DOCKETED

Docket Number:	21-ESR-01
Project Title:	Energy System Reliability
TN #:	244484
Document Title:	Jose Luis Alvarellos Comments - Keep Diablo Canyon operating
Description:	N/A
Filer:	System
Organization:	Jose Luis Alvarellos
Submitter Role:	Public
Submission Date:	8/10/2022 6:30:27 PM
Docketed Date:	8/11/2022

Comment Received From: Jose Luis Alvarellos
Submitted On: 8/10/2022
Docket Number: 21-ESR-01

Keep Diablo Canyon operating

Given that (a) global warming is a reality, caused by anthropogenic GHG emissions, and (b) we have an electricity reliability problem in California, it is imperative that we examine the situation with the Diablo Canyon NPP objectively and rationally (not from the point of view of FUD). Nuclear power is the safest type of electricity production, and what is more it produces no GHG. It is to California's great advantage to keep Diablo Canyon operating for many years to come. Furthermore, given its proximity to the sea, with some retrofitting we may be able to add a de-salination plant, helping with the recurrent California droughts. Le us be rational and keep it OPEN.

Additional submitted attachment is included below.

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

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NOVEMBER 2021

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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.

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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

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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.

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.

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.

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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.

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.
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]

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[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.

[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=2ahUKEwimgv73sLTyAhXEY98KHRPSDIYQFnoECAcQAw&url=https%3A%2F%2Fwww.iea.org%2Freports%2Fnet-zero-by-2050&usg=AOvVaw3ljMp8if_j3WNtmJ1i6jNg

- 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.

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

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[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.

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

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,

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[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")

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 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.

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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.

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

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.

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[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.

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[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.

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 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.

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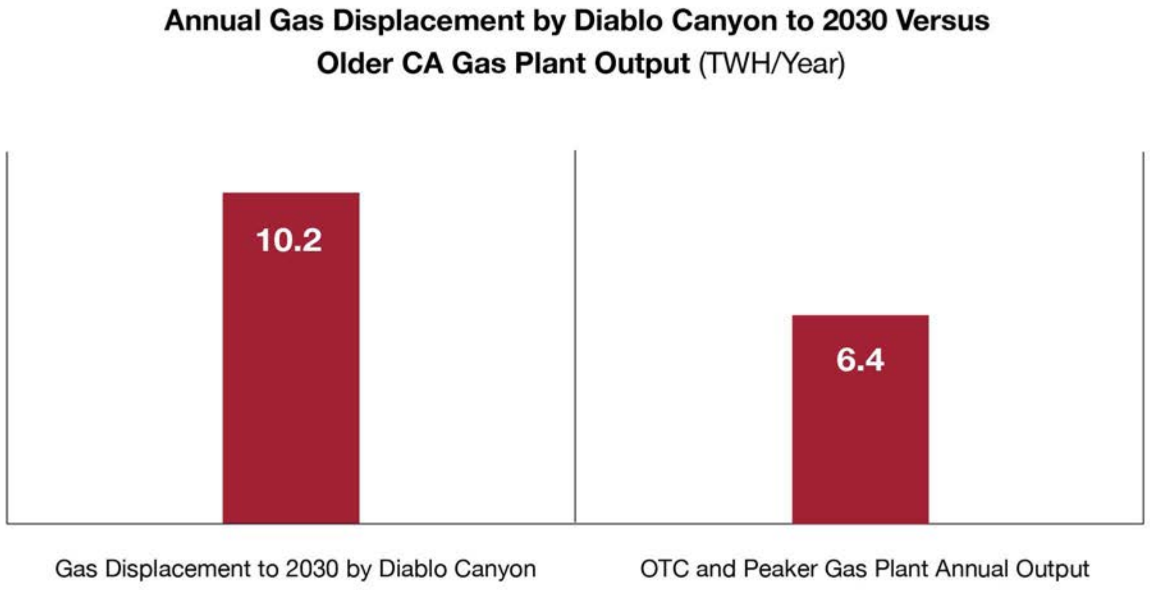
[30] For purposes of this analysis, the units were assumed to run at 100% capacity factor. In practice, due to required maintenance, the recent five-year average capacity factor of the plant has been 90%. However, this difference does not substantially affect the analysis in this chapter.

[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.

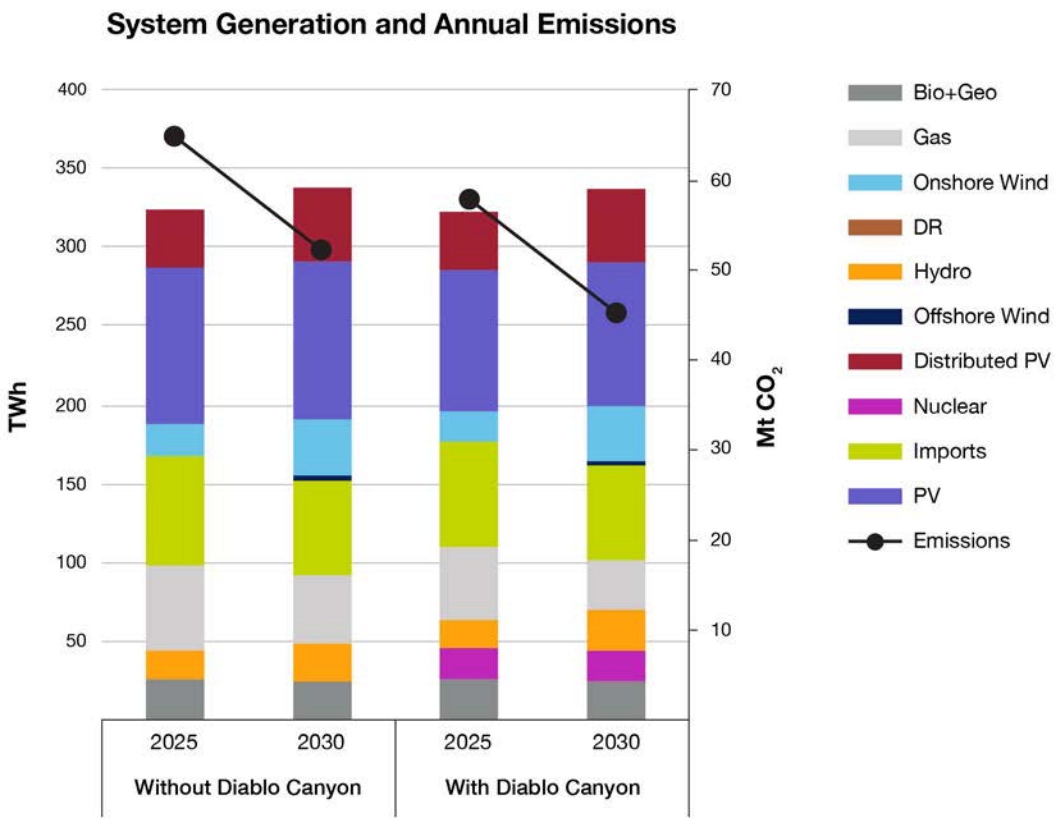
[33] System costs include annualized investment, fixed and variable O&M, fuel, and net import/export generation for 2025-2035. We assumed that annual system and associated costs for the modeled year of 2025 are maintained until 2029, and that modeled 2030 system costs are maintained until 2035.

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

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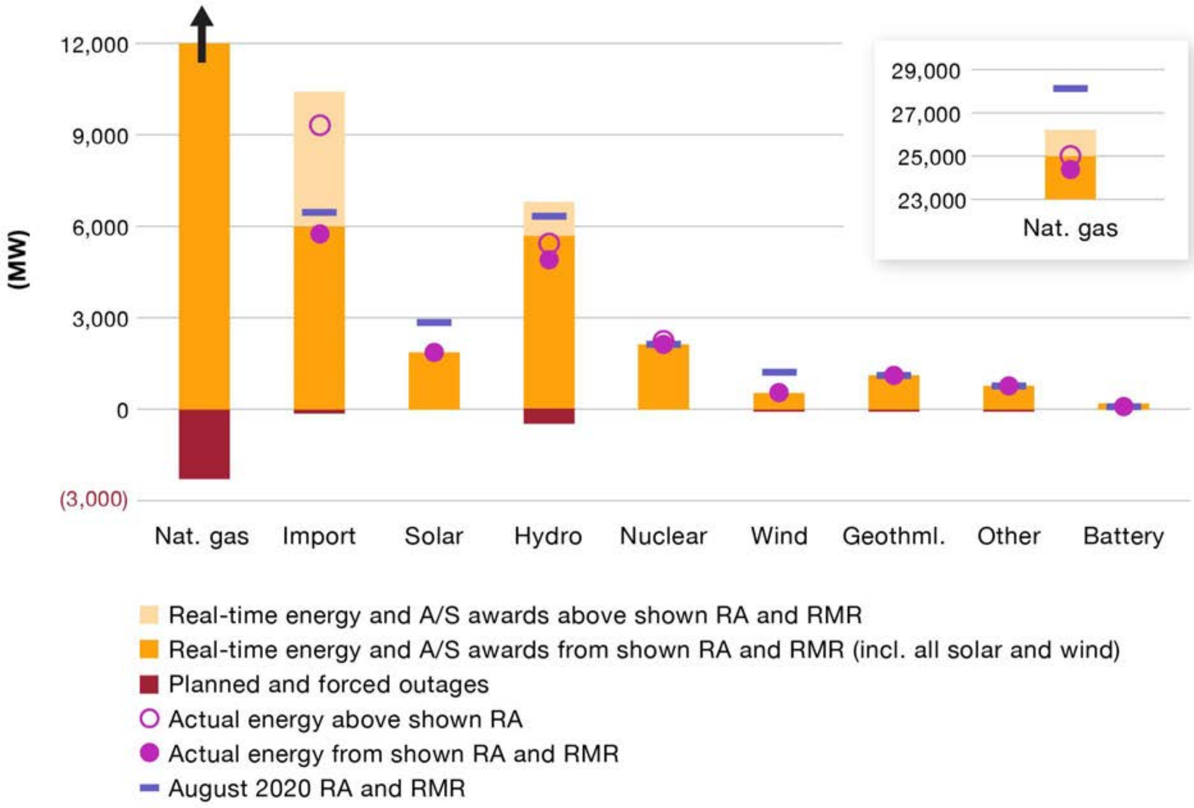
[34] Russo, S., Dosio, A., Graversen, R.G., Sillmann, J., Carrao, H., Dunbar, M.B., Singleton, A., Montagna, P., Barbola, P. & Vogt, J.V., "Magnitude of Extreme Heat Waves in Present Climate and their Projection in a Warming World," *JGR Atmospheres* (2014).

[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

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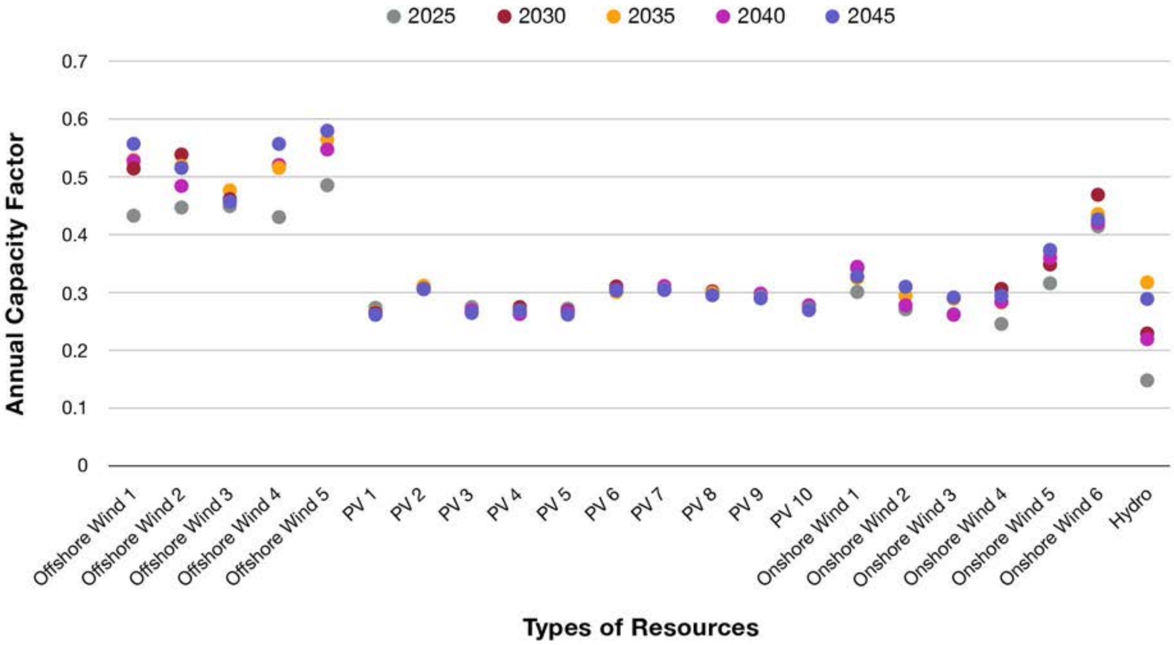
[41] Statewide Energy Demand, https://www.energy.ca.gov/sites/default/files/2019-12/statewide_energy_demand_ada.pdf.

[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

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[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/.

operating patterns are: must-run, 50% flexible, and 100% flexible.[46] The 50% flexible scenario allows 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.

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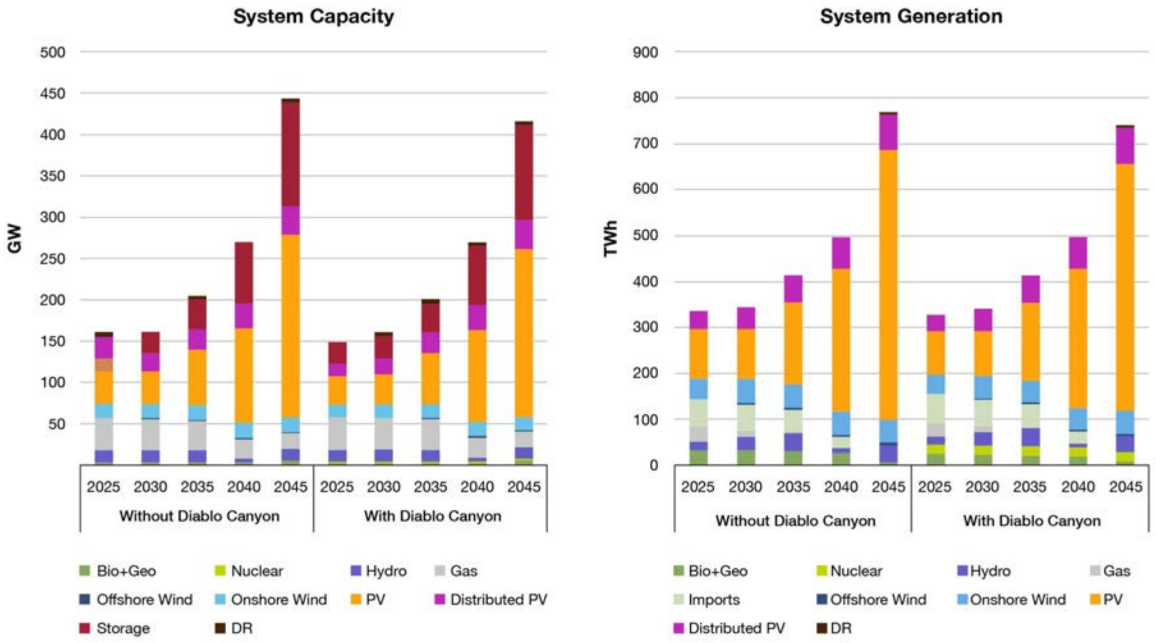
[46] Diablo Canyon's original licensing documents permit a 5% change in output per minute. See https://www.nrc.gov/docs/ML1826/ML18262A094.pdf. However, discussions with plant operators suggest that additional capital expenditure may be necessary to ensure that this performance pattern can be met continuously.

[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.

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[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)

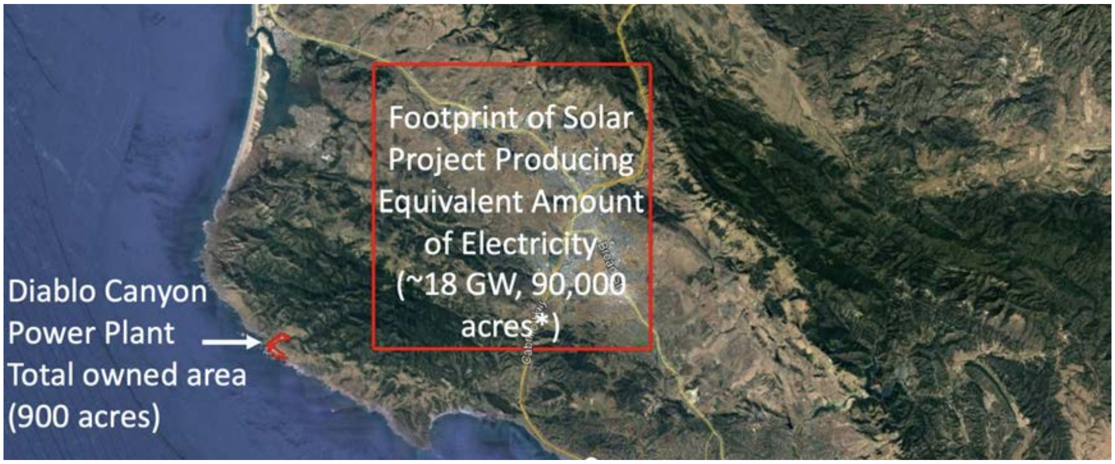

Figure 1-7: Hypothetical spatial footprint of 18 GW of PV compared to the San Francisco metro area (Credit: Lucid Catalyst LLC)

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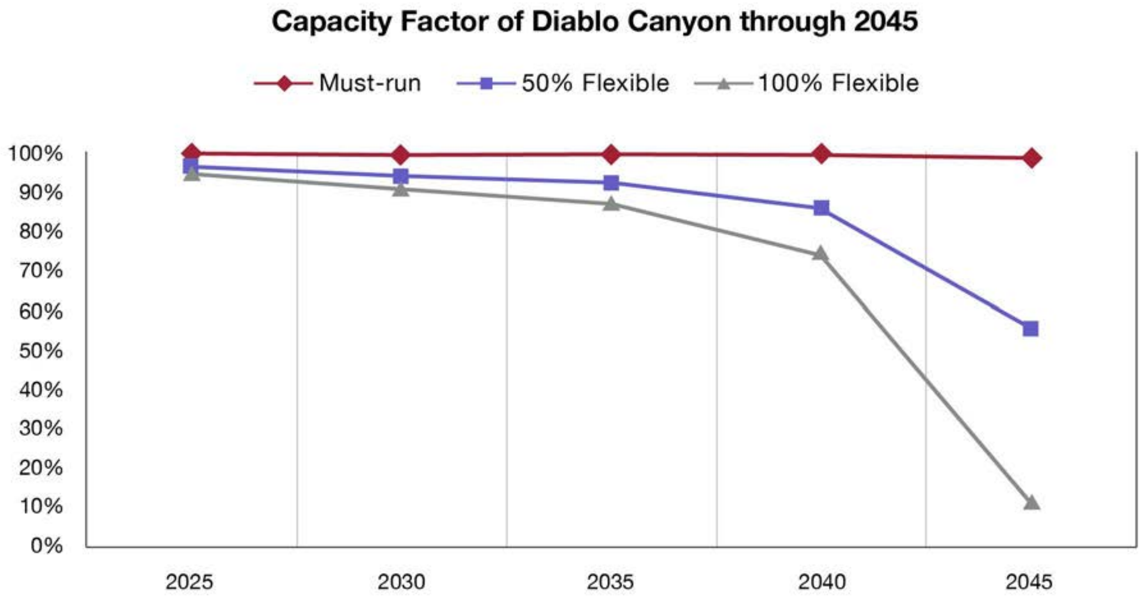
[49] Pacific Gas & Electric Company, FERC Forms No. 1, 2016-2019.

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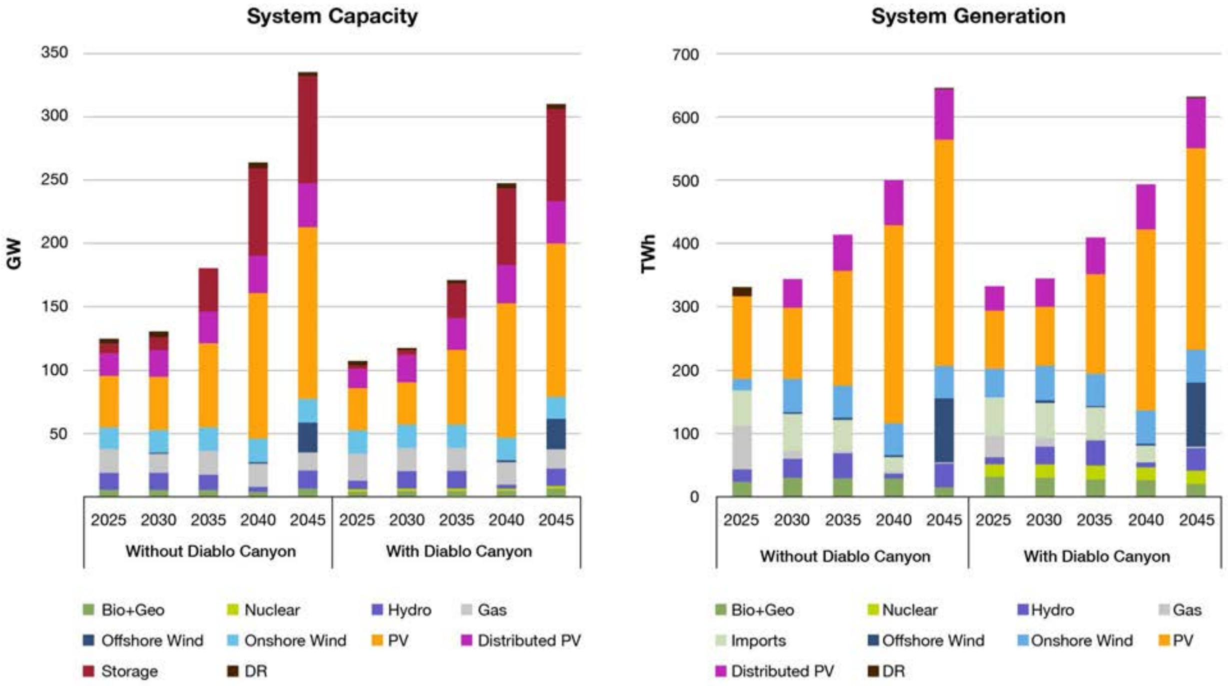
[52] Duration of energy storage is defined as the energy-to-power ratio of the energy storage resource. It is the period during which storage is able to discharge at its full power capacity before fully depleting its energy capacity.

[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.

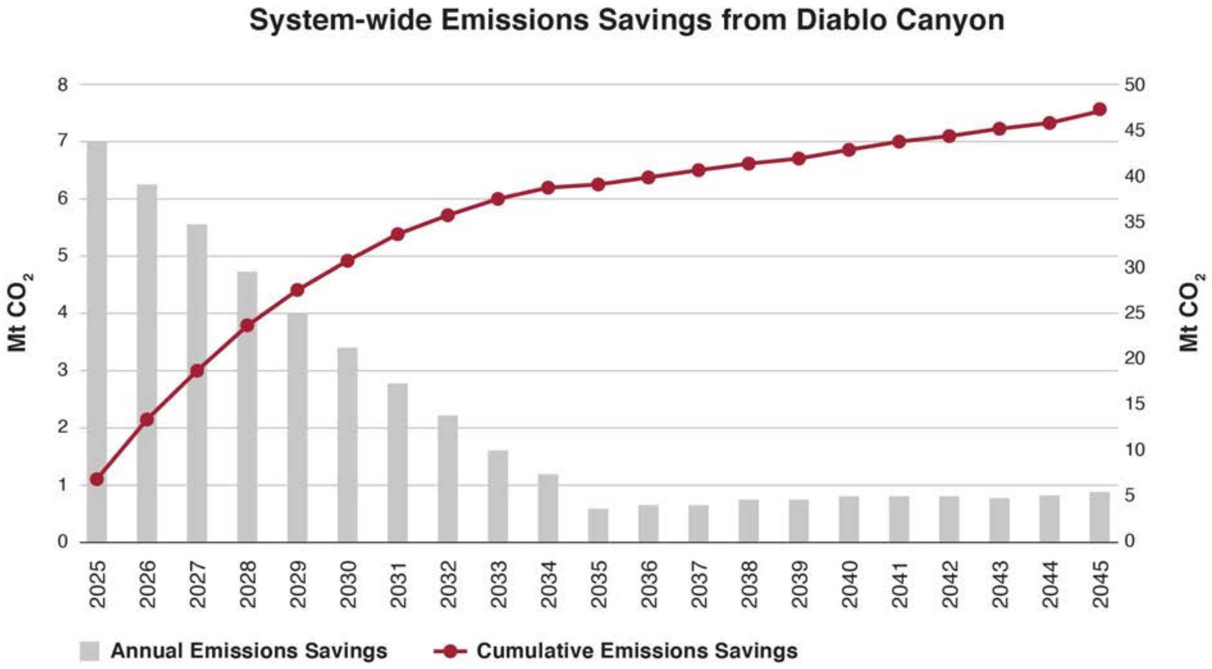
8. A carbon tax instead of a carbon emissions cap

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



Chapter 2

Repurposing Diablo Canyon to meet water intake standards and become a source of desalinated water

By Andrew T. Bouma, Quantum J. Wei, John E. Parsons, Jacopo Buongiorno, John H. Lienhard V

Chapter 2 Key Points:

A desalination facility adjacent to Diablo Canyon could:

- ➔ Augment fresh water supplies to the state as a whole and to critically under-served or overdrafted regions such as the Central Valley
- ➔ Produce fresh water at about half the cost of desal plants similar to the existing Carlsbad plant, but located elsewhere
- ➔ Depending on scale, produce fresh water volumes approaching or exceeding those of the proposed Delta Conveyance Project—but at significantly lower cost
- ➔ Be served by the Diablo Canyon plant , which could meet environmental standards protecting marine life at a cost approximately one-quarter that of prior estimates

Summary

This chapter considers the techno-economic feasibility of constructing a large-scale reverse osmosis desalination plant at the Diablo Canyon nuclear power plant (Diablo Canyon). This arrangement integrates the desalination plant with the nuclear power plant by sharing infrastructure and receiving feedwater and power from the nuclear power plant, forming a water-power co-production system.

A key challenge for continued operation of Diablo Canyon and for any desalination plant is compliance with California's regulations protecting marine organisms from large intake structures. We show how a new brushed-screen intake structure, serving both the nuclear power plant and the desalination plant, achieves compliance. Our understanding is that there are no other technical obstacles to the nuclear plant's license extension. The cost of the new intake is reflected in the cost of power. In our design, warm condenser water from the nuclear power plant flows into the desalination plant, which consists of a pretreatment system similar to that of the existing small-scale desalination plant at Diablo Canyon, followed by a partial two-pass reverse osmosis system and remineralization. Depending on the scale of the plant, either the discharged brine from the desalination system may be commingled and diluted with the excess cooling water, using the existing plant outfall, or a new high-energy diffuser system may be required.

The focus of our analysis is a hypothetical plant of the same size as the existing plant in Carlsbad, CA, but we also include additional analyses of significantly larger plants. When we consider the cost of desalinated water from this arrangement, compared to other desalination plants in California, we find that there are significant economic advantages for a desalination co-production plant at the Diablo Canyon site. At smaller scales, savings result primarily from reduced power costs and the sharing of the new 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 the plant outfall, as well as practical challenges in siting and building a very large plant on the premises.

Key findings of this chapter include:

- The cost of electricity paid by the desalination plant is expected to be 5.4 cents per kWh, a significant reduction from the price of power purchased from the grid.
- The levelized cost of water 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 an additional 20-185 km to offtakers. 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.
- The potential output of Diablo Canyon-powered desalination could make a substantial contribution to offsetting chronic water delivery shortfalls from federal and state water projects, alleviating groundwater overdrafts in the central part of the state, and enabling continued high agricultural production within the constraints of the Sustainable Groundwater Management Act. One of the intermediate sized Diablo Canyon-powered desalination options would produce significantly more fresh water than the highest estimate of the net yield from the proposed Delta Conveyance Project at less than half of the investment cost.
- Additional key data are shown in Table 2-1.

Table 2-1: Table of key results from technoeconomic analysis

	Large-scale at Diablo	Mega-scale at Diablo	Carlsbad Estimated
Capacity (m3/d)	**189,270**	**4,752,000**	**189,270**
Capacity (AFY)	**56,000**	**1,406,000**	**56,000**
Total Capex (Million \$)	599	11,571	1,235
Energy consumption (kWh/m3)	3.5	3.5	3.5
Electricity price (\$/kWh)	\$0.054	\$0.054	\$0.139
Water cost breakdown (\$/m3)			
Capital costs and amortization	\$0.53	\$0.41	\$1.10
Operating costs (excluding energy)	\$0.26	\$0.19	\$0.26
Energy costs	\$0.19	\$0.19	\$0.49

Water price at plant outlet ($/m3)	$0.98	$0.79	$1.84
Water price at plant outlet ($/AF)	$1,207	$978	$2,269

In light of these findings, we believe that building a desalination plant at Diablo Canyon is feasible. The scope of our analysis has been limited to techno-economic feasibility, but of course myriad additional factors should be considered. Consequently, we do not claim that a desalination plant at the Diablo Canyon site is the preferred solution for water needs of the California Central Coast or for wider parts of the state.

2. Scope and purpose

The purpose of this chapter is to explore the technical feasibility, cost, and economic benefits of utilizing the Diablo Canyon nuclear plant as an energy and feedwater source for a collocated reverse osmosis (RO) seawater desalination plant that would supply potable water to the state of California.

Nuclear power, seawater desalination, and the use of the lands on which Diablo Canyon sits are all contentious issues in the state of California. This chapter is not intended to present a policy recommendation or endorsement of any particular course of action. We leave that work to the elected and appointed representatives of the people of California. This chapter is intended as an investigation of the technical and financial feasibility of one approach to repurposing the plant if it continues to operate beyond its current license.

3. Context and reason for study

(a) The water crisis in California

California has a pressing need for additional sustainable fresh water supplies. Historically, California's network of water storage, rivers, and large infrastructure, supplemented by groundwater, have allowed surface water supplies to meet the needs of those in central and southern California. However, increased demand for water and changes in fresh water supply, exacerbated by climate change, have resulted in increasing frequency of shortages.[55] Most evident of these was the prolonged drought of 2012-2016. That drought has been followed by extreme dry conditions in 2020 and 2021.

Historically, water users navigated through these conditions by relying on groundwater. In normal conditions groundwater accounted for somewhere in the neighborhood of 40% of water consumed. However, in many groundwater basins, increased pumping is leading to rapidly deteriorating

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[55] Massoud, E.C., et al., “Projecting Groundwater Storage Changes in California’s Central Valley,” Scientific Reports 8 (2018), 12917, doi:10.1038/s41598-018-31210-1; W., Hanemann, W.M. & Fisher, A.C.,“Water availability, degree days, and the potential impact of climate change on irrigated agriculture in California,” Climatic Change 81 (2007), pp. 19-38, doi:10.1007/s10584-005-9008-z.

groundwater supplies.[56] In response, in 2014, the California Legislature passed, and Governor Brown signed, the Sustainable Groundwater Management Act (SGMA),[57] which will alter the California water horizon forever. The legislation requires all medium and high priority groundwater subbasins (127 in total) to reach conditions of sustainability by 2040. This time frame is relatively short in the context of California water policy.

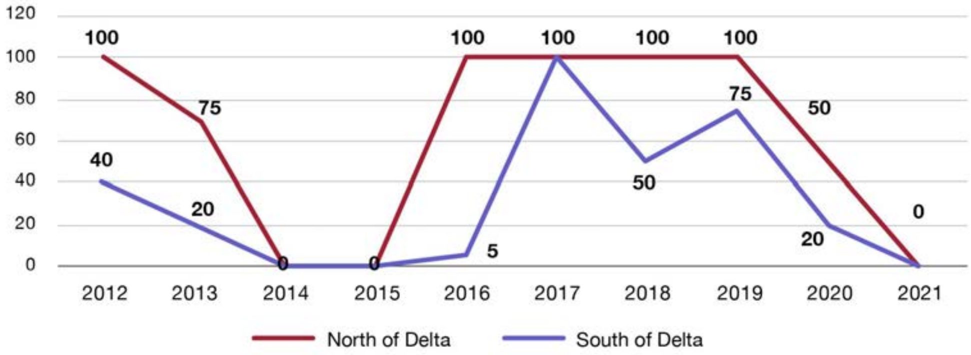
SURFACE WATER SHORTAGES

Federal Central Valley Project Shortages[58]

The Central Valley Project (CVP) (see Fig. 2-2 below) has experienced significant difficulties in meeting its contractual obligations in recent years. Figure 2-1, below, shows the annual deliveries as a percent of contract obligations over the ten-year period beginning in 2012, both north and south of the Delta. Deliveries north of the Delta have ranged from 0% of contract obligations in three of the years to 100% of contract obligations in five years.

During the same period, CVP deliveries to south of Delta agriculture contractors ranged from 0% in three of the years to 100% in only one year. In the remaining six years the allocation of contract supply exceeded 50% in only one year.

Figure 2-1[59]: Central Valley Project Contractor Water Allocations by Water Year – Agricultural only, 2012-2021 (percentage of maximum contract allocation made available)



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[56] Henry, L. "The Central California Town That Keeps Sinking," *New York Times* (May 25, 2021), https://www.nytimes.com/2021/05/25/us/corcoran-california-sinking.html; Faunt, C.C., *et al.*, "Water Availability and Land Subsidence in the Central Valley, California, USA," *Hydrogeology Journal* 24, no. 3 (Nov. 2016), pp. 675-684, doi:10.1007/s10040-015-1339-x; Rodell, M., *et al.*, "Emerging Trends in Global Freshwater Availability," *Nature* 557, no. 7707 (May 2018), pp. 651-659, doi:10.1038/s41586-018-0123-1; Richey, A.S., *et al.*, "Quantifying Renewable Groundwater Stress with GRACE," *Water Resources Research* 51, no. 7 (July 2015), pp. 5217-5237, doi:10.1002/2015WR017349.

[57] Dumas, L., "Implementing the Sustainable Groundwater Management Act in California," *Journal American Water Works Association* 111, no. 7 (July 2019), pp. 27–32, doi:10.1002/awwa.1321.

[58] US Bureau of Reclamation, CVP Historical Water Supply Allocations and 2021 Allocations, https://www.usbr.gov/mp/cvo/vungvari/water_allocations_historical.pdf.

[59] *See* Congressional Research Service, "Central Valley Project: Issues and Legislation, Updated June 3, 2021," https://fas.org/sgp/crs/misc/R45342.pdf.

Figure 2-2: Central Valley Project[60]

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[60] US Bureau of Reclamation, https://www.usbr.gov/mp/cvp-water/index.html.

The allocations of contract supply in the Friant Division of the CVP ranged from 0% to 100%. Historically the allocation of Class 1 supply ranged between 85% and 100%. Typically, the CVP has delivered around 22% of Friant Class 2 contracted supply. During the period 2012 to 2021, the CVP delivered 0% six times and less than 20% twice.

Similarly, CVP municipal and industrial (M&I) contractors have had increasing supply reliability issues. In addition to many small M&I contractors in the Sacramento and San Joaquin Valley, these contractors include the Santa Clara Municipal Water District and the City of Fresno. Most CVP contracts give priority to M&I contractors. Even with that priority, Sacramento Valley M&I contractors received allocations for the 2012 to 2021 ranging from 25% to 100%. A similar allocation range occurred for south of delta M&I contractors.

The collective shortfall of water to allocate to contract supplies has increasingly widened to 2 million acre-feet per year over the last two decades. A large portion of the shortage has occurred south of the Delta.

California State Water Project Shortages[61]

The other major governmental water project is the California State Water Project (SWP) (see Fig. 2-3 below). It primarily provides water to M&I contractors with some going to agricultural contractors primarily in Kern County. The SWP has contracted to deliver 4.17 million acre-feet per year. It has seldom done so.

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[61] California Department of Water Resources, "Notices to State Water Project Contractors," https://water.ca.gov/Programs/State-Water-Project/Management/SWP-Water-Contractors.

Figure 2-3: The State Water Project[62]

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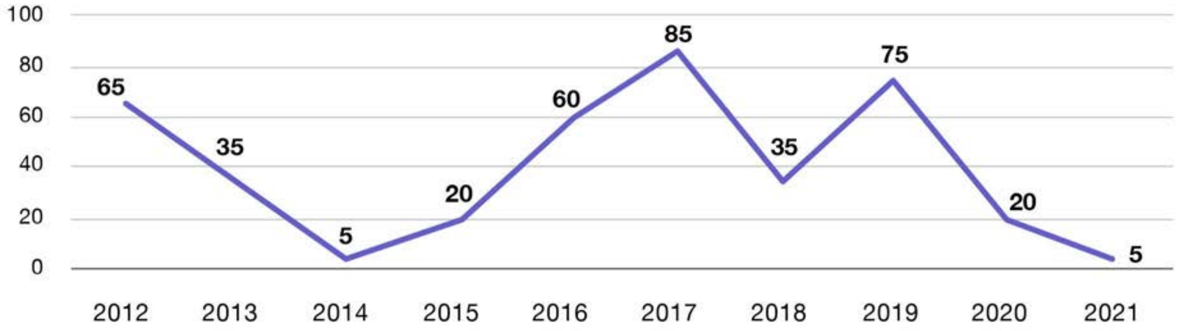
[62] See https://en.wikipedia.org/wiki/California_State_Water_Project#/media/File:California_State_Water_Project.png.

As shown in Figure 2-4, below, in the period 2012 through 2021 it has delivered between 5% and 85% of contract entitlement. Six years were below 50% and only four years above 50%. The shortfall as to contract entitlement through this period was nearly 2.5 million acre-feet.

Figure 2-4[63]: California State Water Project Allocations by Water 2012-2021 (percentage of maximum contract allocation)



SWP Coastal Branch Shortages[64]

The SWP delivers water through the coastal branch of the State Aqueduct to San Luis Obispo and Santa Barbara Counties. San Luis Obispo has a contract entitlement of 25,000 acre-feet per year and Santa Barbara County has a contract entitlement of 45,486 acre-feet per year. During the period 2012 through 2021 the SWP has only delivered 40.21% of contract entitlement on an average annual basis. Consequently, San Luis Obispo County has only received on average 10,052 acre-feet annually. Santa Barbara County has only received on average 17,888 acre-feet annually. The average annual collective shortfall is 42,546 acre-feet.

GROUNDWATER OVERDRAFT

San Joaquin Valley Overdraft[65]

The San Joaquin Valley is the source of many of California's most vexing water problems, including groundwater overdraft. Many parts of one of the most productive agricultural regions in the world rely on groundwater overdraft—pumping water in excess of replenishment—to support their economic enterprise. Figure 2-5 shows the annual overdraft in the San Joaquin Valley:

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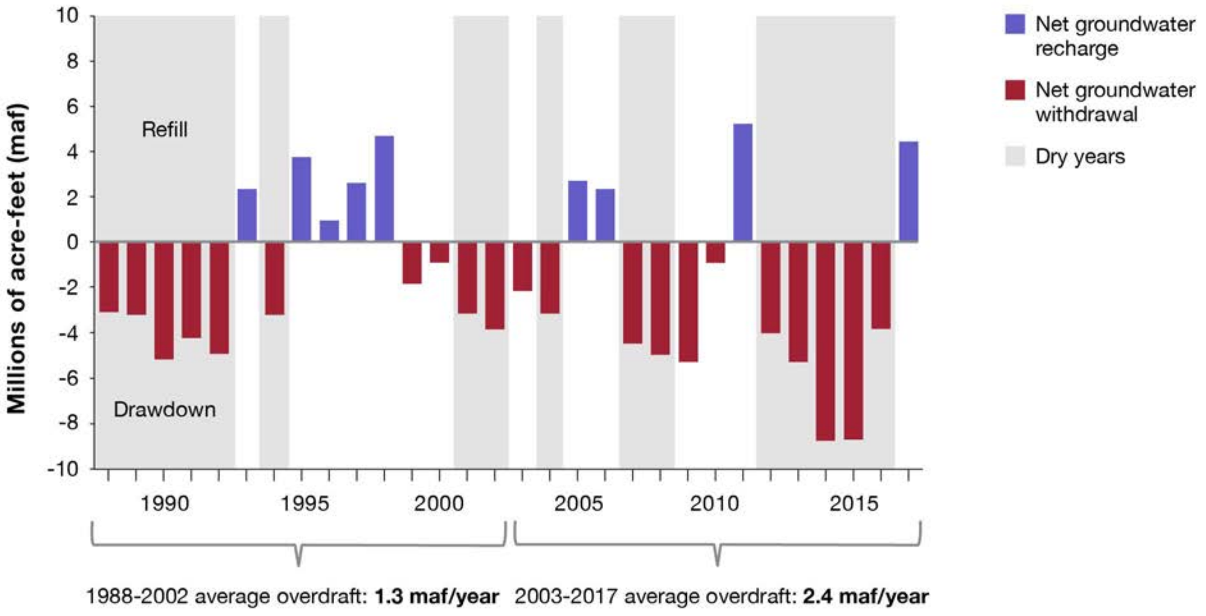
[63] *See* Congressional Research Service, "Central Valley Project: Issues and Legislation, Updated June 3, 2021", https://fas.org/sgp/crs/misc/R45342.pdf.

[64] California Department of Water Resources, "Notices to State Water Project Contractors," https://water.ca.gov/Programs/State-Water-Project/Management/SWP-Water-Contractors.

[65] Hanak, *et al.* (California Public Policy Institute), *Water and the Future of the San Joaquin Valley* (Feb. 2019), https://www.ppic.org/wp-content/uploads/water-and-the-future-of-the-san-joaquin-valley-february-2019.pdf.

Figure 2-5: *Annual groundwater overdraft in the San Joaquin Valley*[66]



The chronic overdraft in the San Joaquin Valley and elsewhere in California was a principal reason for the passage and signing of SGMA. Groundwater Sustainability Agencies (GSAs) in the San Joaquin Valley are now well into implementation of Groundwater Sustainability Plans (GSPs). In critically overdrafted basins, the GSPs will require reductions in pumping to achieve sustainable management of groundwater basins. The average annual overdraft in the San Joaquin Valley is estimated to be 1.8 million acre-feet. The Public Policy Institute of California estimates that only 25% of the region's long-term imbalance can be addressed by development of new water supplies and/or efficiencies. PPIC further estimates that reducing the deficit by reduced pumping alone would require fallowing nearly 750,000 acres of currently productive farmland. In addition to the development of new local supplies, an additional 1,350,000 acre-feet per year would be required to avoid fallowing altogether.[67]

The consequences of fallowing are significant. The San Joaquin Valley accounts for more than $25 Billion in annual farm revenue, up substantially in the last decade (see Fig. 2-6).

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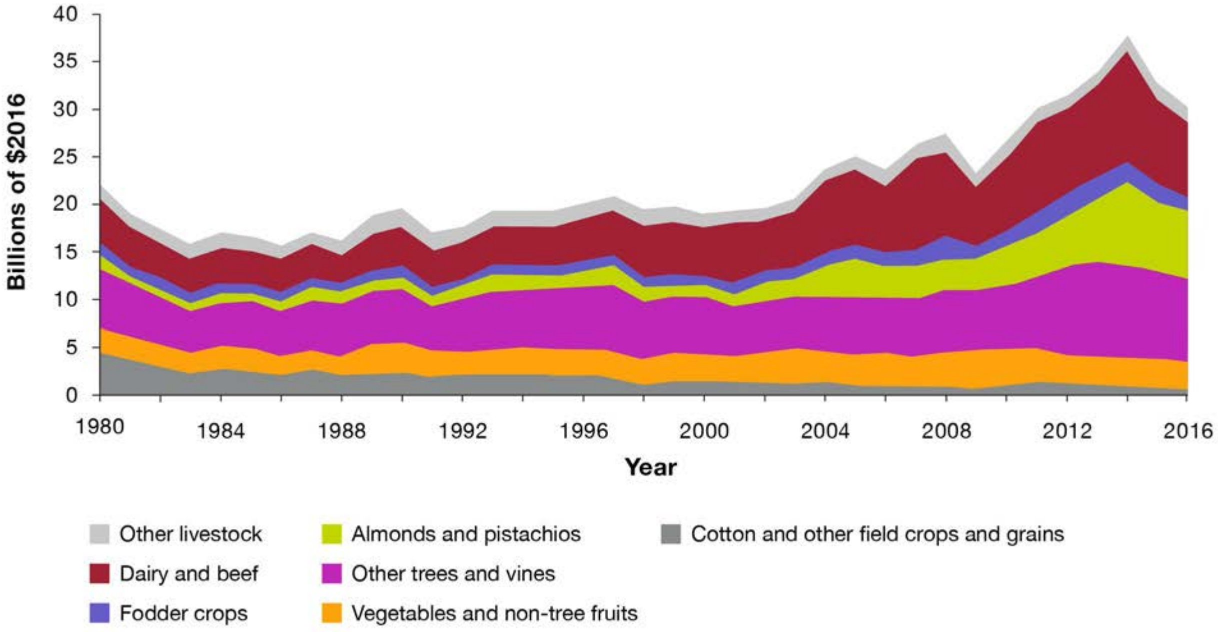
[66] Hanak, *et al.*, *Water and the Future of the San Joaquin Valley, op. cit*.

[67] As noted later in this chapter, a Diablo Canyon desalination plant could produce substantially more than this amount of water.

Figure 2-6: Annual farm revenue in San Joaquin Valley[68]



The California Public Policy Institute modelled three scenarios for the San Joaquin Valley's compliance with the SGMA, absent substantial additional external freshwater supplies. The results, displayed in Table 2-2 below, show substantial losses in each scenario:

1. Meeting SGMA regulations with only local water trading allowed.
2. Meeting SGMA regulations by implementing valley-wide surface water trading (could be limited by regulations, politics, or infrastructure).
3. Same as 2, but with added water supplies, mostly from increased efficiency and additional capture and recharge of runoff.

Table 2-2: Losses from SGMAS compliance, absent significant new external water supplies.[69]

Scenario	Acres Fallowed	Revenue losses	GDP losses	Job losses
1	750,000	$5.3 B	$2.1 B	21,000
2	725,000	$4.4 B	$1.6 B	15,000
3	530,000	$3.9 B	$1.3 B	13,000

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[68] Hanak, *et al.*, *Water and the Future of the San Joaquin Valley*, *op. cit*.

[69] Hanak, *et al.*, *Water and the Future of the San Joaquin Valley*, *op. cit.*

Central Coast Overdraft

The Central Coast is defined as San Luis Obispo County (divided into two principal subbasins: San Luis Obispo Valley and Paso Robles), and Monterey County. Each is evaluated separately.

San Luis Obispo Valley Overdraft

This is a small groundwater subbasin that includes the Edna Valley, city of San Luis Obispo and the San Luis Valley management areas. Aggregate overdraft in this subbasin is about 400 acre-feet per year.[70]

Paso Robles Subbasin Overdraft[71]

The Paso Robles subbasin has been the subject of significant controversy of the last decade. Historic annual groundwater pumping has exceeded replenishment by 12,600 acre-feet annually. In recent years, the deficit has grown because of drought conditions. As a result, the GSA has identified a future overdraft of 13,700 acre-feet per year.

Salinas Valley Overdraft[72]

The Salinas Valley Basin GSA covers 5 contiguous groundwater subbasins. The aggregate historical average annual overdraft is 38,500 acre-feet. The future projected annual groundwater overdraft is projected to be 31,000 acre-feet.

Adding up the above, the total anticipated groundwater overdraft for the relevant Central Coast region is 45,100 acre-feet per year.

(b) Potential desalination solution

Clearly, groundwater basins all over California face re-evaluation of different approaches to achieve sustainable water withdrawal levels. Efficiency projects, infrastructure improvements, or shifting to more water-efficient crops can help to reduce demand. Direct or indirect potable reuse, water transfers, and rainwater capture can help to increase supply. Integrated water management across a diverse portfolio of projects and technologies will be required to bring California's water usage to sustainable levels. Still, on a case-by-case basis, only some of these options may be possible, economical, politically palatable, or adaptable to the changing needs of the population and the planet.

In 2019, Californian Governor Gavin Newsom issued an Executive Order directing state agencies to develop recommendations to ensure water security for all Californians. The resulting report, the 2020 Water Resilience Portfolio, encourages the consideration of desalination as a means to supply water where it is cost effective and environmentally appropriate.

Desalinated water produced at Diablo Canyon could be delivered to several of the basins currently facing overdrafts.

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[70] San Luis Obispo Valley Basin Groundwater Sustainability Plan (Draft), ch. 6, tab. 6-17.

[71] "Paso Robles Sub-basin Groundwater Sustainability Plan" (Jan. 31, 2020), ch. 6, secs. 6.3.2.3, 6.4.2.3 & 6.5.3.3, https://www.slocounty.ca.gov/Departments/Public-Works/Forms-Documents/Committees-Programs/Sustainable-Groundwater-Management-Act-(SGMA)/Paso-Robles-Groundwater-Basin/Final-GSP/Paso-Basin-GSP.pdf.

[72] Salinas Valley Basin Groundwater Sustainability Agency, "Water Budgets," Presented to the SVBGSA Advisory Committee (Mar. 18, 2021), by Montgomery & Assoc., https://svbgsa.org/meetings/.

Central Coast opportunities

The combined groundwater overdraft and Coastal Branch opportunity is approximately 90,000 acre-feet per year. Delivery of the water is relatively simple. To serve the Salinas Valley, desalinated water would need to be operationally integrated into Lake Nacimiento. Delivery to the Paso Robles subbasin could also be achieved from Lake Nacimiento or by exchange of Coastal Branch SWP deliveries. Delivery to the San Luis Obispo Valley Subbasin could be achieved by delivery to the Coastal Branch of the SWP.

Providing make up water for shortfalls in SWP deliveries to San Luis Obispo and Santa Barbara Counties could be made by delivery to the Coastal Branch of the SWP. Such deliveries would need to be upstream of the San Luis Obispo water treatment facility.

SWP, CVP and San Joaquin Opportunities

The opportunity to provide desalinated water to offset SWP and CVP supply shortfalls is well over 4 million acre-feet per year (including southern California delivery shortfalls). There is also significant opportunity to offset groundwater overdraft in the San Joaquin Valley.'

The balance of this chapter explores the opportunity to develop a desalination plant at Diablo Canyon.

There are challenging environmental regulations, a difficult permitting process, and many community and special interest organizations that passionately argue for or against the development of desalination projects. All of these factors can make it difficult, time consuming, and costly for new plants to be permitted and constructed. Despite the challenges of developing desalination projects in California, desalination also offers some unique benefits compared to other means of addressing the water crisis. Desalination is a drought-proof source of water with an inexhaustible supply of feedwater. Regardless of the season or weather, a desalination plant can reliably produce a nearly constant supply of high-quality fresh water. Seawater desalination does not reduce the amount of fresh water available to local ecosystems, fish, other organisms, and the environment at large. When using reverse osmosis, as is proposed in this analysis, all the energy used is electrical energy, meaning that with carbon-free electrical power sources, the water produced by desalination would have a minimal carbon footprint.

Seawater desalination is most commonly performed by forcing water through a semipermeable membrane that blocks the passage of salt, as in reverse osmosis (RO). Evaporation of seawater, with capture of the pure condensate, is also used, as in multi-effect distillation. Seawater desalination is already practiced in California, most notably at the Claude "Bud" Lewis Carlsbad Desalination Plant in Carlsbad, California. This RO plant has a capacity of approximately 190,000 m^3/day (56,000 AFY) and has been operating since 2015. Two other large desalination projects are being developed in California at Huntington Beach and Camp Pendleton.[73] There are also a number of other smaller desalination plants in operation in California, including a plant at Diablo Canyon, which provides water for fire and dust suppression, makeup water for the nuclear reactors, and potable water for human consumption and use.

In many places around the world with limited water resources, desalination has become even more prevalent. Seawater desalination is ubiquitous in the Middle East and North Africa (MENA) region, which contains approximately half of the total global seawater desalination capacity. In this region, Kuwait is an extreme example, with seawater desalination providing nearly all the country's fresh water.[74] Singapore,

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[73] Global Water Intelligence, DesalData, Plants: 2020 Projects, https://www.desaldata.com/.

[74] Global Water Intelligence, DesalData, Global Forecast: 2020 Projects, https://www.desaldata.com/.

another country with limited natural water resources, has turned to a combined strategy that employs water recycling, desalination, and rainwater capture to help reduce water imports from outside the country. Singapore aims to be water independent by 2060, with desalination expected to meet up to 30% of water demand.

(c) Energy as central need for desalination

Seawater desalination has the potential to produce massive amounts of water to augment existing water resources, but desalination is also inherently energy intensive. Thermodynamic limitations mean that pure water cannot be separated from seawater with less than 0.71 kWh of energy per m^3 of fresh water.[75] As fresh water is removed from a given volume of seawater, and the remaining saltwater becomes more concentrated with salts, the energy required to extract more freshwater steadily increases. Seawater reverse osmosis plants typically operate at a recovery ratio of approximately 40-50% (meaning they recover 40-50% of the incoming feedwater as fresh product water, while 50-60% of the feedwater is turned into concentrated brine, which is disposed of). At this recovery ratio, a perfectly efficient, thermodynamically reversible plant would still consume around 1.1 kWh/m^3.[76] Most new plants, with advanced pressure recovery and highly efficient membranes, require 3-4 kWh/m^3 (3.7-4.9 MWh/AF). This energy consumption includes all elements of the desalination plant, such as intake pumps, pretreatment, the actual reverse osmosis system itself, post-treatment, and other plant operations. Additional energy is required for distribution. Distribution energy can become very significant when water is moved over large distances, such as in California's vast network of aqueducts and channels. These energy consumption numbers are put into context in Table 2-3.

Because of the energy intensity, desalination is generally more expensive than freshwater sources. Approximately 25-50% of the total cost of water from new RO plants is attributable to electricity.[77] There are several other mature desalination technologies that could be considered for a desalination plant at Diablo Canyon, but we focus on seawater RO in this analysis, as RO is the most commonly installed desalination technology today due to its relatively low cost compared to other large-scale desalination technologies.

Table 2-3: Energy consumption of water transfer and water treatment processes

Name of water transfer project	Length (km)	Energy consumed (kWh/m3)	Energy use per unit distance (kWh/m3 km)	Reference
West Branch Aqueduct, CA	189,270	4,752,000	189,270	78

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[75] Lienhard, J.H., et al., "Thermodynamics, Exergy, and Energy Efficiency in Desalination Systems," in Desalination Sustainability: A Technical, Socioeconomic, and Environmental Approach, ed. Hassan A. Arafat (Amsterdam, The Netherlands: Elsevier Publishing Co., 2017), pp. 127–206.

[76] Mistry, K.H. & Lienhard, J.H., "Generalized Least Energy of Separation for Desalination and Other Chemical Separation Processes," *Entropy* 15, no. 6 (May 2013), pp. 2046–2080, doi:10.3390/e15062046.

[77] Global Water Intelligence, DesalData, Global Forecast: 2020 Projects, https://www.desaldata.com/.

[78] Plappally, A.K. & Lienhard, J.H., "Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal," Renewable and Sustainable Energy Reviews 16, no. 7 (Sept. 2012), pp. 4818–4848, doi:10.1016/j.rser.2012.05.022.

Coastal Branch Aqueduct, CA	56,000	1,406,000	56,000	79
Transfer from Colorado River to Los Angeles, CA	599	11,571	1,235	80

Water treatment process (excluding pretreatment, post-treatment, etc.)	Energy consumed (kWh/m3)	Reference
Conventional treatment of surface water	0.2–0.4	81
Water reclamation	0.5–1.0	82
Indirect potable reuse	1.5–2.0	83
Brackish water desalination	1.0–1.5	84
Desalination of Pacific Ocean water	2.5–4.0	85

Note: 1 kWh/m^3 *= 1233 kWh/acre-foot*

4. The central question of this chapter

The central question of this chapter is this: considering the regulatory, environmental, and economic constraints, could the continued operation of Diablo Canyon provide additional value to the people of California, beyond the grid services already provided? Specifically, could the combined operation of a large-scale desalination plant with the existing nuclear power plant provide fresh water to Californians more economically than other desalination alternatives? If so, where might that fresh water be used?

Aside from seawater desalination, there are a number of other ways that the plant could provide additional value, including by generating hydrogen, addressed further in Chapter 3. The scope of this chapter, though, focuses exclusively on repurposing it to provide some combination of power and water to the people of California. We understand that decisions regarding which types of power and water resources to invest in are complex, contain myriad value judgments, and involve a large number of stakeholders with a wide variety of interests. The political aspects of building a large-scale desalination plant at Diablo Canyon are outside the scope of this chapter and the larger report. Instead, what we detail in this chapter is, if Californians determine that building large-scale desalination plants is in their

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[79] Plappally and Lienhard, "Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal," op. cit.

[80] Plappally and Lienhard, "Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal," op. cit.

[81] Voutchkov, N., "Energy Use for Membrane Seawater Desalination—Current Status and Trends," Desalination 431 (Apr. 2018), pp. 2–14, doi:10.1016/j.desal.2017.10.033.

[82] Voutchkov, N., "Energy Use for Membrane Seawater Desalination—Current Status and Trends," op. cit.

[83] Voutchkov, N., "Energy Use for Membrane Seawater Desalination—Current Status and Trends," op. cit.

[84] Voutchkov, N., "Energy Use for Membrane Seawater Desalination—Current Status and Trends," op. cit.

[85] Voutchkov, N., "Energy Use for Membrane Seawater Desalination—Current Status and Trends," op. cit.

interest as part of a long-term water security strategy, then building a large-scale desalination plant at Diablo Canyon, powered by nuclear power from the Diablo Canyon Nuclear Power Plant may have economic advantages over other seawater desalination alternatives in the state. Throughout this chapter, we compare the costs and benefits of building a desalination plant at Diablo Canyon to a hypothetical large-scale plant built in California, and also investigate the potential need for desalinated water in areas that fresh water could be transported to. While we have identified several potential water offtakers in this chapter, we have not reached out to determine their interest in such a project. This chapter may serve as an initial feasibility study for potential offtakers considering desalination as a part of their water portfolios.

Diablo desalination project as a water source

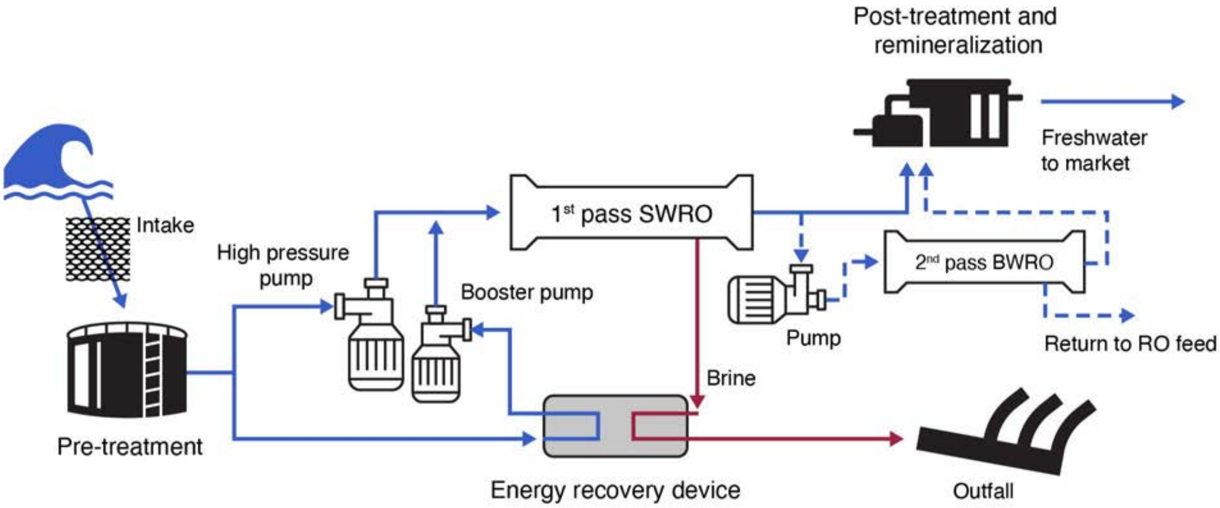
1. Core desalination project concept

We begin our analysis by discussing the basics of reverse osmosis, as well as the basic operation of Diablo Canyon. The power plant's electrical and cooling water output bound what is possible in terms of the size and scope of a hypothetical desalination plant co-located with the power plant. A co-located desalination plant will be powered directly by the nuclear plant, thus reducing charges for electricity transmission and distribution, and allowing for the plants to use a shared seawater intake and outfall. Next, we propose several different configurations for the hypothetical desalination plant, and then go into more depth to determine the requirements of each proposed configuration. The estimated costs of building such projects are discussed in later sections.

(a) Basic Reverse Osmosis system description

Reverse osmosis (RO) is the most commonly used technology for seawater desalination today. At the core of RO systems are semi-permeable membranes, which allow water to pass through while rejecting nearly everything else contained in seawater. Feedwater enters RO plants from large seawater intakes, is pretreated with filters or membranes to remove large particles, silt, bacteria, and other constituents, and can be treated with chemicals to adjust the feedwater chemistry. Next, the water is pumped to high hydraulic pressures, which allow water to permeate through the RO membranes against an osmotic pressure difference across the membrane, separating the feedwater into product water and concentrated brine.

Figure 2-7: Diagram of a basic two-pass reverse osmosis system



The fresh water is further treated to ensure that it is disinfected, and minerals are often added back into the fresh water for taste and to ensure that the water does not corrode pipes. The fresh water is then distributed to end-use points. The brine passes through energy recovery devices (ERD's) so that the hydraulic pressure in the waste stream can be recycled within the system, saving energy. The brine is then pumped back to the ocean, where it is discharged. Approximately 65-80% of the total energy used in the desalination plant is consumed by the RO system, with the remainder being used in the intake, outfall, pretreatment, post-treatment, and other facilities.[86]

(b) Diablo Canyon nuclear power plant conditions relevant to desalination

The Diablo Canyon Nuclear Power Plant uses a once-through cooling system to condense the steam entering the main condenser of the power plant, as well as to provide cooling to a number of other systems. At full load, the design temperature increase of the cooling water is 10°C above the ambient seawater temperature, and the cooling water flow rate is 110 m^3/s (2.8 million AFY).[87] At present, the power plant's open ocean intake is screened with bar racks (9.5 mm bars at 86 mm centers) (3/8-inch bars at 3-3/8-inch centers) and traveling mesh screens (9.5 mm square openings) (3/8-inch square openings) to prevent debris and large biota from entering the plant. Sodium hypochlorite is added as needed to help control micro and macro fouling in the intake tunnels, piping, and the condenser tubes.[88] It is assumed that no other pretreatment is performed at present. Historical intake and discharge temperatures from the power plant, as well as cooling water flow rates, are shown in Figure 2-8.[89] The

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[86] Voutchkov, N., "Energy Use for Membrane Seawater Desalination—Current Status and Trends," op. cit.

[87] "Diablo Canyon Power Plant Units 1 and 2 Final Safety Analysis Report Update" (2013), https://www.nrc.gov/docs/ML1509/ML15098A461.pdf.

[88] "Diablo Canyon Power Plant Units 1 and 2 Final Safety Analysis Report Update," op. cit.

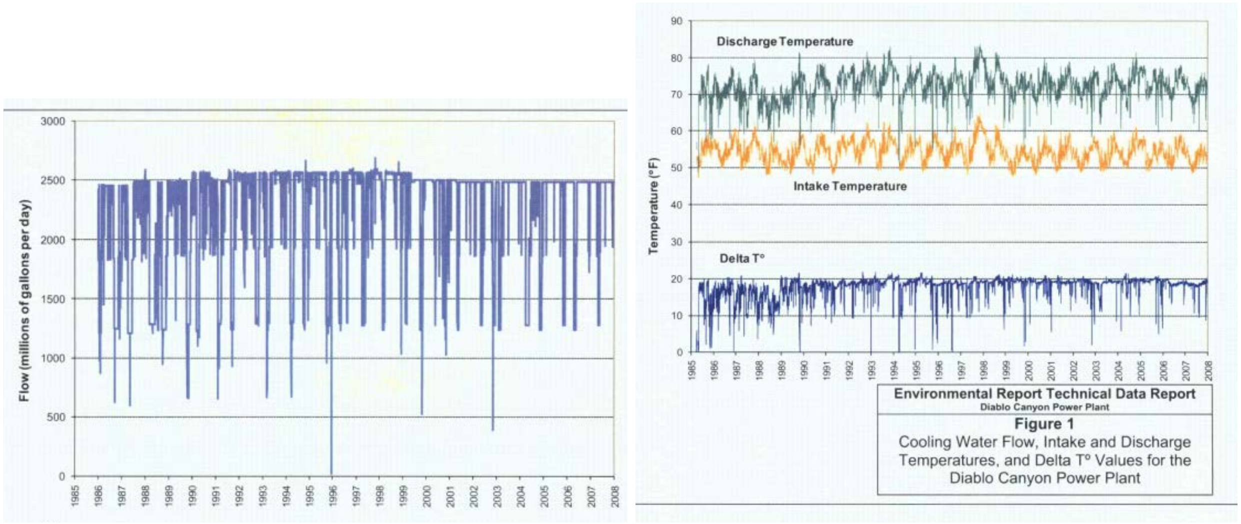
[89] US Nuclear Regulatory Commission, "Diablo Canyon License Renewal Feasibility Study Environmental Report—Heat Shock" (2008), https://www.nrc.gov/docs/ML1116/ML11166A151.pdf.

salinity of the cooling water is assumed to be between 33 and 34 g/kg (~33,500 ppm).[90] A summary of Diablo Canyon effluent conditions, and therefore potential desalination plant intake conditions, is shown in Table 2-4.

Table 2-4: Summary of Diablo Canyon nuclear power plant effluent conditions

	Value	Unite
Temperature	18-27 (65-80)	°C (°F)
Salinity	33.5	g/kg
Flow rate	110 (9.45 million)	m3/s (m3/d)
Pretreatment	Screening and chlorination	

Figure 2-8: Cooling water flow, intake and discharge temperatures for Diablo Canyon power plant[91]



(c) Plant configuration

A seawater reverse osmosis desalination plant could be configured in many different ways at the Diablo Canyon Nuclear Power Plant. Various arrangements can be implemented to meet different water or electricity needs, to respond to temporally variable water and electricity needs, and to achieve compliance with applicable environmental regulations. Four options are investigated in this report to provide a basic understanding of the wide range of possibilities, and to understand how changing some

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[90] Petersen, K.L., et al., "Biological and Physical Effects of Brine Discharge from the Carlsbad Desalination Plant and Implications for Future Desalination Plant Constructions," Water 11, no. 2 (Jan. 2019), p. 208, doi:10.3390/w11020208.

[91] NRC, "Diablo Canyon License Renewal Feasibility Study Environmental Report—Heat Shock," op. cit.

of the key parameters of the hypothetical desalination plant will change outcomes. These options represent a broad range of possibilities, but they by no means cover the entire space of what is possible at Diablo Canyon. The four options are discussed in order of volume of water output and are illustrated in the accompanying figures. Key values are given in Tables 2-5 and 2-6; a basic outline of a generation-desalination system is depicted in Figure 2-9.

Table 2-5: Key boundary values for various desalination plant options

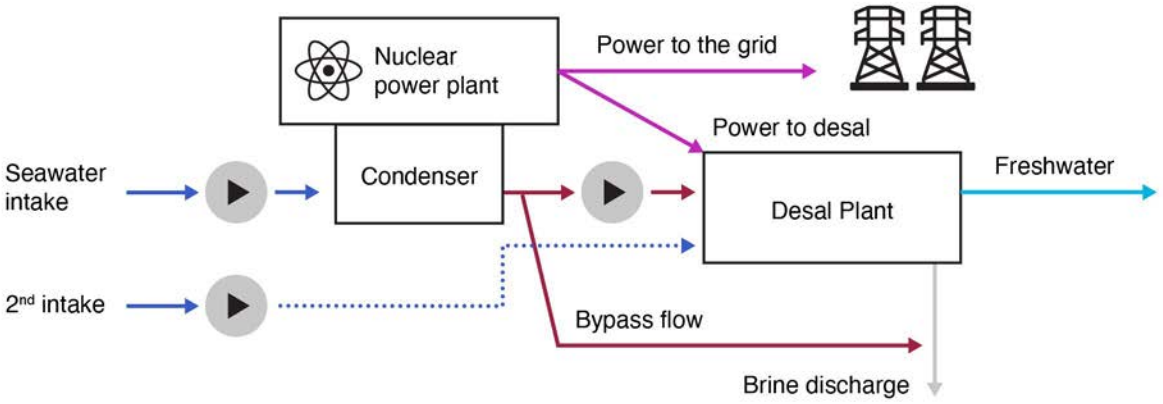
	No desal	**Option 1: Diablo Desalination Plant**
Outfall temperature	Ocean + 10°C	Ocean + 10°C
Outfall salinity	35,000 ppm	36,700 ppm
Outfall flow rate	9,504,000 m3/d 9,504,000 m3/d	9,314,730 m3/d 2,758,155 ac-ft/y
Intake flow rate	9,504,000 m3/d 2,814,000 ac-ft/y	9,504,000 m3/d 2,814,000 ac-ft/y
Product flow rate	N/A	189,270 m3/d 55,845 ac-ft/y
Electricity produced	2240 MW	55,845 ac-ft/y
Electricity to grid	2240 MW	2240 MW

As a high-level, first-order estimate, we assume that all desalination plants will have a specific energy consumption of 3.5 kWh/m^3 (4.32 MWh/AF), defined as the energy consumed per volume of purified product water, and a recovery ratio of 50% (fraction of salty feedwater turned into pure product water). These parameters will fluctuate depending on detailed designs in practice.

Option 1: Large-scale desalination plant similar to existing plants

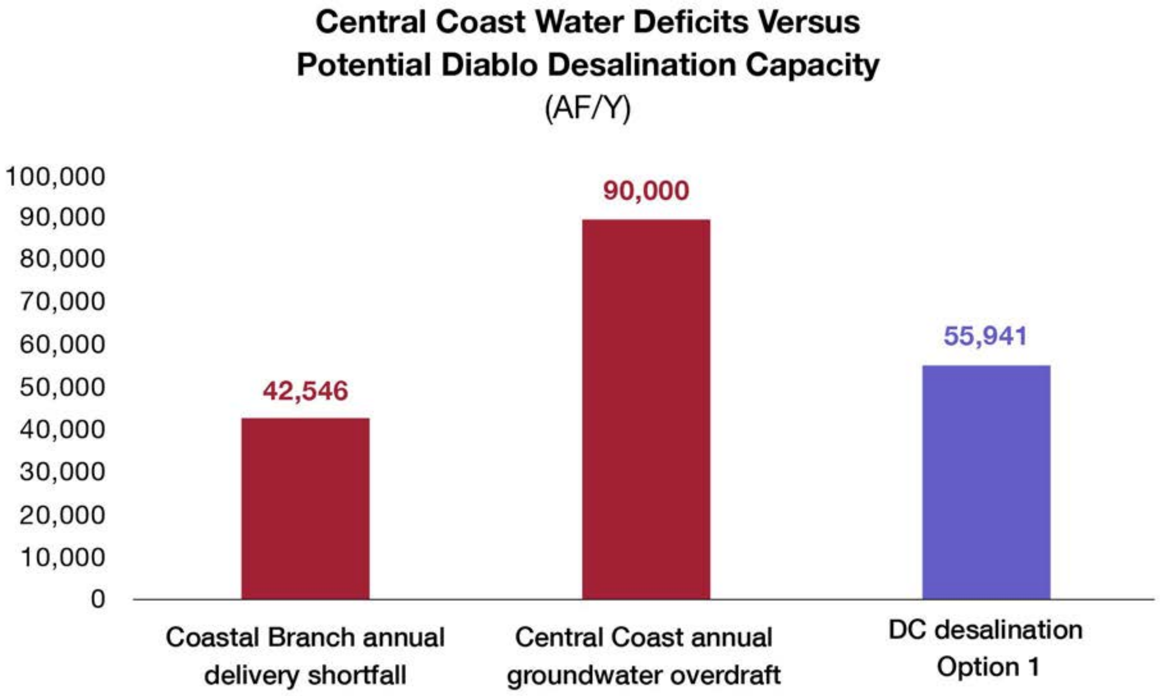
The smallest option we consider in this report is still a large-scale desalination plant, with a capacity of 189,270 m^3/d. This is also the nameplate capacity of the Carlsbad Desalination Plant, and approximately the same size as the proposed plant at Huntington Beach. There are a number of interesting benefits of building at this scale, which will become clearer throughout the chapter. These include lower salinity brines, after the desalination brine is mixed with the power plant cooling water, which would obviate the need for high-energy diffuser outfalls and allow for the existing outfall infrastructure to remain in place. In this configuration, the electrical requirement of the desalination plant is very small compared to the size of the nuclear power plant.

Figure 2-9: Generalized cogeneration-desalination system co-located with a nuclear power plant. Options 1 and 2 have a bypass flow stream, with excess condenser water mixing with brine. Option 3 has no bypass flow. Option 4 has no bypass flow, and is the only option with a second intake.



As noted in Figure 2-10 below, this configuration would make a substantial contribution to serving the Central Coast's current water deficits:

Figure 2-10: Option 1 Diablo Canyon desalination output versus Coastal Branch delivery shortfalls and groundwater overdrafts. Deficit and shortfall sources as cited in above text, and Diablo Canyon desalination Option 1 output per above converted into acre feet



2. Alternative “mega-size” configurations

The seawater intake and the electricity production at the Diablo Canyon Nuclear Power Plant could be used to support a much larger desalination plant than the option presented above. Such “mega-sized” plants would be an order of magnitude larger than today’s largest desalination plants. Building such large plants poses a significant challenge and would certainly have to be done in stages to accommodate practical limitations (e.g., financing, membrane production capacity). We consider three options to provide a basic understanding of the wide range of possibilities.

Table 2-6: Alternative mega-sized desalination plants considered as "what-if" scenarios

	Option 2	Option 3	Option 4
Outfall temperature	Ocean + 10°C	Ocean + 10°C	Ocean + 3°C
Outfall salinity	46,800 ppm	70,000 ppm	70,000 ppm
Outfall flow rate	7,084,800 m3/d 2,098,000 ac-ft/y	4,752,000 m3/d 1,407,000 ac-ft/y	15,379,200 m3/d 4,554,000 ac-ft/y
Intake flow rate	9,504,000 m3/d 2,814,000 ac-ft/y	9,504,000 m3/d 2,814,000 ac-ft/y	30,758,400 m3/d 91,080,000 ac-ft/y
Product flow rate	2,419,200 m3/d 716,000 ac-ft/y	4,752,000 m3/d 1,407,000 ac-ft/y	15,379,200 m3/d 4,554,000 ac-ft/y
Electricity produced	2240 MW	2240 MW	2240 MW
Electricity to grid	1887 MW	1547 MW	0 MW

Option 2: Using half of cooling water from power plant as feedwater
This configuration is a response to the challenging regulatory environment in California. Rather than using the full output of the condenser as feed to the desalination plant, it reduces product water output in favor of an outfall blending scheme that could help to meet environmental regulations without large investments. In this option, Diablo Canyon operates as normal. The desalination plant takes in half of the condenser cooling water, and the other half is used to dilute the brine discharged from the desalination plant. The dilution of the desalination brine would make it easier to comply with the stringent discharge requirements of the California Ocean Plan. A configuration like Option 2 could also be considered if there is not enough water demand to justify building options with larger capacities. Option 2 may also be an intermediate design on the route to building a larger capacity system, which could be built initially, and scaled over time as needed. This configuration also produces excess power that could be sold to the grid, or used for other purposes.

Option 3: Use all cooling water from the power plant as desalination feedwater
In this configuration, the power plant would send all its cooling water to be desalinated. In this case, the energy required to desalinate all the cooling water is less than the power produced by the power plant, meaning that there is excess power that can continue to be sold to the grid. This option does not change

the amount of water taken in from the ocean. We note that Options 1 through 3 would all require the same sized ocean intake, in order to provide enough condenser cooling water to the nuclear plant. This option maximizes the capacity of the desalination plant without increasing the size of the intake infrastructure beyond what would already be required to keep the plant operational.

Option 4: Use all electricity from the power plant to produce water
In this configuration, Diablo Canyon is to be completely separated from the California grid. In this case, all of the power, and all of the cooling water is sent to a desalination plant. Because there is excess power beyond what is required to desalinate the cooling water, additional water is drawn from the ocean to be desalinated. This configuration is the largest of the four configurations in terms of water production.

The enormous capacities of these desalination options are put into perspective in Table 2-7. We note that Option 3 could produce approximately an order of magnitude more water than the world's largest operating desalination plant. Designing mega-scale plants introduces a number of unique challenges. Such a plant would almost certainly be built in stages, and the first step would be a much smaller desalination plant, one that uses only a small fraction of Diablo Canyon's potential feedwater and power output.

Table 2-7: Water at a range of scales

	Capacity	Units
Average water consumption of a Californian (2016)[92]	0.32	[m3/d]
Olympic swimming pool capacity	2500	[m3]
Aqua Claudia (ancient Roman aqueduct)	184,000	[m3/d]
Carlsbad desalination plant (largest desal plant in USA) + Option 1	189,270	[m3/d]
Sorek desalination plant (currently world's largest RO plant)[93]	540,000	[m3/d]
California Aqueduct Coastal Branch pumping capacity at Las Perillas[94]	1,127,865	[m3/d]
Diablo Canyon Option 2	2,419,000	[m3/d]
Diablo Canyon Option 3	4,752,000	[m3/d]
California Aqueduct pumping capacity at Buena Vista[95]	13,223,667	[m3/d]
Diablo Canyon Option 4	15,379,000	[m3/d]

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[92] Brown, B., "Residential Water Use Trends and Implications for Conservation Policy," Budget and Policy Post, 2017, https://lao.ca.gov/Publications/Report/3611.

[93] Global Water Intelligence, DesalData, Plants: 2020 Projects, https://www.desaldata.com/.

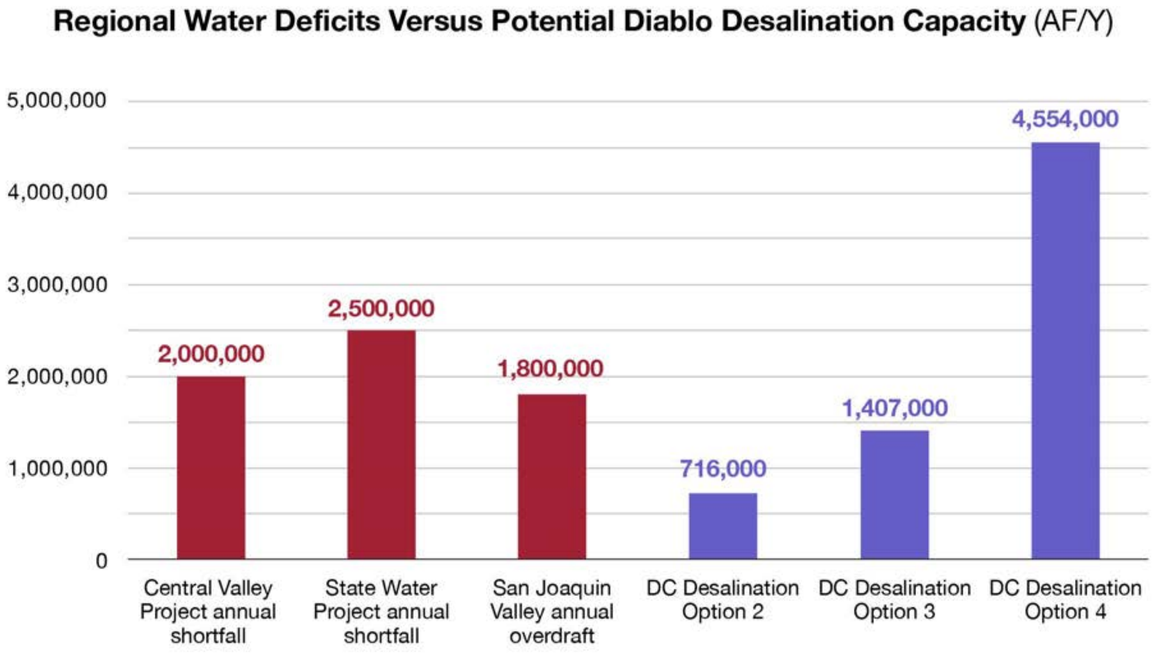
[94] Brown, E.G., Laird, J. & Cowin, M.W., "Management of the California State Water Project," Bulletin 132-14 (Nov. 2015), https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/State-Water-Project/Management/Bulletin-132/Bulletin-132/Files/Bulletin-132-14-r.pdf.

[95] Brown, *et al.*, "Management of the California State Water Project,", *op. cit*.

Central Valley Project average annual deliveries to farms	16,800,000	[m3/d]
California Aqueduct	32,000,000	[m3/d]
Colorado River at Glen Canyon	47,500,000	[m3/d]

Figures 2-11 and 2-12 demonstrate that Options 2, 3 and 4 could make a sizable contribution to offsetting delivery shortfalls from the Central Valley Project and the State Water Project, and alleviating groundwater overdrafts in the San Joaquin Valley. These options are also in the same yield range, or even substantially higher, than the net water exports expected from the Delta Conveyance Project. It is also notable that the projected capital cost of the Delta Conveyance Project, at $15.9 Billion, is more than twice the capital cost of the Diablo Canyon Desalination Option 2, discussed below, which, at a capital cost of approximately $6.5 Billion, yields up to seven times the amount as the DCP. Option 3 would produce 40% more than even the highest estimate of the DCP yield, at a capital cost of $11.6 Billion, $4 Billion lower than the DCP.

Figures 2-11 and 2-12 below: Options 1, 2, 3, and 4 Diablo Canyon desalination output versus CVP and SWP delivery shortfalls per above text, and Delta Conveyance project output range, with Diablo Canyon desalination outputs per above text converted into acre-feet[96]



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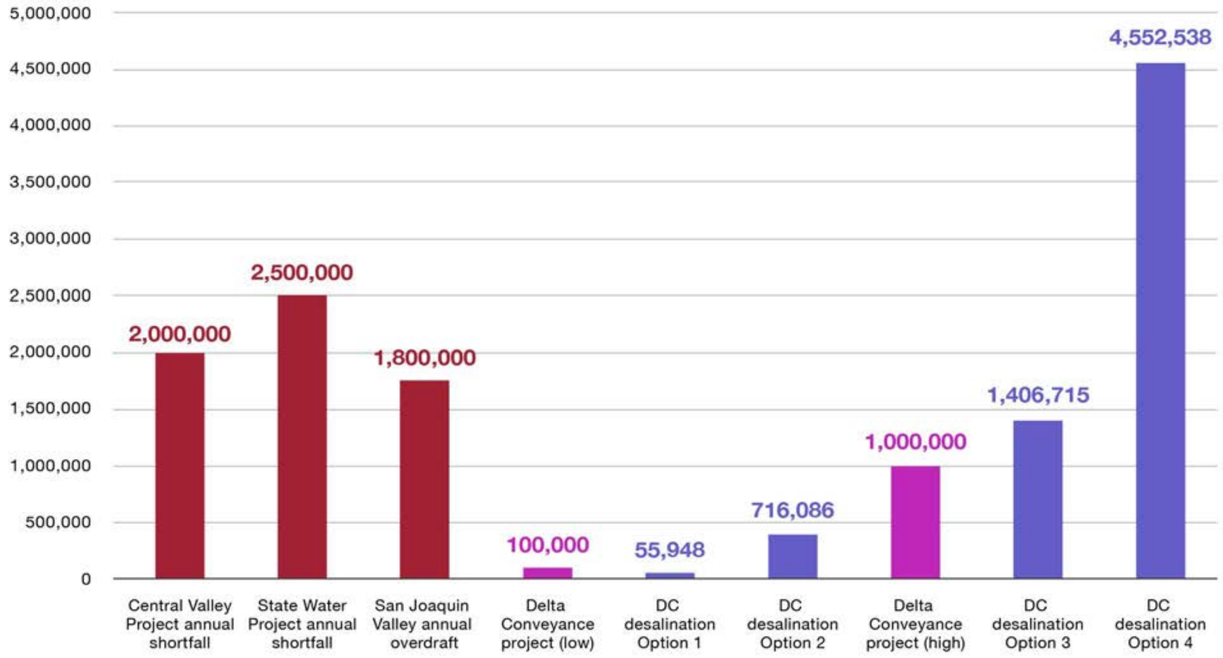
[96] Delta Conveyance project export and cost figures are from Kern County Water Agency, "Overview and Summary of the Delta Conveyance Project" (Oct. 2020), https://www.belridgewsd.com/wp-content/uploads/2020/10/DCP-Summary-and-Overview-Document-Public-Version-002.pdf.

Regional Water Deficits Versus Potential Diablo Desalination Capacity (AF/Y)



(a) Seawater intake

When Bechtel was commissioned to investigate once-through cooling alternatives in 2011,[97] its report noted that the marine waters near Diablo Canyon are significant producers of marine algae, including surface kelp and understory algae; indeed, kelp growth can reach 2 feet per day during the growing season between June and October. The kelp is mowed regularly to avoid problems with the power plant. This area is also subject to tidal fluctuations, waves (normally 5 to 10 feet and reaching 20 to 30 feet during storm events), and wind (typically 10 to 25 mph and sometimes reaching 40 to 50 mph). The water is expected to have a robust fouling community.

If Diablo Canyon is going to continue to operate, and if a desalination plant is co-located with the power plant, the existing power plant seawater intake will need to be modified, retrofitted, or completely rebuilt in order to meet new regulations. As discussed previously, the California Water Quality Control Policy on the Use of Coastal and Estuarine Water for Power Plant Cooling[98] requires that existing power plants using once-through cooling reduce their intake flow rate by 93%. If not feasible, power plants are able to instead put into place measures that reduce the impingement and entrainment of marine life for the facility to a comparable level. If neither of these options are feasible, there are alternative steps that can

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[97] Bechtel, “Alternative Cooling Technologies or Modifications to the Existing Once Through Cooling System for Diablo Canyon Power Plant,” op. cit.

[98] State Water Resources Control Board, “Final Amendment to the Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling” (Sept. 1, 2020), https://www.waterboards.ca.gov/water_issues/programs/ocean/cwa316/docs/otc_policy_2020/final_amendment.pdf.

be taken, on a case-by-case basis, for nuclear power plants to comply with this regulation. These regulations are the primary technical reason for the impending shutdown of the plant.

In addition to the regulations on the power production side, the intake for a co-located power and desalination plant would also have to comply with regulations for desalination plants. In California, desalination intakes are regulated by the California Ocean Plan,[99] which is similar, but slightly more rigid than the regulations for existing nuclear power plants with regard to seawater intakes. The California Ocean Plan also focuses on limiting the impingement and entrainment of marine life. There are two approaches that other desalination projects have taken to meet the key provisions in the California Ocean Plan.

The first is to construct a submerged intake gallery. These intakes are buried 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. The benefits of these intakes are that the filtration performed by the ocean floor can reduce the level of pretreatment required by the desalination plant, and there are almost no effects to aquatic life during normal operation. The downside of these intakes are the upfront capital costs, the destruction of large areas of seafloor habitats initially required to build the intakes, the possibility of affecting freshwater aquifers inland of the intake, and the possibility for high maintenance costs and disruption of ocean habitats throughout the life of the plant if the conditions are not favorable. Important factors for the feasibility of submerged intakes are described by the WateReuse Desalination Committee.[100] Submerged intakes are designed similarly to commonly-used slow sand filters. The design surface loading rate of infiltration gallery filter beds is typically between 0.05 to 0.10 gpm/ft^2 (0.034 to 0.068 L/s-m^2). If a surface loading rate of 0.075 gpm/ft^2 (0.05 L/s-m^2) is assumed, an infiltration gallery large enough to draw in all the intake water for the nuclear power plant would be over 500 acres (2.02 km^2) large. For reference, the footprint of the current intake lagoon at Diablo Canyon is approximately 20 acres (0.08 km^2). Due to the complexity of determining the environmental and economic feasibility of a submerged seawater intake, and the complicated regulatory and permitting framework, we direct our focus in this report to the second approach.

The second approach to comply with the California Ocean Plan is to construct submerged screened intakes. California desalination regulations require that new screened intakes have a mesh size of 1 mm or less, and a flow velocity at the screen of no more than 0.5 feet per second. Although these conditions can lead to rapid fouling of the intake screens, screens can be cleaned by a number of methods, such as with an air burst, mechanical cleaning, or by divers. Screened intakes generally cost much less than submerged intake galleries, and their successful operation is less dependent on the local site conditions, such as the wave action, ocean floor composition, and bathymetry of the area. A detailed design study should investigate all options presented here. For the purpose of this analysis, though, Intake Screens, Inc. (ISI) of Sacramento has provided us initial estimates regarding mechanical brush-cleaned wedgewire screens,[101] which will likely be one of the most competitive options. Similar intake systems have been

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[99] State Water Resources Control Board and California Environmental Protection Agency, "Water Quality Control Plan Ocean Waters of California" (2019), http://www.waterboards.ca.gov.

[100] WateReuse Association, "Overview of Desalination Plant Intake Alternatives" (June 2011), http://www.watereuse.org/sites/default/files/u8/Intake_White_Paper.pdf.

[101] The full ISI analysis is set forth as an appendix to a working paper that parallels this chapter: Bouma, A.T., Wei, Q.J., Parsons, J.E., Buongiorno, J., & Lienhard, J.H, "Water for a Warming Climate: A Feasibility Study of Repurposing Diablo Canyon Nuclear Power Plant for Desalination" (July 2021), http://ceepr.mit.edu/publications/working-papers/761.

specified for the Huntington Beach desalination plant,[102] and are currently being tested at Carlsbad as a potential replacement for the existing intake.[103] We note that there are a number of designs that may be feasible at Diablo Canyon, although we only discuss one here.

Key to ISI's design is a submersible electric-drive assembly that rotates wedgewire screen cylinders between nylon brushes. The exterior of the wedgewire is cleaned by a fixed position external brush (see Fig. 2-13) and the interior of the screen is cleaned by an internal brush that rotates. This brush-cleaning system has proven effective at maintaining a clean screen surface in a number of applications with challenging fouling environments.

Figure 2-13: ISI mechanical brush-cleaned screen operating in Hudson River (Intake Screens, Inc. Report)

Maintenance of a clean screen surface is critical to providing aquatic organism protection, as fouled screens are prone to developing velocity "hot spots," which increase the potential to either entrain or impinge aquatic organisms and/or result in the inability to convey water through the intake screen. ISI's design includes stainless steel wedgewire mesh with openings of no more than 1 mm, and a through-screen velocity of no more than 0.5 ft/s (15 cm/s). Screen material and internal structures are constructed from 2507 Super Duplex stainless steel with cathodic protection and material isolation to protect against corrosion in the marine environment. The system also has antifouling coatings on other surfaces.

A series of vertically-oriented drum screens would be located at least 300 m (1,000 feet) from shore in relatively deep water (>15 m) (>50 ft) to avoid the more sensitive nearshore marine habitats and potential higher aquatic organism densities located in the nearshore area. This is illustrated in Figure 2-14:

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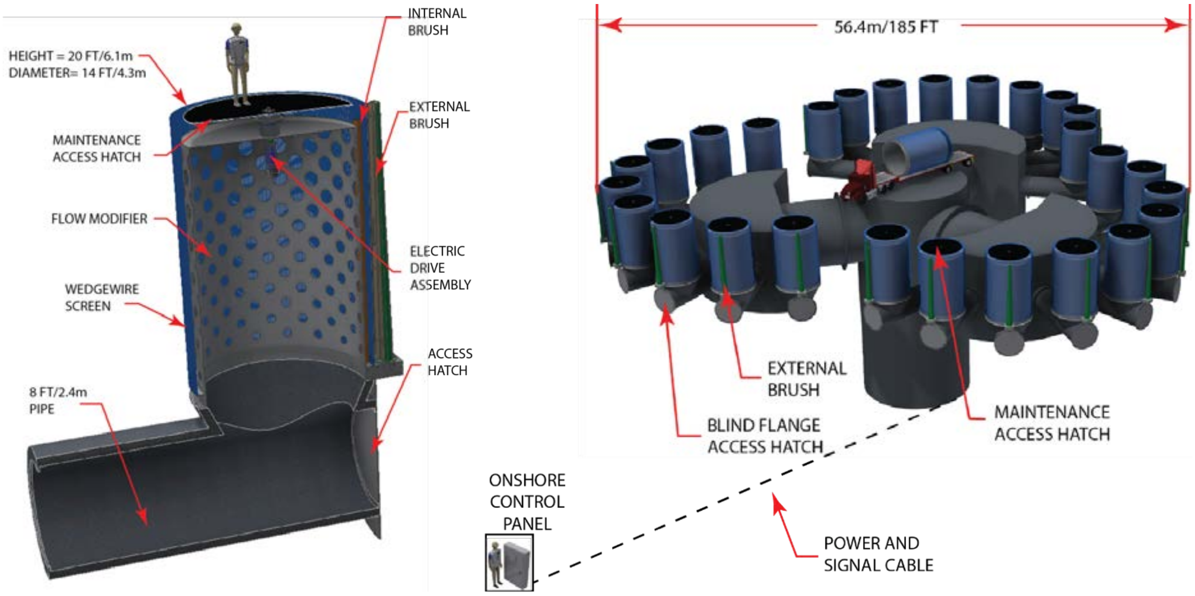
[102] "Order R8-2020-0005 NPDES No. CA8000403 Waste discharge requirements for Poseidon Resources (Surfside) L.L.C., Huntington Beach desalination facility, Orange County" (2020), http://www.waterboards.ca.gov.

[103] Pankratz, T., "SWRO Pilot Intake Is Operational," *Water Desalination Report* (Feb. 2021), https://www.desaldata.com/news/swro-pilot-intake-is-operational.

Figure 2-14: Left: Proposed ISI screen to be used at Diablo Canyon, with a human shown for scale. Right: ISI brushed wedgewire screens on concrete manifold array, with flatbed truck shown for scale (Intake Screens, Inc. Report)



The array of screens is designed to achieve equal withdrawal from each wedgewire screen, and the design also allows for inspections and simplified maintenance and repair. Following the approach used in the Bechtel report, the existing shoreline basin would be closed off from the Pacific Ocean by extending the existing breakwater structure. The new section of breakwater would include a stop log structure so the wedgewire screens could be bypassed should the need arise. The shoreline basin would then be connected to each offshore screen array by a drop shaft below the basin that leads to a bored tunnel and terminates at the manifold array, as illustrated in Figure 2-15:

Figure 2-15: Aerial view of the plant with extended breakwater to isolate lagoon, emergency inlet structure, tunnel extending offshore, and wedgewire screen array for Option 1 (Intake Screens, Inc. Report)

To place the screens in an appropriate offshore, deep water location that minimizes potential impacts to aquatic resources, the tunnel is anticipated to be approximately 335 m (1,100 feet) long. This arrangement allows for the power plant to continue to operate continuously throughout the construction of the new intake, as the existing power plant intake pumps and structure are unchanged. One intake array would be required for Options 1-3, while Option 4, which requires additional feedwater, would require an expanded intake system. Additional information regarding the proposed intake systems can be found in the appendices.

We note that this is just one method of constructing an intake that would meet the needs of the desalination and power plants. The arrangement as shown may need to be modified as additional studies are performed and other requirements are discovered. For example, if the marina inside the breakwater is going to continue to be used for shipping, a different breakwater arrangement may be needed in order to allow the passage of large ships. Possibilities include changing the emergency stoplog structure to something more easily moved, or extending the tunnel to a point closer to the existing intake, and constructing a smaller breakwater or other structure around the outlet, which would allow for the existing breakwater to remain as is. Other options should be investigated, such as Johnson screens with different cleaning mechanisms, and potentially even converting the existing breakwater into a porous dike, which would filter the incoming seawater instead of using a screened intake. For all options, designing around the seismic and environmental concerns will be of utmost importance.

(b) Outfall

The discharge of brine from the desalination presents another challenge. The current power plant outfall consists of surface discharge to Diablo Cove. The hot discharge water is initially carried towards the open ocean by the water's inertia, imparted by the 26 m (85-foot) drop in elevation from the power plant to the shoreline. Beyond Diablo Cove, the buoyancy of the hot discharge causes the thermal plume to spread across the surface, dissipating heat into the atmosphere.[104]

For Option 1, the existing power plant outfall could continue to be used, which would allow for significant capital cost savings.

If a mega-scale desalination plant is constructed (Options 2-4), utilizing warm cooling water from the nuclear station as the feedwater, and discharging brine to the ocean, major changes to the existing outfall scheme will need to be made in order to comply with the new desalination outfall regulations. The California Ocean Plan regulates desalination plant outfalls, and the regulations are designed to limit damage to sensitive coastal ecosystems, especially problems due to high salinity. The California Ocean Plan specifies that brine discharge not exceed two salinity units (parts per thousand) above ambient levels within 100 meters of the discharge point, although this salinity impact zone was extended to 200 meters for other large projects, such as the Carlsbad Desalination Plant. Although Carlsbad's outfall has been shown to have minimal environmental impact,[105] it is unlikely that regulators will allow for similar exceptions. Similar to desalination intakes, outfalls are permitted by first completing site-specific feasibility studies for a number of alternatives, after which regulatory committees determine which alternatives are feasible. These detailed feasibility studies are outside the scope of this report.

One of the challenges with desalination brine is that aqueous solutions become denser as they become more saline. The increased density causes undiluted brine to descend to the ocean floor, creating a localized environment that can be detrimental to, or even kill, aquatic life. This phenomenon can be mitigated by ensuring good mixing of brine with ambient waters by using a network of diffusers, or by discharging in locations with strong currents or surface/internal wave action to enhance turbulent mixing and molecular diffusion of salts. In the case of Diablo Canyon, the fact that the brine is also likely to be warmer than ambient temperature helps to reduce the density of the brine, helping the brine to sink less quickly and mix more rapidly.

The density of the brine, which is important for understanding its mixing and dispersion, is shown as a function of temperature and salinity[106] for all options in Table 2-8. It is unlikely that significant cooling of the brine will occur inside the desalination plant itself, given the high mass flow rates of water and limited heat transfer area of the internal piping.

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[104] NRC, "Diablo Canyon License Renewal Feasibility Study Environmental Report—Heat Shock," *op. cit.*

[105] Petersen, K.L., *et al.*, "Biological and Physical Effects of Brine Discharge from the Carlsbad Desalination Plant and Implications for Future Desalination Plant Constructions," *op. cit.*

[106] Sharqawy, M.H., Lienhard, J.H., & Zubair, S.M., "Thermophysical Properties of Seawater: A Review of Existing Correlations and Data," *Desalination and Water Treatment* 16 (2010), pp. 354–380, doi:10.5004/dwt.2010.1079; Nayar K.G., *et al.*, "Thermophysical Properties of Seawater: A Review and New Correlations That Include Pressure Dependence," *Desalination* 390 (2016), pp. 1–24, doi:10.1016/j.desal.2016.02.024.

Table 2-8: Seawater density as a function of temperature and salinity[107]

Winter	Ocean	Outfall - No desal	Outfall - Option 1	Outfall - Option 2	Outfall - Options 3&4
Temperature	11°C	21°C	21°C	21°C	21°C
Salinity	35,000 ppm	35,000 ppm	36,700 ppm	46,800 ppm	70,000 ppm
Density	1026.8 kg/m^3	1024.7 kg/m^3	1026.0 kg/m^3	1033.7.4 kg/m^3	1051.5 kg/m^3
Summer	**Ocean**	**Outfall - No desal**	**Outfall - Option 1**	**Outfall - Option 2**	**Outfall - Options 3&4**
Temperature	18°C	28°C	28°C	28°C	28°C
Salinity	35,000 ppm	35,000 ppm	36,700 ppm	46,800 ppm	70,000 ppm
Density	1025.4 kg/m^3	1022.7 kg/m^3	1024.0 kg/m^3	1031.6 kg/m^3	1049.2 kg/m^3

A likely option for waste disposal is a brine diffuser system. Diffusers release high velocity brine through a set of nozzles spread over a wide area, helping to quickly mix the brine with the surrounding seawater. Diffusers represent the most environmentally friendly option for brine disposal, and have been utilized at other plants in sensitive ecological environments such as the Sydney Desalination Plant in Sydney, Australia.[108] Brine diffusers have been shown to have minimal impacts on local fish populations.[109] Diffusers are likely to be required for any new large desalination plant in California due to the strict environmental regulations, with the exception of plants co-located with another source of freshwater being discharged, allowing for the commingling and diluting of brine.

(c) Land requirements and siting

Another challenge with building large desalination plants is finding a proper site for the construction of the plant. A desalination plant of the scale of any of the proposed options will require a large piece of land. At the same time, land costs in California are high, and coastal development for desalination projects faces significant regulatory hurdles and red tape. To estimate the required footprint, we considered other large-scale desalination plants, with a special focus on plants that are site-size constrained, such as plants in the United States and Singapore. We found that Carlsbad has one of the highest densities of any plant we considered, with the 189,270 m^3/d plant contained within a footprint of 5.5 acres, giving a density of over 34,000 m^3/d/acre. Because the proposed desalination plant could share certain facilities with the nuclear station (intake, outfall, potential for shared administrative buildings and service roads), and because the large scale should allow for greater effective density (land required for service roads and administrative facilities will not scale linearly with capacity), we believe it is

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[107] Nayar, K.G., et al., "Thermophysical Properties of Seawater: A Review and New Correlations that Include Pressure Dependence," op. cit.; Sharqawy, Lienhard, and Zubair, "Thermophysical Properties of Seawater: A Review of Existing Correlations and Data," op. cit.

[108] Kelaher, B.P., et al., "Effect of Desalination Discharge on the Abundance and Diversity of Reef Fishes," Environmental Science and Technology 54, no. 2 (Jan. 2020), pp. 735–744, doi:10.1021/acs.est.9b03565.

[109] Whitmarsh, S.K., et al., "No Detrimental Effects of Desalination Waste on Temperate Fish Assemblages," ed. Mark Gibbs, ICES Journal of Marine Science (Dec. 2020), doi:10.1093/icesjms/fsaa174.

reasonable that a Diablo Canyon mega-plant could reach a density of 40,000 m^3/d/acre while using off-the-shelf technologies and construction methods. For a large-scale plant, the same density as Carlsbad should be possible. Innovations such as multi-story plants, large-diameter membranes, and compact, advanced pretreatment technologies could help to increase the density even further. The resulting footprint ranges of different options are shown in Table 2-9.

Table 2-9: Estimated land required for various options

Option	Land required [acres]
Option 1	5.5
Option 2	60
Option 3	119
Option 4	384

The area inland of Diablo Canyon is mountainous and would likely not be an economical site on which to build a desalination plant. However, along the coast and still near Diablo Canyon are several coastal areas that are relatively flat and may be able to provide a site for the desalination plant.

Topographical maps and satellite imagery were used to estimate the area of viable land near the nuclear plant. At the scale of Option 1, the land required for a desalination plant could likely be found on or very near the existing plant area, without having to substantially increase the footprint of the combined plant (see Fig. 2-16). For larger options, Crowbar Canyon, just to the northwest of the plant, may have a usable land area of approximately 100-400 acres (see Fig. 2-16). Comparing with Table 2-9, it becomes apparent that regardless of which option is chosen, the plant will likely have to be very densely constructed. There are a number of other possible locations up and down the Diablo Coast that could support a desalination plant, although the preference would be to limit expansion into new areas for environmental protection purposes. Detailed geographical analysis and examination of appropriate sites is outside the scope of this report.

Figure 2-16: Land areas projected onto satellite images of the area near Diablo Canyon. We note that the projected areas are not actual proposed plant sites, but are strictly meant to convey the scale of different project footprints

Figure 2-17: Aerial view of the nuclear station, with Crowbar Canyon in the background

We note, as Figure 2-17 shows, that the coastline from Point Buchon to Point San Luis (approximately 2 miles to the north and 5 miles to the south of the plant) is one of the most pristine coastlines in all of California. The coastline is home to owl limpets, sea palms, and the endangered black abalone, along with a number of other sensitive species. Due to the operation of the nuclear power plant, much of the coastline near Diablo Canyon is currently inaccessible to the public. The lack of human interaction and involvement along this stretch of coast has allowed plant and animal life to truly flourish, especially in the intertidal zone, which contains a vast amount of biodiversity. In Diablo Canyon Decommissioning Engagement Panel meetings, environmentalists have shown concern about opening this coastline up to the public after the impending decommissioning of the nuclear plant. As areas of the California coast that were once inaccessible to the public become publicly accessible, the diverse inhabitants of the intertidal zone are often trampled by “environmental tourists” who flock to the coasts to enjoy nature. Furthermore, sensitive species, such as abalone, are often poached at an alarming rate.[110] Whatever happens at Diablo Canyon, the valuable natural resource that is the Diablo coast must be protected. If a desalination plant is built in the area, careful planning must be done to ensure that these valuable resources are not affected during construction, operation, and eventual decommissioning of the plant. With careful management, the continued operation of the nuclear plant and construction of a desalination plant nearby could help to keep the Diablo coast off limits to the public, providing a protected habitat for the endangered and at-risk species that live there.

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[110] Anders, C., “Water Resources at Diablo Canyon Power Plant and Lands” (2020), https://diablocanyonpanel.org/meetings/2020-panel-meetings/#10-28-20-panel-mtg.

Another consideration is land ownership, zoning, and permitting (see Fig. 2-18). The land Diablo Canyon sits on is zoned as a public facility, while nearby areas that could be used for a desalination plant are zoned as agricultural and rural lands. A desalination plant in the area would likely be located in the coastal zone, which requires additional permits from the California Coastal Commission before construction can begin. Much of the land near Diablo Canyon along the coast is owned by PG&E, or leased by PG&E from Eureka Energy Company.[111]

Figure 2-18: Diablo Canyon lands ownership and land us[112]

If PG&E were to continue to own and operate Diablo Canyon and construct a desalination plant on the adjacent lands they own, no transfer of assets would be required. If PG&E decided to sell the nuclear plant and the land on which it sits to another entity in order to build a desalination plant, California

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[111] PG&E, "Future of PG&E's Diablo Canyon Lands" (accessed Mar. 19, 2021), https://www.pge.com/en_US/safety/how-the-system-works/diablo-canyon-power-plant/diablo-canyon-power-plant/diablo-lands-conservation.page.

[112] PG&E, "Future of PG&E's Diablo Canyon Lands," *op. cit.*

regulations give first rights of refusal to Native American tribes.[113] The area surrounding Diablo Canyon may also contain Native American cultural sites or burial grounds,[114] which could also pose challenges to siting a desalination plant.

To summarize, siting a very large desalination plant (Option 2, 3, or 4) near the nuclear station will be very challenging. The area is pristine, ecologically, and ought to be protected as much as possible. The mountainous terrain will pose significant challenges, as will the political landscape surrounding the lands near the plant. These challenges may be too much overcome, and may render a mega-scale desalination project at Diablo Canyon infeasible. A more modest plant of Carlsbad scale (Option 1), could easily be contained within the already industrialized zone, making this a much more attractive option from an environmental protection perspective.

(d) Effects of product water quality

In order to determine the desalination plant's requirements, it is important to understand the end user of the product water, as different users will have different requirements for water quality. For instance, if product water is discharged to an aqueduct or canal, blending with other water and with further treatment performed before the water reaches a consumer, the desalination product-water requirements may not be very stringent and would have a lower water cost. In this case, single-pass reverse osmosis membranes may be sufficient to reach the desired product water quality.

An ideal RO membrane would allow only water to pass through, rejecting all other constituents present in the feedwater. In practice, these membranes do a very good job, rejecting over 99.7% of NaCl, the major constituent in seawater. However, some other constituents, particularly boron, are rejected at lower rates. While boron is present in lower quantities in seawater (approximately 4.5 mg/L), it is rejected at only 80-90%. Some fruit trees important to California agriculture can be damaged by leaf burn due to boron concentrations over 1 mg/L, and some very sensitive plants, such as avocados, may be damaged at concentrations as low as 0.5 mg/L. This means that for agricultural use, water that passes through a set of membranes may need to undergo a full or partial second pass, whereby either all the water is passed through membranes a second time, or a portion of the product water passes through a second set of membranes, and is blended back in with the water from the first pass. The second pass results in cleaner permeate water, which is fit for agricultural use or, generally, for irrigation of sensitive crops by municipal water supply. We expect that new desalination projects in California will have to meet these strict boron requirements.

Another concern with water from reverse osmosis plants can be the chemical composition of the water in relation to the pipes that the water flows through. Water from desalination plants is low in minerals, alkalinity, and pH. In this state, water tends to corrode and degrade concrete pipes, and leach metals such as copper and lead into the water. To remedy this issue, product water is commonly remineralized by adding directly or dissolving chemicals that contain calcium or magnesium, such as lime, calcite, or

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[113] "Investor-Owned Utility Real Property-Land Disposition-First Right of Refusal for Disposition of Real Property within the Ancestral Territories of California Native American Tribes" (2020), https://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/About_Us/Supplier_Diversity/Final Land Transfer Policy 116.pdf.

[114] Fountain, M., "Everything Cool? A Report on Diablo Canyon's Once-through Cooling Alternatives Breeds More Questions than Answers," *New Times* (San Luis Obispo, CA, 2013), https://www.newtimesslo.com/sanluisobispo/everything-cool-a-report-on-diablo-canyons-once-through-cooling-alternatives-breeds-more-questions-than-answers/Content?oid=2942950.

dolomite. With the proper chemistry achieved, the water will tend to deposit minerals onto pipes, forming a protective coating that helps to prevent corrosion and keep water supplies safe and chemically stable.[115]

While issues of product water quality are important, they are quite routine compared to other challenges when considering a desalination plant at Diablo Canyon. Each hypothetical end user's differing requirements will result in slightly different desalination plant designs, and ultimately in a different cost of water. However, we would expect that meeting the product water requirements of different users would incur the same or very similar costs for any new desalination plant anywhere on the California coast. For example, the capital cost to implement a second pass through membranes to reduce the boron concentration at Diablo Canyon is likely to be very similar to the cost (per m^3) at any other location in California. Furthermore, we expect that most offtakers in the areas near Diablo Canyon will have similar product water requirements, both in terms of boron and remineralization. Therefore, it is unlikely that there are major benefits or disadvantages related to product water quality for a desalination plant at Diablo Canyon compared to any other hypothetical desalination plant.

(e) Desalination plant

The design of the desalination plant itself, consisting of everything from pretreatment to remineralization, is likely to be one of the more routine elements of this project (see Fig. 2-19 for a schematic diagram). Designs for the plant can be informed by the existing small-scale desalination plant that currently serves the nuclear station's needs for drinking water, fire and dust suppression, and power plant makeup water. The existing plant has been operating for over 28 years, and produces 2,450 m^3/d of fresh water (approximately 3 orders of magnitude smaller than the proposed mega-plant). Specifics of the plant design will depend on a number of factors, but one option is presented here.

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[115] National Research Council (US) Safe Drinking Water Committee, "Chemical Quality of Water in the Distribution System," in *Drinking Water and Health*, vol. 4 (Washington, DC: National Academies Press, 1982), https://www.ncbi.nlm.nih.gov/books/NBK216607/.

Table 2-10: Properties of Pacific Ocean seawater[116]

	Value	Units
Total dissolved solids (TDS)	36,000	mg/L
Temperature	14	Degrees C
8.0	8.0	pH
Turbidity	5 (up to 25 during storms)	NTU
Total suspended solids (TSS)	3.6	mg/L
Total organic Carbon (TOC)	3.0	mg/L
Dissolved organic Carbon (DOC)	1.3	mg/L
Chloride	19,000	mg/L
Bromine	70	mg/L
Boron	4.5	mg/L

Using LG Chem's Q+ Projection Software, we have designed a desalination plant to treat incoming feed water from the Pacific Ocean to the standards required for potable drinking water. Typical conditions in the area are given in Table 2-10. The incoming feed is first pretreated to remove potential foulants which may damage the reverse osmosis membranes. The existing plant at Diablo has a pretreatment design consisting of dual media filters, multimedia filters, UV and cartridge filters. Ferric salts and polymer coagulants are used before the filters, and antiscalant before the SWRO. The pretreatment does not include chlorination.[117] The original membranes lasted 13 years and never required clean-in-place due to both the pretreatment design and the operations.[118] Given their success, any new desalination plant sited at Diablo should use the above pretreatment regime as a starting point. Fouling risk may be greater for a new plant with feed that is warmer than raw ocean water.

The pretreated feed then moves to the first pass of reverse osmosis elements. This first pass is a standard design using seven elements in each pressure vessel and an isobaric energy recovery device to recover pressure from the brine stream. The permeate produced during the first pass has a total dissolved solids (TDS) level that is sufficient for drinking water, but contains an amount of boron that is too high (0.86 mg/L) to meet the standards for agricultural use (≤0.5 mg/L) To remedy this, we utilize a partial second pass, similar to the design used in Carlsbad Desalination Plant. Half of the permeate is diverted to a second pass, where the pH is adjusted from 8 to 10 to increase boron rejection.[119] At this

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[116] CDM Smith, "Scwd^2 Seawater Desalination Plant, Phase 1 Preliminary Design, Volume 1" (2012).

[117] Prato, T., *et al.*, "Production of High-Purity Water from Seawater," *Ultrapure Water* 20, no. 8 (2003), pp. 20–25.

[118] Pankratz, T., "What's Your Favorite Plant?" *Water Desalination Report* (2020), https://www.desalination.com/articles/veterans-reminisce.

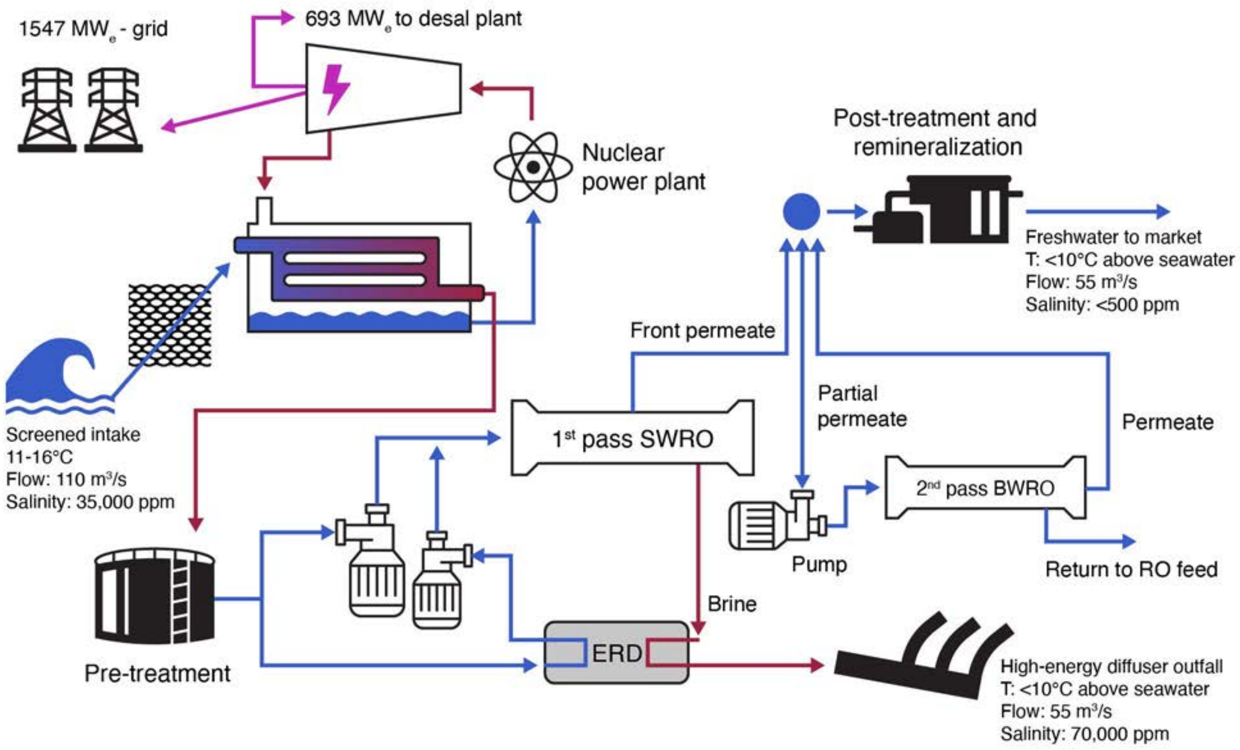
[119] Alabduljalil, S., Alotaibi, S. & Abdulrahim, H., "Techno-Economic Evaluation of Different Seawater Reverse Osmosis Configurations for Efficient Boron Removal," *Desalination and Water Treatment* (2019), doi:10.5004/dwt.2019.24432.

higher pH level, uncharged boric acid (78-80% removal) disassociates to borate ions (>95% removal). The pH-adjusted feed passes through a train of brackish reverse osmosis membrane elements. The permeate from the second pass is blended together with the permeate from the first pass. This final product stream undergoes remineralization and disinfection before being distributed to offtakers.

Again, if we consider the design and operation of this plant in terms of how it may differ from other new desalination plants in California, a few differences stand out. First of all, using seawater that has been warmed by the power plant has two effects on membrane operation. Increasing the temperature increases the water and salt permeability of the membranes. This means that the plant will be able to operate with either a smaller footprint and higher fluxes, or with the same footprint and reduced energy consumption when compared with a plant with cooler feedwater. However, the increased salt permeability will make the membranes less effective at rejecting salts, meaning that the product water will be saltier, and may lead to the need for more passes through membranes or other additional treatment. The other effect of high temperature is an increased propensity for fouling and scaling in membranes, because certain salts will form hard mineral scales more rapidly at higher temperatures. This can be addressed by changing the pretreatment scheme, adding additional antiscalant chemicals, or cleaning membranes more frequently. Although the temperature in a Diablo Canyon desalination plant will be higher than ambient conditions, and higher than other plants in California, the temperatures are still well within the established operating range for desalination plants worldwide. In fact, many of the world's reverse osmosis plants, particularly those in the Middle East, operate with even warmer feedwater.

Ultimately, we expect that the elevated temperatures and subsequent effects on plant design will not have a large impact on the overall cost and feasibility of the plant relative to other hypothetical plants in California. As will be shown in later sections, the potential increase in cost due to minor changes in plant design is small relative to the other savings that result from co-locating the plant with the nuclear station.

Figure 2-19: Diagram of a possible layout for a two-pass RO system integrated with the Diablo Canyon nuclear power plant



(f) Distribution

We consider two baseline scenarios. In the first scenario, a shallow buried pipeline will convey product water from Diablo Canyon all the way to California's Central Valley, where water demand from farmers is outstripping supply. This pipeline would be about 100 km long, with a net elevation gain of 100 m. In the second scenario, a shallow buried pipeline will convey product water from Diablo Canyon to the Coastal Branch of the CA Aqueduct in San Luis Obispo, from which it is delivered to Lake Cachuma above Santa Barbara (see Fig. 2-3 above). This pipeline would be about 30 km long, with a more modest elevation gain of 10 m. In both cases the pipeline would be buried.

Our purpose is to estimate the distribution cost per unit water delivered ($\$/m^3$). The total costs scale linearly with flow rate because a lower flow rate implies a proportionally lower pumping power, fewer pipes and fewer pumps. Therefore, here we present the calculations only for one (high) flow rate, i.e., 4,752,000 m^3/d (1,406,000 ac-ft/y).

For such pipelines, we consider very large pipes (3.5 m ID). Such pipes are commercially available in various materials suitable for water distribution, i.e., extruded HDPE[120] and glass reinforced polyester resin.[121] The assumptions made regarding the pipelines are shown in Table 2-11.

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[120] AGRU, "AGRU to extrude world's largest HDPE pipe," n.d. ("extrud[ing] solid-walled pipe strings made from high-density polyethylene in continuous lengths and outside diameter of up to 610 m (2,000 feet) and 3,500 mm (138 inches), respectively"), https://www.agru.at/en/applications/agruline/grand-opening-ready-for-the-next-level/.

[121] Future Pipe Industries, "Fiberstrong H_2O," n.d., https://futurepipe.com/products/fiberstrong-h2o/.

Table 2-11: Pipeline assumptions

Variable	Value		Units
	Scenario 1	Scenario 2	
Pump isentropic efficiency, p	85		%
Flow rate	55		m3/s
Number of pipes, N	3		-
Pipe length, L	100,000	30,000	m
Elevation gain, h	100	10	m
Pipe inner diameter, D	3.5		m
Surface roughness, ε	0.002		m
Relative roughness, $\lambda = \frac{\varepsilon}{D}$	0.0006		-
Electricity cost[122], Ce	96	54	$/MWh

The pumping power, pumping cost, and specific pumping cost can be determined using standard pipe flow equations. Minor losses are neglected, since the viscous and gravity losses dominate the total pressure drop.

The results of these calculations for the two baseline scenarios considered are shown in Table 2-12.

Table 2-12: Results from water pipeline pumping equations

Options	Pipeline length [km]	Number of pipes [-]	Pressure drop [bar]	Specific energy [kWh/m^3-km]	Pumping cost [$/m^3]
Scenario 1	100	3	18.8	0.0061	0.059
Scenario 2	30	3	3.7	0.0040	0.006

Based on quotes from two pipe vendors (AGRU and Future Pipe Industries), we estimate a total cost of the pipes of $2.2B for the 100 km pipeline (Scenario 1), and $675M for the 30 km pipeline (Scenario 2). These figures include manufacturing, transportation and installation, and are roughly consistent (on a per

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[122] We have assumed that the cost of electricity for pumping in Scenario 2 is the cheaper rate at Diablo Canyon. This assumption is correct for pipelines with a single pumping station located at Diablo Canyon. However, for long pipelines with large elevation changes (Scenario 1), multiple pumping stations will be needed; the remote pumping stations will pay the more expensive grid electricity, so the price reported here for Scenario 1 is an average price for two pumping stations.

unit length and capacity) with other large water distribution pipelines documented by Plappally and Lienhard.[123] Based on quotes from two pump vendors (i.e., Flowserve and Torishima), we estimate the total cost of the pumps for Scenario 1 to be about \$57M, and conservatively assume the same for Scenario 2. The efficiency of these pumps is approximately 85%. Assuming the same financing terms as the rest of the desalination plant, the cost of equipment for the pipeline contributes about 0.086 and 0.028 \$/m^3 to the cost of delivered water, for Scenarios 1 and 2, respectively. Adding the pumping and equipment costs, the total cost of water distribution is 0.145 \$/m^3 and 0.034 \$/m^3 for Scenarios 1 and 2, respectively.

Using the same methodology, we have generated a rough estimate of the cost to send water a variety of distances to a number of different offtakers. Cost estimates are shown in Table 2-13, while distances to other locations can be estimated from Figure 2-20. The cost of distribution includes the costs of equipment and pumping, and can be added to the levelized cost of water at the desalination plant outlet, which is calculated in Table 2-16, to produce the estimated cost of water delivered to the offtaker. Distribution costs can vary significantly from these projections depending on the route taken, resulting elevation change, and other factors.

Table 2-13: Estimate of costs to transport water to different offtakers

Distance/Net elevation gain	End point (from DCPP)	Pressure drop [bar]	Distribution equipment cost [\$/m^3]	Pumping cost [\$/m^3]	Total distribution cost [\$/m^3]
20 km/ 0 m *	Pismo Beach, San Luis Obispo	1.8	0.019	0.003	0.022
33 km/ 120 m *	Lopez Lake, SWP connection	14.7	0.030	0.026	0.056
50 km/ 200 m **	Paso Robles	24.1	0.044	0.076	0.120
55 km/150 m **	Twitchell reservoir, Lake Nacimiento	19.6	0.049	0.062	0.111
110 km/ 200 m **	Lake Cachuma, Cuyama, King City	29.5	0.095	0.092	0.187
185 km/ 0 m **	Monterey, Salinas	16.6	0.159	0.052	0.211

** one pumping station; ** two pumping stations*

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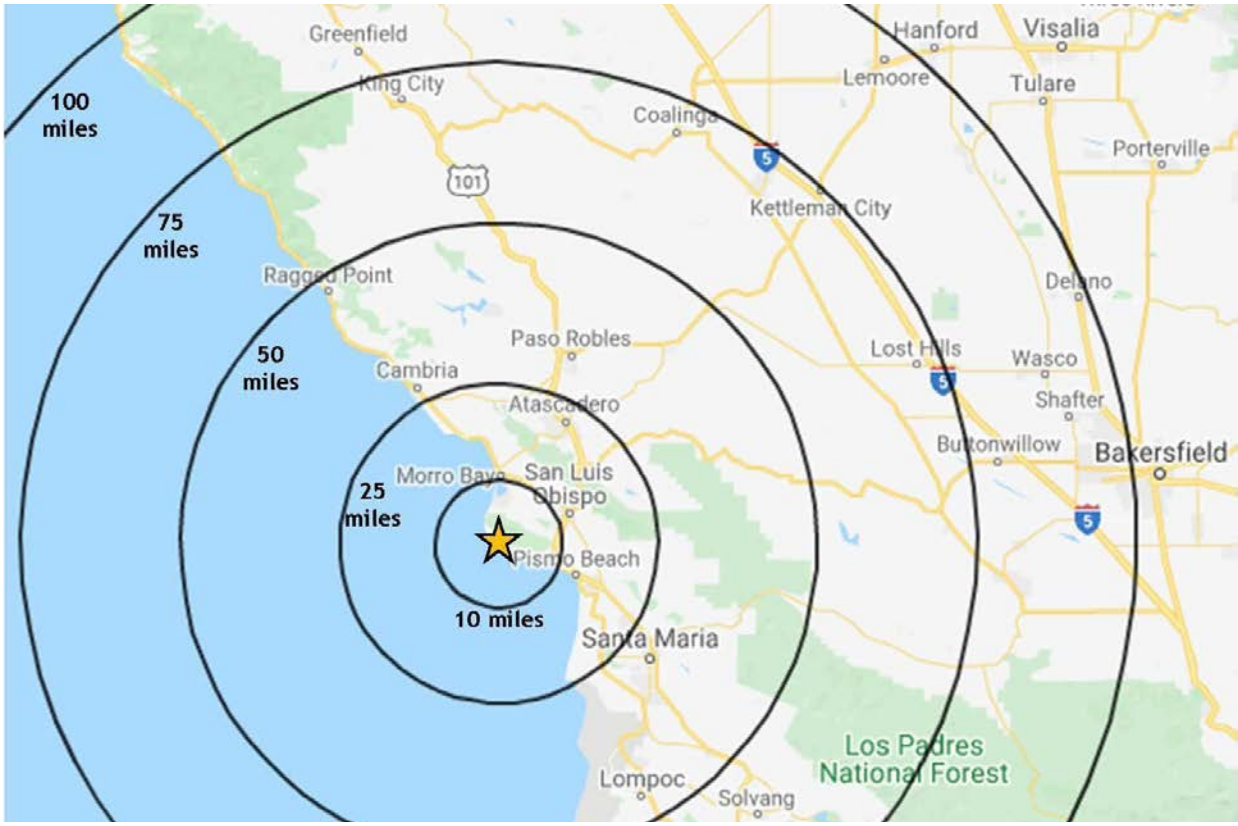
[123] Plappally & Lienhard, “Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal,” op. cit.

Figure 2-20: Map showing distances from the Diablo Canyon Nuclear Power Plant



(g) Construction approach

The construction approach for Option 1 would likely be similar to that of other plants built in California. If larger options are chosen, there will likely be unique issues that arise due to the scale of the project. For example, it is possible that a plant of this size could cause issues with supply chain capacities. Global Water Intelligence projected that a boom in construction of large desalination plants would cause the demand for seawater reverse osmosis membranes to outstrip supply, leading to a supply shortage, increased lead times, and increased membrane prices for the period from 2019-2022.[124] Construction of a plant as large as Option 3 or 4 may cause enough of a spike in demand to create its own materials supply shortage.

Questions around supplier capacities, the ability to move such a large volume of construction supplies into the construction site, laydown area, vehicular access, and more are important questions to answer, but are outside the scope of this report. Unique approaches, such as building portions of the plant offsite and shipping them to Diablo Canyon's existing harbor, should be examined to address these issues. This approach has been used before, such as at Cape Preston, which is located north of Perth in Western

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[124] Pankratz, T., "The Looming Membrane Drought," *Water Desalination Report* (June 2019), https://www.desalination.com/articles/the-looming-membrane-drought.

Australia's Pilbara region. In that case, a 140,000 m^3/d plant was prefabricated off site in sections, and assembled on-site, which helped to reduce both costs and construction time.[125]

It is likely that projects as large as Options 2 through 4 would be constructed in a number of stages or phases, rather than all at once. This approach may have a number of advantages. Although the timeline may be drawn out, and the costs for the plant may increase somewhat, beginning with a smaller plant and building a series of expansions could make zoning, permitting, and construction much easier and cheaper for later stages of the project.

Diablo Canyon nuclear power plant as a power source

There is an excellent match between the power needs of a desalination plant and the power provided by the Diablo Canyon Nuclear Power Plant. Desalination is most economical when the plant operates at a high capacity factor, running 24/7 throughout the year, except for occasional downtime for maintenance. This is exactly the type of power provided economically by Diablo Canyon. As California moves to decarbonize its power grid, the cost advantage of the Diablo Canyon Nuclear Power Plant as a source of zero-carbon, baseload electricity is likely to grow. Since electricity is a major input to desalination, the availability of economical zero-carbon electricity from the nuclear station helps keep the cost of water low.

1. Operational changes to Diablo

Operating a new desalination plant alongside the Diablo Canyon Nuclear Power Plant does not require any major changes to the operation of the plant. We would expect minor changes to include the installation of a series of bypass valves and pipes, such that the power plant can operate while the desalination plant is down for maintenance, and vice versa. Both the Power Plant and the desalination plant require a water intake that conforms to California's environmental requirements for the respective plants. However, co-location enables the two plants to share a common intake structure. We assume this investment is made by the power plant and a portion of the cost is passed along to the desalination plant in proportion to the share of electricity generation used by the desalination plant.

As noted earlier, the major requirement for the power plant is the approval of a license extension for another 20 years. License renewals are usually preceded by certain capital investments needed to prepare the plant for additional years of operation. When PG&E was preparing for its original renewal application, it made the major investments for both units of the power plant. The steam generators were replaced in 2008 and 2009, and the reactor pressure vessel heads were replaced in 2009 and 2010. Those are certainly two of the largest capital expenditures relevant to license renewal. We are not aware of other significant expenditures needed that are related to the license renewal, although there may be some.[126] Although the intake will have to be replaced at the cost of hundreds of millions of dollars, the approach proposed in this analysis, implementing screened intakes with an emergency stoplog structure

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[125] Pankratz, T., "The Big 6's Newest Sibling," *Water Desalination Report* 49, no. 5 (2013), https://www.desalination.com/articles/the-big-6-s-newest-sibling.

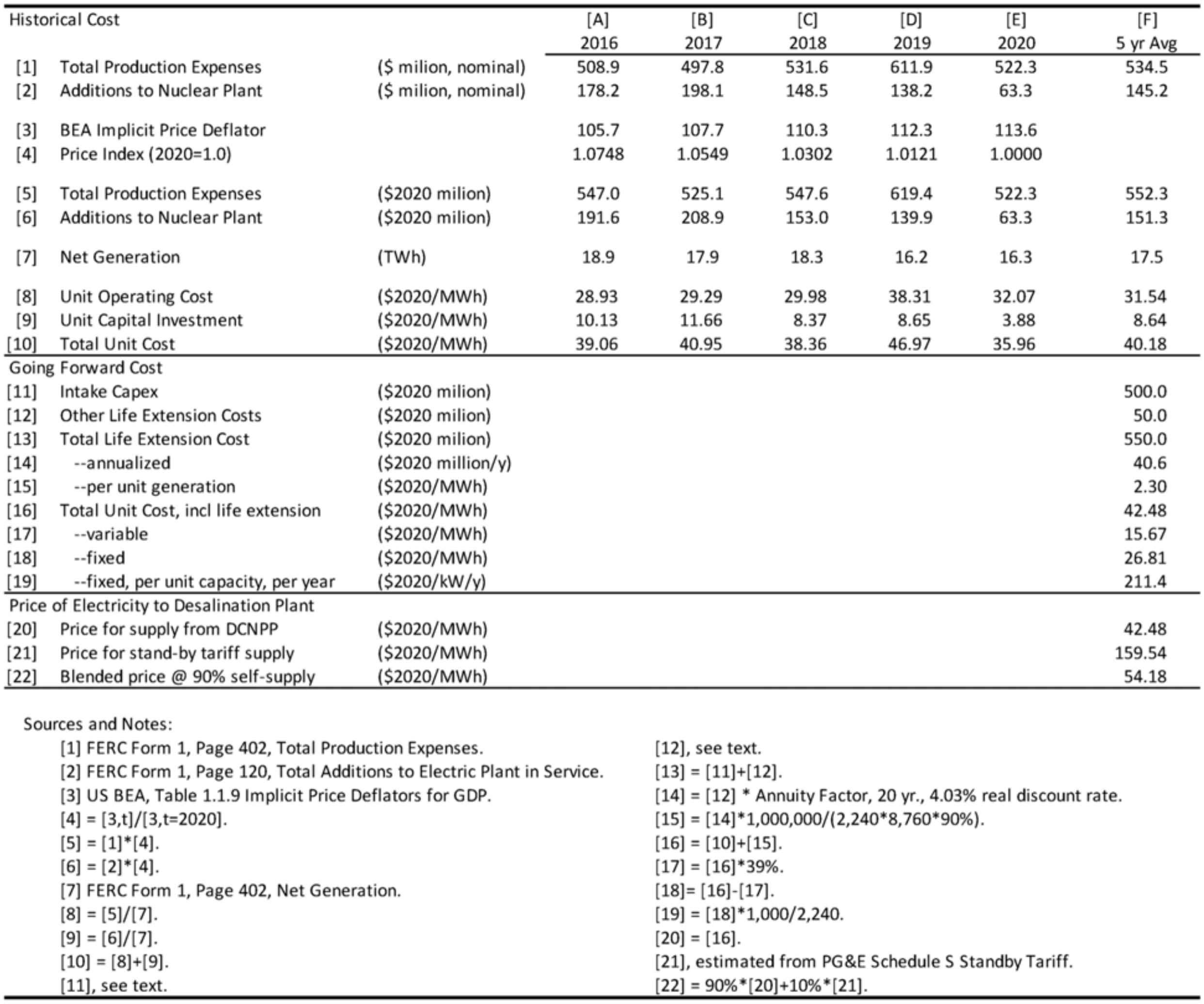
[126] As a part of the original license application renewal process, in June 2011 the NRC issued its Safety Evaluation Report Related to the Diablo Canyon Nuclear Power Plant, Units 1 and 2, Docket Nos. 50-275 and 50-323, Pacific Gas and Electric Company. The report concludes that the requirements of the regulations have been met, and it details a number of License Renewal Commitments.

to allow flow into the intake lagoon, is not considered to be safety related, and should not affect the license renewal process. However, based on PG&E's estimates for the original renewal application process, the license renewal process itself could require up to $50 million.

2. Power costs

Table 2-14 shows the historical cost of electricity from Diablo Canyon Nuclear Power Plant for the five years 2016-2020.[127] The average operating cost was $0.0315/kWh. The average capital investment per unit was $0.0086. The average total cost was therefore $0.0402/kWh.

Table 2-14: Cost breakdown of electricity at Diablo Canyon



Historical Cost			[A] 2016	[B] 2017	[C] 2018	[D] 2019	[E] 2020	[F] 5 yr Avg
[1]	Total Production Expenses	($ milion, nominal)	508.9	497.8	531.6	611.9	522.3	534.5
[2]	Additions to Nuclear Plant	($ milion, nominal)	178.2	198.1	148.5	138.2	63.3	145.2
[3]	BEA Implicit Price Deflator		105.7	107.7	110.3	112.3	113.6	
[4]	Price Index (2020=1.0)		1.0748	1.0549	1.0302	1.0121	1.0000	
[5]	Total Production Expenses	($2020 milion)	547.0	525.1	547.6	619.4	522.3	552.3
[6]	Additions to Nuclear Plant	($2020 milion)	191.6	208.9	153.0	139.9	63.3	151.3
[7]	Net Generation	(TWh)	18.9	17.9	18.3	16.2	16.3	17.5
[8]	Unit Operating Cost	($2020/MWh)	28.93	29.29	29.98	38.31	32.07	31.54
[9]	Unit Capital Investment	($2020/MWh)	10.13	11.66	8.37	8.65	3.88	8.64
[10]	Total Unit Cost	($2020/MWh)	39.06	40.95	38.36	46.97	35.96	40.18
Going Forward Cost								
[11]	Intake Capex	($2020 milion)						500.0
[12]	Other Life Extension Costs	($2020 milion)						50.0
[13]	Total Life Extension Cost	($2020 milion)						550.0
[14]	--annualized	($2020 million/y)						40.6
[15]	--per unit generation	($2020/MWh)						2.30
[16]	Total Unit Cost, incl life extension	($2020/MWh)						42.48
[17]	--variable	($2020/MWh)						15.67
[18]	--fixed	($2020/MWh)						26.81
[19]	--fixed, per unit capacity, per year	($2020/kW/y)						211.4
Price of Electricity to Desalination Plant								
[20]	Price for supply from DCNPP	($2020/MWh)						42.48
[21]	Price for stand-by tariff supply	($2020/MWh)						159.54
[22]	Blended price @ 90% self-supply	($2020/MWh)						54.18

Sources and Notes:

[1] FERC Form 1, Page 402, Total Production Expenses.
[2] FERC Form 1, Page 120, Total Additions to Electric Plant in Service.
[3] US BEA, Table 1.1.9 Implicit Price Deflators for GDP.
[4] = [3,t]/[3,t=2020].
[5] = [1]*[4].
[6] = [2]*[4].
[7] FERC Form 1, Page 402, Net Generation.
[8] = [5]/[7].
[9] = [6]/[7].
[10] = [8]+[9].
[11], see text.
[12], see text.
[13] = [11]+[12].
[14] = [12] * Annuity Factor, 20 yr., 4.03% real discount rate.
[15] = [14]*1,000,000/(2,240*8,760*90%).
[16] = [10]+[15].
[17] = [16]*39%.
[18]= [16]-[17].
[19] = [18]*1,000/2,240.
[20] = [16].
[21], estimated from PG&E Schedule S Standby Tariff.
[22] = 90%*[20]+10%*[21].

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[127] Pacific Gas & Electric Company, FERC Forms No. 1, 2016-2020, https://www.ferc.gov/industries-data/electric/general-information/electric-industry-forms/form-1-electric-utility-annual.

As discussed earlier, continued operation of the power plant would require a new water intake system in order to comply with the California Ocean Plan. The estimated cost, discussed in more detail below, is $500 million.

Levelizing the application cost and intake cost across the plant's generation for a subsequent 20 years of operation at a capacity factor of 90% and a real discount rate of 4.03% adds $0.00230/kWh to the cost of electricity, bringing the total cost of electricity from the Diablo Canyon Nuclear Power Plant to $0.0425.[128]

Our assumption is that the desalination plant can source most, but not all of its electricity needs directly from the nuclear plant at this cost of generation. While it may be possible to coordinate some of the maintenance outages at the desalination plant with the refueling and maintenance outages at the power plant, it is unlikely that all of them can be coordinated. Therefore, the desalination plant will need standby power service from the grid. We assume the desalination plant purchases 90% of its needs directly from Diablo Canyon and 10% of its needs from the grid. Based on PG&E's current tariffs, we estimate the average cost of standby service as possibly as high as $0.1595/kWh. Therefore, the blended cost of electricity to the desalination plant is $0.0542/kWh. This is approximately 40% of the $0.1388/kWh average cost of electricity to California's industrial sector throughout 2019, and a significant savings on the cost of electricity to the desalination plant.[129]

Project economics and economic benefits to California economy

1. Baseline cost of water estimate

One of the main factors determining whether or not a desalination plant is feasible is the levelized cost of water. While estimating the cost of a desalination plant an order of magnitude larger than any plant in existence is not a trivial task, we believe valuable insights may be drawn by estimating these costs. We begin by using projection tools from DesalData,[130] a product of Global Water Intelligence, that uses data from a large number of existing plants to estimate the costs of new desalination plants based on a range of inputs. We use these tools as the basis to estimate desalination plant costs.

Certain direct variable costs (replacement parts, chemicals, electricity) will scale linearly with plant size, while many indirect and labor costs do not. As a baseline, the values shown in Table 2-15 were used as inputs to DesalData cost projection tools, and the output costs were modified using data from additional research in order to make projections.

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[128] The US Energy Information Administration's "Annual Energy Outlook 2021, Electricity Market Module, Feb. 2021," p. 9 reports a nominal discount rate of 5.9%. Assuming an annual inflation rate of 1.8%, this translates to a real discount rate of 4.03%.

[129] The 2012 Water Purchase Agreement for the Carlsbad desalination plant established a formula price based off of the SDG&E tariff. In 2012 that formula gave a price just over $0.092/kWh. The price increases with the SDG&E tariff. In 2012, the average price of electricity paid by industrial companies in California was $0.1072/kWh.

[130] Global Water Intelligence, DesalData, Cost Estimator: 2018,, https://www.desaldata.com/cost_estimator.

Table 2-15: Capex inputs for baseline case in DesalData Cost Estimator

Salinity (mg/L)	35000
Min temp (C)	20
Max temp (C)	26
Pretreatment	Standard
Second pass (%)	50
Remineralization	yes
Intake/outfall	Onerous
Permitting	Onerous
Country	USA

We assumed economies of scale exist for direct capital expenditures up to a capacity of 400,000 m^3/d. Beyond this point, all capital and direct operating costs, except for labor, are assumed to scale linearly with size. This is because economies of scale for direct capital expenditure costs are only projected to exist to a certain point, beyond which additional capacity generally leads to added complexity of flow distribution, treatment and operations. It is assumed that building beyond this scale will lead to multiple identical parallel plants with some shared facilities, such as intake and outfall.[131] We assume that some of the indirect capital costs, such as the cost of legal and professional work, design, and management costs will not scale linearly with capacity, and these line items are one of the primary benefits of building plants at large scales. We assume that civil costs and installation costs will scale directly with system capacity, even though we know that in reality there will be some per-unit cost reductions with large scales. This is an intentional overestimate of these costs, which serves to keep our cost estimates conservative.

In addition to these various engineering, procurement, and construction (EPC) costs, there will be expenditures on various indirect costs. These include pre-construction costs, various owner's costs, as well as transaction fees and closing costs, reserves and contingencies, and interest during construction. For the desalination plant in Carlsbad these items were very large, amounting to 59% of the EPC costs. To maintain consistency with that most recent experience in California, we added an indirect cost item equal to 59% of the total EPC costs itemized above (36% of the total capital cost).

We note that these costs, and the resulting levelized cost of water, shown in Table 2-16, are a first-order estimate, and significant deviations are possible. Using cost trends from plants smaller than 250,000 m^3/day to predict the costs of plants an order of magnitude larger will lead to errors. Detailed design studies would be necessary to produce a more precise cost estimate. However, the purpose of this chapter is not to produce water costs accurate to within a few cents per m^3, but to determine if a desalination project at Diablo Canyon is feasible. Some of these line items, such as intake and outfall

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[131] Voutchkov, N., "Introduction to Desalination Project Design and Delivery" (2020), https://www.suncam.com/miva/downloads/docs/388.pdf.

costs, civil costs, and the financing package numbers can change in ways that will significantly affect the total cost of water as detailed design studies are performed. Factors that can drastically change the price of water are considered in the following subsections.

2. Differentiating Factors

While the methods in the previous section provide a first-order estimate of the cost of the desalination plant, there are a number of factors that could cause the cost of a desalination plant to deviate from predicted values very significantly, which deserve additional attention. Some of these factors are already well known within the desalination community, and are laid out in Global Water Intelligence's Market Forecast.[132] These factors are responsible for the fact that plants of similar size that have been built in the last few decades can have very different costs. We discuss these factors in detail here, with a specific focus on whether they will be important in differentiating a hypothetical Diablo Canyon mega-plant from other plants in California.

(a) Electricity source and electricity costs

High power costs may drive up the overall cost of desalination considerably. As the impetus for this analysis is a large-scale power plant readily available with low-cost power, costs for construction of electrical infrastructure will be very low. The low cost of available power from Diablo Canyon is one of the major advantages that a desalination plant at Diablo Canyon would have over a plant at any other location in California. Low cost, reliable power from the nuclear station can be available for approximately \$0.054/kWh, a major reduction in the cost of power compared to grid-sourced power. This factor is one of the main advantages for a Diablo Canyon plant relative to other plants in California.

Coordinated operation of the desalination and power plants may allow for additional benefits. For example, certain desalination plant designs allow the plant to enter a "hot shutdown" mode, quickly entering a low-power mode while maintaining flow through the membranes.[133] Coordinated operation with the power plant could allow for the desalination plant to opportunistically shut down so that additional power could be sold into the grid in times when rates increase or during emergency shortages.

(b) Seawater and product water quality

Seawater on the California coast is much less saline than more challenging feedwaters, such as those in the Arabian Gulf. While the question of product water quality is highly dependent on the end user of the water, we do not expect challenges that would significantly increase the price of water due to product water quality (i.e., ultrapure product water required for semiconductor manufacturing). We also do not expect the costs to achieve a given product water quality to be significantly different for different desalination plants in California (i.e., the cost of a second pass at Diablo Canyon would be approximately the same as the cost of a second pass at any other California desalination plant). As discussed previously, we do not believe that there will be significant cost increases due to product water

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[132] Global Water Intelligence, DesalData, Global Forecast: 2020 Projects, https://www.desaldata.com/.

[133] Lienhard, J.H., *et al.*, "Low Carbon Desalination: Status and Research, Development, and Demonstration Needs, Report of a Workshop Conducted at the Massachusetts Institute of Technology in Association with the Global Clean Water Desalination Alliance" (Cambridge, MA, Nov. 2016), http://web.mit.edu/lowcdesal/.

requirements that would significantly escalate the capital or operating costs compared to other desalination plants in California.

(c) Red tides and algal blooms

These seasonal phenomena can interrupt plant operation and, if continuous operation is required, additional pretreatment steps may be necessary, such as dissolved air flotation. The Diablo Canyon site is known to have annual acidification events as a result of domoic acid.[134] This harmful algal bloom (HAB) event is caused by the diatom pseudo-nitzschia and makes a neurotoxin which can accumulate in the food chain. Some years are worse than others; when severe, the seawater pH drops 1 unit and microscopic algae multiply. These HAB events also occur at other locations along the California coast and are increasing in frequency, intensity, and duration.[135]

Another seasonal threat that may have an effect on plant operation is the presence of jellyfish. Jellyfish can clog intakes and cause entire plant shutdowns. This has happened at Diablo Canyon several times, including in 2008[136] and 2012.[137] It is unclear how newer intakes will be affected by the problems of algal blooms, red tides, and jellyfish. However, we have not seen evidence that would lead us to expect significant differences between Diablo Canyon and other California desalination plants with respect to these operational challenges.

(d) Contractor experience and labor costs

In regions of the world with many large desalination plants, such as the Middle East, the wealth of historical operating data and the familiarity with the local environmental conditions, laws, regulations, and contract structures allow contractors and engineers to design and build plants with smaller margins for risk, resulting in lower costs. Additionally, labor costs for plant design, construction, and operation in other parts of the world are lower than in the United States. Higher labor costs are factored into the water price, but we do not expect large variations from one part of California to another.

There may be significant advantages for a Diablo Canyon desalination plant in terms of labor costs, due to the scale of the project. Long-term operating labor costs for desalination plants stay relatively constant even with increasing plant capacity, providing a cost advantage for Diablo Canyon over smaller plants. As mentioned previously, with regard to labor and indirect costs associated with plant construction, there would be significant cost savings for a large-scale plant. In summary, we do not expect significant labor cost benefits relative to other California desalination plants at the same scale. Any benefits that are realized would likely be due to the choice of larger-scale plants.

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[134] Schoepke, E., Personal Communication to John Lienhard, 2021.

[135] California Ocean Science Trust, “Frequently Asked Questions: Harmful Algal Blooms and California Fisheries, Developed in Response to the 2015-2016 Domoic Acid Event” (Oakland, CA, 2016), https://www.oceansciencetrust.org/wp-content/uploads/2016/08/HABs-and-CA-Fisheries-FAQ-8.5.16.pdf.

[136] Rigley, C., “Suicidal Jellyfish Jam Diablo Canyon,” *New Times* (San Luis Obispo, CA, Oct. 2008), https://www.newtimesslo.com/sanluisobispo/suicidal-jellyfish-jam-diablo-canyon/Content?oid=2941528.

[137] Sneed, D., “Diablo Canyon Knocked Offline, Powerless against Tiny Jellyfish-like Creature,” *The Tribune* (San Luis Obispo, CA, Apr. 2012), https://www.sanluisobispo.com/news/local/article39201087.html.

(e) Additional pumping requirements, storage, and conveyance

Cost estimates for pumping water to consumers were discussed earlier in this analysis. It is assumed that pumping the intake water from the existing nuclear power plant to the desalination plant does not include significant elevation changes (although this may become a factor depending on the proposed site of the desalination plant). It is assumed the power plant pays to pump seawater through the intake and up 85 feet to the nuclear power plant. Additional pumping costs are relatively straightforward to estimate once a location for the plant and the location of the customer are determined. If additional storage infrastructure is required, such as additional tanks or reservoirs, the capital expenditure could increase significantly. Depending on who the final off takers are, this may be an area where Diablo Canyon could have a significant disadvantage. If there are no offtakers nearby, the costs of constructing long pipelines could outweigh the unique benefits of a Diablo canyon project, making smaller, decentralized desalination plants located closer to the offtakers more feasible. The investigation of potential offtakers, and the determination of the cost to bring water from Diablo Canyon to those customers, should be a primary focus of further detailed investigations.

(f) Financing and length of water purchase agreement

Financing terms can also have a large impact on the total cost of water. An increased debt/equity ratio, and lower interest rates and equity yield allow for greatly reduced water costs. It is estimated the cost of financing amounted to about 1/3 of the total cost of water at Carlsbad, which had a total water cost of $1.61, while Sorek 2, a new plant being built in Israel with a total water cost of $0.405, is expected to have financing costs that are less than 20% of the total water price. The debt/equity split for Carlsbad was 79.5/20.5, versus 85/15 for the new Sorek 2. The interest rate and return on equity for Carlsbad are 5% and 10%, respectively, while for Sorek 2 they are around 2.5% and 8%. The way that water purchase agreements are structured, and investor perception of the project will have a major impact on the feasibility and final cost of water of the project.

We have not been able to find evidence that larger projects receive substantially better financing terms than smaller desalination plants, so we assume for now that financing terms will be similar to those of other desalination plants in California, with a 30-year term and a 4.5% weighted average cost of capital (WACC). We do not assume any differences in financing between plants at Diablo Canyon and other plants in California, although in practice there will be. The way that the project is structured from an ownership and operational standpoint may also have a substantial impact on how the project would be realized as well. In this paper, we have assumed that PG&E owns and operates the power and desalination plants.

(g) Permitting and political opposition

As an example of the challenging permitting situation in California, the ongoing project proposed for Monterey, CA has been going through permitting issues in some capacity for approximately 30 years.[138] Building anything on the coast in California is difficult to do, and a mega-scale desalination plant is potentially a tough sell from a political perspective. The costs, both in terms of time and money, that could be associated with drawn out lawsuits and permitting battles could be a deal breaker for this project. Local support for desalination can be a major factor in determining whether new projects have a path forward.

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[138] Pankratz, T., “28-Years and Counting,” *Water Desalination Report* (Mar. 2019), www.desalination.com.

(h) Intake and outfall

The entire Carlsbad desalination plant project is estimated to have cost $650 million. If regulators require the use of subsurface intakes, the additional cost to retrofit the plant could be up to $800 million.[139] The type of intake and outfall required at Diablo Canyon will greatly influence the total cost of water. While we do not attempt to estimate the cost of subsurface intakes at Diablo Canyon, we can estimate the cost of screened intakes, like those being permitted at Huntington Beach, using existing studies. Bechtel estimated the cost of the undersea pipeline from the intake lagoon, intake screens, and the structure to seal the intake lagoon at approximately $400 million. ISI estimated the cost of rotating intake screens for Options 1-3 at $70-$100 million. While the cost of a seawater intake utilizing the structures of Bechtel attached to the screens of ISI would almost certainly be less than the combined estimated costs of the two projects, as the costs of the screens in the Bechtel report would be avoided, we conservatively estimate the cost of the overall intake at $500 million.

One factor that would need to be addressed is how the intake costs are shared between the desalination plant and power plant. We assume that, for Options 1 through 3, the cost of the intake is borne by the nuclear power plant, and then passed along to customers, including the desalination plant, through the price paid for power. This is because the same large intake needs to be built for the power plant, regardless of which desalination plant option is chosen. For Option 4, the intake is larger than would be required by the power plant itself, so the incremental intake costs are assumed to be completely borne by the desalination plant.

The outfall is more difficult to estimate in terms of financial expenditure, although there are existing projects that can help by providing some precedent. As discussed earlier, the Sydney Desalination Plant uses a diffuser-style outfall to mix undiluted brine with seawater, and is located in a sensitive ecological area with strict environmental regulations, providing an example for Diablo Canyon to follow.[140] The outfall system at that plant is estimated to have cost 20-30% of the total capital expenditure of the plant.[141] The plant has a capacity of 250,000 m^3/d.

At a larger scale, we can consider the Deer Island Wastewater Treatment Plant in Boston, MA. This plant is connected to the largest outfall tunnel in the world, with a capacity that almost exactly matches our proposed Option 3. The tunnel has a peak capacity of 4,921,000 m^3/d. The outfall tunnels down 420 feet below Deer Island, then through a 24-foot diameter tunnel, 9.5 miles out into Massachusetts Bay, where 50 risers bring wastewater to diffusers. This outfall cost $390 million.[142]

Finally, we can also consider the costs that have been estimated to implement screened intakes at the Carlsbad Desalination Plant.[143] We utilize these costs, in addition with what we know about the way

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[139] "Order R8-2020-0005 NPDES No. CA8000403, Waste Discharge Requirements for Poseidon Resources (Surfside) L.L.C., Huntington Beach Desalination Facility, Orange County" (2020), http://www.waterboards.ca.gov.

[140] Breslin, M., "Environmental Report—Seawater Concentrate Discharge Design, Staged Submission 2: Discharge Point, Rev 3" (Sept. 2009), https://www.sydneydesal.com.au/media/1152/2009-seawater-concentrate-discharge-design.pdf.

[141] WatReuse Research Foundation, "Database of Permitting Practices for Seawater Concentrate Disposal" (2015), https://watereuse.org/wp-content/uploads/2015/11/Presentation.pdf.

[142] Massachusetts Water Resources Authority, "Scientists Help End Sewage Discharges to Boston Harbor," MWRA News Release Archive (Sept. 2000), https://www.mwra.com/01news/2000/090600endsewdischarge.htm.

[143] Poseidon Water, "Appendix X Construction Cost Estimates for Intake/Discharge Alternatives Renewal of NPDES CA0109223 Carlsbad Desalination Project Carlsbad Desalination Plant Intake/Discharge Construction Cost Estimates" (Sept. 4, 2015), https://www.waterboards.ca.gov/rwqcb9/water_issues/programs/regulatory/docs/appendices/Appendix_X.pdf.

costs will likely scale with system size, in order to come up with cost estimates. It is assumed that the cost of the outfall system will not rise linearly with the capacity of the outfall, providing additional cost benefits to larger projects.

(i) Environmental expenditure

The costs of land acquisition and the costs of mandated environmental remediation projects are not included in our estimate. As a part of the permitting process, regulators can require additional environmental action to offset any potential environmental damages. For example, the permits for the proposed desalination plant in Huntington Beach would require the plant operator to assume responsibility for the preservation, enhancement and restoration of the Bolsa Chica wetlands.[144] The Carlsbad desalination plant also has a number of preservation and restoration agreements to offset any damage caused by its operation.[145] Land acquisition and environmental remediation projects are likely small costs relative to the scale of the project though. The land lease at Carlsbad is approximately $1.3 million per year, escalating with inflation.[146] The estimated costs of environmental remediation and greenhouse gas credits are on the order of $10 million at Carlsbad, plus several million annually, compared to a total project cost of approximately $1 billion.[147] These expenditures are determined on a case-by-case basis and are outside the scope of this report. However, we do note that there may be advantages for a Diablo Canyon project in this respect, as the desalination plant would be powered with carbon-free electricity, obviating the need for carbon offsets.

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[144] Poseidon Water, "Huntington Beach Desalination Plant to Preserve, Enhance and Restore Bolsa Chica Ecological Reserve" (press release July 2020), https://www.prnewswire.com/news-releases/huntington-beach-desalination-plant-to-preserve-enhance-and-restore-bolsa-chica-ecological-reserve-301091114.html.

[145] Rohit, P.M., "Poseidon Carlsbad's Mitigation Plan Approved by Coastal Commission," *The Log--California's Boating & Fishing News* (May 2019), https://www.thelog.com/local/poseidon-carlsbads-mitigation-plan-approved-by-coastal-commission/.

[146] "Bond Offering Memorandum, Water Furnishing Revenue Bonds, Series 2012," https://www.sdcwa.org/sites/default/files/files/finance-investor/carlsbad-desal-project-limited-offering-memorandum.pdf.

[147] Pankratz, T., "Carlsbad, California," *Water Desalination Report* (2012), https://www.desalination.com/articles/carlsbad-california.

Table 2-16: Projected costs for all options, along with projected costs of building another Carlsbad-sized desalination plant (not co-located with a power plant) somewhere else in California

	Option 1	Option 2	Option 3	Option 4	Carlsbad
Nameplate capacity (m^3/d)	189,270	2,419,000	4,752,000	15,379,000	189,270
Utilization rate (%)	80				
Energy consumption (kWh/m^3)	3.5				
Electricity price ($/kWh)	$0.054	$0.054	$0.054	$0.054	$0.139
Discount rate (%, real)	4.5				
Amortization period (years)	30				
Capital costs (millions of dollars)					
Pretreatment	60	683	1,343	4,345	60
Pumps	23	252	495	1,602	23
Equipment and materials	59	674	1,324	4,285	59
Membranes	14	158	310	1,002	14
Pressure vessels	4	45	88	286	4
Piping, high-grade alloy	31	348	685	2,215	31
Energy recovery devices	3	34	66	214	3
Civil costs	52	595	1,168	3,781	52
Design costs	85	250	300	350	85
Legal and professional	21	100	125	150	21
Installation services	25	279	548	1,545	75
Intake structure total costs	500	500	500	1,545	75
Intake costs paid by desal plant	0	0	0	1,045	75
Outfall	0	647	826	1,456	325
Intake and outfall total	0	647	826	2,500	400
Indirect costs (dev, finance)	222	2,398	4,294	13,277	458
Total capex	**599**	**6,463**	**11,571**	**35,780**	**1,235**
Operating costs (annual, millions of dollars)					
Parts	2	25	49	160	2
Chemicals	5	59	115	373	5

Labor	4	7	7	9	4
Membranes	2	25	49	160	3
Electrical energy	13	168	329	1,065	34
Total annual opex	**25**	**283**	**551**	**1,767**	**46**
Water price breakdown ($/m^3)					
Total capital cost and amortization	$0.53	$0.45	$0.41	$0.39	$1.10
Parts, chemicals, and membranes	$0.15	$0.15	$0.15	$0.15	$0.15
Energy costs	$0.19	$0.19	$0.19	$0.19	$0.49
Labor	$0.07	$0.01	$0.01	$0.01	$0.07
Overheads	$0.03	$0.03	$0.03	$0.03	$0.03
Water price ($/m^3)	**$0.98**	**$0.84**	**$0.79**	**$0.77**	**$1.84**
Water price ($/AF)	**$1,207**	**$1,032**	**$978**	**$952**	**$2,269**

2. Levelized cost of water

With all the factors above considered, we come to an estimate of the levelized cost of water, shown in Table 2-16. The cost of water shown in this table is the cost at the outlet of the desalination plant. The costs of transmission pipelines and pumping energy, shown in Table 2-13, can be added separately to find the total cost of water for each offtaker.

We emphasize again that the purpose of performing this cost estimate exercise is not to accurately project what the total cost of water would be, but to try to make a relative comparison between desalination plants at Diablo Canyon and plants at other locations in California, in order to assess the feasibility of such a plant. As Table 2-16 shows, the cost of water for any Diablo Canyon project is significantly lower than what we would expect for other desalination plants in California, leading us to believe that such a project would be financially feasible. The low cost is due to three main factors: shared infrastructure, lower energy costs, and benefits of scale.

For the smallest plant we examined, the Carlsbad-sized plant, the ability to use the nuclear power plant's condenser water as feed obviates the need to construct a new intake. Additionally, the ability to mix brine with the existing discharge from the power plant while staying within the salinity discharge limits obviates the need to construct expensive outfall infrastructure. These savings, as well as the energy savings, lead to significant price reductions on some of the most expensive line items for a new desalination plant. At much larger scales, the benefits of shared outfall infrastructure are eventually reduced or eliminated due to elevated discharge salinities and increased feedwater requirements. However, the immense scale allows for additional cost reductions, such as reduced design and labor costs.

For all Diablo Canyon plants investigated, there are significant cost reductions relative to other potential desalination projects in the state. Even with reduced costs, these costs are not obviously competitive with many traditional water resources when considering only the current monetary cost. However, it is highly likely that as drought conditions persist and the climate warms, water scarcity may drive up prices beyond their historic averages. For example, in the summer of 2021, some water futures contracts for 1-2 year deliveries were in the range of $900/AF,[148] which is in line with the cost range of desalination Options 3 and 4. In the past, some agricultural water contracts have reached a much higher level.[149] In general, it is reasonable to expect that , as traditional sources are further exploited, the cost of additional water supply will increase, both in terms of financial costs and environmental costs, making alternatives, such as carbon-free desalination, much more attractive.

Conclusion

California is facing intertwined challenges at the nexus of energy, water, and environment. In this chapter, we set out to determine whether co-locating a desalination plant with the Diablo Canyon nuclear station would be technically feasible and might produce water more cheaply than other large-scale desalination alternatives. We considered what potential large-scale and mega-scale desalination alternatives might look like, and we considered the plant design, siting, intake, outfall, distribution, power sources, and integration with Diablo Canyon. We have shown that, as configured, a desalination plant at the nuclear station is very likely to be economically attractive when compared to other seawater desalination alternatives. The final costs of water, including distribution, are between $0.79 and $1.19 per m^3 within a distribution radius of 100 miles from Diablo Canyon. This water production would be powered with a carbon-free source, and it would be free from the risks of drought and shifting weather patterns. Such a plant represents a significant reduction in the cost of desalinated water when compared to large-scale desalination alternatives at other sites, which we estimate to cost at least $1.84 per m^3.

This estimate is preliminary, and significant site-specific development would be required to produce a more precise cost of water. Significant challenges will accompany siting the plant, developing an intake and outfall plan that will receive approval from all regulators, and developing a construction plan that deals with the remote and environmentally sensitive nature of the area. The current timeline of the Diablo Canyon nuclear plant's closure, structuring water purchase agreements, and a host of political issues may also pose challenges to such a project. However, we believe we have shown in this chapter that, with Diablo Canyon's continued operation, building a large-scale desalination plant on-site is feasible and economically attractive. Further, this plant would help to secure California's water and energy supplies in a carbon-free manner.

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[148] CME Group, "Nasdaq Veles California Water Index,"

https://www.cmegroup.com/markets/equities/nasdaq/nasdaq-veles-california-water-index.settlements.html.

[149] In 2014, for instance, according to the California Public Policy Institute, "some water changed hands in Kern County for $1,250/acre-foot." Hanak, *et al.* (California Public Policy Institute), *Water and the Future of the San Joaquin Valley* (Feb. 2019), https://www.ppic.org/wp-content/uploads/water-and-the-future-of-the-san-joaquin-valley-february-2019.pdf. This is in line with the cost of Option 1.

Chapter 3

Assessing the Value of Diablo Canyon as a source of low-cost, clean hydrogen

By Justin Aborn

Chapter 3 Key Points:

- ➔ Hydrogen plant connected to Diablo Canyon could produce clean hydrogen to meet growing demand for zero-carbon fuels, and serve a significant portion of projected 2045 need
- ➔ Diablo Canyon hydrogen could cost up to 50% less than hydrogen produced from solar and wind power with a small fraction of the land footprint

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Introduction

To decarbonize the California economy, many studies suggest that a substantial amount of hydrogen will be needed for transportation segments that cannot be easily electrified, for industrial heat and processes, and for balancing a highly variable electric grid. But to meet California's climate goals, this hydrogen must come from a zero-carbon process. This chapter explores how a portion of the Diablo Canyon output could be dedicated to zero-carbon hydrogen production.

The proposed hydrogen plant is part of a multiple-commodity production concept that also includes a seawater desalination plant (see Chapter 2, above). The companion desalination plant is an important element of this assessment, given that fresh water from the desal plant, as H_2O, is itself the ultimate source of hydrogen. The hydrogen plant's H_2 production is based on breaking down the water molecule by electrolysis.

We find that a hydrogen plant included as part of a Diablo Canyon facility which is engaged in multiple-commodity production could manufacture up to 110 million kilograms (kg) of hydrogen a year at a competitive price of \$2-\$2.50 per kg. The production volume is a significant fraction of California's projected H_2 demand.

Our analysis here builds on the findings of Chapter 2 regarding the siting of a desalination plant at Diablo Canyon, which would be needed to provide freshwater as an input to the hydrogen plant.

Several unique advantages attend to siting hydrogen production adjacent to the Diablo Canyon plant and a desalination facility. First is the proximity of a fully dispatchable power plant, which can provide low-cost electricity to the hydrogen electrolysis facility, as well as high-temperature steam, which increases the efficiency of the electrolysis process. Second is the ability of the hydrogen plant to take advantage of the desalination plant, share capital costs, and thereby have ready access to relatively low-cost, pristine freshwater.

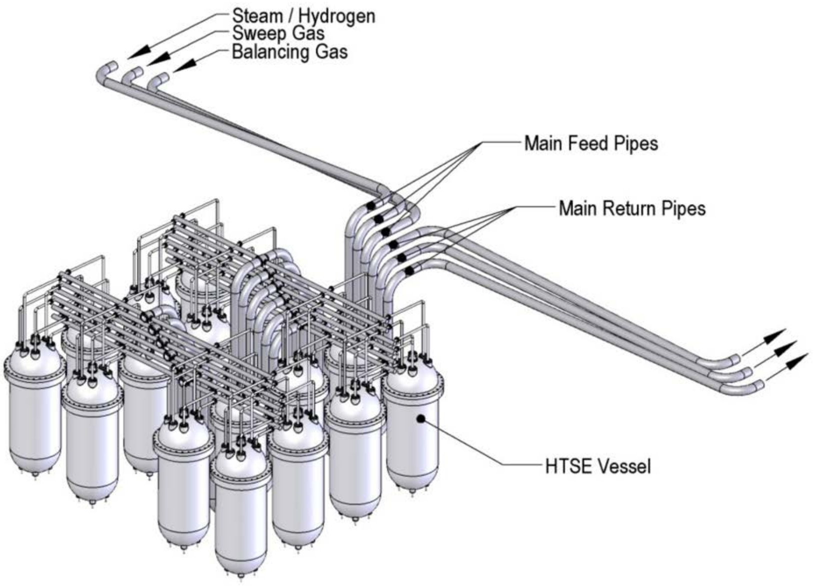
Other potential synergies exist that are not fully explored in this chapter. For example, recent research suggests that electrolyzing seawater can extract valuable dissolved minerals, such as calcium carbonate and magnesium carbonate, thus adding to revenue.[150] It can also remove carbon from seawater and sequester it as a solid. Here, though, we focus only on the direct process of hydrogen production.

Description of a hydrogen production plant at Diablo Canyon

1. Hydrogen production technology

The hydrogen production technology selected for this proposed application is known as high-temperature steam electrolysis (HTSE), which uses electricity-driven, solid-oxide electrolyzer (SOE) cells. The SOE cells are packaged in "stacks" and housed inside pressure vessels. These pressure vessels ensure that water, in the form of steam, is maintained at the necessary temperature and pressure, and in the desired proximity to the cells, required to orchestrate its electrolytic separation into gaseous hydrogen and oxygen. Key inputs to HTSE are electricity and steam. An example of the implementation of the pressure vessels and corresponding piping is shown in Figure 3-1.

Figure 3-1: Example of implementation of high-temperature steam electrolysis



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[150] Plante, E., La, C., Simonetti, D., Wang, J., Al-Turki, A., Chen, X., Jassby, D. & Sant, G.N., "Saline Water-based Mineralization Pathway for Gigatonne-scale CO_2 Management," *ACS Sustainable Chemistry and Engineering* (2021), https://doi.org/10.1021/acssuschemeng.0c08561.

The HTSE technology was selected from among alternatives that included both thermochemical processes and electrolytic processes. Because electricity is the dominant expense, and for reasons outlined further below, HTSE was selected for this analysis.

(a) Considerations regarding alkaline electrolysis

The technology known as alkaline electrolysis is a well commercialized technology and in that regard is a commercially in-hand alternative to HTSE. The rationale for choosing to analyze HTSE is based on its attractive technical and economic performance.

All hydrogen production that uses water electrolysis splits water molecules into hydrogen and oxygen. All water electrolysis faces the same splitting-energy-demand, which is dictated by the chemical nature of the water molecule[151]. It can be helpful to recognize that energy can only do two things: heat things up or push things around. The science of thermodynamics uses the terminology “heat” and “work.”

To split water, electrolysis applies some energy as “heat” and some energy as “work.” Electrolysis processes differ by how they go about applying this energy. They also differ in how much is applied as heat and how much is applied as work. Electricity is needed to apply energy as work. Roughly speaking, heat sets the water molecule on the chopping block, and electricity delivers the final decisive molecular chop. The hotter it is, the less electricity you need. Figure 3-2[152] depicts this dynamic (the graph’s caption presents the information using the more exacting thermodynamic terminology).

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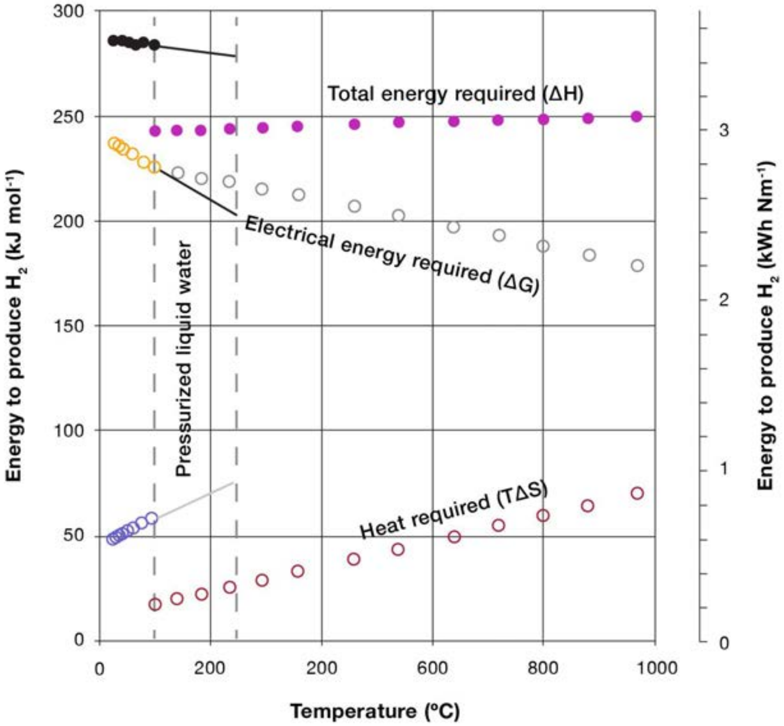
[151] Water electrolysis is an endergonic transformation.

[152] Godula-Jopek, A., Millet, P., Guillet, N., Laurencin, J., Mougin, J., Bourasseau, C. & Guinot, B., *Hydrogen Production by Electrolysis* (A. Godula-Jopek, Ed.) (Munich, Germany: Wiley-VCH Verlag GmbH & Co., 2015), doi:10.1002/9783527676507, as

cited by Lindblad, K., “An Economic Feasibility Study of Hydrogen Production by Electrolysis in Relation to Offshore Wind Energy at Oxelösund,” KTH Royal Institute of Technology, School of Engineering Sciences (2019), p. 17, fig. 18, www.kth.se.

Figure 3-2: Energy to produce hydrogen: entropy, enthalpy, and Gibbs free energy as a function of temperature at 1 bar. Solid line represents liquid pressurized water[153]



In view of the heat and work dynamics, the nuclear power plant context offers HTSE a powerful advantage over alkaline electrolysis, that advantage being access to steam. Water in the form of steam contains more heat than liquid water does, and most alkaline electrolysis processes are supplied water in liquid form by the electrolyte. Liquid water is typically cooler than steam, and as well, the alkaline electrolysis process must address the “energy-hump” of water vaporization (note the “knee” in Figure 3-2 at water’s boiling point of 100° C) that HTSE completely avoids. Hot steam is one reason why HTSE consumes less electricity per kilogram of produced hydrogen. Because electricity is a more valuable and expensive form of energy than heat, which translates into a significant economic advantage for HTSE.[154] At very high temperatures an HTSE process operating at 750° to 950° C requires about 30% less electricity than a conventional alkaline process fed with liquid water. Overall, an HTSE process can produce hydrogen at efficiencies above 50% as opposed to about 40% for conventional electrolysis such as alkaline electrolysis. In addition, HTSE cells can operate at high current densities and higher

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[153] Godula-Jopek, *et al., Hydrogen Production by Electrolysis* (2015), *op. cit.*

[154] HTSE in this analysis is estimated to consume 38 kWhe/kg, versus alkaline’s 44 to 50 kWhe/kg, with possible additional electricity for driving compressors to compress hydrogen to pipeline pressure and for removing any traces of potassium hydroxide (KOH) used in the process’s alkaline electrolyte solution.

See https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis.

pressures which reduces the size of the equipment. Alkaline processes may also incur additional electricity consumption to compress hydrogen to delivery-pipeline pressure.[155]

Going forward, the pragmatic process at the time of a firm technical decision would assess the technical risk and consider the project's risk appetite regarding commercialization maturity. Depending on the outcome of such a process, the project could choose to take up risk mitigation strategies that could choose to focus on one technology versus another, or perhaps consider implementing two competing technologies. Such a risk assessment is not taken up by this analysis.

(b) HTSE commercialization

HTSE is in its early commercialization phase now.[156] The technology builds on massive investment in Solid-Oxide Fuel Cell (SOFC) technology, which also is now being commercially deployed. HTSE's relatively high conversion rate from electrical energy to hydrogen mass flow, as well as its inherent ability to directly translate the addition of thermal energy into increased hydrogen mass flow, means that HTSE offers particularly attractive hydrogen production efficiency (all the more so because it requires less electricity from the nuclear station). This report's view of HTSE is also supported by a December 2020 US national laboratory report, which stated: "Of all the reviewed hydrogen production methods, HTSE systems are the closest to commercialization within current LWRs."[157]

2. Hydrogen production electricity allocation

In this assessment, a fixed 500-MWe portion of Diablo Canyon's electrical generation capacity is allocated to hydrogen production. This proposed allocation, equal to 22% of Diablo Canyon's total capacity, would yield 109 million kg of hydrogen per year. This would be a meaningful contribution to California's projected 2035 hydrogen demand, which ranges from 500 million kg to 1,200 million kg[158] (see Fig. 3-3 below). Smaller or larger plants could be considered, though.

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[155] Gardiner, M., "DOE Hydrogen and Fuel Cells Program Record #9013," US Department of Energy (2009). *See* http://energy.gov/sites/prod/files/14012_fuel_cell_system_cost_2013.pdf.

[156] "Haldor Topsoe to build large-scale SOEC electrolyzer manufacturing facility to meet customer needs for green hydrogen production" (press release, Mar. 4, 2021). *See* https://blog.topsoe.com/haldor-topsoe-to-build-large-scale-soec-electrolyzer-manufacturing-facility-to-meet-customer-needs-for-green-hydrogen-production. Topsoe will invest in a manufacturing facility producing highly efficient solid-oxide electrolyzers (SOEC) with a total capacity of 500 MW per year with the option to expand to 5 GW per year.

[157] Talbot, P.W., McDowell, D., Richards, J., Cogliati, J., Alfonsi, A., Rabiti, C., Boardman, R.D. (INL), Bernhoft, S., de la Chesnaye, F., Ela, E., Hytowitz, R., Kerr, C., Taber, J., Tuohy, A. & Ziebell D. (EPRI),

"Light Water Reactor Sustainability Program Evaluation of Hybrid Flexible Plant Operation and Generation Applications in Regulated and Deregulated Markets Using HERON, INL/EXT-20-60968 Revision 0" (Dec. 2020), p. 26, https://lwrs.inl.gov/Flexible Plant Operation and Generation/Evaluation_HybridFPOG_Applications_Regulated_Using_HERON.pdf.

[158] See California Energy Commission, "Roadmap for the deployment and buildout of renewable hydrogen production plants in California" (2020), p. 22, fig. 18, https://cafcp.org/sites/default/files/Roadmap-for-Deployment-and-Buildout-of-RH2-UCI-CEC-June-2020.pdf.

Figure 3-3: Potential future renewable hydrogen (RH) demand in California (source: California Energy Commission)[159]

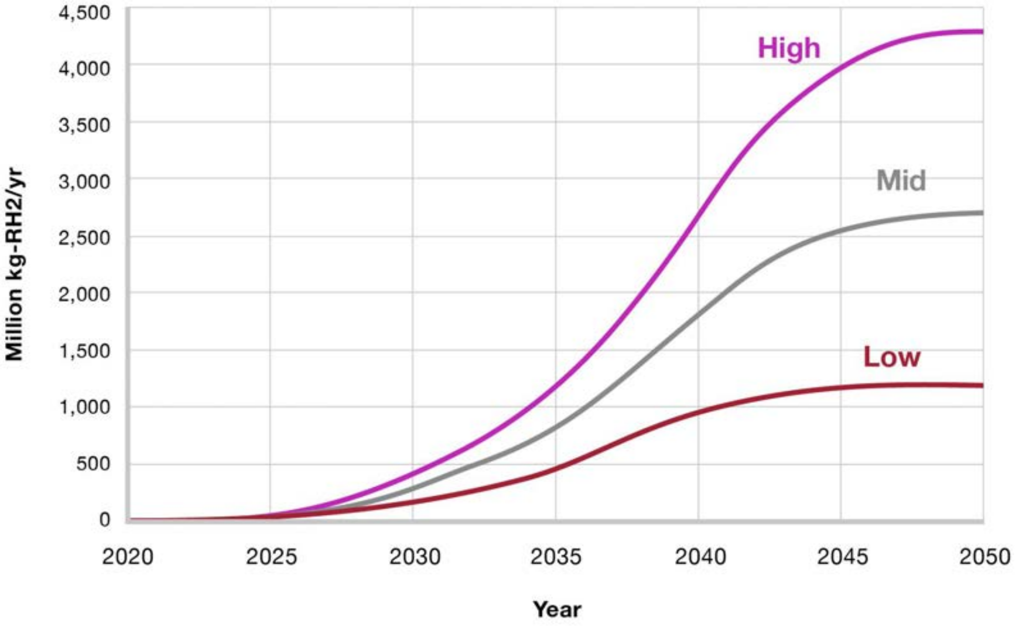

Table 3-1 lists the proposed hydrogen plant power allocation alongside those of the companion production commodities of the integrated plant.

Table 3-1: Diablo Canyon multiple commodity power allocation (in MW)

Desalination allocation (Option 2)[160])	353
Hydrogen production allocation	**500**
Energy DAM[161] allocation	500
Residual (energy RTM[162] + AS[163] (DAM & RTM)) allocation	887
Total Diablo Canyon capacity	2,240

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[159] *See* California Energy Commission, "Roadmap for the deployment and buildout of renewable hydrogen production plants in California," *op. cit*.

[160] "Option 2" is the second of four desalination plant options studied by the MIT team in Chapter 2. Option 2 achieves a desalinated water flow rate of 2,419,200 m^3/day. Option 2 was chosen as an ambitious, yet realistic option from the four considered by the MIT team in Chapter 2—both given the state's growing need for fresh water and the constraints identified in that chapter regarding Options 3 and 4.

[161] Day-Ahead Market electricity sales market.

[162] Real-Time Market electricity sales market.

[163] Ancillary Services grid stability product.

3. Hydrogen production water allocation

Clean, fresh water (H_2O) is the primary physical feedstock for hydrogen production. In this analysis, the hydrogen plant receives its fresh water supply from the companion desalination plant. The daily demand is listed in Table 3-2. At 500 MWe from the nuclear units, the hydrogen plant consumes 0.11% of the desalination plant's output.

4. Hydrogen plant specification

The proposed hydrogen's plant capacity is considerably larger than most currently operating or proposed H_2 production facilities.[164] Table 3-2 lists its basic specifications.

Table 3-2: Hydrogen plant specifications

Hydrogen plant electrical consumption (MWe)	500
Hydrogen plant nuclear heat consumption (MWt)	51
Hydrogen production capacity (tonne/day)	315
Hydrogen plant water consumption (m^3/day)	2,681
Hydrogen plant fenced-in footprint (acres)	21

5. Hydrogen plant footprint

The hydrogen plant footprint is estimated at approximately 20 acres; added to the 60 acre Option 2 desalination plant discussed in Chapter 2, the total polygeneration plant footprint is estimated at 80 acres.

6. Hydrogen plant integration with Diablo Canyon

The HTSE hydrogen production process requires energy inputs of electricity and heat. As discussed, HTSE's process requirements are well matched to a nuclear power plant, which inherently offers both.

(a) Electricity supply

Beyond the discussion immediately below, no unconventional accommodations are required for Diablo Canyon to supply electricity to the hydrogen plant.

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[164] For example, the world's largest electrolyzer, recently completed, yields 8.2 tons per day of hydrogen, or 2,920 tons per year (20 million kg/year). See http://www.gasprocessingnews.com/news/construction-of-worlds-largest-pem-electrolyzer-completed.aspx.

The nature of the hydrogen production process allows the power purchase agreements of the electricity-generation business and the hydrogen-production business to reflect a range of service levels. Specifically, these are service levels that relate to the availability or flexibility of the electricity supply. Production levels of the HTSE process can be varied, presenting opportunities for flexible power purchase agreements that may allow for even more attractive pricing. In this analysis, we do not assume that the hydrogen facility's potential flexibility leads to lower electricity prices. The estimated pricing and costs are presented in Table 3-4 (per-kilogram hydrogen production parameters).

The hydrogen plant is flexible within the constraint of needing to avoid large, rapid temperature swings in the solid oxide cells, which are known to reduce the SOFCs' life and efficiency.[165] The exact modes of temperature cycling operation have yet to be experimentally confirmed, but an indicative metric is manufacturers' recommended startup and shutdown thermal gradients of no more than 2° C per minute[166]—a datapoint that provides a sense of acceptable temperature gradients. When power needs fluctuate, cells can be maintained in a "hot standby mode," using a small fraction of full-load capacity (2.7%). In this mode, there is little to no effect on stack performance.[167] This makes it possible to operate the plant as a flexible demand resource. When the plant needs to be cycled down for a longer period (e.g., weeks), it is allowed to cool in a controlled manner[168] and "parked" indefinitely. An analysis of the impacts on cells thus "parked" has concluded[169] that suitably maintained cells exhibit "very favorable"[170] performance, with low[171] degradation rates. Optimizations may involve any or all temperature maintenance strategies, including insulation, thermal heat maintenance, and electrical heat maintenance.

From the hydrogen customer's perspective, the extent of the hydrogen plant's flexibility will be dictated by the customer's delivery agreements and the availability of storage. Storage may be implemented at the production site or at the consumption site. Storage may be owned and operated by either the producer or by the customer. (The role of such storage, however, is beyond the scope of this assessment.)

(b) Heat supply

To integrate with Diablo Canyon, the proposed hydrogen plant will require a steam pipe that connects to Diablo Canyon's nuclear heat supply. The Diablo Canyon nuclear station consists of two reactor units. Each is a Westinghouse pressurized water reactor (PWR) of approximately 1,100 MW designed in the "4-loop model" configuration—a reference to the four steam generators[172] that surround each reactor unit. Figure 3-4 illustrates this configuration. The steam produced by the steam generators transfers heat energy to the proposed hydrogen plant discussed here.

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[165] O'Brien, J.E., Zhang, X., O'Brien, R.C., Hawkes, G.L., Hartvigsen, J.J., Elangovan, E., Tao, G., *et al.*, "Summary Report on Solid-oxide Electrolysis Cell Testing and Development" (2012), INL/Ext-11-24261, https://inldigitallibrary.inl.gov/sites/sti/sti/5394148.pdf.

[166] Frick, K., Talbot, P., Wendt, D., Boardman, R., Rabiti, C., Bragg-Sitton, S., Levie, D., *et al.*, "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest," Idaho National Laboratory (2019), p. 9, https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_18785.pdf.

[167] Frick, K., *et al.*, "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest," op. cit., p. 10.

[168] Six to seven hours.

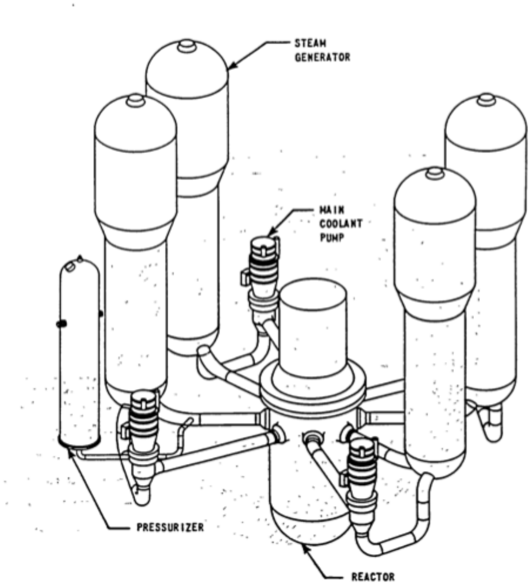
[169] More than 1,000 hours.

[170] O'Brien, J.E., *et al.*, "Summary Report on Solid-oxide Electrolysis Cell Testing and Development," *op. cit.*, p. v.

[171] Less than 3% per 1,000 hours.

[172] 51-series, U-tube steam generators.

Figure 3-4: Westinghouse PWR nuclear steam supply system, showing the four steam generators of its "4-loop" model [173,174]



(i) Quantity of heat

The proposed hydrogen plant consumes 51 MWt of Diablo Canyon's total heat production of 6,749 MWt.[175] This heat consumption is 0.8% of Diablo Canyon's total capacity,[176] or 1.5% of a single unit's. These small heat diversions are considered to have a de minimis impact on Diablo Canyon's operation. (Nonetheless, any such change in a nuclear plant's operational profile requires review by the federal Nuclear Regulatory Commission.)

(ii) Delivering heat from Diablo Canyon to the hydrogen plant

The proposed hydrogen plant's integration with Diablo Canyon is very similar to a parallel integration study conducted by the Idaho National Laboratory (INL).[177,178] Steam for the HTSE plant would be extracted just upstream of the high-pressure stage of the steam turbine, and downstream of the nuclear plant's steam generators.

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[173] Westinghouse, *Westinghouse Technology Manual*, Ch. 17.0: Plant Operations. https://www.nrc.gov/docs/ML0230/ML023040268.pdf.

[174] Westinghouse Technology Manual Ch. 17.0, *op. cit*., p. 3-14, fig. 3.2-3.

[175] Westinghouse Technology Manual, Ch. 17.0, *op. cit*., pp. 2-3, tab. 2-1.

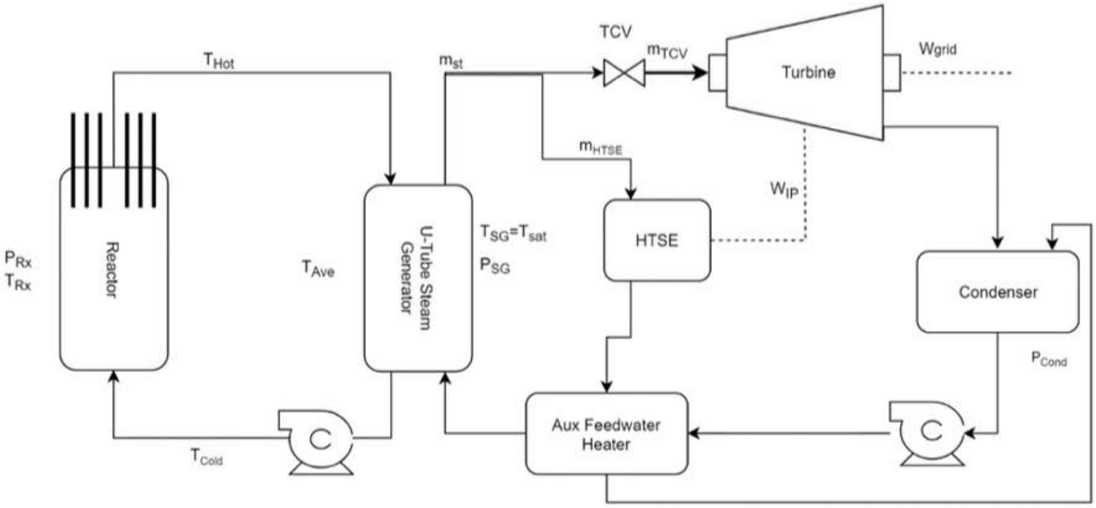
[176] Unit 1: 3,338 MWt; Unit 2: 3,411 MWt.

[177] Frick, K., et al., "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest," op. cit.

[178] Frick, K., et al., "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest," op. cit.

Figure 3-5 shows this type of integration, depicting the output of the U-tube steam generator (center), split into two legs. One leg feeds the steam turbine via a turbine control valve (TCV), while the other feeds the HTSE system. (Diablo Canyon's steam generators are also U-tube steam generators.)

Figure 3-5: Diagram of PWR nuclear reactor, showing U-tube steam generator and steam-tap point for the HTSE process[179]



As discussed above, the nuclear heat source is accessed via Diablo Canyon's steam supply. The steam is conveyed from the nuclear station to the hydrogen plant by a steam pipeline.

(iii) Heat availability

As discussed above, each of the Diablo Canyon's reactor units is outfitted with its own steam generators. Each Diablo Canyon reactor unit can be taken offline independently. To enhance the proposed hydrogen plant's availability, temperature management, and operational resilience in the face of planned multi-week refueling outages every 20 months, the hydrogen plant steam interconnection includes provision for flexible access to either of Diablo Canyon's nuclear steam systems.

Hydrogen plant cost

The INL study[180] includes a cost analysis of a reference plant. That research has been scaled to correspond to the size of the proposed hydrogen plant at Diablo Canyon. In some cases, qualitative differences between the two have required that cost estimates be separately adapted to the hydrogen plant examined here.

Some costs that are beyond the scope of this assessment have not been estimated or tabulated here; these include land procurement and regulatory fees. Other costs are estimated as a percentage of total

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[179] Frick, K., *et al.*, "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest," *op. cit.*, p. 32, fig. 21.

[180] Frick, K., *et al.*, "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest," *op. cit.*

capital invested (TCI) for the hydrogen plant; these percentages are shown in brackets in Table 3-5's corresponding line item. Cost data below is expressed in 2019 US dollars, unless otherwise noted.

1. Hydrogen plant capital cost

The INL analysis includes a cost study; the cost and scale of the INL plant have been extrapolated to the proposed capacity of 500 MWe for the plant proposed here. Costs of the nuclear steam delivery system have been calculated[181] to a 1,500-meter pipeline (the INL study analyzed a scenario with a 1,000-meter pipeline). All capital costs are displayed in Table 3-3 below.

Table 3-3: Capital cost, HTSE based 315 tonne/day hydrogen production facility proposed for Diablo Canyon

Total overnight capital cost	
Direct	
Vessel	$124,735,015
Feed and utility system	$7,386,0571
Sweep gas system	$22,682,118
Hydrogen/steam system	$30,098,117
Hydrogen purification system	$56,064,925
Nuclear steam delivery system	$6,626,037
Indirect	
Site preparation	$14,626,352
Engineering and design	$24,377,253
Contingencies and contractor's fee	$43,879,056
Legal fees	$4,875,450
Total Capital Invested (TCI)	**$335,350,381**

2. Hydrogen cost per kilogram from energy and feedstock

The cost of electricity dominates the variable cost of hydrogen, essentially accounting for 100%[182] of the energy and feedstock expenses. Given this, it is worthwhile to exhaustively explore strategies to reduce

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[181] Krull, P., Roll, J. & Varrin, R.D. "HTSE Plant Cost Model for the INL HTSE Optimization Study" (Reston, VA: Dominion Engineering, Inc., Mar. 2013), Report No. R-6828- 00-01, *as cited in* INL/EXT-19-55395, Revision 1.

[182] 99.6% to 99.7%.

electricity expense. One cost-reduction approach considers quality of service—the expected (and agreed to) level of reliability. Table 3-4 presents the cost-effectiveness of two approaches for the purchase of electricity. A self-generation strategy contemplates that electricity produced only by Diablo Canyon itself is supplied to the hydrogen plant.[183] A grid-backed strategy contemplates that Diablo Canyon arranges for high-availability electricity—whether from the nuclear plant itself or from the grid. During generation outages at Diablo Canyon, high-availability could be achieved by orchestrating electricity delivery from other grid-connected generators. The cost differential of such a service is dominated by electricity price shown in Table 3-4.

Table 3-4: Per-kilogram hydrogen production parameters

	Self-Generated Electricity	**Grid-Backed Electricity**
Cost of electricity ($/MWh)	**$42.480**	**$54.180**
Cost of water ($/m^3)	$0.840	$0.840
Cost of nuclear heat ($/MWt)	$0.010	$0.010
Specific electricity consumption, hydrogen (MWh/kg)	0.038	0.038
Specific water consumption by electrolysis, hydrogen (m^3/kg)	0.009	0.009
Specific nuclear heat consumption, hydrogen (MWt/kg)	0.004	0.004
Cost of electricity per kg of hydrogen ($/kg)	$1.616	$2.062
Cost of electrolysis water per kg of hydrogen ($/kg)	$0.007	$0.007
Cost of nuclear heat per kg of hydrogen ($/kg)	$0.000	$0.000
Specific cost, energy and feedstocks, of hydrogen ($/kg)	**$1.623**	**$2.069**

Note that in Table 3-4 the cost of nuclear heat is reported to be $0.01/MWt. This number is intended to signal that the cost is deemed too low to meaningfully calculate, but could become significant if a hydrogen plant's heat demand—for example, a far higher-capacity plant—was of a level that affected the output of its companion electricity plant.

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[183] The cost of electricity from Diablo Canyon takes into account the capital additions required for the plant's intake modifications described in Chapter 2.

3. Hydrogen plant operating cost

Operating costs include capital costs allocated over a 10-year[184,185] period and a debt fraction of 40%, which results in a discount rate of 5.9%, an inflation rate of 1.8% yields a real discount rate of 4.03%.[186]. Levelized cost assumes a 95% availability factor for hydrogen production and a 20-year plant life expectancy. The SOE cell stacks are replaced every seven years.[187]

4. Total levelized cost of hydrogen from the proposed plant

Tables 3-5 and 3-6 combine all capital and operating costs into a levelized cost of hydrogen for self-generation and grid-backed generation, respectively.

Table 3-5: Levelized cost of hydrogen production, self-generated electricity

Levelized cost of production, self-generation, hydrogen	
Capacity factor	0.95
Total Capital Investment (TCI)	$335,350,381
Capital period (years)	20
Real discount rate (%)	4.03%
Annualized capital expense ($)	$24,735,804
Cost of energy and water per kg produced hydrogen ($/kg)	$1.623
Annual hydrogen production after capacity factor (kg)	109,358,113
Annual variable expense ($)	177,541,708
SOE cell stacks at $50/kWe (7-year life)	$22,448,357
Capital period (years)	7
Real discount rate (%)	4.03%
Annualized SOEC replacement expense ($)	$3,743,915
Administration, overhead ($), [.5% of TCI]	$1,676,752
Maintenance ($), [1% of TCI]	$3,353,504
Insurance & property tax ($), [2% of TCI]	$6,707,008

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[184] US Internal Revenue Service, “How to Depreciate Property,” Pub. 946, Cat. No. 13081F (2020), http://www.irs.gov/pub/irs-pdf/p946.pdf.

[185] Modified Accelerated Cost Recovery (MACR) asset class 28.0 (Manufacture of chemicals and allied products qualifying as a refinery context).

[186] US Energy Information Administration’s “Annual Energy Outlook 2021, Electricity Market Module, Feb. 2021,” p. 9 reports a nominal discount rate of 5.9%. Assuming an annual inflation rate of 1.8%, this translates to a real discount rate of 4.03%.

[187] Frick, K., et al., “Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest,” *op. cit.*, p. 21.

Annual administration	$11,737,263
Staff count	25
Average staff salary ($)	$100,000
Annualized staff expense ($)	$2,500,000
Total annual expense ($)	**$220,258,690**
Levelized cost of hydrogen ($/kg)	**$2.01**

Table 3-6: Levelized cost of production, grid-backed generation

Levelized cost of production, self-generation, hydrogen	
Capacity factor	0.95
Total Capital Investment (TCI)	$335,350,381
Capital period (years)	20
Real discount rate (%)	4.03%
Annualized capital expense ($)	$24,735,804
Cost of energy and water per kg produced hydrogen ($/kg)	$2.0693
Annual hydrogen production after capacity factor (kg)	109,358,113
Annual variable expense ($)	226,248,788
SOE cell stacks at $50/kWe (7-year life)	$22,448,357
Capital period (years)	7
Real discount rate (%)	4.03%
Annualized SOEC replacement expense ($)	$3,743,915
Administration, overhead ($), [.5% of TCI]	$1,676,752
Maintenance ($), [1% of TCI]	$3,353,504
Insurance & property tax ($), [2% of TCI]	$6,707,008
Annual administration	$11,737,263
Staff count	25
Average staff salary ($)	$100,000
Annualized staff expense ($)	$2,500,000
Total annual expense ($)	**$268,965,770**
Levelized cost of hydrogen ($/kg)	**$2.46**

The result is a levelized cost of hydrogen at $2.01/kg for self-generated electricity and at $2.46/kg for grid-backed generation. This compares favorably with current estimated production costs of zero-carbon hydrogen.

Figure 3-6: Comparison of hydrogen production cost estimates

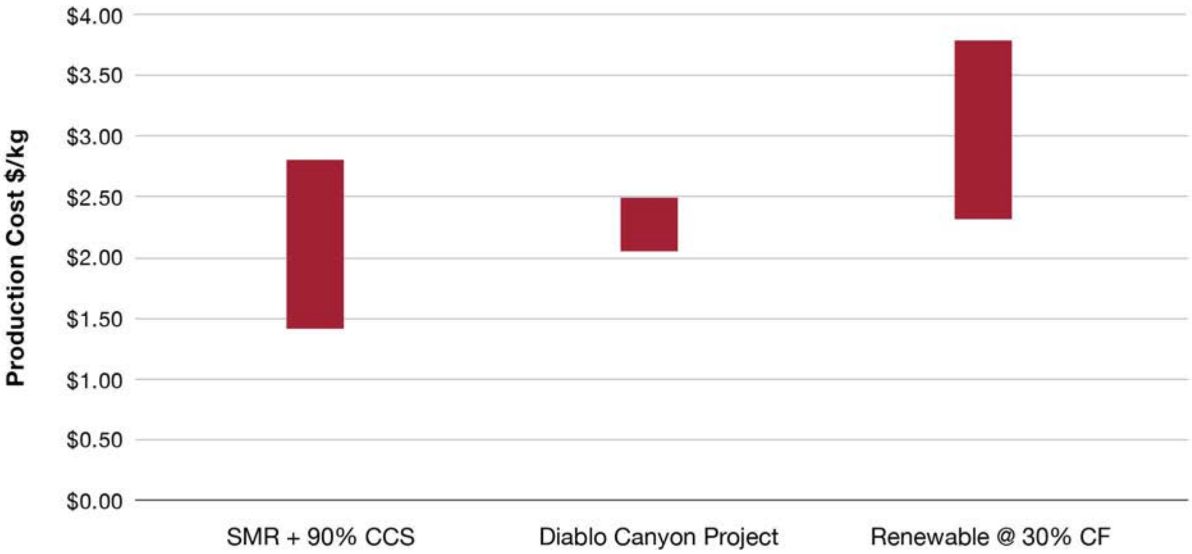

Figure 3-6 above compares hydrogen production cost estimates for this study to typical values reported by the International Energy Agency for (i) steam-methane reforming (SMR) with 90% carbon capture and sequestration (CCS), and (ii) for electrolysis, assuming renewable electricity at a 30% capacity factor (CF).[188] Each comparison is based on near-term technology performance, and includes a range of primary input costs. For the SMR + CCS case, a range of natural gas (NG) costs between $3 and $11 per MMBtu is shown. For the renewable electrolysis case, a range of electricity costs between $20/MWh and $50/MWh of electricity is shown.

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[188] International Energy Agency, "The Future of Hydrogen" (June 2019), p. 54, fig. 18, https://www.iea.org/reports/the-future-of-hydrogen.

Chapter 4

Assessing the value of Diablo Canyon as a flexible resource providing multiple outputs

By Justin Aborn

Chapter 4 Key Points:

- ➔ Operating Diablo Canyon as a polygeneration facility—with coordinated and varying production of electricity, desalinated water, and clean hydrogen—would provide multiple services to California and further increase the value of the Diablo Canyon electricity plant by nearly 50% (and more, if water prices were to substantially increase)
- ➔ Further economic benefit could accrue if Diablo Canyon capacity services were marketed to the California grid

Introduction

Building on previous chapters, this final chapter considers a distinct question: Whether a Diablo Canyon complex can further optimize its value to California by flexibly directing electricity and heat from the nuclear plant to the grid, to the desalination plant, or to the hydrogen plant—or to all three. We examine this question through the application of multiple commodity analysis. The goal of multiple commodity analysis is to compare the revenue that may be derived by allocating Diablo Canyon's electrical generation capacity to the production of several saleable commodities—specifically, electricity as energy, electricity as several forms of ancillary services, desalinated water, and hydrogen.

Summary of results

Our analysis assesses revenue by determining the commodity dollar value per megawatt-hour (MWh) of the electricity allocated to producing that commodity. The rationale is that, for every MWh produced by Diablo Canyon, there is a choice to be made regarding how to best use that unit of electrical production. The result of this analysis, detailed below, is that the dollar-value of desalination (turning salt water into fresh) achieves the highest dollar value (in $/MWh) of any of the options examined in the selected commodity portfolio. When outputs are blended in various configurations, subject to estimated performance the value of the plant varies around $70/MWh, considerably higher than the levelized cost of Diablo Canyon electricity ($42/MWh), or the blended price of Diablo Canyon plus market electricity of $54/MWh, as calculated in Chapter 2. This value ignores the potential for additional revenue by marketing capacity services to the California grid.

Study parameters

1. Commodities studied in this analysis

The commodities studied were selected and agreed to by energy technology and energy market subject-matter experts. The criteria for selection were that the portfolio be (i) technically achievable; and (ii) a plausibly valuable configuration to key constituencies. In that regard, strong weight was accorded to the experts' perception of the commodity portfolio's value to the state of California, to the California grid, and to California residents. The selected portfolio is not the only plausible one; but it does offer a reasonable assessment of a multiple-commodity scenario.

(a) Electricity

Electrical production is sold both in the form of energy and in the form of ancillary services. Both forms are exchanged and priced on the day-ahead market (DAM) and the real-time market (RTM).

(i) Energy

Electricity sold as "energy" is the most conventionally familiar form in which electricity is sold. It is akin to the electric generation (in kWh) flowing into a home or business through a customer's electric meter.

(ii) Ancillary services

Ancillary services relate to grid operations. Here, the ancillary services selected for detailed analysis are: non-spinning reserve, spinning reserve, and "regulate up, and regulate down" service, which commits the unit to continuously adjust output to maintain required grid frequency. Ancillary services are sold to grid infrastructure managers.

(b) Desalinated water

Fresh water is a valuable commodity used for myriad purposes. Its importance to California and the structure and value of a desalination plant adjacent to the Diablo Canyon nuclear unit are examined in Chapter 2 of this report.

(c) Hydrogen

Hydrogen is a valuable commodity used in myriad applications, especially energy-related applications—particularly in segments of the transportation sector that cannot be easily electrified, for industrial heat and processes, and to balance a highly variable electric grid. The structure and value of an adjacent hydrogen plant is examined in Chapter 3 of this report.

The Model

1. Model inputs

Our model calculates predicted revenue that may be earned by an integrated facility that consists of the Diablo Canyon nuclear station and companion freshwater- and hydrogen-production plants.

(a) Analysis resolution

The analysis here examines one year of operation at hourly resolution using publically available hourly price data for 2020, a 366-day leap year. Consequently, the model examines 8,784 hourly dispatch and market bid decisions.

(b) Capacity factor

The analysis assumes 100% plant availability. Although this assumption is unrealistic in practice, its use allows for a more realistic assessment of the value of capacity. The rationale is that any other approach would require us to determine which hours of the year were productive. Plant shutdowns do have known maintenance scheduling protocols, but, because the model uses hourly price data, inclusion of even a fully anticipated maintenance outage could correspond to a particularly advantageous (or disadvantageous) period financially. Assuming 100% availability avoids uncertainty of this type. Of course, aggregate revenue must be reduced to reflect more realistic plant operations. A typical availability heuristic is 90%, which approximates Diablo Canyon's achieved capacity factor.[189] The effects of availability are presented below in Tables 4-7 and 4-8.

(c) Power allocation

Each hour, the model allocates capacity among uses all of Diablo Canyon's 2,240 MWe of production. In the scenario considered here, water production receives its full allocation of 353 MWe capacity, in line with Option 2 in Chapter 2. Hydrogen production receives its full 500 MWe capacity allocation, in line with Chapter 3.

The remaining 1,387 MWe are sold as energy (500 MWe) on the day-ahead market, and as energy on the real-time market and ancillary services on both markets (887 MWe), using a deterministic price-taking algorithm described below.

Table 4-1: Diablo Canyon power allocation by product

Desalination allocation	353
Hydrogen production allocation	500
Energy DAM allocation	500
Residual (energy RTM + AS (DAM & RTM)) allocation	887
Total Diablo Canyon capacity	2,240

(d) Price data

In this analysis, electricity is priced per megawatt-hour. Water is priced per cubic meter. Hydrogen is priced per kilogram. All commodity prices are sales prices.

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[189] Diablo Canyon Power Plant capacity factor: 90.93% (2017); 87.25% (lifetime). *See* https://en.wikipedia.org/wiki/Diablo_Canyon_Power_Plant.

(i) Water price data

This report analyzes the effect of the water sales price as distinct from the water production cost. Water is sold to end-users in myriad ways that may involve connection fees, capacity fees, and other considerations—with prices varying widely. This analysis uses an unwavering, fixed water price of \$0.77 per cubic meter (\$/m^3), which is \$950/acre-foot.[190] The revenue result tables (Tables 4-6 and 4-7) list the corresponding water sales price; the revenue sensitivity to water price appears in Table 4-9.

(ii) Hydrogen price data

As with water, we analyze the effect of the hydrogen sales price as distinct from the hydrogen production cost. Hydrogen prices vary and cannot yet be expressed with high confidence. Albeit wide, a price range for hydrogen of \$3/kg to \$10/kg may be a useful reference.[191] The revenue result tables list the corresponding hydrogen sales price; the revenue sensitivity to hydrogen price appears in Table 4-9.

(iii) Electricity price data

Electricity price data for Diablo Canyon's 2020 market area are from the California Independent System Operator (CAISO) Open Access Same-time Information System (OASIS)[192]—for both the day-ahead market and the real-time market.

With the exception of approximately four (contiguous) hours, all 2020 hours are accounted for. The missing hours are populated with the preceding hour's price. Price data expressed as hourly values are used directly. Where price data is set forth in 15-minute intervals, as is the case for ancillary services, the four interval values are averaged to form a single hourly figure.

2. Model dynamics

(a) Hour-by-hour production and selling decisions

The results presented in this report reflect a reasonably simplified dispatch and sales strategy that achieves the modeling objective, which is to compare the relative commodity revenue performance of multiple commodities produced at Diablo Canyon. The ultimate goal is to present a transparent and understandable data-driven revenue scenario to act as a baseline.

It should be noted that production and sales strategies can take many forms. They may be optimized to pursue higher sales revenue, or to advance goals other than revenue. Examples of pertinent alternative strategies and goals are briefly discussed below. The dispatch and sales strategies chosen for this study are detailed below.

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[190] A 2019 Public Policy Institute of California report estimates a maximum agricultural water buyer willingness to pay at \$900/acre-foot. *See* Escriva-Bou, A., "Water and the Future of the San Joaquin Valley, Technical Appendix A: Updated Assessment of the San Joaquin Valley's Water Balance,"

https://www.ppic.org/wp-content/uploads/0219ehr-appendix-a.pdf. But it should be noted that recent California water futures contracts have already reached \$914/acre-foot. *See* CME Group, "Nasdaq Veles California Water Index," https://www.cmegroup.com/markets/equities/nasdaq/nasdaq-veles-california-water-index.settlements.html.

[191] Eichman, J., Townsend, A., & Melaina, M., "Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets," National Renewable Energy Laboratory (2016), www.nrel.gov/publications.%0Ahttps://www.nrel.gov/docs/fy16osti/65856.pdf.

[192] California ISO (CAISO) Open Access Same-time Information System (OASIS), http://oasis.caiso.com/mrioasis/logon.do.

(i) Water production and sales modeling strategy

The selected desalination plant configuration is "Option 2," as specified by the desalination plant design analysis in Chapter 2, above. Option 2 produces 2,419,200 m^3 of fresh water per day and consumes 353 MWe of electricity.

The revenue analysis sets production performance at this fixed value for all hours of the year. All water produced is presumed to be sold. Water sales price is presented in the revenue results table.

(ii) Hydrogen production and sales modeling strategy

The selected hydrogen plant configuration produces 315,380 kilograms of hydrogen per day and consumes 500 MWe of electricity, as discussed in Chapter 3.

The revenue analysis sets production performance at this fixed value for all hours of the year. All hydrogen is presumed to be sold. The H_2 sales price is presented in the revenue results table.

(iii) Electricity production and sales modeling strategy

Diablo Canyon's electricity production is modeled at a fixed level of 2,240 MWe, from which a fixed 1,387 MWe is allocated for sale as electricity.

Electricity is sold on the day-ahead and real-time markets through an intricate bidding process, described more fully in CAISO documents.[193]

The process requires generators to submit bids specifying both a price and a quantity. A valid bid includes the generator's proposed price per megawatt-hour ($/MWh), along with a proposed megawatt-hour quantity (MWh). The grid system operator's market resolution system collects proposed bids and then awards accepted bids. There is no guarantee that a bid will be accepted. The intent is to establish a market-based mechanism whereby generators have an incentive to produce electricity in a financially efficient manner.

Each electricity product is priced by an independent market specific to that product. Each product market operates both a real-time market (RTM) and a day-ahead market (DAM). Electricity transactions that take the market-determined price, without a bid, occur on the real-time market. The prices shown in Tables 4-2 and 4-3 provide an indication of the two electricity markets' price behavior.

Table 4-2: Energy prices during 2020

Product	Minimum Price During Year ($/MWh)	Average Price During Year ($/MWh)	Maximum Price During Year ($/MWh)
Energy, DAM	$(10.34)	$34.78	$1,062.64
Energy, RTM	$(31.57)	$28.83	$933.17

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[193] California ISO (CAISO) Open Access Same-time Information System (OASIS). Day-ahead market; operating procedure, http://www.caiso.com/documents/1210.pdf.

Table 4-3: Ancillary service prices during 2020

Product	Minimum Price During Year ($/MWh)	Average Price During Year ($/MWh)	Maximum Price During Year ($/MWh)
Non-Spinning Reserve, DAM	$ -	$2.65	$950.61
Non-Spinning Reserve, RTM	$ -	$1.55	$769.17
Reg. Down, DAM	$ -	$9.45	$207.26
Reg. Down, RTM	$ -	$6.48	$305.01
Reg. Up, DAM	$0.10	$9.81	$962.54
Reg. Up, RTM	$ -	$7.52	$798.50
Spinning Reserve, DAM	$0.10	$5.70	$950.61
Spinning Reserve, RTM	$ -	$3.72	$769.17

(b) Market strategy

As in any market, pathways may exist to “play” the market to seek a higher selling price. The California electricity market experiences noteworthy price volatility, as can be seen in Tables 4-2 and 4-3. Prices over $1,000/MWh occur. Negative prices, whereby electricity buyers are paid to take power, also occur. This analysis is based on historical electricity prices, and is therefore a price-taking analysis, rather than an attempt to represent the results of active participation in market bidding.

(i) Negative price hours

To conservatively assess revenue earned, the market protocol applied here does not attempt to gain from negative price hours. Although Diablo Canyon standing alone would be unlikely to benefit from negative pricing, the addition of a desalination plant and hydrogen plant create the possibility of financial reward from negative pricing. This is discussed in more detail below.

(ii) Energy sales modeling strategy

The analysis allocates Diablo Canyon generation capacity as shown in Table 4-4.

Table 4-4: Diablo Canyon power allocation by product (in MWe)

Desalination allocation	353
Hydrogen production allocation	500
Energy DAM allocation	500
Residual (energy RTM + AS (DAM & RTM)) allocation	887
Total Diablo Canyon capacity	2,240

Our analysis holds constant the percentage of the plant's power allocated to water, hydrogen, and the energy day-ahead market (DAM). The balance of the plant's total capacity is assigned to the combined, real-time energy market, and to the real-time and day-ahead ancillary service markets.

With regard to the day-ahead market, this analysis assumes that the full allocation can be sold at the hourly market-settled price.

The capacity that remains after serving water, hydrogen, and the DAM is then sold on the real-time market (RTM), minus whatever bids may have been won for ancillary services. The total capacity sold equals the full production capacity of the Diablo Canyon nuclear plant.

(iii) Ancillary services sales modeling strategy

To approximate the revenue that may accrue to sales into the ancillary services market, our analysis applies a rudimentary, deterministic protocol for making hour-to-hour decisions to bid for electricity products.

The protocol establishes a fixed minimum price ($50) at which the protocol "plays" in that hour's bidding (the "price hurdle").[194] It also bids a specific, invariant quantity of megawatt-hours. These MWh bid levels were assigned the modest values of 100 MWh for DAM and 50 MWh for RTM, based on the rationale that such low numbers would be accepted with reasonable confidence. To determine whether a bid is won, the price of energy on the RTM compared to DAM for that hour is taken as a proxy for market receptivity.

Table 4-5: Ancillary service market bid settings

Product	Price hurdle to bid ($)	Energy bid (MWh)	Count of Hours won
Non-Spinning Reserve, DAM	$50	100	90
Non-Spinning Reserve, RTM	$50	50	38
Reg. Down, DAM	$50	100	69
Reg. Down, RTM	$50	50	216
Reg. Up, DAM	$50	100	110
Reg. Up, RTM	$50	50	119
Spinning Reserve, DAM	$50	100	32
Spinning Reserve, RTM	$50	50	40

To assess the sensitivity of the ancillary services modeling strategy, alternative market bid settings were examined. Both lower and substantially higher bid hurdles were found to have minimal impact on final revenue results. Lower bid settings sold power at cheap times. Higher bid settings missed out on

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[194] The $50/MWh price was selected to be low enough to encourage bidding, yet higher than the average price of a MWh during 2020 (*see* Table 4-2).

reasonably attractive hours of the year. In short, this exploration found that the settings in Table 4-5 are arguably "optimal" in that they maximize the revenue earned by ancillary services under the described deterministic protocol.

Nonetheless, this result does not imply that these bidding parameters represent real-world behavior. For example, boosting the size of the MWh bid would certainly increase the total MWh applied to serving ancillary service customers. However, support for larger MWh ancillary service bids was not identified in the publicly available CAISO/OASIS database; thus, the 100 MWh and 50 MWh energy bids were adopted as conservative estimates.

Revenue results

Total annual revenue results are presented below, as well as annual totals for each high-level product portfolio category. Megawatt-hours dispatched are reported. Revenue rate per MWh is reported overall, as well as by portfolio category.

1. Base case

The base case results take the price of water to be \$0.77 per cubic meter (\$950/acre-ft) and the price of hydrogen to be \$3.00 per kilogram, as discussed above. The price of electricity services sold is a function of publicly available electricity prices and the modeling strategy applied here.

Table 4-6 shows revenue resulting from the product portfolio described above. These results present a relatively unaggressive revenue scenario (for example, limiting real-time market sales to a maximum of 50 MWh) and thus represent low-end results. Notable is the \$220 per megawatt-hour value assigned to desalination. Also of interest is desalination's relatively high-revenue fraction, given its modest use of Diablo Canyon's electricity output.

Table 4-6: Revenue (base case water and hydrogen prices, and 100% availability)

Product	Annual Revenue	Revenue Fraction	MWh Dispatched	MWh Fraction	Revenue Per MWh
Energy	\$376,022,041	26.7%	12,158,033	61.8%	\$31
Ancillary Services	\$8,659,630	0.6%	50,750	0.3%	\$171
Desalinated water at \$0.77 per m^3	\$681,922,290	48.3%	3,100,752	15.8%	\$220
Hydrogen at \$3.00 per kg	\$344,286,856	24.4%	4,366,625	22.2%	\$79
Total	\$1,410,890,818	100%	19,676,160	100%	\$72

(a) Interpretation of revenue results with respect to availability

Table 4-7 explicitly depicts how Diablo Canyon's availability affects annual revenue and overall revenue rate (\$/MWh). Specifically, the table shows that a decrease in annual power generation (i.e., power plant outages) reduces overall revenue. These results assume that all production lines are affected similarly, meaning that the overall revenue per successfully generated MWh remains the same.

Table 4-7: Revenue results calculated for three availability values

Availability of electricity generation	100%	95%	90%
Annual revenue	$1,410,890,818	$1,340,346,277	$1,269,801,736
Revenue/MWh	$72	$72	$72

(b) Using revenue results with mixed production availability

Table 4-8 explicitly depicts how Diablo Canyon's companion production plants' availabilities affect annual revenue and product revenue rates. This table shows in clear fashion how the availability level of each plant directly affects that plant's total revenue. (Plant availability figures, although within reasonable range, should not be taken as engineering projections.)

Table 4-8: Mixed production availability examples

Availability of electricity generation	100%	100%	100%
Availability of desalination plant	100%	95%	90%
Availability of hydrogen plant	100%	98%	95%
Electricity generated (MWh), total	19,676,160	19,676,160	19,676,160
Electricity consumed and sold by desalination (MWh)	3,100,752	2,945,714	2,790,677
Electricity consumed and sold by hydrogen production (MWh)	4,366,625	4,279,293	4,148,294
Electricity sold to energy and ancillary service markets, as expected (MWh)	12,208,783	12,208,783	12,208,783
Desalination-allocated electricity, reallocated to electricity markets (MWh)	0	155,038	310,075
Hydrogen-allocated electricity, reallocated to electricity markets (MWh)	0	87,840	219,600
Revenue rate, $/MWh, desalination	$219.92	$219.92	$219.92
Revenue rate, $/MWh, hydrogen	$78.85	$78.85	$78.85
Revenue rate, $/MWh, energy and ancillary services	$31.51	$31.51	$31.51
Annual revenue $, desalination	$681,922,290	$647,826,176	$613,730,061

Annual revenue $, hydrogen	$344,286,856	$337,401,119	$327,072,513
Annual revenue $, energy and ancillary services, as expected	$384,681,672	$384,681,672	$384,681,672
Annual revenue $, energy and ancillary services, by reallocation	$0	$7,652,733	$16,689,325
Annual revenue $, total	$1,410,890,818	$1,377,561,699	$1,342,173,570
Revenue/MWh overall	**$71.71**	**$70.01**	**$68.21**

2. Revenue sensitivity considerations

The effects of commodity price variations, the availability of carbon credits related to hydrogen production, and the operational choice of “buying” energy during periods of negative RTM pricing are considered below.

(a) Revenue sensitivity to water price and hydrogen price

Table 4-9 presents the effect of water price and hydrogen price on overall revenue rate.

Table 4-9: Sensitivity of overall revenue rate ($/MWh) to water price and hydrogen price (base case prices in bold)

Overall $/MWh		Water price ($/m^3) ($/acre-ft)			
		$0.41 [$500]	$0.77 [$950]	$1.00 [$1,233]	$1.50 [$1,850]
Hydrogen price ($/kg)	$1.00	$43.63	$60.04	$70.38	$92.89
	$3.00	$55.29	**$71.71**	$82.04	$104.55
	$5.00	$66.96	$83.37	$93.71	$116.22
	$7.00	$78.62	$95.04	$105.37	$127.88

(b) Revenue sensitivity to carbon credits for hydrogen

The annual production of the posited 500 MWe hydrogen plant is 114,762,285 kilograms of H_2.

Hydrogen production may qualify for carbon credits of some type, but the details and qualification requirements at this point are uncertain enough to elude precise calculation. Table 4-10 below illustrates the revenue effect of a range of hypothetical carbon credit prices (these prices are presented for reference only).[195]

Table 4-10: Aggregate value of hydrogen production carbon credits at several $/kg credit values

	$0.10	**$0.20**	**$0.40**	**$0.80**	**$1.60**	**$3.20**
114,762,285kilograms hydrogen	$11,476,229	$22,952,457	$45,904,914	$91,809,828	$183,619,656	$367,239,313

(c) Revenue sensitivity to buying energy during negative RTM pricing

As shown in Table 4-2, negative prices were seen in 2020: ($10.34)/MWh on the DAM, and ($31.57)/MWh on the RTM. In 2020 there were 207 hours of negative pricing on the RTM.

In light of this, the desalination plant and the hydrogen plant could plausibly “buy” electricity for their operation, which, at times of negative pricing, would amount to being paid to operate those plants. This would augment the revenue streams for desalinated water ($220/MWh) and hydrogen ($79/MWh), and for that reason may present an interesting operational and fiscal strategy. Moreover, it might provide an additional (compensable) grid stabilization service by buying electricity during periods of excess production at other generators that, for whatever reason, are unable to curtail their own production.

To use this strategy, Diablo Canyon itself would likely need to ramp down its own production to the extent dictated by the amount of “negative power” on offer. The following revenue analysis uses as a scenario an outlier illustrating the idea that the nuclear plant could be ramped down by the entire electricity capacity attributed to both the desalination plant and the hydrogen plant—in other words, by (353 + 500 =) 853 MWe. Here, the average of the 207 negatively-priced-hours is ($2.98)/MWh. Purchasing all of those hours at the full 853 MWe power level would be worth $525,647.

3. Flexible production considerations

Flexible electric power generation and consumption is a valuable capability that is familiar to grid participants. A Diablo Canyon nuclear plant integrated with electricity consuming facilities such as those proposed would offer considerable flexibility of significant value to the state of California, the California power grid, and the state’s residents. The value of this flexibility is not quantified here, but is discussed at the end of Chapter 1, above.

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[195] One way to connect carbon prices to hydrogen production is drawn from the California Air Resources Board’s Low Carbon Fuel Standard (LCFS). This program seeks to reduce the carbon intensity of California transportation fuels by offering credits for low-carbon fuel production that displaces traditional fossil fuels—such as gasoline, diesel, and jet fuel. Although LCFS does not currently include hydrogen on its list of alternative fuels, the program does assign a dollar value to each megatonne (Mt) of avoided carbon emissions. For 2020, that value averaged just slightly below $200/Mt of CO_2. Applying the LCFS fossil fuel equivalency mapping used by the program, along with hydrogen’s low heating ratio of 120 MJ/kg, would yield an LCFS value of approximately $2/kg of hydrogen production. Nonetheless, because the LCFS program does not address hydrogen as an alternative fuel, this calculation provides only the roughest of benchmarks (though it would fit squarely within the range of values set forth in Table 4-10). For more information about the LCFS program, *see* https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm.

4. Capacity value of Diablo Canyon

Diablo Canyon offers significant systemic value as a firm, carbon-free, stabilizing resource. It may be able to receive additional revenue by entering into capacity contracts, also known as resource adequacy contracts. In California, such resource adequacy arrangements are currently fulfilled by bilateral contracts. Such contracts set out the terms whereby generators commit to energy production readiness if called upon. Such contracts may earn revenue that is additional to the revenues modeled in this chapter. In 2019, the weighted average price for capacity was $3.46/kW-month.[196] For a 2000 MW plant such as Diablo Canyon, this can amount to over $80 Million in annual revenue.

This chapter's analysis does not model possible revenue that may be derived from capacity contracts.

Depending on the portfolio of production agreements, grid regulations, and the capacity contracts themselves, capacity contracts could affect the revenue estimates presented here. Nonetheless, Diablo Canyon may consider whether its production, returns, agreements, and regulatory framework could also accommodate providing capacity services to the grid. If so, while difficult to quantify, capacity services may present a source of additional revenue, particularly in the face of increasing[197] grid participation of variable renewable resources, a market dynamic that tends to increase the value of capacity services.

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[196] California Public Utilities Commission, “2019 Resource Adequacy Report” (Mar. 2021), https://www.cpuc.ca.gov/RA/.

[197] Jenkin, T., Beiter, P. & Margolis, R., “Capacity Payments in Restructured Markets under Low and High Penetration Levels of Renewable Energy” (2016), https://www.nrel.gov/docs/fy16osti/65491.pdf.

Appendix 1:

Potential Diablo Canyon Ownership and Operating Business Models

Although Pacific Gas and Electric Company (PG&E) is the current owner, licensee, and operator of the two Diablo Canyon Nuclear Power Plant (Diablo Canyon) units, this report makes no assumptions as to the identity or status of any future owner or operator of the plant. Rather, the report examines the inherent attributes of the facility to provide electric capacity and energy for grid distribution, water desalination, or electrolysis-based hydrogen production, irrespective of ownership.

PG&E is a signatory to the 2015 agreement not to seek re-licensing and to close the plant. Theoretically, it could seek a new agreement with the signing parties whereby it resumes the relicensing process and seeks to maintain its owner and/or operator status. In the alternative, the Diablo Canyon units could be sold or transferred to, and operated by, another entity.

Although PG&E may seem the logical candidate to own and/or continue operation of the Diablo Canyon nuclear plants, given its historic role and institutional knowledge, it is also true that the company faces other daunting challenges that will command management time and attention. First among these is the need to fortify the existing transmission and distribution grid against catastrophic failures that lead to wildfires; the company has estimated that it will spend approximately $40 billion on system upgrades and hardening over the next five years. This alone is an enormous managerial and financial challenge. PG&E emerged from its recent Chapter 11 filing with some $38 billion in debt and is in the process of rebuilding its leadership team. In addition, the company is dealing with the need to adapt to the new realities of climate change, distributed generation, the integration of renewables, and the future of natural gas, among other significant issues.

Although this report is agnostic with respect to the plant's proprietary status, we note that there are several possible ownership models. These include:

1. Sale of the facility to another utility company, presumably one with extensive nuclear operating experience.
2. Retention of ownership of Diablo Canyon by PG&E, but with operations contracted to another utility or third party.
3. Sale or transfer the facility to an existing or (more likely) newly-created non-profit public authority. That authority would contract for the operation of the plant.
4. Sale or transfer the facility to a joint-powers authority, which is another form of municipal ownership.
5. Pursuant to California law, sale or transfer the facility to an electric cooperative, which is a non-profit, customer-owned enterprise.

Each of these models has advantages and disadvantages. Commercial ownership brings with it likely expertise and potential economies of scale, if the operator has experience with other, similar nuclear capacity.

Public ownership would have several positive aspects, including, among other things, greater public acceptance of the continued operation of the plant, access to tax-exempt financing to lower capital expense costs, and potential tax advantages. Moreover, if the plant is operated as a hybrid “polygen” unit, maximizing financial results by varying power, water, and hydrogen production may or may not be consistent with optimal social and environmental outcomes. Accordingly, either a regulatory overlay on commercial operations or a public ownership chartered to achieve optimum social results may be required.