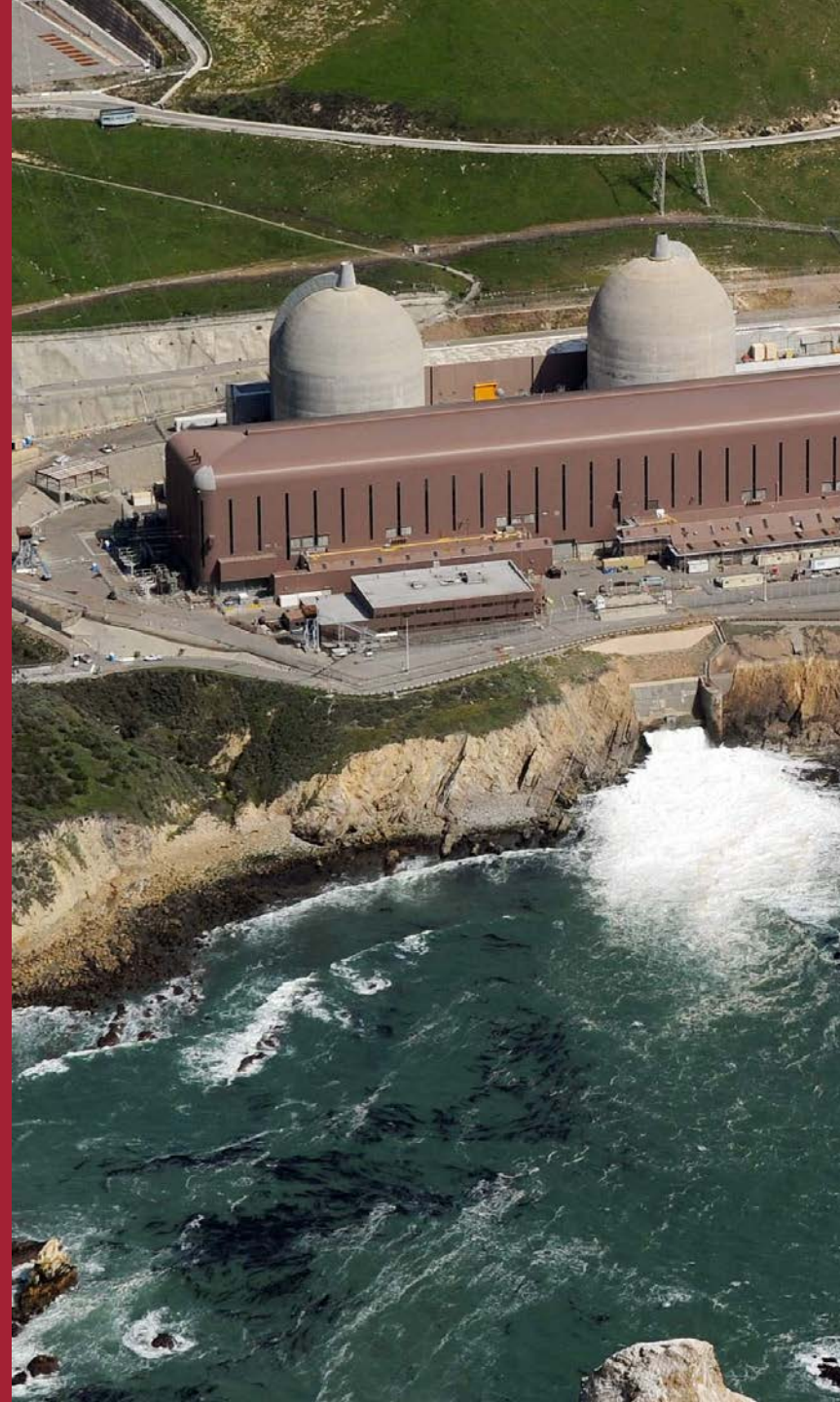
An Assessment of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production



Background and Motivation for Study

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.

Background and Motivation for Study

But in the intervening three and half years, several new developments have occurred:

- SB 100 and EO B-55-18
- A variety of studies affirming need for clean firm zero carbon energy to decarbonize grid
- Reliability challenges in 2020 and likely ongoing
- Severe drought
- 30 x 30 EO
- NRC determination that Diablo Canyon can withstand the types of seismic hazards re-evaluated after Fukushima.

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.

Funding for study was all from internal university resources and philanthropic donations; no money from industry was sought or accepted.

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What the study team analyzed

Electricity.
The potential contribution of Diablo Canyon to achieving zero emissions for the electricity sector at lower cost, maintaining reliability at lower cost, supporting grid integration of variable energy, and limiting carbon dioxide emissions during the transition.

Desalination.
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.

Hydrogen.
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.

Polygeneration.
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.

Top Line Conclusions

Electricity-10 year delay:
Delaying the retirement of Diablo Canyon to 2035 would:

- Reduce California power sector carbon emissions by more than 10% annually from 2017 levels and reduce reliance on gas
- Save a total of $2.6 Billion in power system costs between 2025 and 2035
- Bolster system ability to mitigate brownouts as demonstrated by reliable performance during Aug 2020 brownouts

Electricity to 2045 and beyond:
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.

Top Line Conclusions (II)

Desalination:
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 and Central Coast, producing fresh water volumes equal to or substantially exceeding those of the proposed Delta Conveyance Project—but at significantly lower investment cost

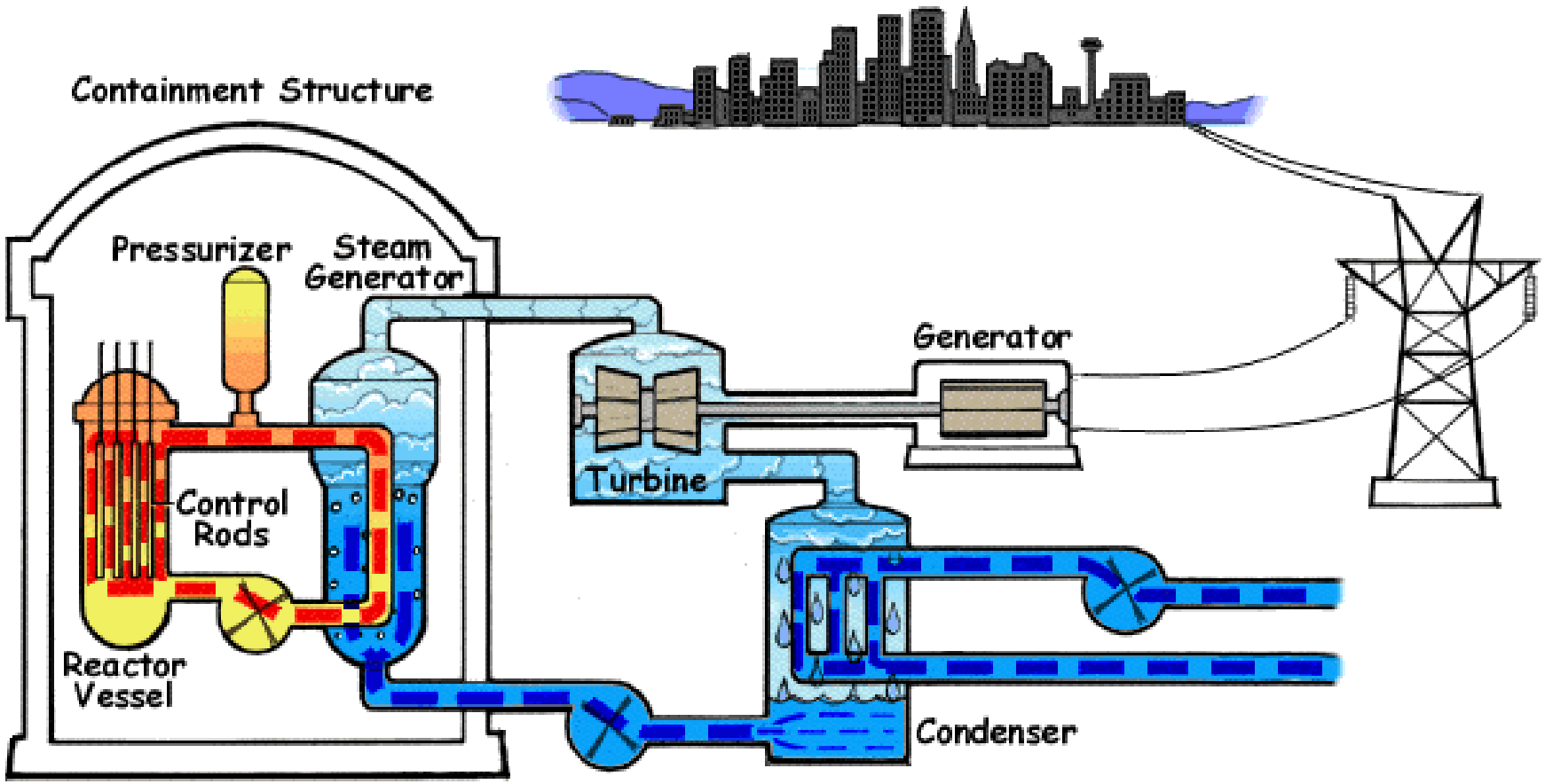
Hydrogen:
A hydrogen plant connected to Diablo Canyon could produce clean hydrogen to meet growing demand for zero-carbon fuels, at a cost up to 50% less than hydrogen produced from solar and wind power, with a much smaller land footprint

Polygeneration:
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)

While this was not intended as a definitive study, these conclusions warrant a further consideration of extending the life of the Diablo Canyon plant beyond 2025.

Nuclear Power: Intro and Specific Considerations for Diablo

In a nuclear power plant the fission heat is converted into electricity



Pressurized Water Reactor (PWR)

NUCLEAR PLANTS EMIT NO CO_2 OR CRITERIA POLLUTANTS, AND DO NOT REQUIRE A CONTINUOUS FUEL SUPPLY

Fuel energy content

COAL (C): $C + O_2 \rightarrow CO_2$ + *1 unit of energy*

NATURAL GAS (CH_4): $CH_4 + O_2 \rightarrow CO_2 + 2H_2O$ + *2 units of energy*

NUCLEAR (U): $^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n$ + *50 million units of energy*

Fuel Consumption, 1000 MWe Power Plant (~740,000 homes)

COAL: 6750 ton/day of coal

NATURAL GAS: 64 m^3/sec of gas

} Need for continuous fueling can impact reliability of electricity supply (e.g., polar vortex)

NUCLEAR: 300 kg/day of natural U

} Refuel every 18-24 months

LOWEST LAND USAGE AND HIGHEST CAPACITY FACTOR OF ALL ENERGY SOURCES

NUCLEAR: >90% capacity factor **~2260 MW_e/km^2**

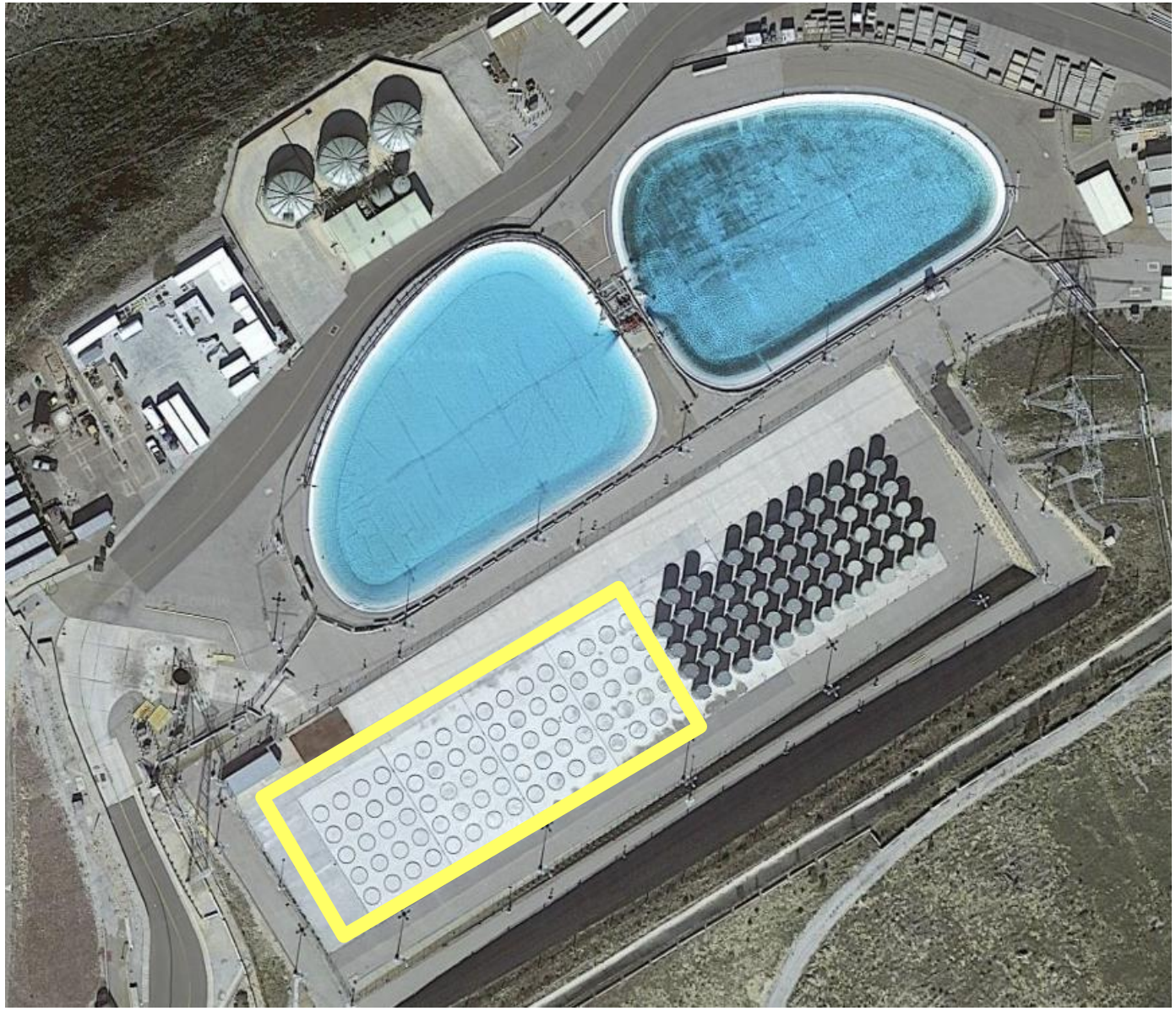
SOLAR*: <30% capacity factor **~6 MW_e/km^2**

WIND*: <40% capacity factor **~1 MW_e/km^2**

*L. M. Miller, D. W. Keith 2018 Environ. Res. Lett. 13 104008


Nuclear waste storage area

This is all there is to it, after over 35 years of operation



There is more than enough room for another 20 years of operation

The seismic question

Following the Fukushima accident in 2011, the NRC reviewed the Diablo Canyon Nuclear Power Plant's ability to withstand external events (e.g., earthquakes, tsunamis, floods, tornadoes, wildfires, hurricanes) of exceptionally rare and severe magnitude ('beyond design basis events').

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

May 8, 2020

Mr. James M. Welsch
Senior Vice President, Generation
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SUBJECT: 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

Using NRC's state-of-the-art seismic methodologies, DCNPP was subject to a series of new evaluations, both generic (i.e., fleet wide) and specific (i.e., specific to the Diablo canyon site). For example, proximity of DCNPP to various faults and DCNPP site's high elevation with respect to sea level were taken into account in the seismic and flood protection analyses, respectively.

PREVENTION

After 9 years of assessment the NRC's conclusion (NRC letter, 8th May 2020) is that "existing seismic capacity or effective flood protection [at Diablo Canyon] will address the unbounded reevaluated hazards." (That is, Diablo was designed and built to withstand with significant extra margins the largest earthquakes that the US NRC requires it to withstand.) Further, "The staff confirmed that the conclusions in the various staff assessments continue to support a determination that no further regulatory actions are required for Diablo Canyon." (That is, no seismic retrofits are necessary.)

MITIGATION

As an additional level of protection, DCNPP (along with all other nuclear plants in the US) has been retrofitted with special equipment and procedures known as FLEX. FLEX is meant to ensure reliable cooling of the reactor core and spent fuel pool under a hypothetical scenario in which all design-basis safety systems have been disabled by a severe external event.

OVERSIGHT

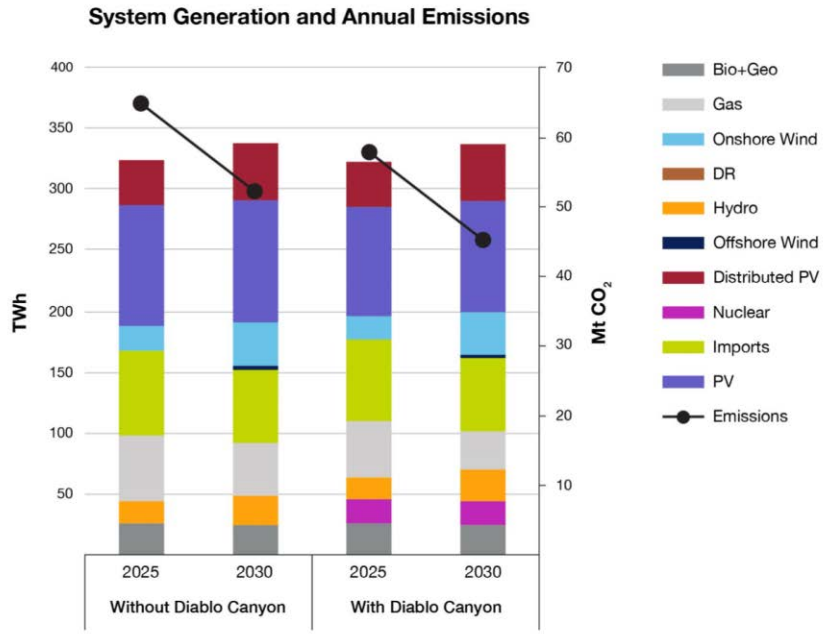
An Independent Peer Review Panel of seismic experts (reporting to the CPUC) and the CA-appointed Diablo Canyon Independent Safety Committee regularly review the latest seismic-hazard information for the site.
Like all nuclear power plants in the US, Diablo's compliance with the post-Fukushima rules is subject to continuous monitoring by the NRC under the Reactor Oversight Process.

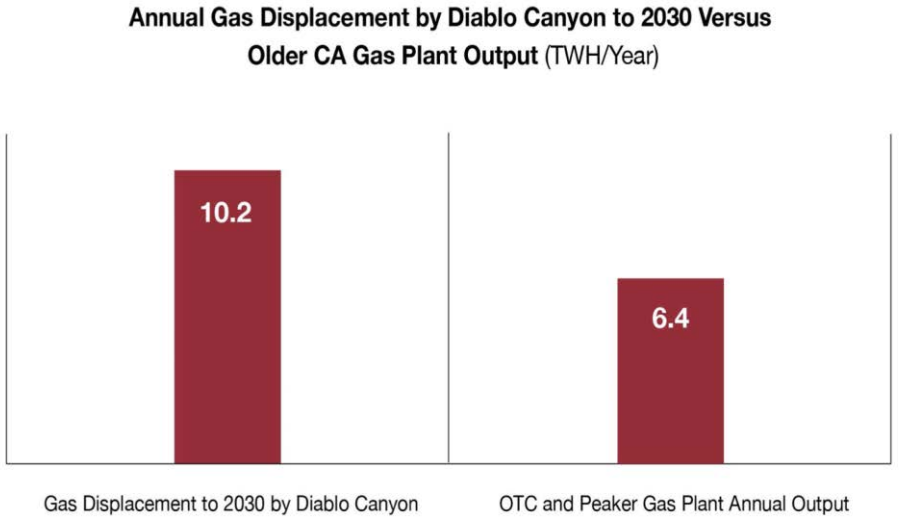
DCNPP: Electricity Market and Carbon Reductions

Diablo Canyon and Electricity Carbon Reductions 2025-2030

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 2030 by approximately 10.2 TWh per year, more than the output of the state's older gas peaker and once through cooling units.

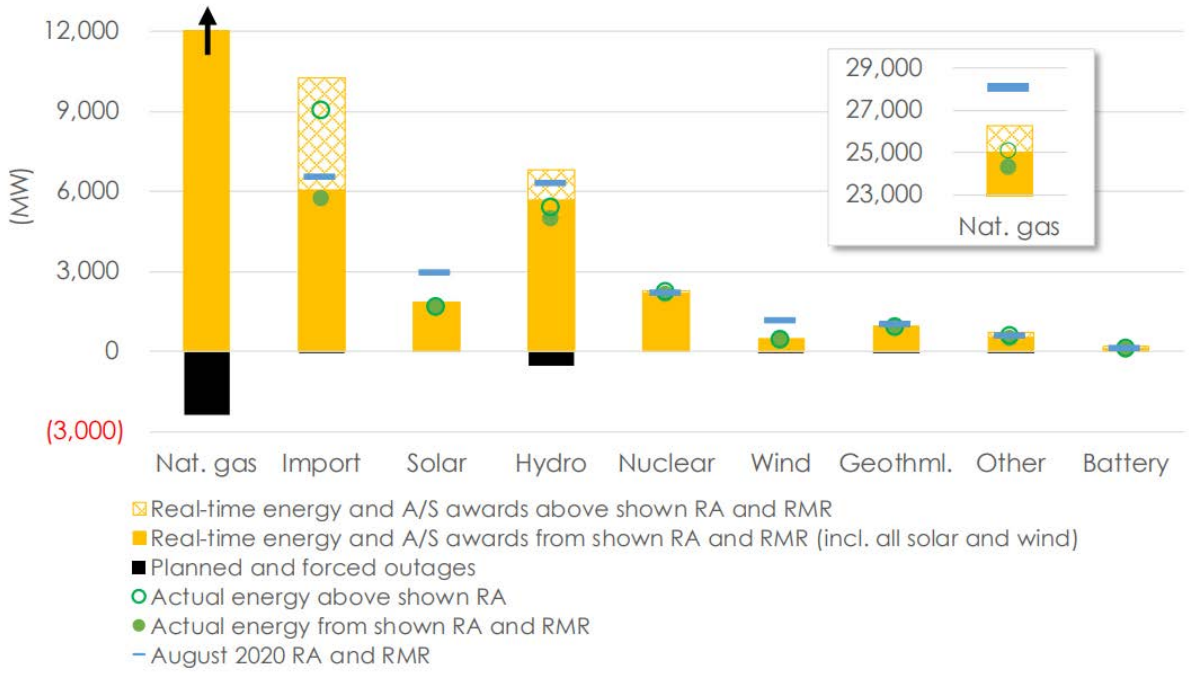
In doing so, Diablo Canyon would also reduce California carbon emissions by an average of 7 Mt CO_2 a year from 2025-2030, corresponding to an 11% reduction in CO_2 from the electricity sector relative to 2017 levels, for a cumulative total of 35 Mt CO_2 to 2030.





Diablo Canyon and Electricity from 2025-2035

Maintaining Diablo Canyon in the period 2025-2035 would also save $2.6 Billion in power system costs. 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.



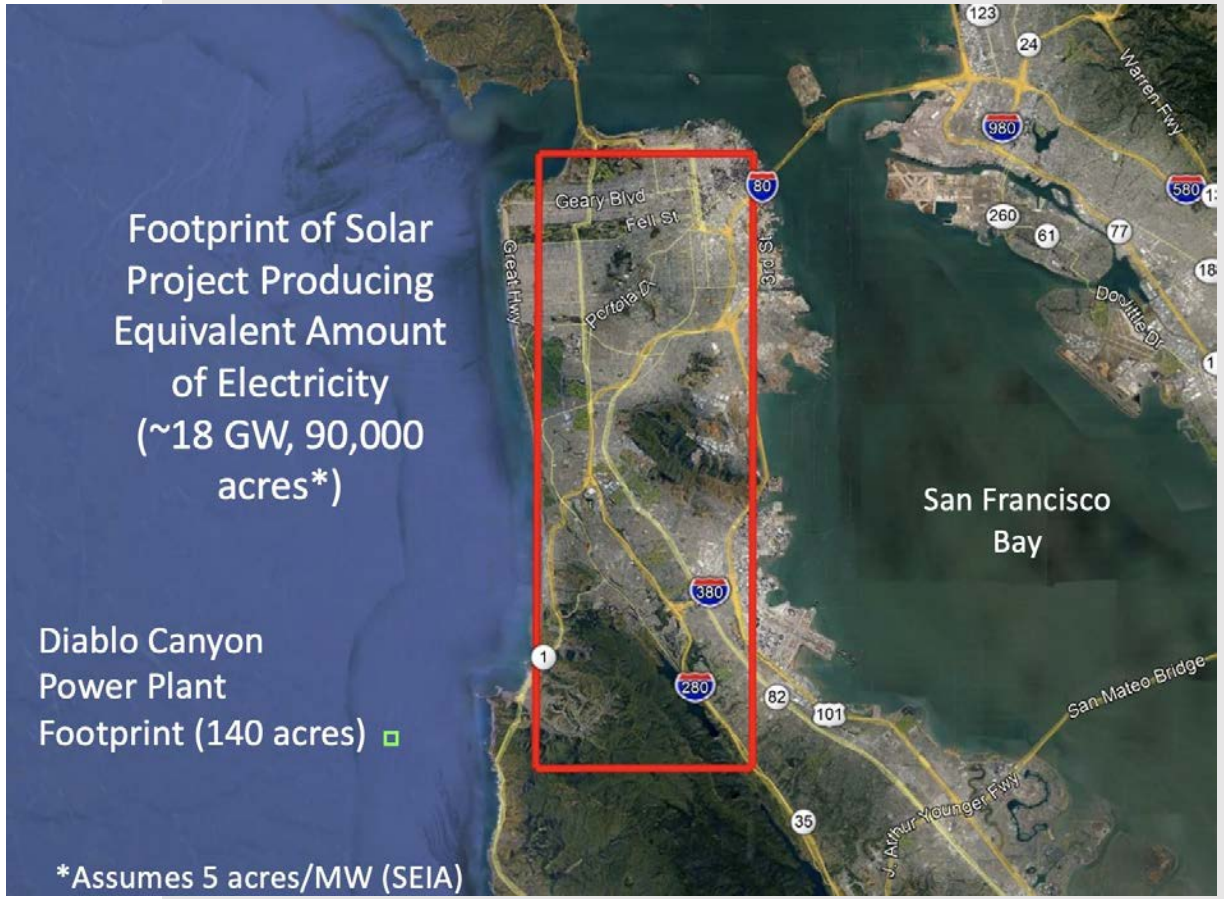
August 14 2020 Net Demand Peak (6:51 p.m.) – Real-Time Awards and Actual Energy Production vs. August 2020 Shown RA and RMR (Updated) (Taken from the 2021 Root Cause Analysis[1]

[1] http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf

Diablo Canyon and Electricity to 2045

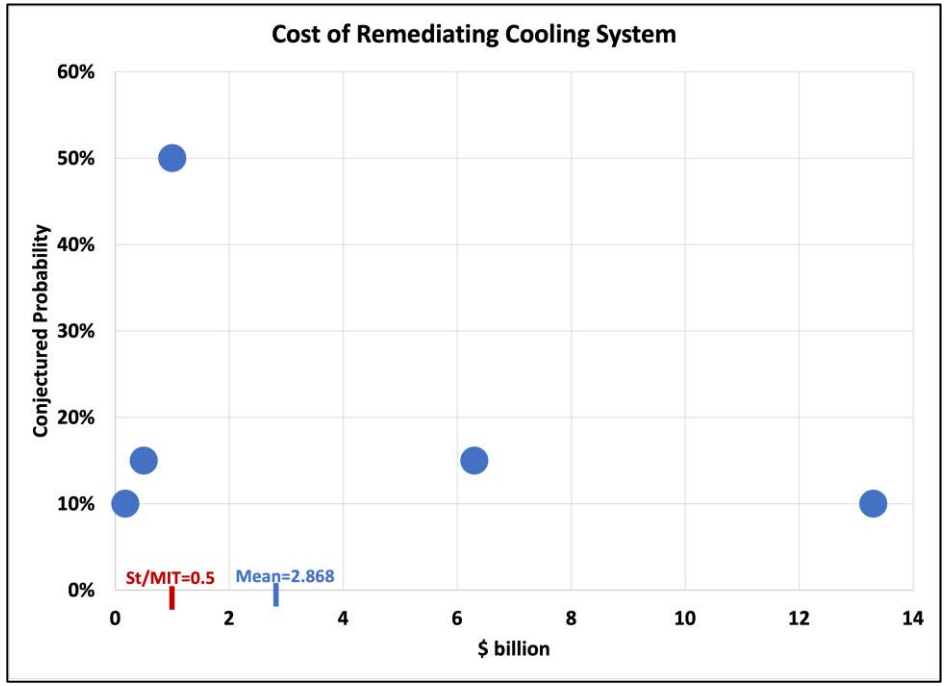
Even assuming that siting of new renewable energy was unconstrained by land use or other considerations, keeping Diablo Canyon online would:

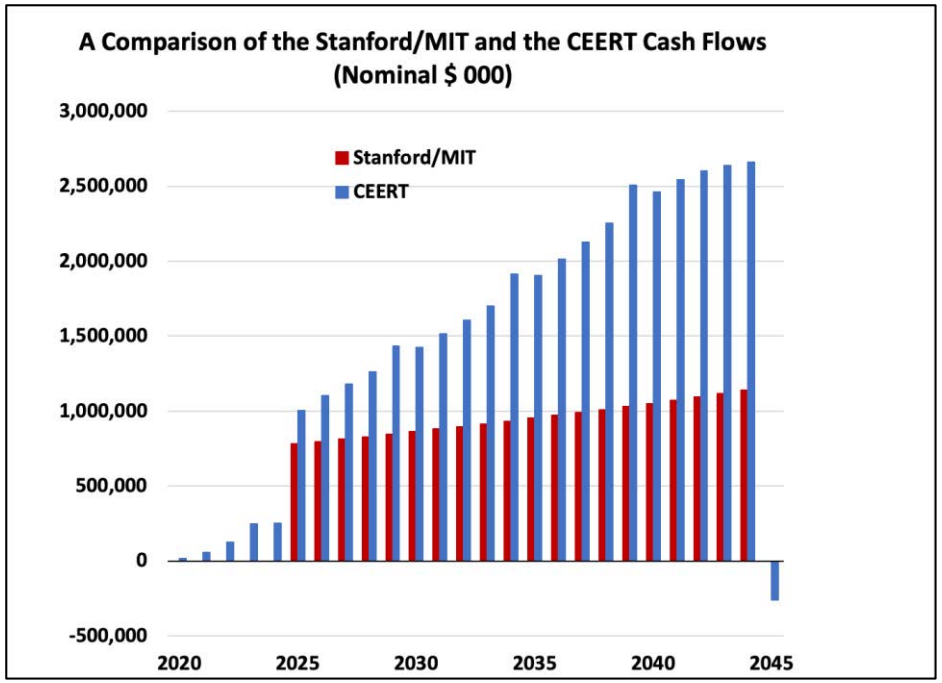
- Save the state a total of $15-16 Billion between 2025 to 2050
- Spare 90,000 acres of land by avoiding the need for 18 GW of solar PV.
- If siting of new PV were constrained by land use considerations to a total of 60 GW (consistent with recent annual deployment rates), savings from Diablo Canyon would grow to $21 Billion.



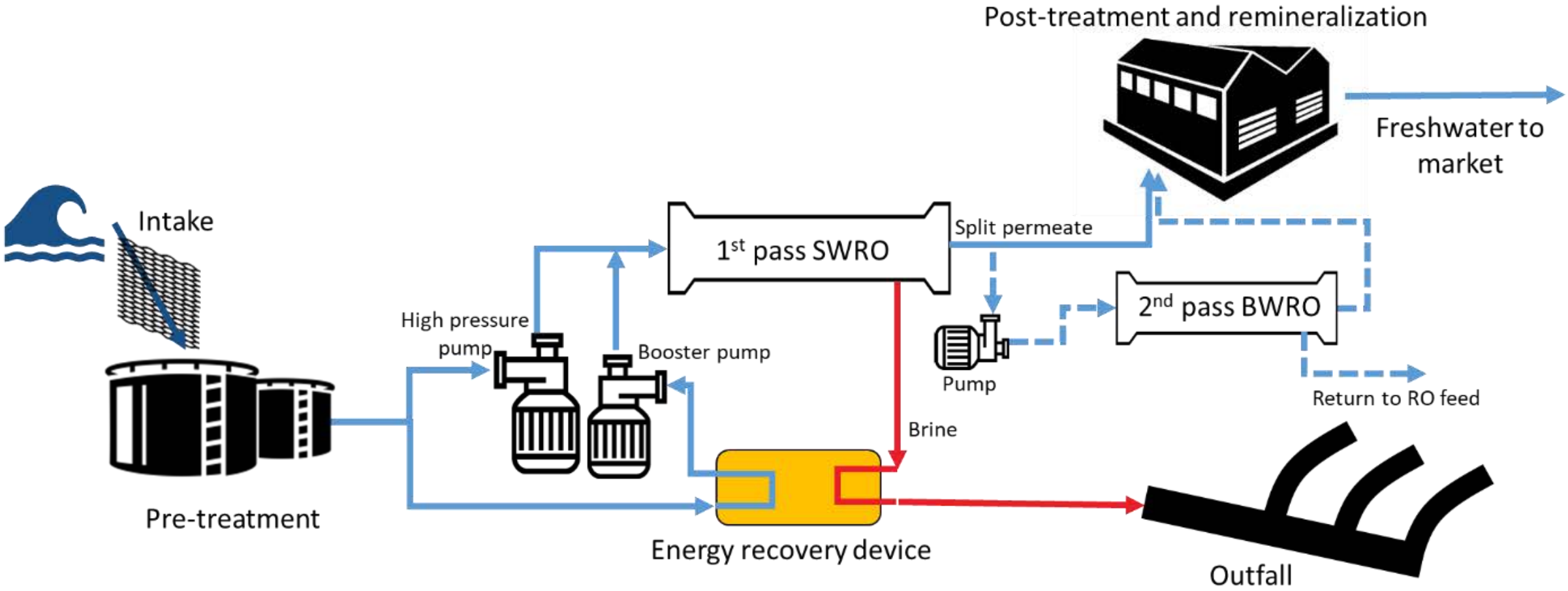
Divergent Estimates of the Cost of Electricity from Diablo Canyon

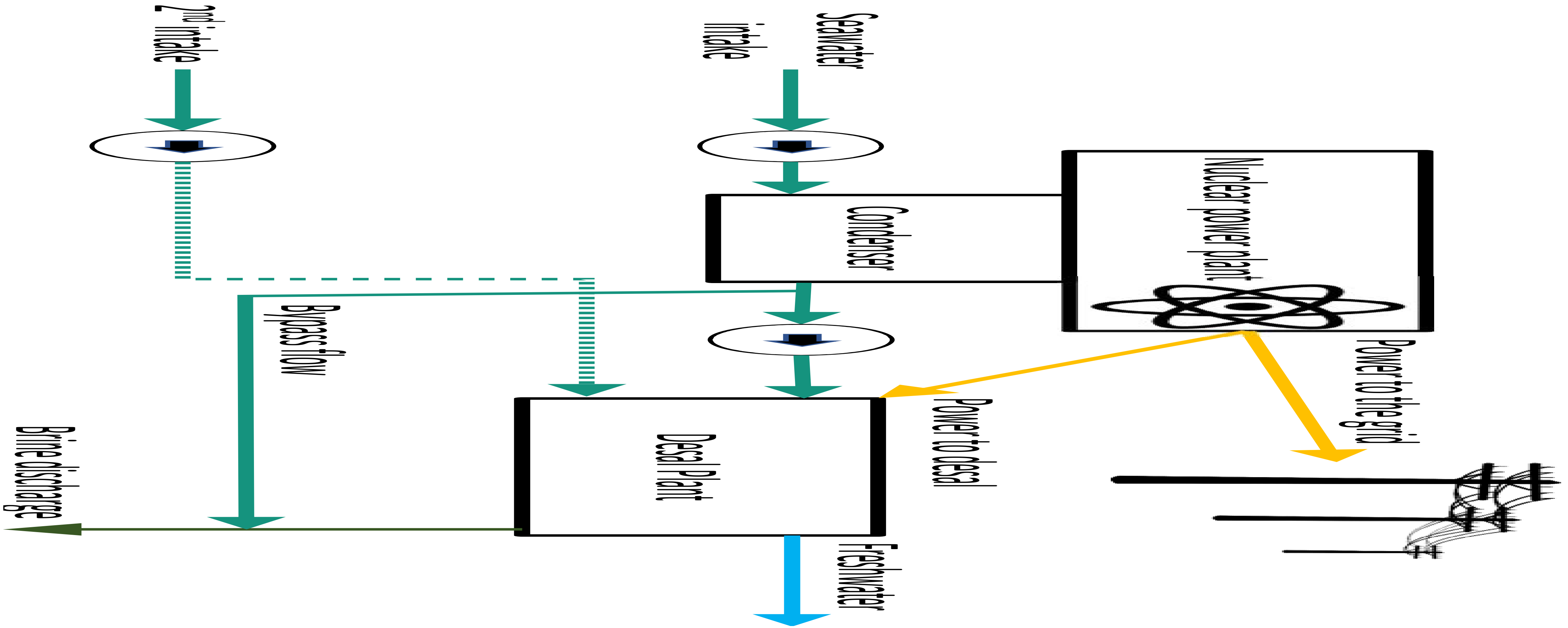
- Stanford/MIT estimated busbar cost of electricity going forward is $42.48/MWh.
- Versus estimates made in 2016 at the CPUC hearing on closure…
- PG&E est. $102-219/MWh.
  - Based on an estimated $2.868 billion cost of remediating the cooling system, versus $500 million.
  - Recoups sunk cost of life extension.
- CEERT est. $69-72/MWh
  - Adjustments to make good comparison.
  - Assumes Diablo Canyon costs increase much faster than inflation.





Potential Large Desalination Plant at DCNPP


Post-treatment and remineralization
Freshwater to market
Intake
1st pass SWRO
Split permeate
2nd pass BWRO
High pressure pump
Booster pump
Pump
Return to RO feed
Brine
Pre-treatment
Energy recovery device
Outfall


2nd intake
Seawater intake
Nuclear power plant
Condenser
Bypass flow
Power to the grid
Power to desal
Desal Plant
Brine discharge
Freshwater

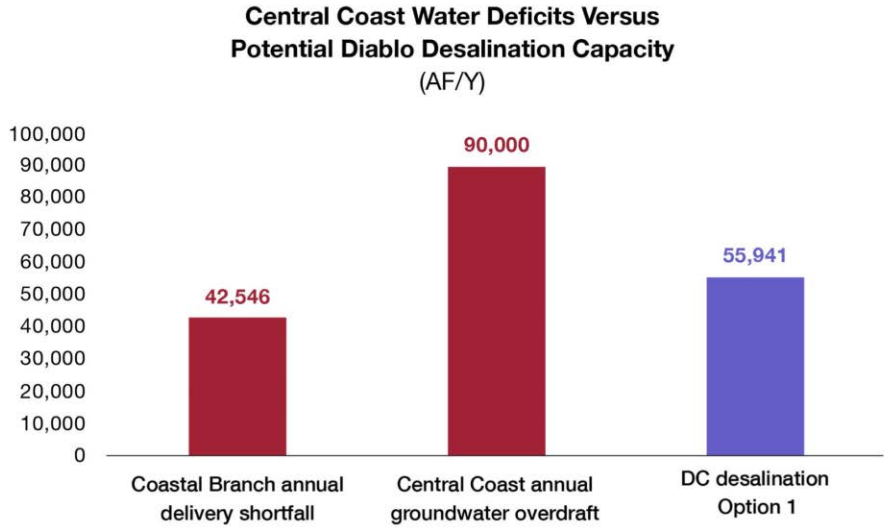
	Capacity	Units
Average water consumption of a Californian (2016)	0.32	[m^3/d]
Olympic swimming pool capacity	2500	[m^3]
Aqua Claudia (ancient Roman aqueduct)	184,000	[m^3/d]
Carlsbad desalination plant (largest desal plant in USA) + Option 1	189,270	[m^3/d]
Sorek desalination plant (currently world's largest RO plant)	540,000	[m^3/d]
California Aqueduct Coastal Branch pumping capacity at Las Perillas	1,127,865	[m^3/d]
Diablo Canyon Option 2	2,419,000	[m^3/d]
Diablo Canyon Option 3	4,752,000	[m^3/d]
California Aqueduct pumping capacity at Buena Vista	13,223,667	[m^3/d]
Diablo Canyon Option 4	15,379,000	[m^3/d]
Central Valley Project average annual deliveries to farms	16,800,000	[m^3/d]
California Aqueduct	32,000,000	[m^3/d]
Colorado River at Glen Canyon	47,500,000	[m^3/d]
Average applied water use in California, 1998-2015	261,000,000	[m^3/d]
Mississippi River	1,550,000,000	[m^3/d]
Amazon River	18,000,000,000	[m^3/d]

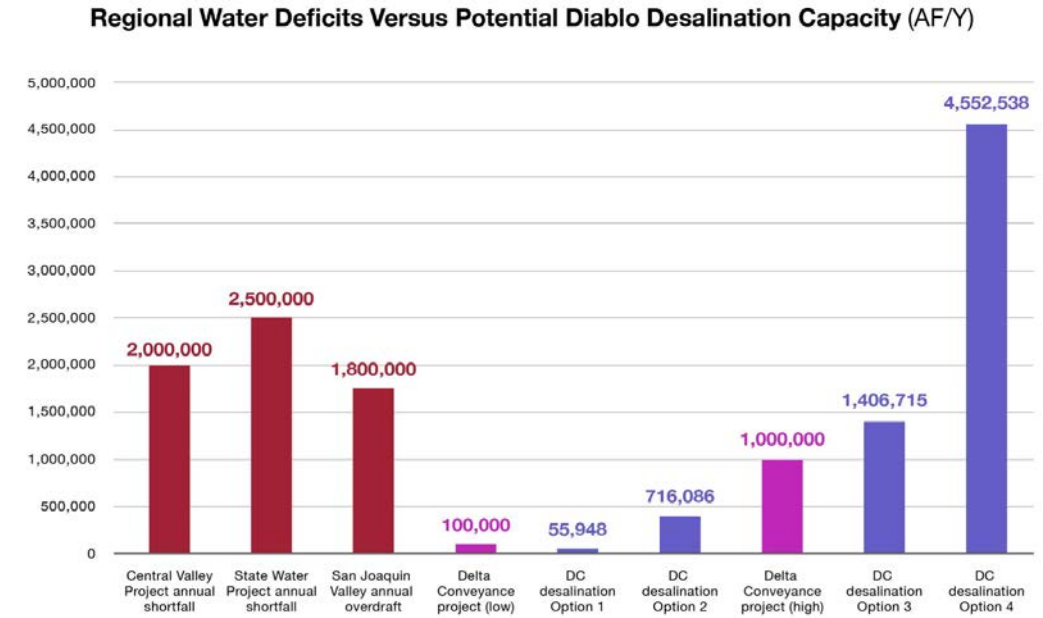
Diablo Canyon Coupled to Desalination

Diablo Canyon could be a powerful driver of low cost desalination to serve urban, industrial, and agricultural users.

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 current statewide shortfalls and the proposed Delta Conveyance Project, but at significantly lower investment cost.





Diablo Canyon Coupled to Desalination

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.

	Large-scale at Diablo	Mega-scale at Diablo	Carlsbad Estimated
Capacity (m^3/d)	**189,270**	**4,752,000**	**189,270**
Capacity (AFY)	**56,000**	**1,406,000**	**56,000**
Total Capex (Million $)	599	11,571	1,235
Energy consumption (kWh/m^3)	3.5	3.5	3.5
Electricity price ($/kWh)	$0.054	$0.054	$0.139
Water cost breakdown ($/m^3$)			
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	$0.49
Water price at plant outlet ($/m^3$)	**$0.98**	**$0.79**	**$1.84**
Water price at plant outlet ($/AF)	**$1,207**	**$978**	**$2,269**

The Intake Challenge

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.

The Intake Solution

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.

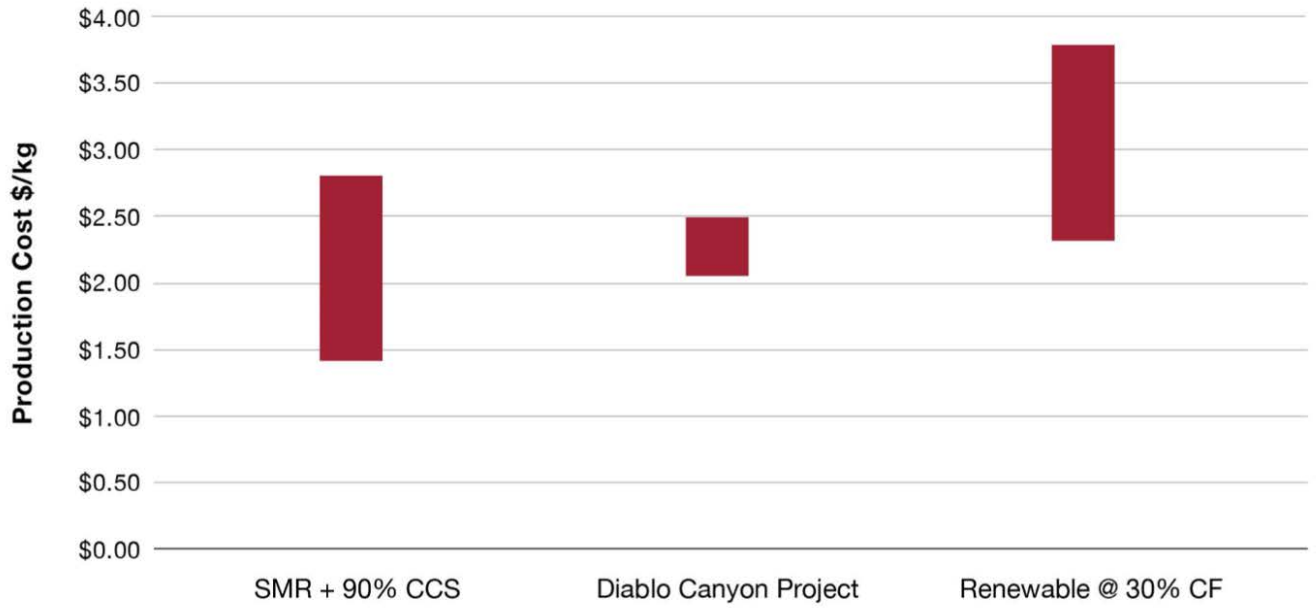
Diablo Canyon and Hydrogen

California will likely need hundreds of millions of kilograms of hydrogen-based, zero-carbon fuels annually.

As with renewables, producing hydrogen from nuclear energy results in no carbon emissions.

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, and roughly the same cost as “blue hydrogen.”

Figure 3-6: Comparison of hydrogen production cost estimates



Diablo Canyon and "Polygeneration"

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.

Challenges and Conclusions

- At the federal level, the plant relicensing process would have to be reinitiated (although the plant can operate pending NRC review).
- 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.
- Approval 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.
- Ownership and operator would need to be determined, and CPUC and NRC approval of any license transfer.
- 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.**