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Energy and Water without Carbon: Integrated Desalination and Nuclear Power at Diablo Canyon

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Abstract

A seawater reverse osmosis (SWRO) desalination plant collocated with an existing nuclear plant would have low electricity costs, can share the power plant's seawater intake and outfall, and would have zero carbon footprint during operation. Unlike thermal desalination technologies, electrically-driven SWRO is ideal for retrofitting existing power plants because the turbines and condensers would not need expensive modifications. Here, we evaluate the techno-economic feasibility of collocating a large-scale SWRO plant with an existing nuclear power plant, specifically the 2.2 GW_e Diablo Canyon Nuclear Power Plant on California's central coast. The seawater that cools the nuclear plant's condensers provides the feed water for desalination. The desalination brine is diluted with the remaining condenser coolant before discharge to the ocean. A brushed-screen intake structure, serving both the nuclear power plant and the desalination plant, can comply with strict California regulations protecting marine organisms. This coproduction arrangement has a significant cost advantage relative to a stand-alone desalination plant. The levelized cost of water (LCOW) ranges from \$0.77 to \$0.98 per m^3 of fresh water, with water distribution to offtakers adding US\$0.02 to \$0.21 per m^3 over 20–185 km. In comparison, California's largest desalination plant, in Carlsbad, has an LWOC of about US\$1.84 per m^3. These cost savings result from reduced power costs (about US\$0.054 per kWh) and from sharing some expensive infrastructure. Further, nuclear electricity allows a Carlsbad-size SWRO to avoid 47 kt/y of CO_2 emissions relative to grid electricity. Examination of substantially larger desalination plants introduces additional considerations. This study is the first to show that collocated SWRO and nuclear power are strongly coupled and have a significant economic advantage over seawater desalination at other sites. These benefits should apply to dozens of existing nuclear power plants worldwide.

Keywords: desalination, nuclear power, techno-economic analysis, reverse osmosis, low-carbon

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Nomenclature

Acronyms

DCNPP	Diablo Canyon Nuclear Power Plant
EPC	Engineering, Procurement, & Construction
GHG	Greenhouse Gas
ISI	Intake Screens, Incorporated
LCOW	Levelized Cost of Water
NF	Nanofiltration
NRC	Nuclear Regulatory Commission
O&M	Operations and maintenance
PG&E	Pacific Gas & Electric
PPIC	Public Policy Institute of California
RO	Reverse osmosis
SEC	Specific energy consumption
SGMA	Sustainable Groundwater Management Act
SWRO	Seawater reverse osmosis
TDS	Total dissolved solids
WACC	Weighted average cost of capital

Subscripts

e	Electrical energy or power
th	Thermal energy or power

1. Introduction

The rapidly changing global climate is disrupting historical patterns of rainfall and water supply. Severe and lasting water shortages are becoming more common and widespread, so that existing water infrastructure cannot provide stable resources in some regions. Seawater desalination can help bridge this gap. However, to avoid amplifying the climate crisis, carbon emissions associated with seawater desalination must be minimized.

Desalination systems may be powered with a variety of carbon-free energy sources, including established technologies such as wind, solar, and hydropower, as well as with novel carbon-free alternatives [1–4]. Many of these carbon-free power sources face complications from intermittency, small scale, availability, or lack of maturity that make them less attractive for powering essential water infrastructure. Hydropower and nuclear power are the only well-established low-carbon sources that deliver baseload power without the need to store electrical energy. In many parts of the world, hydropower capacity cannot be expanded; and, in addition, hydropower can be driven offline by an extended drought, a time when desalination may be most necessary. Nuclear electricity is uniquely able to provide baseload water and power supplies to regions experiencing water scarcity without causing carbon emissions [5–8]. In addition, for a given water demand, baseload operation of a desalination plant minimizes the size of the plant.

In practice, nuclear desalination has only been applied sparingly and at small scale, most often to produce water for the on-site needs of a nuclear power plant. Most of the nuclear desalination plants in existence today have capacities of less than 10,000 m^3/d. The notable exception was the Shevchenko plant in Aktau, Kazakhstan, which used thermal energy from a 1,000 MW_{th} liquid sodium fast breeder reactor to provide energy for a multi-stage flash desalination plant with a capacity of 80,000–145,000 m^3/d [9]. That plant operated reliably from its opening in 1973 until its closure in 1999.

The combination of nuclear power and desalination has been investigated for many years in the academic literature [10–13], has been a recurring interest of the International Atomic Energy Agency [14–18], and for a time had a dedicated academic journal.[1] The bulk of that research focused on using waste heat from the nuclear plant to drive thermal desalination processes. Indeed, the potential coupling to reverse osmosis has been described as both simple and weak. [10]. In this work, we show for the first time that a strong coupling can exist through shared intake and outfall infrastructure, which, together with the savings on electrical transmission, distribution, and other non-energy tariff charges, results in a dramatic reduction of the cost of water relative to an SWRO plant located elsewhere.

We highlight a very important distinction between using nuclear thermal desalination and nuclear-SWRO. Nuclear thermal desalination requires access to the steam used in the power plant, and as result is not easily suited to a retrofit of an existing nuclear plant given the cost of making changes to large steam turbines and condensers. Coupling to SWRO requires *no* changes to the power cycle. Nuclear-SWRO is very well suited to retrofit of an existing nuclear power plant.

[1] The International Journal of Nuclear Desalination was published from 2003 to 2011.

The documented benefits of co-locating nuclear power and desalination include reduced costs, improved energy and water demand response, and reduced carbon emissions [19–23]. In the case of SWRO, additional benefits may result from the use of condenser cooling water as desalination feedwater, both in terms of seawater intake costs and in terms of improved seawater reverse osmosis (SWRO) membrane performance [24].

We performed a high-level analysis of 179 nuclear power stations around the world [25] and found that approximately 30 of them are seawater cooled and located in water-stressed regions, making these power stations potential candidates to co-locate with desalination plants. If even 10 of these nuclear power stations diverted all their power to collocated desalination plants, the combined freshwater output would approximately equal the current global seawater desalination capacity.

We consider as a case study the existing Diablo Canyon Nuclear Power Plant (DCNPP). DCNPP is a 2.2 GW_e facility located on the central California coast. California exemplifies today's challenges at the water-energy nexus. In recent years, the state has struggled with drought and wildfires, and it has suffered rolling power blackouts during summer months. In summer 2021, the Oroville, CA hydropower reservoir dropped so low that the plant is expected to shut down. California's Water Resources Board has stated that climate change is expected to increase the frequency, severity, and duration of these droughts [26].

For a collocated desalination plant to be viable, we determined that seven broad metrics must be satisfied:

- Regulations — Both the nuclear and desalination plants must be able to be operated safely, within the bounds of regulatory constraints.
- Intake — Sufficient seawater must be transported from the ocean or nuclear power plant to the desalination plant.
- Plant design — The desalination plant must produce water of sufficient quantity and quality for its intended use.
- Location and siting - It must be feasible to construct the desalination plant near the nuclear power plant.
- Outfall — Desalination brine must be disposed of while mitigating environmental concerns.
- Distribution — There must be a customer willing to pay for the water within a reasonable distance.
- Cost — The price of water must be competitive with or cheaper than comparable alternatives.

We assessed these factors for a number of different cases, ultimately showing that all four cases addressed in this study are likely feasible from a technoeconomic standpoint.

Our economic model accounts for reductions in total infrastructure costs through shared water intake and outfall structures, the actual electricity generation costs at DCNPP, the savings on electricity tariff charges, the cost of the SWRO plant, water transmission costs, the cost of meeting environmental regulations, and also project financing costs. Our results show compelling cost savings, largely attributable to the elimination of electrical transmission charges and savings from shared seawater infrastructure. There are also potential benefits to building at very large scale, given the capacity of a large nuclear plant. These advantages are not unique to the case of DCNPP, and similar advantages are likely to exist at hundreds of other sites.

This study is also the first to show that low carbon desalination can be economically viable within the strict environmental protection regulations of California. California regulates ocean intake and discharge associated with both power and desalination facilities. These regulations can strongly affect the cost of desalinated water and of power, and we have addressed them in our techno-economic analysis.

2. Background and constraints

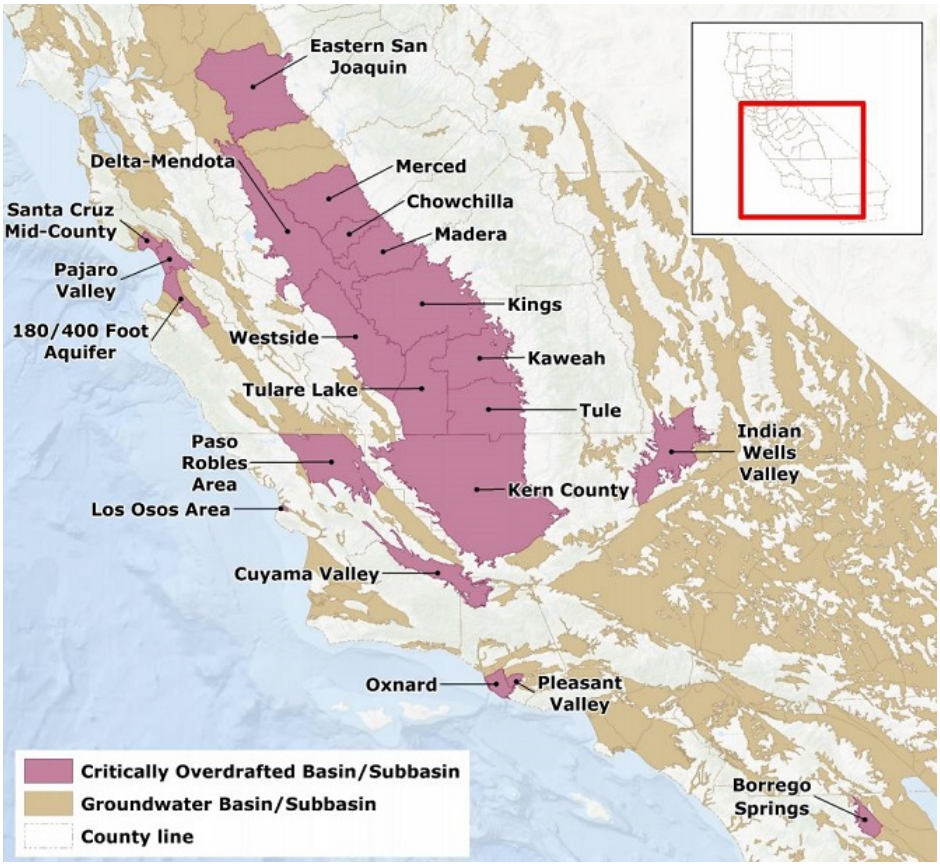

Figure 1: Map from the California Department of Water Resources showing critically overdrafted groundwater basins in California. A basin or subbasin is considered critically overdrafted when negative environmental, social, or economic impacts would result if current water management practices are continued [27].

2.1. The need for drought-proof and sustainable water supplies

California has a pressing need for additional sustainable fresh water supplies. As a result of increased demand for water and changes in freshwater supply, exacerbated by climate change, unsustainable groundwater pumping has become common [28, 29]. In many groundwater basins, increased pumping is leading to rapidly deteriorating groundwater supplies, reduced groundwater quality, and subsidence. In response, California enacted the Sustainable Groundwater Management Act (SGMA) in 2014 [30]. This legislation requires critically over-drafted groundwater basins to achieve sustainability by 2040.

To illustrate the severity of the problem in California, we consider the San Joaquin Valley, one of the most productive agricultural regions in the world, which relies heavily on groundwater overdraft to support its economic enterprise. The average annual overdraft in the San Joaquin Valley is estimated to be 1,800,000 acre-feet (6,000,000 m^3/d). The Public Policy Institute of California (PPIC) estimates that only 25% of the region's long-term imbalance can be addressed by development of new conventional water supplies and/or efficiencies [31]. The PPIC further estimates that reducing the deficit by reduced pumping alone would require fallowing nearly 750,000 acres (3,000 km^2) of currently productive farmland. In addition to the development of new local supplies, an additional 1,350,000 acre-feet per year (4,560,000 m^3/d) would be required to avoid fallowing altogether.

A number of technologies and approaches will be needed to address California's water challenges. Aside from desalination, other methods of increasing water supply or reducing demand should be investigated, including direct or indirect potable reuse, rainwater capture, water transfers, efficiency initiatives, and promotion of less water-intensive crops. Desalination, though, is unique in its ability to reliably produce water regardless of shifting weather and climate conditions. A desalination plant located at Diablo Canyon would be a drought-proof source of water that could help the regions surrounding Diablo Canyon to reach their water sustainability goals.

2.2. The Diablo Canyon Power Plant

The Diablo Canyon Nuclear Power Plant comprises two identical units (Westinghouse 4-loop pressurized water reactor design) with a combined power output of 2240 MW_e. DCNPP is located near Avila Beach on the Central Coast of California, and is owned and operated by Pacific Gas and Electric (PG&E). DCNPP 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 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 DCNPP is approximately 90%. The DCNPP generation cost is about US$40 per MWh_e (including fuel, O&M, and capital costs) [32], thus we estimate that the plant is an economically viable electricity generator in the California market at the present time. DCNPP currently supplies 7.9% of California's electricity and 15% of California's carbon-free electricity.

In November 2009, PG&E applied to the NRC for a 20-year license extension of DCNPP beyond its initial expiration date of 2024-2025. Nearly all nuclear power plants in the US have obtained a 20-year license renewal from the NRC. The review was prolonged by post-Fukushima regulatory changes and by specific concerns about the seismic risk of DCNPP, both of which were resolved. The plant is sited in a generally high-seismic-risk area, and a fault line that runs near the plant. Of course, DCNPP was designed and licensed for this particular site. After the Fukushima accident in 2011, all nuclear power plants in the U.S., including DCNPP, were asked to re-evaluate their seismic and flooding risks. NRC's evaluation of DCNPP's seismic risk is summarized in a recent NRC letter [33]. After a 9-year long review using the latest geophysical methodologies and data, the NRC conclusively determined that DCNPP is a seismically safe facility. Continued operation will not require costly seismic upgrades. The license renewal process was ultimately interrupted by the 2016 decision to close the plant. PG&E formally withdrew the application in March 2018. The impending shutdown of Diablo Canyon is driven mainly by policies regarding once-through cooling for power plants.

2.3. Regulatory and Environmental Constraints

Regulatory and environmental constraints will present numerous challenges to building a desalination plant near DCNPP. The policy nominally driving the closure of DCNPP is the California Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling [34]. This policy is designed to reduce marine organism mortality due to flows through power plants that use once-through cooling. Similar regulations are in place to regulate desalination plants, and are further discussed in Section 4.1. In order to comply with the regulations, 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 of marine organisms to a comparable level. The policy provides alternative measures for nuclear power plants to fulfill the requirements, which are evaluated on a case-by-case basis. In 2011, PG&E commissioned a study by Bechtel to investigate options that would bring DCNPP into compliance with this policy [35]. 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. PG&E chose not to move forward with any of the options examined at the time.

Discharge from a collocated nuclear and desalination plant would also be highly regulated. The California Ocean Plan specifies that brine discharge not exceed two salinity units (parts per thousand) above ambient levels outside of a brine mixing zone that extends 100 meters from the brine discharge point [36]. Approaches for complying with this regulation are further discussed in Section 4.2.

Making the development of a nuclear power and desalination co-production system more challenging is the marine environment near DCNPP. Normal wave activity ranges from 5 to 10 feet (1.5–3 m), with storms generating waves of up to 30 feet (9 m) [35]. Winds are commonly 10 to 25 miles per hour (16–40 kph) and can reach 40 to 50 miles per hour (64–80 kph). Kelp in the area can grow at a rate of 2 feet (0.6 m) per day during peak growing season, and is regularly mowed by DCNPP to prevent problems with the current intake system. The Diablo Canyon site is known to have annual acidification events as a result of domoic acid [37]. When severe, the seawater pH drops 1 unit and microscopic algae multiply. Harmful algal bloom events also occur at other locations along the California coast and are increasing in frequency, intensity and duration, potentially causing operational challenges for desalination plants. Another seasonal environmental threat is created by jellyfish. Jellyfish can clog intakes and cause entire plant shutdowns, as happened at DCNPP in 2008 [38] and 2012 [39]. It is unclear how advanced intake designs will be affected by the problems of harmful algal blooms and jellyfish.

The coastline from Point Buchon to Point San Luis (approximately 2 miles (3 km) to the north and 5 miles (8 km) to the south of DCNPP) is one of the most pristine coastlines in all of California. The coastline is home to at least 20 threatened or endangered species [40, 41]. Owing to the presence of the nuclear power plant, much of the coastline near Diablo Canyon has remained inaccessible to the public. In Diablo Canyon Decommissioning Engagement Panel meetings [42], environmentalists have shown concern about opening this coastline to the public after the impending decommissioning of DCNPP. As areas of the California coast that were once inaccessible become open to the public, sensitive species have been trampled by visitors and endangered black abalone have been poached at an alarming rate. If a desalination plant is built in the area, careful planning must be done to ensure that damage to this pristine environment is mitigated during construction, operation, and eventual decommissioning of the plant. With careful management, the continued operation of DCNPP 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.

In addition to environmental and regulatory constraints, the political landscape in California regarding both desalination and nuclear power is contentious. The people of California must decide for themselves whether to invest in desalination or other measures to combat the water crisis, and whether nuclear power should be a part of California's future energy portfolio. Our focus of this work, instead, is on the technoeconomic feasibility of a large desalination plant at Diablo Canyon, framed as the following question: *If DCNPP is re-licensed and if Californians determine that large-scale desalination plants are part of their long-term water security strategy, then will a large-scale desalination plant at Diablo Canyon have economic advantages over other seawater desalination schemes?*

3. Desalination plant configurations

Seawater desalination at DCNPP might use any of a variety of technologies, but we will consider only reverse osmosis (RO). RO is generally the least expensive and most energy-efficient desalination technology [43]. Although the large amount of heat rejected by a nuclear plant is a potential resource for thermal desalination (e.g., via multi-effect distillation), effective utilization of this heat would require modification of the plant's steam cycle. Further, reverse osmosis would consume less additional nuclear fuel than thermal desalination [44]. We consider desalination configurations that use seawater from the once-through cooling system as the feedwater. The seawater is first used as a coolant on the tube-side of the condenser, where its temperature rises by 10°C above the intake seawater temperature. Then, a portion of the seawater is sent to the desalination plant, with the rest discharged. Various RO arrangements can be chosen to meet different water or electricity needs, to respond to temporal changes in power or water demand, or to achieve compliance with applicable environmental regulations. Four options are investigated in this report. 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. Key values are given in Table 1. Based on our simulations of RO plant conditions and energy consumption in Section 4.3, we estimate a specific energy consumption of 3.5 kWh_e/m^3 (energy consumed per volume of purified product water), and a recovery ratio of 50% (fraction of salty feedwater turned into pure product water).

Table 1: Key parameters for desalination plants at a variety of scales.

	Current Conditions	*Option 1*	*Option 2*	*Option 3*	*Option 4*	*Units*
Fresh water production capacity	N/A	189,270	520,000	4,752,000	15,379,200	m^3/d
Intake flow rate	9,504,000	9,504,000	9,504,000	9,504,000	30,758,400	m^3/d
Outfall flow rate	9,504,000	9,314,730	8,984,000	4,752,000	15,379,200	m^3/d
Outfall temperature	Ocean+10°C	Ocean+10°C	Ocean+10°C	Ocean+10°C	Ocean+3°C	°C
Outfall salinity	35,000	35,700	37,000	70,000	70,000	ppm
Electricity to grid	2,240	2,212	2,164	1,547	0	MW

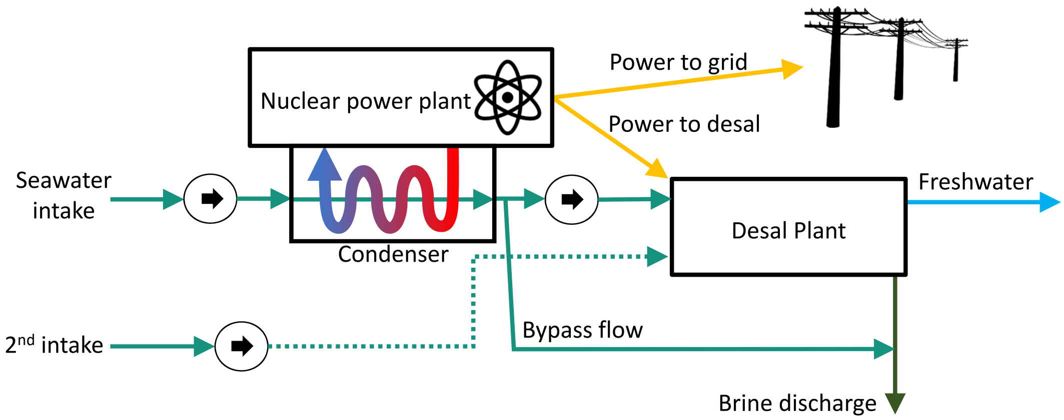

Figure 2: Diagram of a generalized cogeneration-desalination system co-located with a nuclear power plant. Options 1 and 2 have a bypass flow stream and do not have a second intake. Option 3 has no bypass flow or second intake. Option 4 has no bypass flow, but does have a second intake.

3.1. Large-scale desalination 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 size is also the nameplate capacity of the Carlsbad CA Desalination Plant and is approximately the same size as the proposed plant at Huntington Beach, CA. In this configuration, the 28 MW_e requirement of this desalination plant is very small compared to the 2240 MW_e output of the nuclear power plant. While this option does not enjoy some of the economies of scale of even larger plants, there are some distinct benefits of operating a plant this size. Because the volume of brine is small relative to the volume of the discharged power plant cooling water, the combined discharge stream's salinity is not increased significantly, allowing for the existing outfall structure to be used, reducing capital costs. Additionally, a plant of this size will be easier to site, design, permit, and build than a much larger plant.

The second option we consider is a plant that maximizes capacity while continuing to use the existing outfall structure. By performing a simple salt mass balance on the existing power plant cooling water, and assuming all salt is rejected by the RO membranes, we find that any desalination plant producing less than approximately 520,000 m^3/d would not raise the salinity of the discharge by more than two parts per thousand at the discharge location if the brine is well mixed with the existing outfall water. It is likely that an even larger plant could be built using the existing outfall, as some additional dilution of the brine will occur inside the 100 meter brine mixing zone specified by the California Ocean Plan. The dynamics of salt dispersion and dilution, however, are specific to the local environment and outside the scope of this analysis. Therefore, we conservatively choose to consider a plant with a capacity of 520,000 m^3/d to represent the largest possible plant that could be operated without requiring a new outfall to comply with Ocean Plan regulations.

3.2. *Mega-scale desalination plants*

The existing flow of condenser cooling water and the electricity production at DCNPP could be used to support a much larger desalination plant than the options presented in the previous section. Such "mega-sized" plants could be an order of magnitude larger than today's largest desalination plants. Building such large plants poses a significant challenge. Construction would certainly have to be done in stages to accommodate practical limitations (e.g., supply chain limitations, construction timelines). We consider two mega-scale options to provide an understanding of the wide range of possibilities.

In our third 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 still less than the power produced by the power plant, meaning that power can continue to be sold to the grid. We note that Options 1–3 would all require the same-sized ocean intake, in order to provide enough condenser cooling water to DCNPP. Option 3 maximizes the capacity of the desalination plant without increasing the size of the intake infrastructure beyond what would be required to re-license DCNPP.

In the fourth configuration, DCNPP 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. Option 4 is similar in capacity to the maximum capacity of the proposed Sacramento River Delta water diversion project [45].

4. Plant design

Having determined the range of scales possible at DCNPP, we now consider what a desalination plant would look like under the different scenarios proposed in Section 3. We include a basic analysis of the technologies used, from intake to outfall to distribution, and discuss plant siting and construction considerations.

4.1. Intake

As discussed in Section 2.3, regulations regarding seawater intakes are one of the primary technical reasons that DCNPP is slated to be closed, and regulations also pose a challenge for permitting new desalination plants in California. A new shared seawater intake would also have to comply with regulations for desalination plants, which are laid out in the California Ocean Plan [36]. There are two approaches to constructing intakes that comply with these regulations.

The first approach is to build a submerged intake gallery. Submerged intake galleries 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. While they provide better protection for wildlife after their construction, submerged intake galleries would likely be impractical for a large nuclear power plant [10]. Assuming a design loading rate for the flow of seawater through the ocean floor's surface of 0.05 L/s-m^2 (0.075 gpm/ft^2) [46], an infiltration gallery large enough to supply DCNPP's current cooling water load would require over 2 km^2 (500 acres) of seafloor to be excavated during construction. For reference, the footprint of the current intake lagoon at Diablo Canyon is less than 8 hectares (20 acres).

The second approach is to construct screened intakes. California Ocean Plan 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 ft/s (15 cm/s). 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 to build than submerged intake galleries, and their successful operation is less dependent on the local site conditions, such as the ocean floor composition and bathymetry of the area. For the purpose of this analysis, Intake Screens, Inc. (ISI) of Sacramento provided initial estimates regarding mechanical brush-cleaned wedgewire screens, which serve as an example of a cost-competitive option [32]. Similar brushed screen intake systems have been specified for the proposed Huntington Beach desalination plant, and are being tested at the Carlsbad plant [47].

The brushed screen intake design includes a submersible electric-drive assembly that rotates wedgewire screen cylinders between nylon brushes. Multiple rotational cleanings a day help to reduce blockages, prevent fouling, and to keep through-screen velocities low, thereby reducing the potential for aquatic organism impingement and entrainment. A series of vertically-oriented drum screens would be located at least 300 meters from shore in relatively deep water (>15 m) to avoid the more sensitive nearshore marine habitats and potential higher aquatic organism densities located in the nearshore area.

Following the approach used in the Bechtel report [35], one possible design would require the existing shoreline basin to 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 tunnel, as shown in Figure 3. This arrangement would allow the power plant to continue operating throughout the construction of the new intake, as the existing power plant intake pumps and structure are unchanged. Additional information regarding the proposed intake systems can be found in our extented report on this topic [32]. An alternative approach could include constructing a smaller basin within the existing structure, allowing the existing lagoon remain open to shipping traffic. A detailed design study should investigate all options presented here, as well as alternatives such as Johnson screens with different cleaning mechanisms, or conversion of the existing intake lagoon structure into a porous dike. For all intake designs, considering the seismic and environmental concerns will be of special importance.

Figure 3: Aerial view of existing DCNPP intake lagoon with superimposed lines showing one possible approach to building a new intake structure. Dotted lines represent an additional impermeable basin with a tunnel extending offshore, connected to a wedgewire screen array for Options 1–3. Option 4 requires two additional tunnel and screen arrays. The new basin would have an emergency water inlet to ensure water flow to the reactors in case of blockages, damage, etc.

Bechtel estimated the cost of the undersea pipeline from the intake lagoon, intake screens, and the structure to seal the intake lagoon at approximately US$400 million [35]. ISI estimated the cost of rotating intake screens for Options 1–3 at US$70–100 million [32]. Therefore, we conservatively estimate the cost of the overall intake at US$500 million. We assume that, for Options 1–3, the cost of the intake is borne by the nuclear power plant and reflected in the price of electricity, as the same large intake is required by 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.

4.2. Outfall

The discharge of brine from the desalination plant presents another challenge. While the preferred method of discharge from desalination plants is to commingle brine with another freshwater source being discharged (such as wastewater effluent), there are no large freshwater discharge sources near DCNPP. The current power plant outfall consists of surface discharge to Diablo Cove, where the warm water spreads across the ocean's surface, dissipating heat into the atmosphere and surrounding ocean [48]. While the effects of discharging warm water have been a concern in the past, and have been investigated over DCNPP's lifetime, the current outfall infrastructure meets regulations and is not preventing DCNPP's continued operation.

The salinity limits for discharge contained in the California Ocean Plan, discussed previously in Section 2.3, would not allow brine to be discharged exclusively through the existing outfall when the desalination plant capacity is substantially over 520,000 m^3/d.

For larger plants, open ocean discharge using the existing infrastructure may not be possible. In this case, 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. They have been shown to have minimal impacts on local fish populations [49], and have been employed with success at other plants in sensitive ecological environments such as the Sydney Desalination Plant in Sydney, Australia [50].

The cost of a diffuser outfall is more difficult to estimate than the intake, although there are existing projects that can guide our estimate. As discussed earlier, the Sydney Desalination Plant uses a diffuser-style outfall to mix undiluted brine with seawater. The outfall system at that plant is estimated to have cost 20-30% of the total capital expenditure of the 250,000 m^3/d plant [51]. At a larger scale, we can consider the Deer Island Wastewater Treatment Plant in Boston, Massachusetts. This plant is connected to the largest outfall tunnel in the world, with an outfall capacity of 4,921,000 m^3/d, nearly the same volume flow rate that would be required by Option 3. That outfall tunnels downward 420 feet (128 m) below Deer Island, then through a 24-foot (7.3 m) diameter tunnel, 9.5 miles (15.2 km) out into Massachusetts Bay, where 50 risers bring wastewater to diffusers. This outfall cost US$390 million in the year 2000 [52]. Finally, we can also consider the costs that have been estimated to implement a high energy diffuser system at the Carlsbad desalination plant ($US128 million in direct costs) [53]. Ultimately, we chose to model the outfall cost based on the Carlsbad plant, scaling the cost with outfall size. Actual costs will require a detailed design analysis.

4.3. Reverse osmosis system

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. Designs for the plant can be informed by the existing small-scale desalination plant that currently serves DCNPP's needs for drinking water, fire and dust suppression, and power plant makeup water. The only major change in feedwater conditions will be the feedwater temperature. The existing plant has been operating for over 28 years, and produces 2,450 m^3/d of fresh water.

The existing plant has a pretreatment design consisting of dual media filters, multimedia filters, UV and cartridge filters. Ferric salts and polymer coagulants are added before the filters, and antiscalants are added before the RO train [54]. The original membranes lasted 13 years and never required clean-in-place due to both the pretreatment design and the operations [55]. Given the operational success of the existing plant, any new desalination plant sited at Diablo should use the existing pretreatment regimen as a starting point.

Specifics of the plant design will depend on a number of factors, including the water quality requirements of the offtaker. One option is presented here. Using LG Chem's Q+ Projection Software, we investigated different desalination plant layouts that would treat incoming feedwater from the power plant to the standards required for potable drinking water. Typical feedwater conditions are given in Table 2. We found that using a system with the pretreatment approach described above, followed by a partial two-pass RO system similar to the one used at Carlsbad would produce water of sufficient quality for municipal and agricultural use. The permeate produced during the first pass has a total dissolved solids 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).[2] To remedy this, a partial second pass is utilized, in which half of the permeate undergoes a pH adjustment and a second pass through brackish water reverse osmosis elements. The pH is adjusted from 8 to 10 to increase boron rejection [56]. At this higher pH level, uncharged boric acid (78-80% removal) disassociates to borate ions (>95% removal). The permeate from the second pass is blended together with the permeate from the first pass.

The final product stream undergoes remineralization and disinfection before leaving the plant. The remineralization process achieves a stable and safe water chemistry by adding directly or dissolving chemicals (lime, calcite, dolomite) which contain calcium or magnesium. Without this step, desalinated water is low in minerals, alkalinity, and pH, and the water tends to corrode and degrade pipes and leach metals such as copper and lead into the water [57]. The energy consumption of the RO portion of the plant is estimated to range from 2.6-3.0 kWh/m^3 depending on ocean conditions. When factoring in energy required in the other portions of the plant (intake, pretreatment, posttreatment, etc.) [58, 59], we estimate the average annual energy consumption of the entire plant, excluding distribution, to be 3.5 kWh/m^3.

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. One is the location of the plant near a source of nuclear power. Due to the nuclear plant's redundant physical separation between all radioactive sources (i.e., reactor core, dry cask storage area, etc.) and the desalination plant, the risks for radioactive contamination of the desalinated water is practically

[2] Boron is present in relatively low quantities in seawater (approximately 4.5 mg/L), and is rejected by modern membranes at 80-90% (compared to 99.7% for NaCl). Some very sensitive plants, such as avocados, may be damaged by leaf burn at boron concentrations as low as 0.5 mg/L. Thus, for agricultural use, an SWRO system may need to be designed with a full or partial second pass to produce product water that is fit for agricultural use or, generally, for irrigation of sensitive crops by water taken from a municipal water supply. We expect that new desalination projects in California will have to meet these strict boron requirements.

Table 2: Properties of Pacific Ocean seawater [60].

	Value	*Units*
Total dissolved solids	36,000	mg/L
Temperature	10–18	°C
pH	8	pH
Turbidity	5 (<25 during storms)	NTU
Total suspended solids	3.6	mg/L
Total organic carbon	3	mg/L
Dissolved organic carbon	1.3	mg/L
Chloride	19,000	mg/L
Bromine	70	mg/L
Boron	4.5	mg/L

non-existent. We do not expect significant modifications will be need to be made to plant operations or design due to the proximity to a nuclear reactor.

Another difference is the feedwater temperature. The background seawater temperature ranges from approximately 10-18°C, but will be warmed by 10°C before entering the desalination plant. Seawater that has been warmed by the power plant condensers has several effects on membrane operation: the water and salt permeability of the membranes increase, and the fouling and scaling propensity also increase. Increased water permeability will allow the plant to operate with either a smaller footprint and higher water fluxes, or with the same footprint and reduced energy consumption when compared to 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, so that a higher percentage of water must undergo a second pass or require additional treatment. In our simulations, raising the feed temperature from 15°C to 25°C reduces the first stage feed pressure from 63 to 59 bar while maintaining membrane area, but increases the permeate TDS from 69 to 154 mg/L, prompting the increased flow through the second pass. Certain salts form hard mineral scales more rapidly at higher temperatures, also hurting plant performance. Membrane fouling may occur more rapidly at high temperatures as well [61]. 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 of commercial desalination membranes. In fact, desalination plants on the Arabian Gulf commonly operate with feedwater temperatures over 30°C.

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 desalination options 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 DCNPP. [3]

4.4. Water transmission

After fresh water is produced, it must be conveyed to the point of eventual use. To estimate the cost of transmission per unit water, we first consider two baseline scenarios. In the first scenario, a shallow buried pipeline conveys product water from Diablo Canyon to California's Central Valley. This pipeline would be about 100 km long, with a net elevation gain of 100 m. In the second scenario, a shallow buried pipeline conveys product water from Diablo Canyon to the Coastal Branch of the California Aqueduct in San Luis Obispo, from which it is delivered to Lake Cachuma, just north of Santa Barbara. This pipeline would be about 30 km long, with a more modest elevation gain of 10 m. The total costs of such pipelines are assumed to scale linearly with flow rate, as a lower flow rate requires a proportionally lower pumping power, fewer pipes and fewer pumps. Therefore, we present the calculations only for one (high) flow rate, i.e. 4,752,000 m^3/d (Option 3). For such pipelines, we consider three very large parallel pipes, each with an internal diameter of 3.5 m. Such pipes are commercially available in various materials suitable for water distribution, such as extruded HDPE and glass reinforced polyester resin. An isentropic pump efficiency of 85% is assumed. The pumping power, pumping cost, and 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 electricity cost is assumed to be US$96 per MWh_e for the first scenario, and US$54 per MWh_e for the second scenario [4]. The estimated costs of pipelines and pumps are based on quotes from vendors [32], and include manufacturing, transportation, and installation. The energy requirements are roughly consistent (on a per unit length and capacity basis) with other large water distribution pipelines documented by Plappally and Lienhard [64].

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 3. Distances to additional locations can be estimated from Figure 4. The total distribution cost can be added to the levelized cost of water at the desalination plant outlet, which is calculated in Table 4, to produce the estimated cost of water delivered to the offtaker. Distribution costs can vary significantly from these projections depending on the route taken, precise elevation changes, and other factors.

4.5. Siting and construction

For a large-scale plant such as Options 1 and 2, the construction approach 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

[3] Collocation of a desalination plant with a nuclear power plant is a version of distributed generation. An overview of the history of distributed generation in the U.S., of the diverse system benefits, including cost savings, and utility tariff design is provided in [62]. Stand-by tariff design determines the extent to which the collocated desalination captures benefits: [63] provides an analysis of an optimal design.

[4] 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 rate, so the price reported here for Scenario 1 is an average price for two pumping stations, one of which is located at DCNPP.

Table 3: Estimate of costs to transport water to a variety of potential offtakers.

Distance/Net elevation gain	End point (from DCNPP)	Pressure drop [bar]	Equipment cost [US$/m^3]	Pumping cost [US$/m^3]	Total distribution cost [US$/m^3]
20 km/ 0 m *	Pismo Beach, San Luis Obispo	1.8	0.019	0.003	0.022
30 km/ 10 m *	State Water Project connection	3.7	0.028	0.006	0.034
33 km/ 120 m *	Lopez Lake	14.7	0.03	0.026	0.056
50 km/ 200 m **	Paso Robles	24.1	0.044	0.076	0.12
55 km/150 m **	Twitchell Reservoir, Lake Nacimiento	19.6	0.049	0.062	0.111
100 km **	Central Valley	18.8	0.086	0.059	0.145
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

the project. For example, a plant of this size could cause issues with supply chain capacities due to the demand for supplies and equipment, especially the RO membranes [65]. It is likely that projects as large as Options 3–4 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 easier and cheaper for later stages of the project.

Questions around supplier capacities, the ability to move 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 was used at Cape Preston, north of Perth in Western Australia's Pilbara region. In that case, a 140,000 m^3/d plant was pre-fabricated offsite in sections, and assembled on-site, which reduced both costs and construction time [66].

Another challenge with building large desalination plants is finding a proper site for the construction. Finding a large plot of land near DCNPP that can be developed will face both challenging terrain and regulatory hurdles.

To estimate the required plant 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. Using either published literature [67] or a combination of published data and satellite imaging tools, the density of a number of desalination plants was

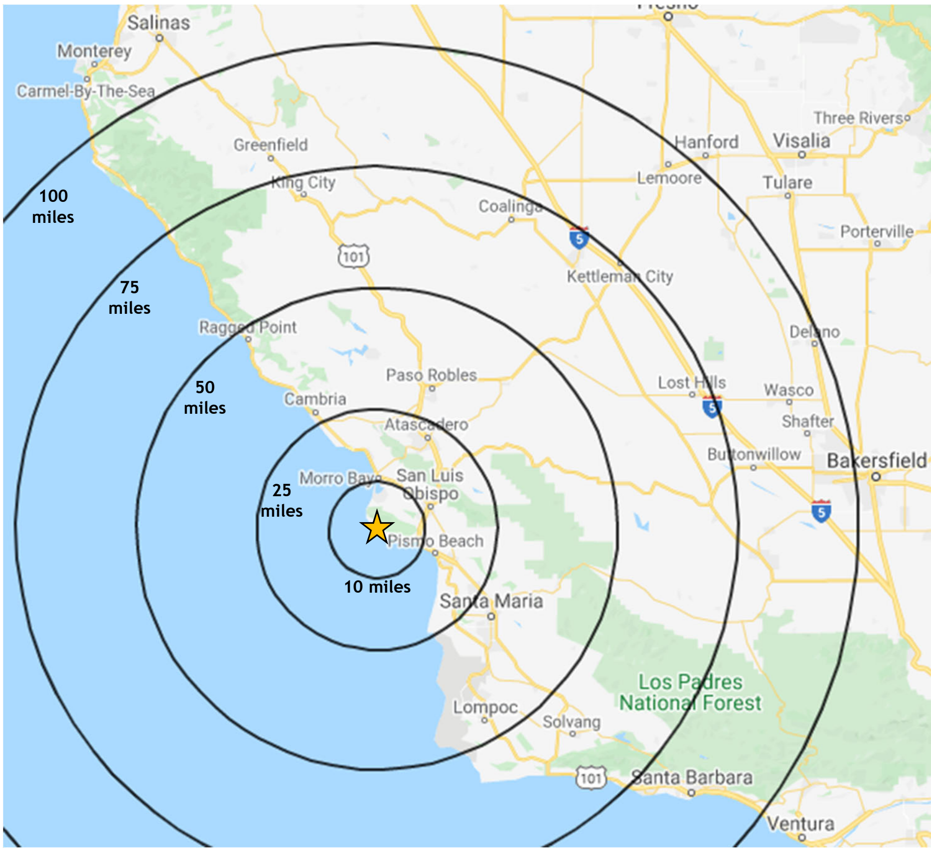

Figure 4: Map showing distances from the Diablo Canyon Nuclear Power Plant to other locations in central California. Distance, as well as elevation change, are major factors in the cost of water transmission.

evaluated. We found that Carlsbad has a very high density, containing a 189,270 m^3/d plant within a footprint of about 5.5 acres (2.2 ha), for a density of approximately 35,000 m^3/d/acre.

Because the proposed desalination plant could share certain facilities with DCNPP (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 increased capacity), we believe it is reasonable that a Diablo Canyon mega-plant could reach a density of 40,000 m^3/d/acre using off-the-shelf technologies and construction methods, while smaller plants could achieve the same density as Carlsbad. Innovations such as multi-story plants, large-diameter membranes, and compact, advanced pretreatment technologies could help to increase the density even further. We estimate that the land requirement would be approximately 5.5 acres, 13 acres, 120 acres, and 385 acres for options 1–4, respectively (2.2, 5.2, 49, and 156 ha).

In terms of locating the plant, the area inland of DCNPP is mountainous and would not be an economical site on which to build a desalination plant. However, along the coast and still near DCNPP are several 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 DCNPP. At the scale of Options 1 and 2, the land required for a desalination plant could likely be found on or very near the existing power plant area, without having to substantially increase the footprint of the combined plant. For larger options, Crowbar Canyon, just to the northwest of DCNPP, may have a usable land area of approximately 100–400 acres. A number of alternative locations up and down the Diablo Coast may be able to support a desalination plant, although the preference would be to limit expansion into new areas for environmental protection purposes. Detailed site analysis is outside the scope of this paper.

If a site is found that would be economically, technically, and environmentally viable, additional regulatory hurdles must be cleared. A desalination plant would likely be located in the coastal zone, which requires additional permits from the California Coastal Commission. PG&E currently owns much of the land near DCNPP, but if they were to sell land to another entity in order to build a desalination plant, California regulations give first rights of refusal to Native American tribes [68]. The area surrounding DCNPP may also contain Native American cultural sites or burial grounds [69], which must be respected when siting a desalination plant.

To summarize, siting a very large desalination plant (Option 3 or 4) near DCNPP will be very challenging. The area is ecologically pristine and should be preserved. The mountainous terrain will pose significant challenges, as will political, regulatory, and land-rights considerations. These challenges may render a mega-scale desalination project at DCNPP infeasible. In contrast, a more modest plant, on the order of Carlsbad scale (Option 1) and up to several times larger, could likely be contained within the already industrialized zone, making this a much more viable option.

5. Technoeconomic analysis

One of the main factors determining whether or not a desalination plant is feasible is the levelized cost of water. There are large uncertainties in estimating the cost of water from a desalination plant an order of magnitude larger than any plant in existence. Still, we believe valuable insights may be drawn from estimating these costs. We begin by using cost estimation tools from DesalData [67], a product of Global Water Intelligence, that applies 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, adding in our own analysis and research to produce a levelized cost of water (LCOW). To simplify the process of estimating the LCOW, overall cost can be broken into capital costs, operating costs, and financing costs. Additional detail on the cost models and process used in this analysis, as well as more detailed cost breakdowns, can be found in other reports by the authors [32, 70].

5.1. Capital costs

Direct capital costs for most equipment, such as the costs of pumps, membranes, pipes, etc. are extrapolated from the DesalData cost estimator, while the intake and outfall costs are estimated using other approaches described previously. We assume that there are economies of scale for direct capital costs for small scale plants. For freshwater capacities ranging from 0 - 400,000 m^3/d, capital costs follow power law equations of the form

$$\text{capital cost} = a \cdot \text{capacity}^k \tag{1}$$

k ranges from approximately 0.71 to 0.94 throughout the reverse osmosis literature [67, 71, 74], and in our analysis, we use $k = 0.84$. At capacities larger than 400,000 m^3/d, all direct capital costs are assumed to scale linearly with size. This is because economies of scale for direct capital 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. We assume that building beyond this scale will essentially lead to multiple identical parallel plants with some shared facilities, such as intake and outfall [71]. As was mentioned previously, the per-m^3 cost differences at Diablo Canyon and elsewhere in California are assumed to be relatively small when considering the actual water treatment portions of the plan (i.e., pretreatment, RO, post-treatment and remineralization). The most significant cost differences are a result of intake and outfall costs, as discussed in Sections 4.1 and 4.2.

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. The economies of scale for indirect capital costs are one of the primary benefits of building at large scales. These costs were estimated using the authors' engineering judgment. We assume that civil costs and installation costs will scale directly with system capacity, although in reality there will be some per-unit cost reductions at large scale. This conscious overestimate of these costs serves to keep our estimates conservative.

In addition to these engineering, procurement, and construction (EPC) costs, there will be expenditures on additional 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 (i.e., 36% of the total capital cost).

5.2. Operating costs

Direct operating costs (e.g. replacement parts, chemicals, electricity), are assumed to scale linearly with plant size and are straightforward to estimate using the DesalData cost estimator. Indirect costs, such as overhead and labor costs, do not scale linearly with plant capacity. Due to the inherently energy intensive nature of desalination, however, the bulk of the operating costs come from the cost of electricity. Thus, operating a desalination plant at Diablo Canyon, where the cost of power is low relative to alternatives, provides a major cost advantage.

Examining the historical cost of electricity from DCNPP for the five years 2016–2020 produces an average total cost of US$0.040/kWh [32]. 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, at an estimated cost of US$500 million, as well as costs to relicense the plant. 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 US$0.002/kWh to the cost of electricity, bringing the total cost of electricity from the Diablo Canyon Power Plant to $0.042. Our assumption is that the desalination plant can source most, but not all of its electricity needs directly from DCNPP 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 the Diablo Canyon Power Plant 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 US$0.160/kWh. Therefore, the blended cost of electricity to the desalination plant is US$0.054/kWh. This amount is only 40% of the US$0.139/kWh average cost of electricity to California's industrial sector throughout 2019, and the difference represents a significant savings on the cost of electricity to the desalination plant.

5.3. Financing costs

Financing terms can have a significant impact on the cost of water. We estimate that the cost of financing amounted to about one third of the total cost of water at Carlsbad, which is currently sold for approximately $\$2.15/m^3$, while Sorek 2, a new plant being built in Israel with a total water cost of $\$0.41/m^3$, is expected to have financing costs that are less than 20% of the total water price [67, 72]. The way that water purchase agreements are structured, and the amount of risk perceived by investors, can 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). The way that the project is structured from an ownership and operational perspective may also have a substantial impact on how the project would be realized as well. In this analysis, we have assumed that PG&E owns and operates the power and desalination plants.

5.4. Levelized cost of water

The above information was used to produce preliminary levelized cost of water (LCOW) estimates, which are shown in Table 4. The resulting LCOW can be added to the estimated distribution cost to determine the estimated total cost of water delivered to the offtaker.

We note that these costs, and the resulting levelized cost of water, are a first-order estimate, and significant deviations are possible. Using cost trends from plants smaller than 250,000 m^3/d 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 accurate cost estimate. However, the purpose of this report is not to produce water costs accurate to within a few cents per m^3, but to determine whether a desalination project at Diablo Canyon is technically and economically feasible. Some line items could have deviations from our estimated costs that would significantly affect the total cost of water, or even the final determination of feasibility, as detailed design studies are performed. Some of these factors are discussed in the following section.

Table 4 also shows the estimated annual reduction in greenhouse gas (GHG) emissions, in CO_2 equivalents. These savings were calculated using a capacity factor of 90% and data from the California Greenhouse Gas Emissions

Table 4: Estimated levelized cost of water breakdown (not including distribution).

	Option 1	Option 2	Option 3	Option 4	Carlsbad Equivalent
Nameplate capacity [m^3/d]	189,270	520,000	4,752,000	15,379,000	189,270
Discount rate [%, real]	4.5				
Amortization period [years]	30				
Utilization rate [%]	80				
Energy consumption [kWh/m^3]	3.5				
Electricity price [$/kWh]	0.054	0.054	0.054	0.054	0.139
SWRO direct EPC cost [Million $]	194	472	4,311	13,949	194
Indirect EPC cost [Million $]	183	447	2,141	6,053	183
Intake and outfall cost [Million $]	0	0	826	2,500	400
Indirect development & financing [Million $]	222	542	4,294	13,277	458
Total capex [Million $]	599	1,460	11,571	35,780	1,235
Non-electric opex [Million $, annual]	13	28	220	702	13
Energy costs [Million $, annual]	13	36	329	1,065	34
Total opex [Million $, annual]	26	64	549	1,767	47
Water price breakdown					
Capex and amortization [US$/$m^3$]	0.53	0.47	0.41	0.39	1.10
Opex and overhead [US$/$m^3$]	0.25	0.21	0.19	0.18	0.25
Energy [US$/$m^3$]	0.19	0.19	0.19	0.19	0.49
Water price [$/$m^3$]	0.98	0.87	0.79	0.77	1.84
Water price [US$/AF]	1,207	1,069	978	952	2,269
GHG reduction, CO_2 equivalents [kt/y]	48	132	1202	3890	N/A

Inventory [73]. The value represents the annual carbon emission for each plant if it were powered by the California electrical grid, using the grid-average emission for 2018, 220 gCO_2/kWh.

5.5. Additional considerations

Figure 5 shows the sensitivity of the levelized cost of water calculated with respect to the Option 2 case for a number of changes from the base case assumption. This analysis shows that the largest increases in water cost would

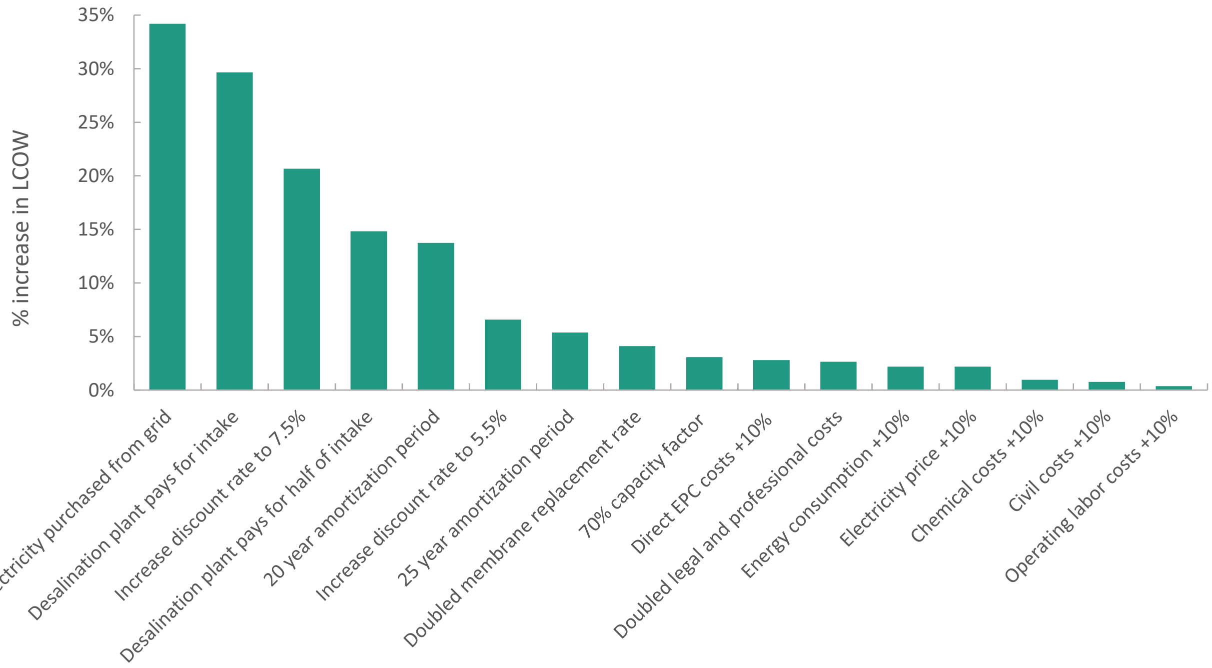

Figure 5: Bar graph showing the sensitivity of the levelized cost of water to various changes from a base-case scenario. Option 2 was used as the base case.

come from the breakdown of two of the most important assumptions — that electricity can be purchased from the nuclear power plant, and that the intake costs are shared or paid for by the nuclear power plant. The next several most important factors are related to the financing terms and the amortization period, emphasizing the critical importance of negotiating a favorable deal with investors. Changes in capital costs had a lessened impact on levelized cost of water. This sensitivity analysis also informs us of the applicability of our approach to other existing nuclear power plants. Most of the savings on the levelized cost of water can be attributed to savings on the intake and outfall structure, and savings on non-energy components of the electricity tariff charge. Thus, in locations where environmental regulations on water intake and outfall are stringent and infrastructure is expensive, the savings will be significant; where environmental regulations are not stringent, the savings will be modest or negligible. Similarly, where the non-energy components of the industrial electricity tariff are high, savings from collocation will be large, and vice-versa.

In addition to these factors, there are other factors that could lead to large changes in water cost, many of which have already been mentioned. Regulatory changes could modify plant requirements or change which technologies can be used. Plant site considerations could significantly affect civil and construction costs, but their overall contribution to the cost of water is not high. If additional storage infrastructure is required to meet the needs of offtakers, such as additional tanks or reservoirs, or if distribution pipelines are required to traverse very challenging terrain, the capital costs could increase significantly. The identification of potential offtakers, and the determination the cost to bring water from Diablo Canyon to those customers, should be a primary focus of further detailed investigations.

The alternative of having a number of smaller desalination plants distributed along the coast could reduce water transmission costs. However, examination of Tables 3 and 4 shows that the cost of a pipeline is more than offset by the energy savings of operating at Diablo Canyon. Further, the savings on capital costs of a single large plant would also offset the cost of a long pipeline: smaller plants are almost always more expensive on a per m^3 basis. As stated in Section 5.1, the literature includes a number of correlations of desalination plant cost with scale, typically power law equations of the form

$$\text{cost} = a \cdot \text{capacity}^k$$

where k ranges from approximately -0.06 to -0.29 on a per unit volume basis for reverse osmosis [67, 71, 74]. For $k = -0.16$, moving from a large scale desalination plant of 200,000 m^3/d to several smaller plants on the scale of 50,000 m^3/d would raise the price of water by an additional 25%.

A Diablo Canyon plant may have minor advantages when it comes to environmental offsets and operational synergies. As a part of the permitting process, regulators have required additional environmental action, such as habitat restoration and maintenance projects, to offset potential environmental damages. Desalination plants can also be required to purchase carbon offsets due to their large power consumption. A Diablo Canyon project has advantages in this respect because the desalination plant would be powered with carbon-free electricity, obviating the need for carbon offsets. As the cost of offset projects is unique to each plant, we do not attempt to estimate them here, and we do not include them in the estimated cost of water.

Co-locating and jointly operating water and power production may produce additional operational advantages. Desalination plants have been shown to be able to reduce their output by 60% in a matter of seconds [75]. This ability to perform a "hot shutdown" could provide added flexibility that would allow the combined plant to ramp down water production and increase power available to the grid in times when power prices increase. These power cost fluctuations can occur regularly (e.g., due to intermittency of renewables), seasonally, or sporadically (e.g., during heat waves or wildfire events). This ability to opportunistically shift production towards water or power could provide additional value for the combined plant or for the grid at large.

Finally, the political and regulatory implications of proposing the construction of a desalination plant at Diablo Canyon cannot be understated. As an example of the challenging permitting situation in California, a proposed desalination project for Monterey, California has been going through permitting challenges in some capacity for approximately 30 years [76]. Building anything on the coast in California is difficult, and a mega-scale desalination plant is potentially a tough sell from a political perspective. Local support for desalination can be a major factor in determining whether new projects have a path forward [77], so the local community's perceptions of desalination projects should also be examined in a detailed design study. It is possible that a local community that has benefited from large power production infrastructure for decades would be more receptive to large water infrastructure as well, potentially making local permitting easier.

6. Conclusion

In this paper, we set out to determine whether co-locating a seawater reverse osmosis desalination plant with a nuclear power plant would be technically feasible and might produce water more cheaply than other large-scale desalination alternatives. We considered potential large-scale and mega-scale desalination alternatives, and we considered the plant design, siting, intake, outfall, distribution, power sources, and integration with the DCNPP. Our economic analysis accounts for the cost of upgrading the power plant's water intake structure to meet California's current environmental regulations. This work is the first to demonstrate that substantive coupling and economic benefits can result from collocating nuclear power and reverse osmosis desalination.

We have shown that, as configured, a desalination plant at DCNPP is very likely to be economically attractive when compared to other seawater desalination alternatives in California. The final costs of water, including distribution, are between US$0.79/m^3 and US$1.19/m^3 within a distribution radius of 100 miles (160 km) from DCNPP. 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 significantly reduces the cost of desalinated water in comparison to large-scale desalination alternatives at other sites in California, which we estimate to cost approximately US$1.84/m^3.

Further, we have shown that these economic benefits can be obtained within the context of California's strict ocean protection regulations while emitting zero carbon into the atmosphere. A Carlsbad-size SWRO plant using nuclear power rather than averaged grid power avoids CO_2 emissions of 47 kt/y.

Reverse osmosis desalination is ideally suitable for retrofitting an existing nuclear facility to produce water. Historically, investigations of integrated nuclear power and desalination have focused on using rejected thermal energy from power production to drive evaporative desalination technologies, an approach that modifies the steam cycle of the plant. For SWRO, no substantive modification of the nuclear plant is required. We have shown that electrically-driven SWRO benefits strongly from collocation with nuclear power through reduced electricity and infrastructure costs. We believe that this potential extends well beyond the specific case of DCNPP, and that similar savings may be possible at many other sites.

Our analysis of DCNPP is of course a very preliminary study. 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 can 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 DCNPP's closure, structuring water purchase agreements, and a host of political issues may also pose challenges to such a project.

Finally, even with the cost reductions detailed here, desalination is often not cost competitive with traditional water resources, or water reuse. However, as traditional sources become further strained, as more emphasis is placed on low carbon energy, and as droughts pose greater threats to a stable water supply, the value of augmenting water resources with desalination will likely increase. We believe we have shown that, with DCNPP's continued operation, building a large-scale desalination plant on-site would be feasible and economically attractive relative to other potential desalination plants. This plant could become another tool in mitigating the intertwined challenges at the nexus of energy, water, and environment, and in helping to secure California's water and energy supplies in a carbon-free manner.

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