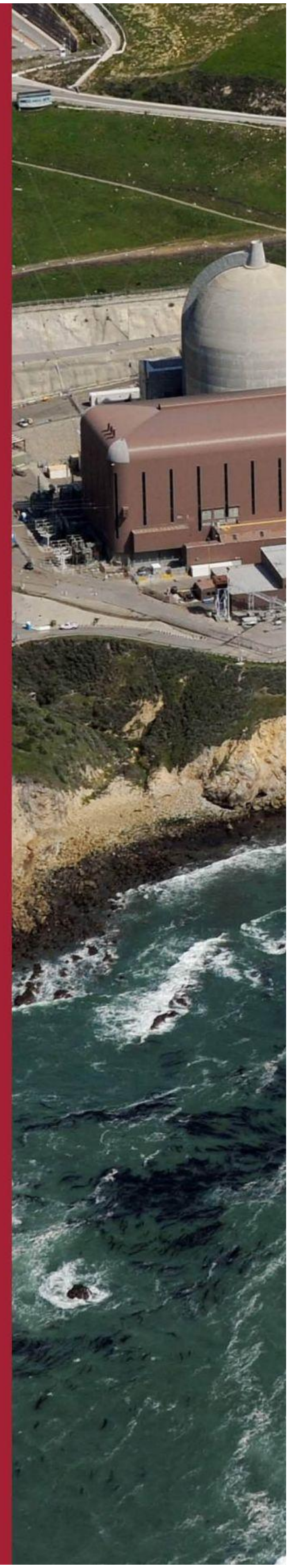

NOVEMBER 2021

Authors and Acknowledgements

Justin Aborn is a Senior Consultant at LucidCatalyst, LLC, and performed the analysis in and wrote Chapters 3 and 4.

Ejeong Baik is a Ph.D candidate in the Department of Energy Resources Engineering at Stanford University, and led the analysis and writing in Chapter 1 on electricity.

Sally Benson is Professor of Energy Resources Engineering at Stanford University, and contributed to Chapter 1 analysis and co-led overall report conceptualization and editing.

Andrew T. Bouma is a Ph.D. candidate in the Department of Mechanical Engineering at the Massachusetts Institute of Technology, and performed the desalination technology analysis in Chapter 2.

Jacopo Buongiorno is the TEPCO Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology (MIT), Director of the MIT Center for Advanced Nuclear Energy Systems, and Director of Science and Technology at the MIT Nuclear Reactor Laboratory, and led the overall analysis in Chapter 2, and co-led overall report conceptualization and editing.

John H. Lienhard V is the Abdul Latif Jameel Professor of Water and Mechanical Engineering at MIT and Director of the Abdul Latif Jameel Water and Food Systems Lab, and supervised the water and desalination technology analysis in Chapter 2.

John Parsons is Senior Lecturer, MIT Sloan School of Management, and Associate Director of the Center for Energy and Environmental Policy Research, and led the economic analysis in Chapter 2 and contributed to economic analysis throughout the report.

Quantum J. Wei is a Ph.D. candidate in the Department of Mechanical Engineering at the Massachusetts Institute of Technology, and performed the desalination technology analysis in Chapter 2.

Disclaimer: The views and opinions expressed in this report are those of the authors and do not necessarily reflect the official policy or position of the organizations they are affiliated with.

The authors acknowledge substantial contributions to this report from Jeffrey Koseff, William Alden and Martha Campbell Professor of Engineering at Stanford University, and Hunter Johnson, MS student, Civil and Environmental Engineering Department at Stanford University.

The authors wish to acknowledge funding for this project from the MIT Center for Energy and Environmental Policy Research, the Abdul Latif Jameel Water and Food Systems Lab, the MIT Center for Advanced Nuclear Energy, the Rothrock Family Fund, the Pritzker Innovation Fund, The Rodel Foundation, Ross Koningstein, and Zachary Bogue & Matt Ocko.

Table of Contents

Executive Summary

Key study findings:

➔ **Delaying the retirement of Diablo Canyon to 2035** would reduce California power sector carbon emissions by more than 10% from 2017 levels and reduce reliance on gas, save $2.6 Billion in power system costs, and bolster system reliability to mitigate brownouts; if operated to 2045 and beyond, Diablo Canyon could save up to $21 Billion in power system costs and spare 90,000 acres of land from use for energy production, while meeting coastal protection requirements.

➔ **Using Diablo Canyon as a power source for desalination** could substantially augment fresh water supplies to the state as a whole and to critically overdrafted basins regions such as the Central Valley, producing fresh water volumes equal to or substantially exceeding those of the proposed Delta Conveyance Project—but at significantly lower investment cost

➔ **A hydrogen plant connected to Diablo Canyon could produce clean hydrogen** to meet growing demand for zero-carbon fuels, at a cost up to 50% less than hydrogen produced from solar and wind power, with a much smaller land footprint

➔ **Operating Diablo Canyon as a polygeneration facility**—with coordinated and varying production of electricity, desalinated water, and clean hydrogen—could provide multiple services to California, including grid reliability as needed, and further increase the value of the Diablo Canyon electricity plant by nearly 50% (and more, if water prices were to substantially increase under conditions of worsening drought).

In January 2018, the California Public Utilities Commission approved a multiparty settlement to fully and permanently shut down the Diablo Canyon nuclear power plant when the current federal license period for the plant's second unit expires in 2025. Diablo Canyon currently provides 8% of California's in-state electricity production and 15% of its carbon-free electricity production. In its decision, the Commission found that the plant was not cost effective to continue in operation, that it was not needed for system reliability, and that its value for reducing greenhouse gas emissions was unclear. But in the intervening three and half years, several new developments have occurred:

- In September 2018, the California Assembly and Senate approved and then-Governor Edmund G. Brown, Jr. signed Senate Bill 100, which requires California to supply all electricity in the state from zero-carbon sources. In the same month, Governor Brown signed Executive Order B-55-18, directing the state to achieve climate neutrality, also by 2045.
- A variety of studies have emerged in the last year suggesting that two essential pillars of achieving a zero-carbon economy at affordable cost include (i) significant electrical capacity that is always available and not weather dependent, and (ii) a reliable and low-cost source of

zero-carbon fuels, such as hydrogen, for portions of the economy that cannot be easily electrified.
- In August and September 2020, California experienced a series of challenges to statewide electric reliability, encountering blackouts and brownouts as available electrical capacity fell below demand, a condition that is likely to recur during this decade.
- There is mounting evidence that, due to climate change and other factors, California faces increasing danger of severe water shortages, as evidenced by the most recent Emergency Drought Proclamation of May 2021.
- California has committed to increasing the share of lands set aside for conservation purposes to 30% of the total area of the state, which underscores the imperative of limiting use of land for energy production and other industrial purposes.

These developments led a joint study team from Stanford University and the Massachusetts Institute of Technology to re-examine the potential value of Diablo Canyon in addressing some or all of these overlapping challenges in the coming decades. (The study team was assisted on hydrogen and multiple product research by Justin Aborn at LucidCatalyst, an energy analysis firm).

The study team analyzed:

- The potential contribution of Diablo Canyon to achieving the state's zero-carbon goal for the electricity sector and its overall economic goals for 2030 and 2045 at lower cost, maintaining reliability at lower cost, supporting grid integration of variable energy, and limiting carbon dioxide emissions during the transition.
- The potential for Diablo Canyon to serve as an effective low-cost, zero-carbon energy source to power desalination to provide fresh water to water-stressed areas of the state.
- The potential for the nuclear plant to provide low-cost, zero-carbon hydrogen for California's transportation, industrial, and commercial building sectors, as well as for thermal balancing in the state's electric system.
- The value of the plant if it were configured to provide a mixture of grid electricity, hydrogen, and desalinated water throughout the year, operating as a "polygeneration" facility that could also provide reliability services to the grid.

The team's analysis in all cases accounted for additional capital and operating costs necessary for Diablo Canyon to meet legal requirements for the protection of marine life, as well as the cost of modifications to the plant and other facilities needed for the production of hydrogen and desalinated water.

The key conclusions of the report include:

- **The near-term value of Diablo Canyon for zero-carbon electricity (2025-2035)**
  Even assuming rapid and unconstrained buildout of renewable energy, the continued operation of Diablo Canyon would significantly reduce California's use of natural gas for electricity production from 2025 to 2035 by approximately 10.2 TWh per year. In doing so, Diablo Canyon would also reduce California carbon emissions by an average of 7 Mt CO_2 a year from 2025-2035, corresponding to an 11% reduction in CO_2 from the electricity sector relative to 2017 levels, for a cumulative total of 35 Mt CO_2 from 2025-2030 alone. Maintaining Diablo Canyon to 2035 would also save $2.6 Billion in power system costs from 2025-2035. During this period, Diablo Canyon would also provide firm electric capacity, which would be especially valuable during electric reliability events such as those that occurred in August 2020, when the absence of Diablo Canyon would have tripled the state's electricity shortage from 1 GW to more than 3

GW.

- **The longer-term value of Diablo Canyon for zero-carbon electricity (to 2045 and beyond)**
  Over the longer term, and even assuming that siting of new renewable energy was unconstrained by land use or other considerations, keeping Diablo Canyon online would save the state $15-16 Billion. In addition, continuing Diablo Canyon in operation to 2045 and beyond would spare 90,000 acres of land by avoiding the need for 18 GW of solar PV. If siting of new PV were constrained by land use considerations to a total of 60 GW (consistent with recent annual deployment rates), savings from Diablo Canyon would grow to $21 Billion. Even if the emissions cap for the electricity system were to be replaced by a carbon tax, Diablo Canyon could save as much as 50 Mt CO_2 in cumulative emissions through 2045.

- **The value of Diablo Canyon to produce fresh water**
  Desalination could be used to augment water supplies throughout the central portion of the state, particularly in critically overdrafted basins and low-level reservoirs, as well as during years when aqueduct delivery falters. This study finds that Diablo Canyon could be a powerful driver of desalination to serve urban, industrial, and agricultural users.

  The report shows that a plant equal in size to the currently operating Carlsbad desalination plant would have a roughly 50% lower cost of water at Diablo Canyon. Significantly larger plants that could be constructed on the site are shown to produce water volumes in the same range as the proposed Delta Conveyance Project, but at significantly lower investment cost.

  Cost savings result from a variety of factors. At smaller scales, savings result primarily from reduced power cost inputs for the desalination operation and the sharing of intake and existing outfall structures, At larger plant capacities, there is potential for additional cost savings from economies of scale. However, at larger capacities, other challenges arise, including increased infrastructure needs, especially around plant outfall, as well as practical challenges of siting and building a very large plant on the premises.

  This study finds that Diablo Canyon could power a desalination complex between the size of the Carlsbad plant or up to 80 times the output of the Carlsbad plant. The levelized cost of water from these options falls in a range from $0.77 to $0.98 per m^3 ($952 to $1,207 per acre-foot) of fresh water at the plant outlet, with distribution costs adding an additional $0.02 to $0.21 per m^3 ($27 to $260 per acre-foot) to transport the water to offtakers at distances from 20-185 km. For comparison, the cost to build additional Carlsbad-sized plants in California as stand-alone desalination plants is approximately $1.84 per m^3 ($2,270 per acre-foot) of fresh water at the plant outlet, roughly twice as much.

- **The value of Diablo Canyon as a source of low-cost hydrogen**
  To achieve a zero-carbon economy, California will likely need hundreds of millions of kilograms of hydrogen-based, zero-carbon fuels annually. Hydrogen is currently produced from unabated natural gas, which results in significant carbon emissions. As with renewables, producing hydrogen from nuclear energy results in no carbon emissions. The preliminary analysis here suggests that, with heat-assisted electrolysis, Diablo Canyon could produce 110 million kilograms of hydrogen annually at a cost of $2.01-2.46/kg. This is up to half less than the range of current costs of hydrogen produced from solar or wind power, while utilizing a small fraction of the space required for those other generation sources. Hydrogen production at the Diablo Canyon site would also likely be cost-competitive with the hydrogen produced from natural gas

with carbon capture, today's least expensive form of zero carbon hydrogen production.

- **The value of Diablo Canyon in providing multiple outputs**
  Our analysis also considered the potential to repurpose the nuclear plant to provide multiple products simultaneously—grid electricity, desalinated water, and hydrogen. The analysis concludes that production of these three products could substantially increase the value of Diablo Canyon equivalent to $70/MWh, a substantial premium over the blended polygeneration plant's blended power costs of $54/MWh. If the price of California water increases substantially as global warming and drought continue, the blended revenue and value from the plant could run much higher, equivalent to $82-104/MWh. These values ignore the potential for additional revenue by marketing capacity services to the California grid. In a polygeneration configuration, the electricity output of Diablo Canyon plant could be directed to provide varying amounts of electricity to the power grid, desalination or hydrogen production, respectively, to maximize revenue, provide grid reliability, or meet other objectives, as needed.

- **Meeting the requirements of California's coastal protection policy**
  The California Water Quality Control Policy on the Use of Coastal and Estuarine Water for Power Plant Cooling requires that existing power plants using once-through cooling decrease their intake flow rate by 93% to reduce impingement and entrainment of marine life. If that is not feasible, plants may instead implement measures that achieve the same result. If neither option is possible, alternative steps may be available, on a case-by-case basis, to allow nuclear power plants to comply. This regulatory policy is the primary technical reason for the impending shutdown of Diablo Canyon, as the cost of meeting this requirement was thought to be prohibitive. The assumed approach was to construct a submerged intake gallery below the surface of the ocean floor, and use the sand and sediments on the ocean floor as a natural filter to ensure that marine life does not enter the intake. However, this approach poses both significant costs and environmental challenges. As a feasible alternative, this study proposes—and examines in depth—the use of mechanical brush-cleaned wedgewire screens, which will be substantially less costly. Similar intake systems have been specified for the Huntington Beach desalination plant, and are currently being tested at Carlsbad as a potential replacement for the existing intake.

Why is a re-examination of Diablo Canyon called for? Given that the plant is scheduled to close, it may seem straightforward to simply allow that process to run its course. And, indeed, this analysis outlines in detail the many and considerable challenges to maintaining Diablo Canyon and repurposing it to achieve the goals described in the following pages. At the federal level, the plant relicensing process would have to be reinitiated. Chief among the challenges at the state level is the need to obtain approval of a newly engineered water intake system (as is described in this report), as well as the licensing of brine discharge from the desalination process. Approvals will also be required for construction of adjacent or distributed desalination plants, hydrogen electrolysis facilities, and associated pipes and transmission wires. Stakeholders who were part of the settlement leading to the closure of the plant would need to be re-engaged, and there will also likely be opposition in principle among some to the use of nuclear energy in any form, for any purpose.

While these challenges are substantial, so are the potential gains. This preliminary analysis is intended to allow policymakers and the public to consider weighing the benefits and tradeoffs associated with maintaining or rededicating Diablo Canyon in light of other new and urgent challenges that face California: achieving a livable climate and the mandate for a zero-carbon economy under SB 100 and

Executive order B-55-18, providing affordable and reliable electric and non-electric energy, furnishing adequate fresh water in a world of growing water stress, and reducing pressure on California's limited land resources.

This study was not intended to be and should not be considered to be a definitive analysis of those benefits and tradeoffs. That will require further investigation. But the authors submit that the conclusions of this report present sufficient grounds for further study and debate by setting forth a prima facie case for extending the operations of the Diablo Canyon nuclear plant.

Introduction:

Context and motivation for this analysis

Background on Diablo Canyon

The Diablo Canyon Nuclear Power Plant (Diablo Canyon) comprises two identical units (Westinghouse 4-loop pressurized water reactor design) with a combined power output of 2240 MW_e. Diablo Canyon is located near Avila Beach on the Central Coast of California, and is owned and operated by Pacific Gas and Electric Company (PG&E). The facility directly employs some 1,500 workers with an annual payroll of about $226 million. It pays an estimated $26.5 million in state and local taxes annually. Diablo Canyon started commercial operations in the mid-1980s. Its Nuclear Regulatory Commission (NRC) licenses are set to expire in 2024 (Unit 1) and 2025 (Unit 2).

Both units are currently in the so-called Column 1 of the NRC Action Matrix, i.e., there are no ongoing nuclear regulatory issues. Each unit runs nearly continuously, except for an outage of 2-4 weeks every 18 months during which the reactor is shut down for refueling and maintenance. The 3-year-average capacity factor for Diablo Canyon is about 90%. The Diablo Canyon generation cost is about $40/MWh (including fuel, O&M, and Capex)[1]; thus we estimate that the plant is an economically viable electricity generator in the CA market at the present time and would likely remain so for the foreseeable future.To date the plant has been operated to provide baseload to the grid, although the plant design and license can accommodate more flexible operation including load following. The economic analysis in the report explores this option.

In November 2009 PG&E applied to the NRC for a 20-year license extension of Diablo Canyon beyond its initial expiration date of 2024-2025. The review was prolonged by post-Fukushima regulatory changes and by specific concerns about the seismic risk of Diablo Canyon, both of which were resolved.[2] Separately, in order to continue operating the plant, PG&E would have to make a significant investment to bring it into compliance with California water cooling regulations.

The license renewal process was ultimately interrupted by a 2016 decision to close the plant, as further described below. PG&E formally withdrew the application in March 2018.

Nearly all nuclear power plants in the US have obtained a 20-year license renewal from the NRC. From receipt of an application to a decision on license renewal, NRC staff conducts reviews in less than 22 months (longer if there was an adjudicatory hearing).[3] If resumed, review of the Diablo Canyon license renewal might very well be even shorter given that a large fraction of the review has already been performed in 2009-2018. We note that, if at the expiration of its current license the NRC is still reviewing the application, the plant can continue to operate until the NRC completes its review.

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[1] PG&E Co., FERC Form 1 (2016, 2017, 2018, 2019, 2020), https://www.ferc.gov/industries-data/electric/general-information/electric-industry-forms/form-1-electric-utility-annual.

[2] US Nuclear Regulatory Commission, "Diablo Canyon Power Plant, Unit Nos. 1 and 2 –Documentation of the Completion of Required Actions Taken in Response to the Lessons Learned from the Fukushima Dai-Ichi Accident (letter dated May 8, 2020 from Robert J. Bernardo, NRC, to James M. Welsch, PG&E), https://www.nrc.gov/docs/ML2009/ML20093B934.pdf.

[3] US Nuclear Regulatory Commission, "Reactor License Renewal Process," n.d., https://www.nrc.gov/reactors/operating/licensing/renewal/process.html.

One question about Diablo Canyon's license extension is related to seismic risk. The plant is sited in a generally high-seismic-risk area (most of California is very seismic), and also there is a fault line that runs near the plant. Of course, Diablo Canyon was designed and licensed for this particular site. After the Fukushima accident in 2011, all nuclear power plants in the US, including Diablo Canyon, were asked to re-evaluate their seismic and flooding risks. We reviewed the latest NRC documentation on Diablo Canyon's seismic risk. This is summarized in a very recent NRC letter,[4] which concludes that PG&E has demonstrated the plant's capacity to withstand the types of seismic hazards re-evaluated after Fukushima. No further actions have been required by the NRC.

In summary, we anticipate that there will be no nuclear regulatory or safety impediments to continuing the operation of Diablo Canyon beyond 2024-2025. The impending shutdown of Diablo Canyon, then, is driven mainly by policies regarding once-through cooling for power plants.

The cooling intake issue

The California Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling[5] is designed to protect marine organisms from power plant intakes. In order to comply with the legislation, power plants must either reduce their cooling water intake by 93% compared to the designed flow rate or implement other operational or structural changes to reduce impingement and entrainment mortality to a comparable level. In 2011, PG&E commissioned a study by Bechtel to investigate options that would bring Diablo Canyon into compliance with this legislation. Bechtel examined a number of options, including forced and passive wet and dry air cooling, which would have reduced the water intake of the plant, and two types of screened intakes, which would not have reduced water flow but would have reduced impingement and entrainment mortality.[6] PG&E chose not to move forward with any of the options examined at the time.

The Closure Settlement

In January 2018, the California Public Utilities Commission approved a multiparty settlement to permanently shut down the Diablo Canyon Nuclear Power Plant when its current federal license period expires in 2025.[7] In its decision, the PUC recited the following "findings of fact":

1. Continuing operation of Diablo Canyon Unit 1 beyond 2024 and Unit 2 beyond 2025 would require renewal of NRC licenses, and would not be cost effective.
2. The retirement of Diablo Canyon will not cause adverse impacts on local or system reliability.

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[4] US NRC, "Diablo Canyon Power Plant, Unit Now 1 and 2, Documentation of the Completion of Required Actions Taken in Response to the Lessons Learned from the Fukushima Dai-Ichi Accident," https://www.nrc.gov/docs/ML2009/ML20093B934.pdf

[5] "Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling," 23 California Code of Regulations (CCR) § 2922 (May 4, 2010, as amended through Nov. 30, 2020) (implementing federal Clean Water Act § 316(b) (33 USC § 1326(b)), https://www.waterboards.ca.gov/water_issues/programs/ocean/cwa316/policy.html.

[6] Bechtel Power Corp., "Alternative Cooling Technologies or Modifications to the Existing Once-Through Cooling System for Diablo Canyon Power Plant," Rept. No. 25762-000-30H-G01G-0001 (Sept. 17, 2014), https://www.waterboards.ca.gov/water_issues/programs/ocean/cwa316/rcnfpp/docs/bpc091714_1.pdf.

[7] California Public Utilities Commission, "Decision Approving Retirement of Diablo Canyon Nuclear Power Plant," No. 18-01-022 (Jan. 11, 2018, issued Jan. 16, 2018), https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M205/K423/205423920.PDF; see California Public Utilities Commission, Proposed Decision of ALJ Haga, "Application of Pacific Gas and Electric Company for Authorization to Establish the Diablo Canyon Decommissioning Planning Cost Memorandum Account (U39E.)" (mailed Aug. 6, 2021), https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M397/K529/397529753.PDF.

3. The impact of the retirement of Diablo Canyon on GHG emissions is not clear.[8]

Developments Since the 2018 Settlement and CPUC Decision

In the intervening three and half years, several new developments have occurred that led to this study:

- In September 2018, the California Assembly and Senate approved, and then-Governor Jerry Brown signed, Senate Bill 100,[9] which requires that all California electricity be zero carbon by 2045.
- In the same month, Governor Brown signed Executive Order B-55-18,[10] which mandates that the state achieve climate neutrality for the entire economy, also by 2045.
- A variety of studies have emerged in the past year suggesting that two essential pillars of achieving a zero-carbon economy at affordable cost are: (i) a significant amount of zero-carbon electricity capacity that is always available and not weather-dependent, (ii) a reliable and low-cost source of zero-carbon fuels such as hydrogen for portions of the economy that cannot be easily electrified.[11]
- In August 2020, California experienced a series of challenges to electric reliability, as available electrical capacity fell below demand, with blackouts and brownouts occurring across the state. With reliability challenges continuing, this situation could happen again in the coming decade.
- Evidence is increasing that, due to climate change and other factors, California faces growing danger of severe and chronic water shortages, as signalled by the most recent Emergency Drought Proclamation of May 2021.[12]
- In October 2020, Governor Gavin Newsom signed Executive Order N-82-20,[13] which aims to protect from development 30% of California's land and oceans—thus underscoring the imperative of limiting the use of land for energy production and other industrial purposes.

Against a backdrop of accelerating climate change effects, the issue is clear: water shortages brought on by persistent drought and limitations on groundwater extraction; a dearth of clean, firm carbon-free electric capacity; and the urgent need to refuel or electrify the transportation sector collectively compel a reassessment of plans to shutter Diablo Canyon.

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[8] California Public Utilities Commission, "Decision Approving Retirement of Diablo Canyon Nuclear Power Plant," No. 18-01-022 (Jan. 11, 2018, issued Jan. 16, 2018), at p. 57, https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M205/K423/205423920.PDF.

[9] California Legislative Information, Bill Information, "SB-100 California Renewables Portfolio Standard Program: emissions of greenhouse gases," n.d., https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100.

[10] https://www.californiabiodiversityinitiative.org/pdf/executive-order-b-55-18.pdf.

[11] See, e.g., Cohen, A., Olson, A., Kolster, C., Victor, D.G., Baik, E., Long, J.C.S., Jenkins, J.D., Chawla, K., Colvin, M., Jackson, R.B., Benson, S.M., & Hamburg, S.P., "Clean Firm Power is the Key to California's Carbon-Free Energy Future," Issues in Science and Technology (Mar. 24, 2021), https://issues.org/california-decarbonizing-power-wind-solar-nuclear-gas/; Net-Zero America: Potential Pathways, Infrastructure, and Impacts (Princeton University), https://netzeroamerica.princeton.edu/?explorer=year&state=national&table=2020&limit=200; International Energy Agency, Net Zero by 2050 Scenario (May 2021), https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwimqv73sLTyAhXEY98KHRPSDIYQFnoECAcQAw&url=https%3A%2F%2Fwww.iea.org%2Freports%2Fnet-zero-by-2050&usg=AOvVaw3ljMp8if_j3WNtmJ1i6jNg

[12] Executive Department, State of California, "Proclamation of a State of Emergency" (signed by Gov. Gavin Newsom, May 10, 2021), https://www.gov.ca.gov/wp-content/uploads/2021/05/5.10.2021-Drought-Proclamation.pdf.

[13] Executive Order N-82-20 (signed by Gov. Gavin Newsom Oct. 7, 2020), https://www.gov.ca.gov/wp-content/uploads/2020/10/10.07.2020-EO-N-82-20-.pdf.

Accordingly, a joint study team organized by Stanford University and the Massachusetts Institute of Technology undertook this effort to re-examine the value of Diablo Canyon in meeting California's critical energy and water needs in the coming decades.

The study team analyzed:

- Diablo Canyon's potential contribution to achieving California's zero-carbon electricity and economic goals in 2045 at lower cost, while limiting carbon dioxide emissions during the transition.
- The potential for Diablo Canyon to serve as a low-cost energy source to power a desalination facility able to provide significant quantities of fresh water to water-stressed areas of the state, such as the Central Coast.
- The potential for Diablo Canyon to produce low-cost hydrogen for California's transportation, industrial and building sectors, as well as thermal balancing in the state's electric system.
- The value of Diablo Canyon to the California economy, if it were configured to provide a mixture of grid electricity, hydrogen, and desalinated water on a flexible basis throughout the year.

The team's analysis accounted for additional capital and operating costs to Diablo Canyon associated with meeting the California Coastal Commission's requirements for the protection of marine life, as well as the cost of modifications to the plant and other facilities needed for the production of hydrogen and desalinated water.

The report also outlines in detail the many and considerable challenges to maintaining Diablo Canyon and repurposing it to achieve the goals described in the following pages. At the federal level, the plant relicensing process would need to be reinitiated. Chief among the challenges at the state level is obtaining approval of a new engineered water intake system for the plant as proposed in this report, as well as licensing of brine discharge from the desalination process. Approvals will also be required for construction of adjacent or distributed desalination plants, hydrogen electrolysis facilities, and associated pipes and transmission wires. Stakeholders who were part of the settlement leading to the closure of the plant would need to be re-engaged, and there will also likely be opposition in principle among some to the use of nuclear energy in any form, including Diablo Canyon, for any purpose.

While these challenges are substantial, so are the potential gains. This preliminary analysis is intended to allow policymakers and the public to consider weighing the benefits and tradeoffs associated with maintaining or rededicating Diablo Canyon in light of other new and urgent challenges that face California: achieving a livable climate and the mandate for a zero carbon economy under SB 100 and Executive order B-55-18, providing affordable and reliable electric and non-electric energy, furnishing adequate fresh water in a world of growing water stress, and reducing pressure on California's limited land resources.

This study was not intended to be and should not be considered to be a definitive analysis of those benefits and tradeoffs. That will require further investigation. But the authors submit that the conclusions of this report present sufficient grounds for further study and debate by setting forth a prima facie case for extending the operations of the Diablo Canyon nuclear plant.

Chapter 1

Assessing the value of the Diablo Canyon as a source of clean, firm electric power

By Ejeong Baik and Sally M. Benson

Chapter 1 Key Points:

Near term (2025-2035), retaining Diablo Canyon would:

- ➔ Reduce California carbon emissions by more than 10% from 2017 levels
- ➔ Save $2.6 Billion in power system costs
- ➔ Bolster system reliability to mitigate brownouts
- ➔ Reduce California natural gas use by 10 TWh annually, more than the output of California's once-through cooling and peaking gas plants

Longer term (to 2045 and beyond), retaining Diablo Canyon would:

- ➔ Save up to $21 Billion in power system costs
- ➔ Spare nearly 100,000 acres of land from use for energy production

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Introduction

California has long been a leader in climate policy. Currently an executive order is in place to transition to a carbon-neutral economy by 2045.[14] One of the key statutes supporting the executive order is Senate Bill 100, which establishes the goal of achieving a 100% clean energy electric grid by 2045. Although the electricity sector is currently responsible for only about 15% of total GHG emissions in California,[15] a decarbonized electricity sector remains central to the full decarbonization of the state's economy. This is because strategies to decarbonize other economic sectors—such as transportation, industry, and residential and commercial buildings—will require additional end-use electrification.[16] In short, to serve an increasing share of the economy's energy demand and ensure that California's zero-GHG goal is met, the electricity grid will need both to grow and to fully decarbonize. At the same time, given this anticipated growth in electrification and electricity demand during the transition, it will be important to

[14] Executive Order B55-18 (signed by Gov. Jerry Brown Sept. 10, 2018), https://www.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf.

[15] California Air Resources Board, "California Greenhouse Gas Emissions for 2000 to 2018," p. 6, https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2018/ghg_inventory_trends_00-18.pdf.

[16] Cohen, A., *et al.*, "Clean Firm Power is the Key to California's Carbon-Free Energy Future," *op. cit*. (California "[e]nergy planners estimate that ... electrification will increase California's peak demand for electricity from 50 gigawatts today to 100 gigawatts midcentury")

maintain affordable electricity prices, which is critically important for an economy that is becoming increasingly dependent on electricity for meeting its energy needs.

Several studies have assessed various pathways for California to meet its SB100 goals.[17,18,19] Most utilize capacity expansion and dispatch models, which assess cost-optimal portfolios of generation and storage resources to meet future load and policy goals. Because these studies make varying assumptions about load growth, technology availability, and policy interpretation, they have resulted in a range of resource portfolios. Despite these differences, however, the studies reach two major, consistent conclusions: (i) utility-scale PV and storage capacity will need to continue to grow substantially beyond the current level of less than 20 GW, ultimately becoming responsible by 2045 for the bulk of clean energy generation; and (ii) the cost of this transition can be significantly reduced if the mix includes large amounts of clean, firm power. Clean firm power is defined as a low- to no-CO_2 emission source of electricity that can be dispatched to meet electricity demand whenever it is needed. As the transition to zero-carbon electricity proceeds, one of the greatest challenges that California faces is the need—in both the near and long term—to maintain reliability.

In the summer of 2020, the state suffered reliability challenges due to an increase in electricity demand from a heat wave, and supply shortfalls from resource planning targets have not kept pace to ensure sufficient resources that can be relied upon to meet demand in the early evening hours. [20] As a result, the California Independent System Operator (CAISO) declared an emergency leading to rotating power interruptions.[21] With climate change projected to worsen seasonal heat waves, maintaining a reliable grid in California will be critical going forward. Maintaining reliable electricity supplies during extended periods of cloudy weather during the winter is also crucial, particularly in light of the anticipated reliance on electricity for heating residential and commercial buildings.

In such an environment, the Diablo Canyon nuclear power plant, with its twin 1100 MW reactor units, can contribute to the decarbonization of California's electricity sector in several ways. First and foremost, the plant is a clean resource, much like PV and wind. It emits no carbon dioxide. But, unlike PV and wind, it also is a firm resource—it can supply power to the grid at a steady, sustained rate over long periods, regardless of atmospheric or solar conditions. As a result, Diablo Canyon offers the ability to provide reliable electricity output, while also contributing to further cost-effective decarbonization.

The following section provides the results of an analysis conducted to assess Diablo Canyon's value toward the decarbonization of California's electricity sector.

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[17] Cohen, A., *et al.*, "Clean Firm Power is the Key to California's Carbon-Free Energy Future," *op. cit*.

[18] California Energy Commission, *SB 100 Joint Agency Report: Charting a path to a 100% Clean Energy Future* (2021), https://www.energy.ca.gov/news/2021-03/california-releases-report-charting-path-100-percent-clean-electricity.

[19] Baik, E., Chawla, K., Jenkins, J.D., Kolster, C., Patankar, N.S., Olson, A., Benson, S.M., & Long, J., "What Is Different about Different Net-zero Carbon Electricity Systems?" *Energy and Climate Change* (2021), 100046, ISSN 2666-2787, https://doi.org/10.1016/j.egycc.2021.100046.

[20] CAISO, *Root Cause Analysis; MidRoot cause analysis; mid-August 2020 Extreme Heat Wave* August 2020 extreme heat wave [final report] (Jan. 13, 2021), *see* p. 97, http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf.

[21] California ISO, "ISO Requested Power Outages Following Stage 3 Emergency Declaration; System Now Being Restored" (Aug. 15, 2020), http://www.caiso.com/Documents/ISORequestedPowerOutagesFollowingStage3EmergencyDeclarationSystemNowBeingRestored.pdf.

Role and value of Diablo Canyon in California's near-term electricity future

In the near-term, California seeks to meet 60% of its generation with certified renewable resources via the state's Renewable Portfolio Standard (RPS), which was established by Senate Bill 100. Specifically, the system must meet a 47% RPS standard by 2025, rising to 60% by 2030. To assess the role and value of Diablo Canyon, a capacity expansion and dispatch model was used to compare the near-term grid composition in California through 2030—with and without Diablo Canyon.

1. Assumptions

The analysis was conducted using urbs, a capacity expansion and dispatch model[22] that has previously been used in a comprehensive study of California's SB100 policy.[23] We examined California's grid composition through 2030 by modeling the 2025 and 2030 grids. For each of these years, CAISO's annual load and hourly load shapes were obtained from the California Energy Commission's load profile forecast[24] and then were scaled to the full California state load.[25] Table 1-1 summarizes the load and associated policy goals for the two modeled years. Assumptions regarding existing resources, future potential, operating characteristics, fuel costs, and capital cost of future resources were taken from California's 2019-20 Integrated Resource Planning process (IRP).[26] The analysis also assumed mid-levels of CO_2 prices based on California's 2019-20 IRP. Table 1-2 summarizes the resources modeled for expansion in the model.

[22] Dorfner, J., "urbs: A linear optimization model for distributed energy systems," https://urbs.readthedocs.io/en/latest/.

[23] Baik, E., *et al.*, "What Is Different about Different Net-zero Carbon Electricity Systems?", *op. cit*.

[24] California Energy Commission, "Electricity and Natural Gas Demand Forecast" (2021), https://efiling.energy.ca.gov/Lists/DocketLog.aspx?docketnumber=19-IEPR-03.

[25] CAISO load was assumed to be 82% of the full state load, based on 2019-20 Integrated Resource Planning assumptions. *See* https://www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/ElectPowerProcurementGeneration/irp/2018/Prelim_Results_Proposed_Inputs_and_Assumptions_2019-2020_10-4-19.pdf.

[26] 2019-20 Integrated Resource Planning Process, https://www.cpuc.ca.gov/General.aspx?id=6442459770.

Table 1-1: Modeled California load growth and associated policy goals

	2016[27]	2025	2030
California Electricity Demand	284 TWh	310 TWh	315 TWh
Peak Load	62 GW	63 GW	63 GW
Modeled Policy Goals		47% RPS	60% RPS
Behind-the-Meter PV Capacity	5 GW	15 GW	20 GW

Table 1-2: Summary of resources modeled for expansion, as well as their associated capital costs and additional expansion capacity allowed

	Capital Costs in 2030 ($/kW)[8]	Additional expansion capacity allowed through 2030[8]
PV	$821/kW	No limit
Onshore Wind	$1,553/kW	+12 GW in-state and out-of-state
Offshore Wind	$3,421/kW	+500 MW[28]
Storage (li-ion batteries)	$105/kW; $145/kWh	No limit
Biomass	$4,701/kW	+1 GW
Geothermal	$4,948/kW	+3 GW
CCGT	$1,001/kW	No limit
Peaker	$852/kW	No limit
Demand Response	operated at $600/MWh	+5 GW

Diablo Canyon was modeled as a 2240 MW generator with a variable cost of $15/MWh and an annual fixed cost of $197/kW-yr, which reflects the additional capital costs from water intake modifications as specified in Chapter 2.[29] The plant is assumed to be a must-run generation source. Two scenarios, one with Diablo Canyon and another without, compare the two systems and assess the potential role and value of Diablo Canyon in terms of cost, emission reduction, and reliability.

2. Near-term value of Diablo Canyon

Utilizing Diablo Canyon as an electricity resource in 2025 and 2030 reduces overall system capacity needs in both years. With the plant, the system requires approximately 3.4 GW less PV and

[27] Statewide Energy Demand, https://www.energy.ca.gov/sites/default/files/2019- 12/statewide_energy_demand_ada.pdf.

[28] 500 MW of offshore wind is assumed to be invested in by 2030

[29] *See* Table 2-14 for variable and fixed cost assumptions for Diablo Canyon. The 2020 dollars in Table 2-14 are adjusted to 2016 dollars to be consistent with urbs assumptions.

approximately 2.7 GW less energy storage in 2025 and 2030. This follows from the fact that Diablo Canyon contributes 2.2 GW towards system reliability, while being capable of annually generating approximately 19.6 TWh,[30] thus reducing the need for other clean resources (e.g., PV and storage) to meet system loads.

In addition to providing California system capacity, Diablo Canyon's generation helps reduce system reliance on natural gas and imports. In fact, with the plant online, California's annual system demand for natural gas-generated power through 2030 declines by an average of 10.2 TWh, and for imported electricity, by 0.4 TWh (by 21% and 1%, respectively). It is worth noting that the 19.6 TWh of Diablo Canyon output exceeds the total recent annual output of all of the state's aging, once-through cooling and peaker plants (see Figure 1-1 below).[31] By burning less gas and importing less power, the state system with Diablo Canyon is able to achieve significantly lower emissions levels—an average of 7 Mt CO_2 a year, corresponding to an 11% reduction in CO_2 from the electricity sector relative to 2017 levels.[32] Cumulatively, from 2025 to 2030, emissions savings could reach 35 Mt CO_2 (Fig. 1-2). As a result of the overall lower system capacity needs as well as less gas generation and imported power, 10-year system savings from 2025-2035 for California with Diablo Canyon amount to approximately $2.6 Billion,[33] relative to the system without Diablo Canyon.

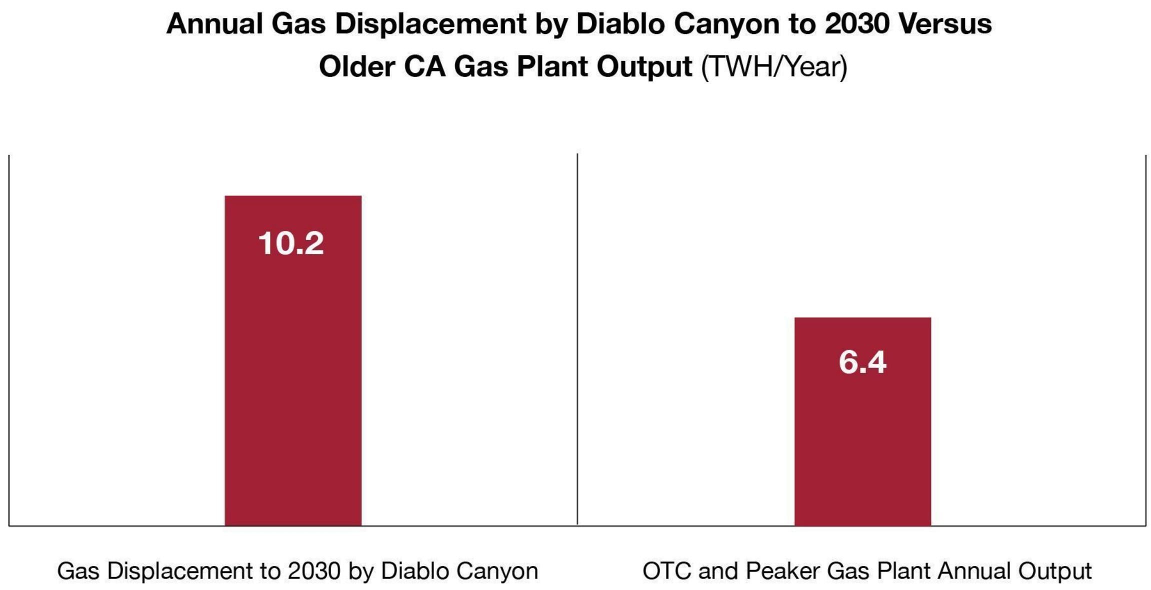
[30] For purposes of this analysis, the units were assumed to run at 100% capacity factor. In practice, due to required maintenance, the recent five-year average capacity factor of the plant has been 90%. However, this difference does not substantially affect the analysis in this chapter.

[31] In 2018, California's aging once-through cooling and peaker plants produced approximately 6.4 TWh. *See* "CPUC Staff Paper—Thermal Efficiency of Natural Generation in California 2019 Update," p. 10, tab. 1, at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwih8o-9vNTxAhVXFlkFHYAiDzgQFjAAegQIDxAD&url=https%3A%2F%2Fefiling.energy.ca.gov%2FGetDocument.aspx%3Ftn%3D233380%26DocumentContentId%3D65895&usg=AOvVaw0bFvC7I0pMBLgBEZb4c2ZP.

[32] California Air Resources Board, "California Greenhouse Gas Emissions for 2000 to 2018," https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2018/ghg_inventory_trends_00-18.pdf.

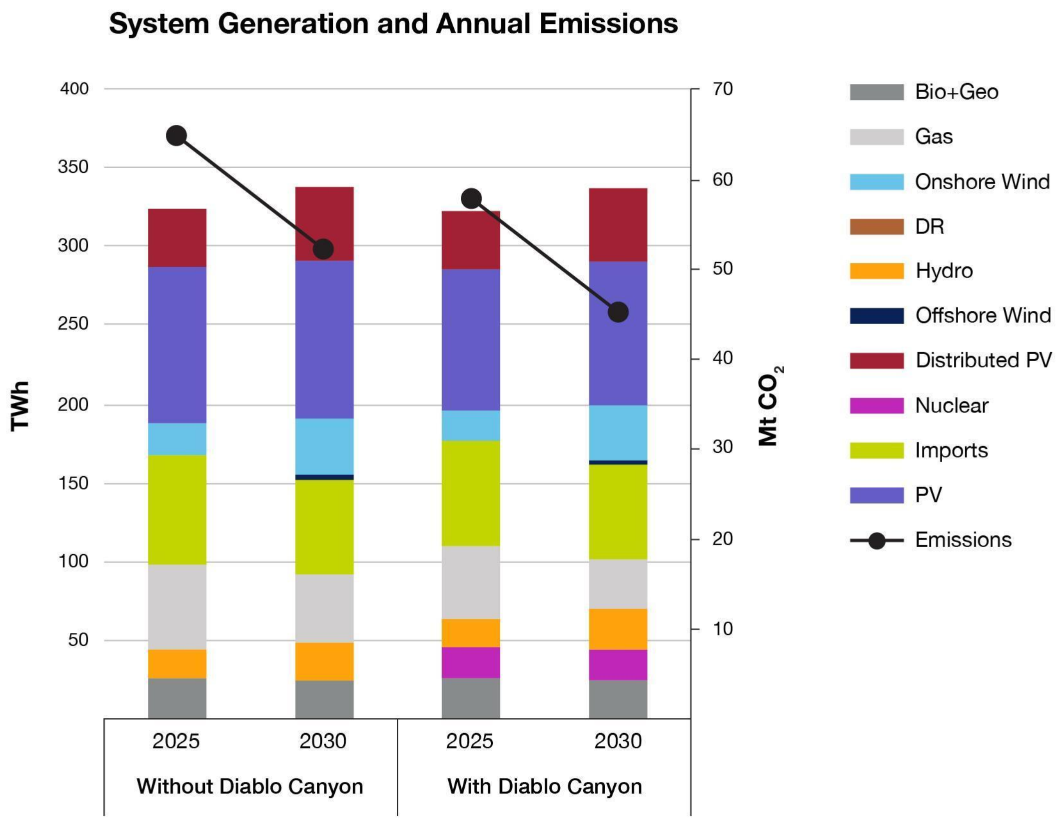
[33] System costs include annualized investment, fixed and variable O&M, fuel, and net import/export generation for 2025-2035. We assumed that annual system and associated costs for the modeled year of 2025 are maintained until 2029, and that modeled 2030 system costs are maintained until 2035.

Figure 1-1: Annual gas displacement by Diablo Canyon versus older California gas plant output. (Source: see note 31).



Fundamentally, our modeling analysis shows that, in the near-term, under California's current decarbonization requirements and goals, Diablo Canyon can help the state achieve greater emissions reductions sooner, at a lower cost, with less reliance on natural gas and imported electricity, and with lower system capacity needs.

Figure 1-2: System generation and CO_2 reduction in 2025 and 2030, with and without Diablo Canyon



3. Near-term reliability support provided by Diablo Canyon

As mentioned, California faced reliability challenges in August 2020. These were compounded by several factors, including climate change-induced extreme heat and resource planning targets that were not kept in pace throughout the transition to a clean and affordable grid.[17] As heat waves are anticipated to grow more extreme,[34] California was preparing for reliability challenges during the summer of 2021 and beyond.

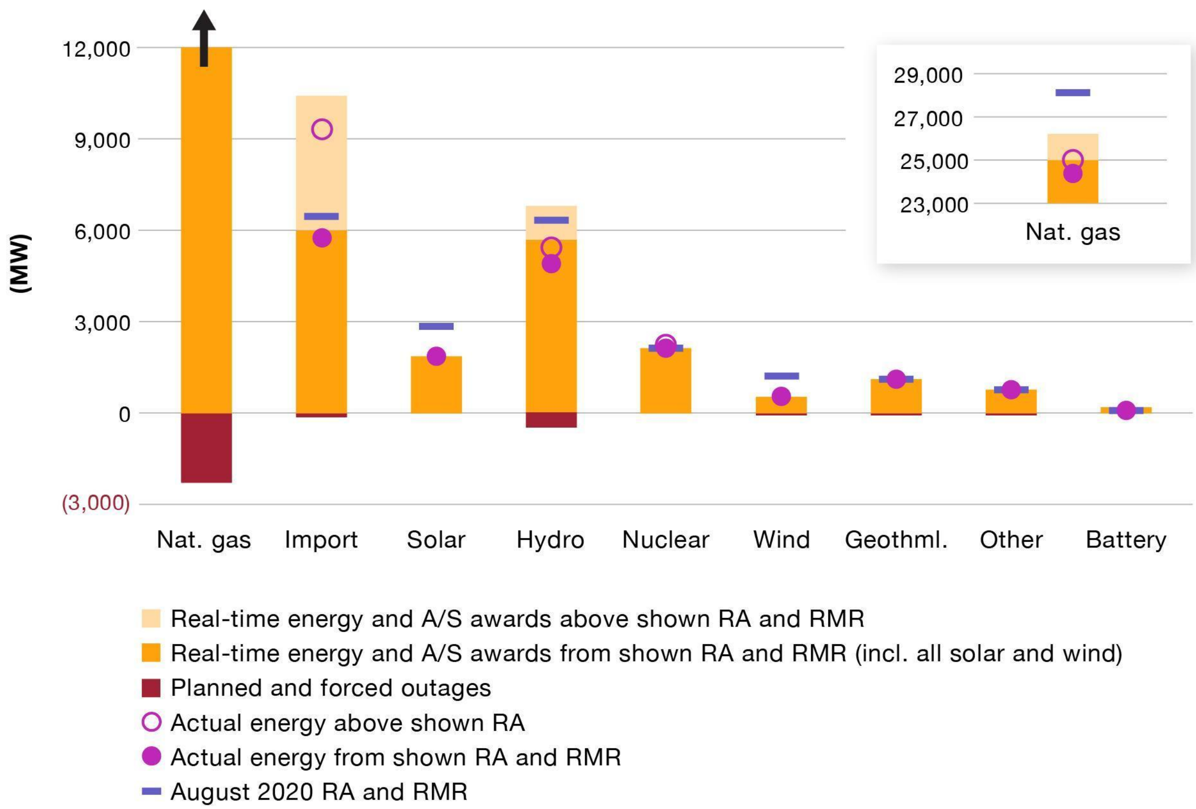
A 2021 report by CAISO on the root causes of the power interruptions sparked by the mid-August 2020 extreme heat wave provided an in-depth analysis of how various electricity resources responded to the reliability challenge.[35] Across all resources that contributed more than 1 GW of Resource Adequacy (RA) and Reliability Must-Run (RMR) expectations, only nuclear and geothermal power consistently met the monthly RA and RMR expectations, while also achieving awarded provision of real-time energy and

[34] Russo, S., Dosio, A., Graversen, R.G., Sillmann, J., Carrao, H., Dunbar, M.B., Singleton, A., Montagna, P., Barbola, P. & Vogt, J.V., "Magnitude of Extreme Heat Waves in Present Climate and their Projection in a Warming World," *JGR Atmospheres* (2014).

[35] CAISO, *Root Cause Analysis; Mid-August 2020 Extreme Heat Wave* [final report] (Jan. 13, 2021), *see* p. 97, http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf.

ancillary services (A/S) (See Figure 1-3 below). This underscores the robustness of these resources across different weather conditions and reliability challenges.

Figure 1-3: Performance of Diablo Canyon versus other energy resources in August 2020 heat wave



August 14 2020 Net Demand Peak (6:51 p.m.) – Real-Time Awards and Actual Energy Production vs. August 2020 Shown RA and RMR (Updated) (See note 35).

Role and value of Diablo Canyon in California's long-term electricity future

To consider the longer-term benefits of Diablo Canyon and its potential role in reaching a 100% clean energy grid in California by 2045, we used the urbs model to compare the grid-composition in California through 2045, with and without Diablo Canyon. Within this 25-year modeling horizon (2020-2045), five years were modeled (2025, 2030, 2035, 2040, and 2045), each with varying loads and policy goals that must be met on an annual basis.

1. Assumptions

Similar to the near-term analysis, the input assumptions for different resources modeled were taken largely from California's 2019-20 IRP.[36] The assumptions for 2025 and 2030 remained consistent with the previous analysis, with the exception of additional emissions constraints modeled in tandem with RPS policy (Tab. 1-3). The trajectory of emissions constraints declines in a linear fashion from existing 2020 levels to zero in 2045.[37] We added these constraints to reflect the intent of California policy to maintain consistent and steady progress towards a zero-carbon power grid by 2045, rather than assuming that all emissions progress can be loaded into the last few years of this period.

The 2025 and 2030 loads were derived from hourly CAISO profiles estimated by the California Energy Commission,[38] and are scaled to full California state load.[39] The load assumptions and hourly shapes for years after 2030 were scaled 2030 load profiles based on load growth assumptions applied in the 2019-20 IRP process.[40]

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[36] 2019-20 Integrated Resource Planning Process, https://www.cpuc.ca.gov/General.aspx?id=6442459770.

[37] Current California GHG Emission Inventory Data, https://ww2.arb.ca.gov/ghg-inventory-data.

[38] California Energy Commission, "Electricity and Natural Gas Demand Forecast, 2021," https://efiling.energy.ca.gov/Lists/DocketLog.aspx?docketnumber=19-IEPR-03.

[39] CAISO load assumed to be 82% of full state load, based on 2019-20 IRP planning assumptions (2019-20 Integrated Resource Planning Process, https://www.cpuc.ca.gov/General.aspx?id=6442459770).

[40] 2019-20 Integrated Resource Planning Process, https://www.cpuc.ca.gov/General.aspx?id=6442459770.

Table 1-3: Modeled California load growth and associated policy goals modeled for each year

	2016[41]	2025	2030	2035	2040	2045
California Electricity Demand	284 TWh	310 TWh	315 TWh	372 TWh	429 TWh	487 TWh
Peak Load	62 GW	63 GW	63 GW	69 GW	76 GW	83 GW
Modeled Policy Goals		47% RPS 47 MMT CO_2 emissions constraint	60% RPS 33 MMT CO_2 emissions constraint	60% RPS 22 MMT CO_2 emissions constraint	60% RPS 11 MMT CO_2 emissions constraint	60% RPS 0 MMT CO_2 emissions constraint
Behind-the-Meter PV Capacity	5 GW	15 GW	20 GW	25 GW	30 GW	35 GW

The resources modeled for expansion consist of those summarized in Table 1-4. Note that capital costs are assumed to change throughout the 25-year modeling period, based on projections from the 2019-20 IRP process.

Table 1-4: Summary of resources modeled for expansion, as well as their associated capital costs and additional allowed expansion capacity

	Capital Costs in 2045 ($/kW)[42]	Additional expansion capacity allowed through 2045[10]
PV	$710	No limit
Onshore Wind	$1,548	+12 GW in-state and out-of-state
Offshore Wind	$2,109	+8 GW[43]
Storage (li-ion batteries)	$89/kW $124/kWh	No limit
Biomass	$4,425	+1 GW
Geothermal	$4,756	+3 GW
CCGT	$950	No limit
Peaker	$806	No limit
Retrofit Gas with Carbon Capture and Storage	$1,200	No limit
Demand Response	operated at $600/MWh	+5 GW

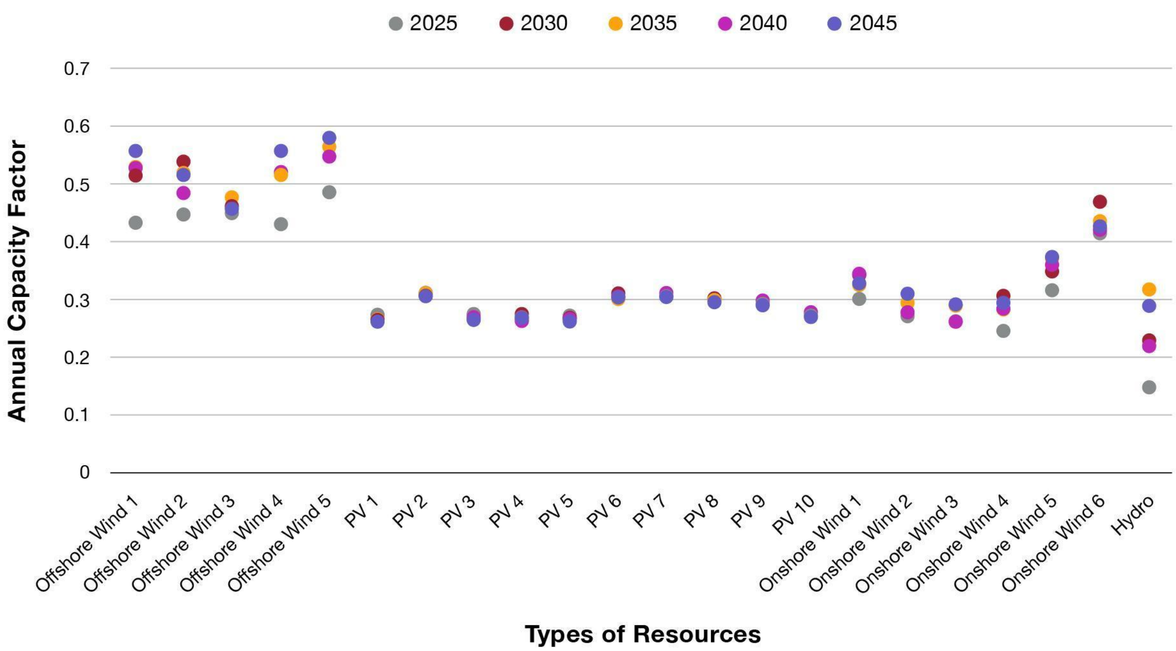
[41] Statewide Energy Demand, https://www.energy.ca.gov/sites/default/files/2019-12/statewide_energy_demand_ada.pdf.

[42] 2019-20 Integrated Resource Planning Process, https://www.cpuc.ca.gov/General.aspx?id=6442459770.

[43] Growth rate of offshore wind limited to +20% every 5 years starting from the modeled 500 MW build in 2030. Additional sensitivity with 22 GW of offshore wind potential available considered as well.

To understand the effect of weather variation, the annual generating profiles and capacity factors for non-firm generating resources—including PV, onshore wind, offshore wind, and some hydro[44]—are modeled under differing capacity factor assumptions for each modeled year. Figure 1-4 summarizes these assumptions.

Figure 1-4: Assumed capacity factors for modeled intermittent resources during each of the five years. PV shows relatively low variation across weather years relative to onshore wind. Offshore wind and hydro show the greatest variation. Note that some modeled resources are sited outside of California, but assumed to be importable. Weather year profiles are taken from Renewables.Ninja[45]



2. Scenarios

Four long-term reference scenarios (through 2045) were run—one without Diablo Canyon, and three with it. Each of the three "with" scenarios contains differing assumptions about the operating pattern of Diablo Canyon. The variation is based on the possibility that Diablo Canyon will provide electricity to the grid more flexibly in the future, either by ramping its generation up or down, or by allocating some fraction of that generation to such non-grid applications as H_2 production or desalination. The three operating patterns are: must-run, 50% flexible, and 100% flexible.[46] The 50% flexible scenario allows

[44] 70% of existing hydro capacity is considered non-dispatchable based on its pattern of behavior under historical weather year conditions.

[45] Pfenninger, S. & Staffell, I., Renewables.ninja, https://www.renewables.ninja/.

[46] Diablo Canyon's original licensing documents permit a 5% change in output per minute. See https://www.nrc.gov/docs/ML1826/ML18262A094.pdf. However, discussions with plant operators suggest that additional capital expenditure may be necessary to ensure that this performance pattern can be met continuously.

Diablo Canyon to operate as low as 50% minimum load, with the ability to ramp up or down by 50% of its full capacity in an hour. The 100% flexible scenario allows Diablo Canyon to run without a partial load limit or ramp-up limitation. All of these scenarios achieve the goal of a carbon-neutral grid by 2045 and none of the scenarios permits fossil fuel generation after 2045.

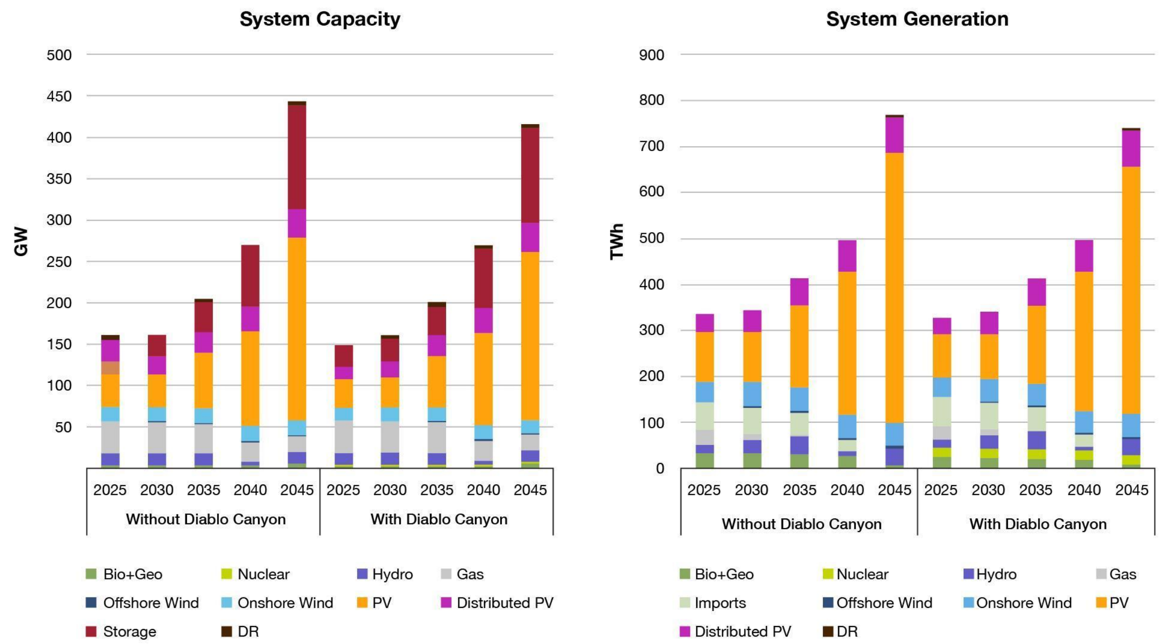
To test the potential impact of constrained PV siting, two additional scenarios with PV capacity limited to 100 GW and 60 GW, respectively, are considered. The scenario with 60 GW of PV also allows natural gas power plants to be retrofitted with carbon capture and storage. Another scenario that allows additional offshore wind potential with unlimited growth rate is also considered. Each of the scenarios are modeled with and without Diablo Canyon. Finally, a scenario with a linearly increasing carbon tax relative to a carbon cap is considered below.

3. Decarbonization of electricity sector with and without Diablo Canyon

Regardless of the operating patterns of Diablo Canyon, retaining Diablo Canyon in the generation mix through 2045 and beyond in the reference scenario provides the electricity system with $15-16 Billion between 2025-2050[47]. The cost savings come from the reduced capacity build required system-wide to maintain reliability in the absence of generation and capacity of Diablo Canyon. Overall, the addition of approximately 18 GW of PV and 11 GW (100 GWh) of energy storage would be needed by 2045 in a carbon-free electricity system that did not include Diablo Canyon. As a result, systems without Diablo Canyon will experience 27-43 TWh in additional curtailment compared to systems with Diablo Canyon. The high degree of curtailment in 2045 is consistent with previous studies of a 100% renewable energy grid in California.[1,6] Figure 1-5 shows the amount of generation and capacity required to meet demand (including both in-state and imported generation)—both with Diablo Canyon (as a must-run) and without it.

[47] System costs include annualized investment, fixed and variable O&M, fuel, and net import/export generation for 2025-2050. We assumed that the annual system and associated costs for the modeled year of 2045 are maintained until 2050.

Figure 1-5: System capacity and generation for California decarbonization pathways, without Diablo Canyon as must-run, and with it



The additional PV capacity required to replace Diablo Canyon would have significant land use implications as well. Figures 1-6 and 1-7[48] show the hypothetical spatial footprint of the additional 18 GW of PV required,totaling 90,000 acres, compared with the current footprint of the Diablo Canyon site (140 acres for actual plant and adjacent facilities and 900 acres of owned area) in the context of the San Luis Obispo region and the San Francisco metropolitan area.

[48] The 750-acre boundary for Diablo Canyon is cited in US Energy Information Administration, "State Nuclear Profiles: California Nuclear Profile 2010" (Apr. 26, 2010), https://www.eia.gov/nuclear/state/archive/2010/california/. The 140-acre developed footprint and 12-acre footprint inclusive of all buildings associated with power production was estimated using the following sources: *Google Earth*, earth.google.com/web/ and Solar Energy Industries Association, "Siting, Permitting & Land Use for Utility-Scale Solar" (2021), https://www.seia.org/initiatives/siting-permitting-land-use-utility-scale-solar.

Figure 1-6: Hypothetical spatial footprint of 18 GW of PV near the Diablo Canyon plant (Credit: Lucid Catalyst LLC)

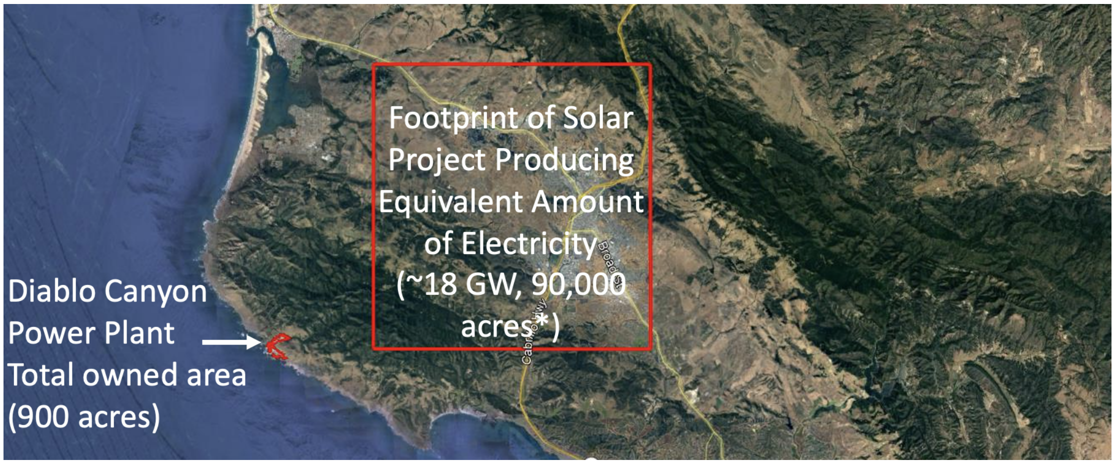
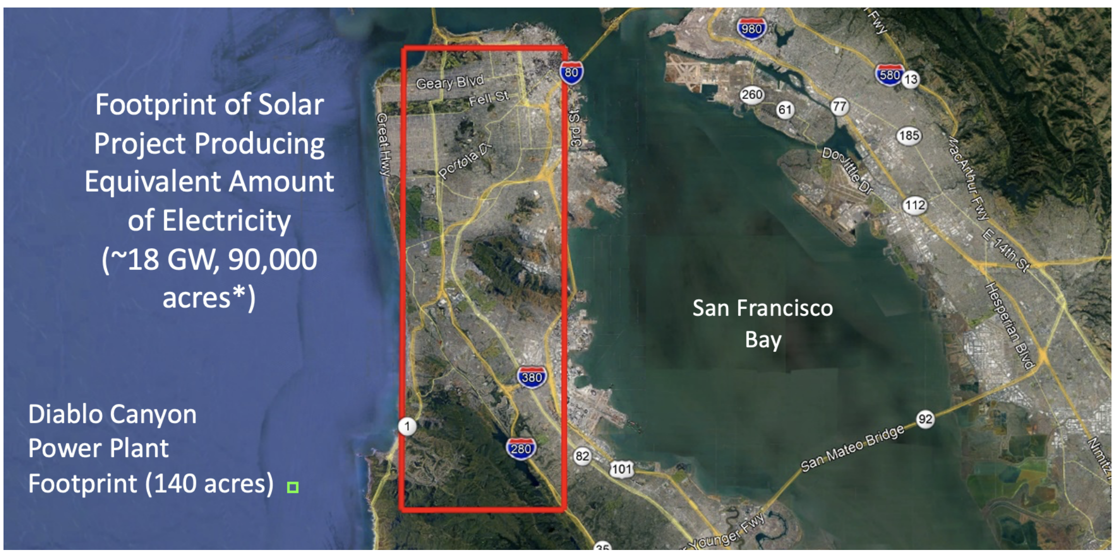


Figure 1-7: Hypothetical spatial footprint of 18 GW of PV compared to the San Francisco metro area (Credit: Lucid Catalyst LLC)



4. Impact of differing operating patterns on capacity value of Diablo Canyon

Flexible power from Diablo Canyon lowers system costs further. Between 2025 and 2050, the 50% and 100% flexible systems were $1.2 Billion and $1.7 Billion less expensive, respectively, than the must-run scenario (which, as noted, itself saves some $15 Billion over the same period). A 100% flexibly dispatched Diablo Canyon runs at approximately a 12% annual capacity factor in 2045, which reduces curtailment by 13% (17 TWh) annually compared to its being operated as a must-run unit. However, the plant's various operating patterns made a negligible difference in the capacity and generation shares of the overall California system.

In a net-zero electricity system that lacks a significant share of clean, firm resources, PV and storage capacity must be built well beyond system peak to maintain reliability. Although PV and storage can operate efficiently when matched to modest demand, and also when overall system needs are high (e.g., July), there are also times when large shares of PV or storage capacity, built to meet peak demand, are not needed—but remain available. At those times, PV displaces other clean resources that have higher variable or fixed costs, e.g., biomass, geothermal, and nuclear.

In the case of Diablo Canyon, a must-run requirement means that excess PV generation will occur more frequently—and that means additional curtailment, more waste, and higher cost. Operating Diablo Canyon as a must-run resource also results in lower utilization of resources with lower variable costs—i.e., biomass and geothermal. The bottom line: must-run leads to somewhat higher overall system costs. Although the overall impact of operating Diablo Canyon as a variable resource is limited, maintaining a more flexible operating profile allows for better utilization of other zero-carbon resources, such as PV, biomass, and geothermal, which can increase the systemic value of Diablo Canyon in the long run.

5. The implications on the operation of Diablo Canyon

Diablo Canyon power plant, with its two ~1100 MW reactors, produced approximately 16-19 TWh of electricity annually between 2012 and 2020.[49, 50] This implies that the plant is operated at baseload nearly all the time (the 3-year-average capacity factor for Diablo Canyon is about 90%).[29]

In the 50% and 100% flexible scenarios, the capacity factor of Diablo Canyon is optimized within the model, and as a result the capacity factor changes over the years. Until 2035, regardless of the plant's operating characteristics, the plant's annual capacity factor remains above 80%, consistent with historical operating patterns. Beyond 2040, though, with the advent of partial or total flexibility, Diablo Canyon provides much less power to the grid. For example, in 2045, at 100% flexibility, the annual capacity factor declines to 12% (see Fig. 1-8). The lower capacity factor implies that Diablo Canyon is accommodating higher shares of PV and energy storage. For both the 50% and 100% flexible scenarios, Diablo Canyon is utilized more during the winter, when PV generation is not sufficient to meet loads, and during periods of sequential cloudy days.

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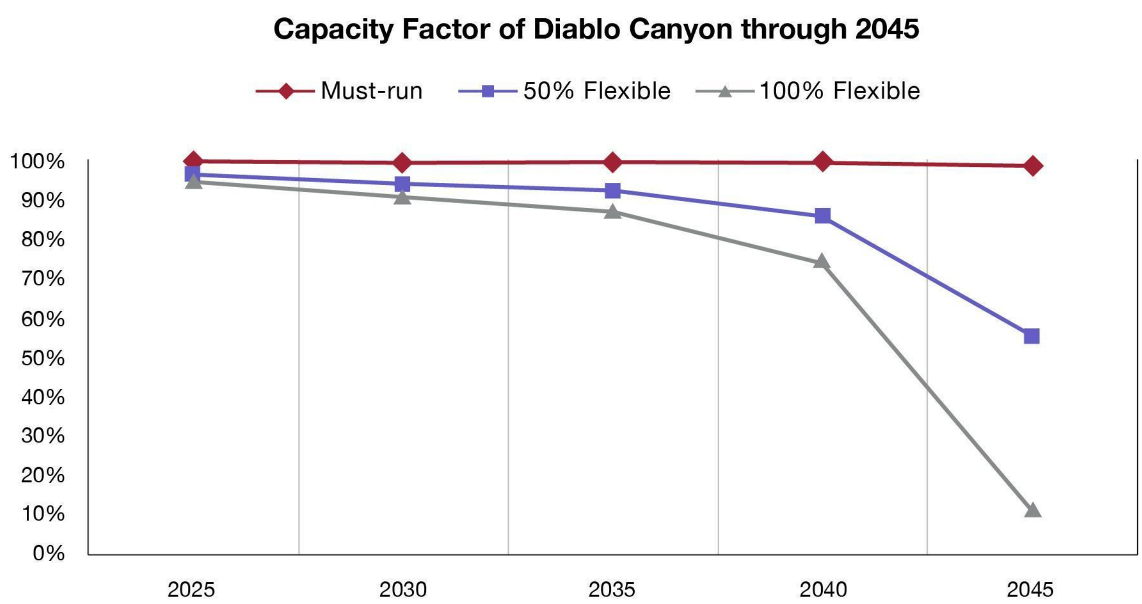
[49] Pacific Gas & Electric Company, FERC Forms No. 1, 2016-2019.

[50] California Energy Commission, Electric Generation Capacity and Energy, https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy.

Figure 1-8: Change in annual capacity factors for Diablo Canyon under different operating capability assumptions, as modeled



Flexible operating scenarios reflect additional opportunities for Diablo Canyon to utilize its energy output for purposes other than grid electricity, particularly after 2035. This includes seawater desalination or the production of hydrogen for use in decarbonizing other parts of the economy, as discussed in subsequent chapters of this report. This shows that Diablo Canyon's future utility in a grid with high levels of renewable resources may involve far lower capacity factors, which in turn could allow for other effective applications of its significant energy output. But even if limited to producing only grid electricity, Diablo Canyon provides significant value.

6. Impact of limited PV capacity and synergies with other clean firm resources

In all scenarios that meet the net-zero carbon grid goal by 2045, PV capacity by 2045 increases to beyond 200 GW. PV is a cost-effective renewable resource that will be essential for decarbonizing the grid. However, maintaining reliability while balancing PV's diurnal and seasonal output requires substantial PV capacity and, thus, large amounts of land. In California, land protection can limit the availability of land for renewable resource development.[51] To investigate the consequences of limited land availability for PV, we need to perform further analysis with models that incorporate siting constraints.

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[51] Wu, G.C., Leslie, E., Allen, D., Sawyerr, O., Cameron, R., Brand, E., Cohen, B., Ochoa, M. & Olson, A., Power of Place: Land Conservation and Clean Energy Pathways for California (2019), https://www.scienceforconservation.org/products/power-of-place.

When PV capacity is limited to 100 GW, or about half the amount selected under the optimal unconstrained scenario, significantly more energy storage is required to ensure reliability throughout the year. Under this scenario, all PV generation is either stored and later utilized or utilized immediately. For these scenarios we allow the model to determine the optimal storage duration.[52] For example, energy storage increases from 10 hours in the unconstrained scenario to over 200 hours in the 100 GW PV scenarios. Instead of overbuilding the PV resource (as in the unconstrained scenario), at the lower capacity level (i.e., 100 GW), it would be necessary to, in effect, overbuild the storage resource in order to maintain reliability throughout the year. In the future, geological storage of hydrogen produced from electrolysis may provide cost effective storage at the scale indicated here.

Exploring a further restriction, a linear projection of current growth rates of PV would result in less than 60 GW of PV built by 2045.[53] In a system with PV capacity limited to 60 GW, and with load growth and technology assumptions through 2045, the model is not able to identify a reliable system for 2045 without thermal electricity, regardless of Diablo Canyon's availability. However, under conditions of limited PV (at 60 GW), if given the option, the model chooses to build approximately 25 GW of natural gas-fired generation with carbon capture and storage (gas-CCS) to reliably meet load and the 2045 net-zero carbon grid goal. Under the scenarios that have limited PV availability and include gas-CCS, Diablo Canyon saves $21 Billion relative to the nuclear plant's absence; $5-6 Billion more than in the case with unlimited PV availability.

The increases in the value of Diablo Canyon largely come from two factors. The first is the limited PV capacity that increases the value of all other clean generation resources. The second reason stems from the fact that systems supported by a wider range of clean firm resources are more flexible, and result in further cost savings than a system relying on a single clean firm resource.[54]

7. Impact of additional offshore wind capacity

An additional scenario that assumes unconstrained growth rate of a potential of 22 GW of offshore wind was considered to assess the impact of broader availability of renewable resources within California. In the previous scenarios, the growth constraint imposed within the model resulted in only small capacities of offshore wind capacity invested in by 2045. In this scenario, without any growth constraints, the system invests in the full capacity of offshore wind available to meet the state's decarbonization goals by 2045. Developing approximately 22 GW of offshore wind reduces the capacity of PV needed in-state from over 200 GW (Figure 1-5) to approximately 130 GW by 2045 (Figure 1-9). Regardless, PV remains the largest source of generation in the state.

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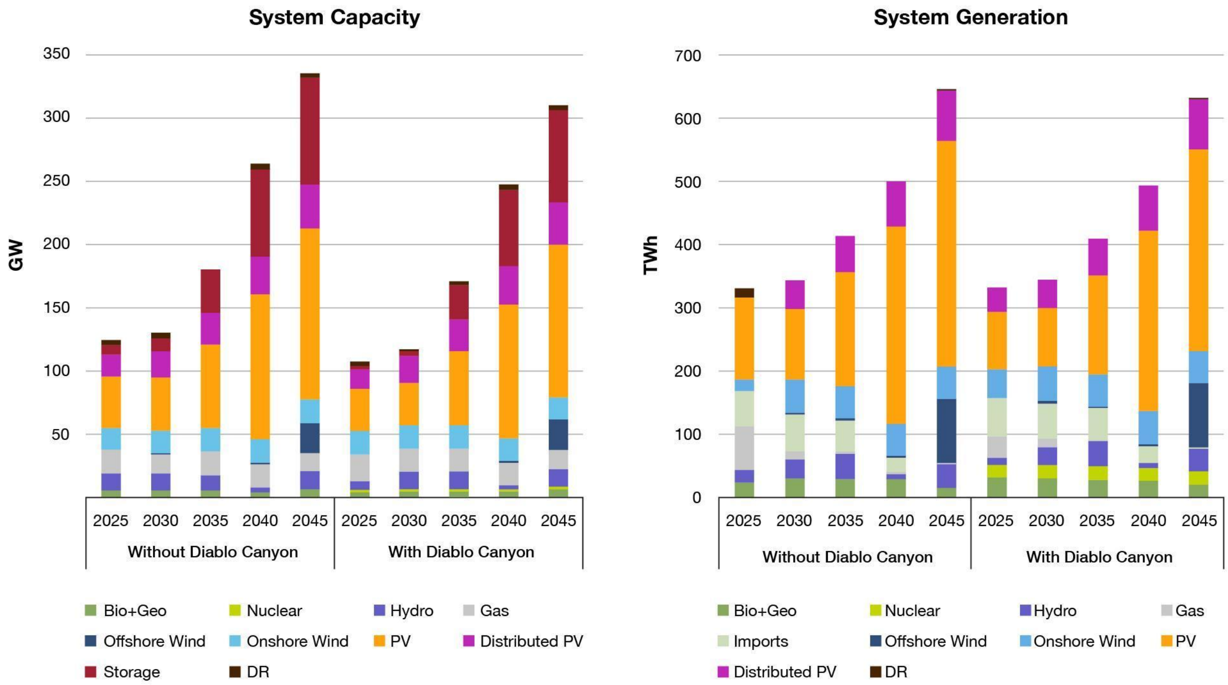
[52] Duration of energy storage is defined as the energy-to-power ratio of the energy storage resource. It is the period during which storage is able to discharge at its full power capacity before fully depleting its energy capacity.

[53] The maximum PV build occurred in 2016 when 2.67 GW came online. If this maximum rate were sustained, California would add 64 GW of PV by 2045 on top of a currently installed base of 12.75 GW today. *See* https://ww2.energy.ca.gov/almanac/renewables_data/solar/index_cms.php#:~:text=In%202019%2C%20solar%20PV%20and,12%2C338%20megawatts%2C%20are%20in%20California. However, if the historical 2012-2019 average of annual installation is assumed, California would add only 33 GW by 2045 for a total of 45.75 GW. *See* https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy.

[54] Baik, E., *et al.*, "What Is Different about Different Net-zero Carbon Electricity Systems?", *op. cit*.

Figure 1-9: System capacity and generation for California decarbonization pathways with additional offshore wind potential, without Diablo Canyon as must-run, and with it



Even with abundant availability of offshore wind, having Diablo Canyon operate through 2045 and beyond results in $14 Billion in cost savings relative to a comparable system without Diablo Canyon. Diablo Canyon provides value by reducing PV and energy storage capacity needs by 15 GW and 9GW (109 GWh), respectively. Ultimately, regardless of the availability of various sources of renewables, the value of Diablo Canyon as a clean firm resource in California's decarbonized grid is robust. Having more offshore wind does not significantly diminish the value of Diablo Canyon, further emphasizing that they are not necessarily competing resources, but resources that can complement each other in achieving cost-effective decarbonization.

8. A carbon tax instead of a carbon emissions cap

Given numerous policy options that are available for California to reduce emissions, we assess how the value of Diablo Canyon changes under a CO_2 tax assumption instead of an emissions cap. In these scenarios, no emissions cap is set, and instead, a steadily increasing CO_2 tax starting at $100/ton in 2030 and rising to $250/ton in 2045 is postulated—with and without Diablo Canyon.

Under a steadily increasing CO_2 tax, there are residual emissions in the system both with and without Diablo Canyon, not reaching a net-zero carbon grid. However, a system with Diablo Canyon saves $7 Billion between 2025-2050relative to one without Diablo Canyon. Although the cost savings are smaller than in the reference scenarios, the plant's emissions-reduction value is significant. As Figure 1-10 below shows, Diablo Canyon has the potential to save an aggregate of ~50 Mt of CO_2 emissions between 2025 and 2045 relative to the scenario without Diablo Canyon. Annual emissions savings is greatest prior to

2035, when the system still contains significant natural gas generation that can be effectively displaced by Diablo Canyon.

Figure 1-10: Annual and cumulative emissions difference between the scenarios with and without Diablo Canyon for each year, 2025-2045. Unmodeled years' emissions calculated using linear interpolation between two modeled years