The Economic Value of Offshore Wind Power in California

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Energy+Environmental Economics

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Foreword

In January 2016, Trident Winds Inc. submitted the first unsolicited lease request in California to the U.S. Bureau of Ocean Energy Management for the installation of a commercial scale floating offshore wind farm off the Central California coast. At that time, despite California's ambitious clean energy and climate goals, few in California had considered offshore wind a viable resource worth including in the state's long-term energy plans.

Immediately following Trident Winds' unsolicited lease request, state and local leaders, policy makers, clean energy industry experts, and sustainability advocates started to ask questions: "How would offshore wind help California achieve its clean energy and climate goals? Is it cost competitive? What economic and system benefits could offshore wind provide?"

During the 2018 Global Climate Summit, Castle Wind LLC – a joint venture between Trident Winds Inc. and EnBW North America Inc. – approached E3, the leading experts on California's electricity market and the clean energy transition, to discuss various scenarios that would enable California to meet its ambitious clean energy and climate goals with the least-cost energy portfolios. In an effort to determine the overall importance of this new substantial clean energy resource, Castle Wind commissioned E3 to conduct a study quantifying the economic value and other benefits of offshore wind.

Castle Wind's objective for the study was to start a dialog between elected officials, state agencies and the industry on the **benefits of including offshore wind in the state's long-term energy planning efforts**. The study was not intended to, nor does it, answer questions related to labor benefits, transmission impacts/benefits, or where offshore wind farms could be installed.

Offshore wind offers California an abundant, domestic, and currently untapped clean energy resource. This study demonstrates that offshore wind is a valuable resource that should be embraced by the State of California in its quest to achieve its clean energy and climate goals at the least cost.

The next step in realizing the now-quantified economic and system benefits of offshore wind is to develop and implement a **Strategic Plan** for offshore wind in California. It is up to elected officials, policy makers, the offshore wind industry, other key stakeholders, and the State of California to make this happen.

The offshore wind industry is ready, willing, and able to invest its resources to advance the responsible development of offshore wind to California to realize its associated economic and system benefits.

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Executive Summary

Offshore wind power is growing rapidly around the world, driven by dramatic cost reductions and increased interest in carbon-free energy sources. While most offshore wind projects to date have utilized fixed-base platforms, there is growing commercial experience with floating-base applications that will unlock wind resources in deeper waters, such as those off the coast of California.

California is a large potential market for offshore wind due to its ambitious clean energy policies and economy-wide greenhouse gas (GHG) reduction goals. While California leads most states in renewable energy deployment, it will need several times more renewable energy capacity than is currently installed to meet its long-term policy commitments.

While California has studied optimal pathways and different scenarios for meeting its clean energy goals, it has yet to fully investigate its offshore wind potential. California's long-term planning studies, which inform the state's energy procurement, transmission investment, and associated policy decisions, have not formally modeled offshore wind as a future supply option for GHG-free energy. For this reason, Castle Wind has asked E3 to study the economic value of offshore wind in meeting California's policy goals and to determine the potential market size and systemwide cost savings if offshore wind were to be deployed at scale. This study seeks to close a longstanding information gap by investigating the potential role of offshore wind to help meet California's long-term policy goals.

In this study, E3 used its RESOLVE model – a resource planning tool used in many groundbreaking renewable energy studies in California and nationwide – and analyzed offshore wind economics using key input assumptions provided by Castle Wind. The RESOLVE model was given an unlimited amount of offshore wind potential in order to estimate the optimal capacity without regard to current federal offshore wind call areas or to existing onshore transmission limitations. The study finds that **offshore wind could be a valuable and significant resource for meeting the state's long-term climate goals**:

- Our analysis finds that **the least-cost portfolio for meeting the state's energy goals would include 7-9 GW of offshore wind by 2040.** This represents enough energy to power four million homes and meet approximately 10 percent of the state's electricity needs.

- Modeling results across all scenarios found that including **offshore wind in the state's energy mix would produce ratepayer savings of approximately $1 to $2 billion on a net present value (NPV) basis.**

- **Potential ratepayer savings from offshore wind increase over time**. Floating offshore wind becomes part of the least-cost portfolio by 2030, with demand increasing consistently in subsequent years as California's policy goals become more stringent.

- The study also evaluates offshore wind relative to other resource options including out-of-state onshore wind (e.g., from Wyoming or New Mexico), and finds that **offshore wind remains a valuable and least-cost resource option even if out-of-state wind is developed in the future**. This is due to offshore wind's proximity to in-state electricity demand and existing transmission infrastructure.

While this study identifies the economic opportunities presented by offshore wind, it does not make any policy recommendations or purport to answer questions related to offshore wind transmission needs, lease areas, future performance and cost improvements, supply chain and infrastructure development, and associated investment and job creation, each of which may merit more detailed studies. Instead, this report focuses on the high-level economics of offshore wind and the potential scale at which this resource may help achieve California's long-term policy goals.

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Disclaimer Required by the California Public Utilities Commission

This report has been prepared by E3 for Castle Wind, a joint venture between Trident Winds Inc. and EnBW North America, Inc..

This report is separate from and unrelated to any work E3 is doing for the California Public Utilities Commission (CPUC). The CPUC did not participate in this project and does not endorse the conclusions presented in this report.

E3 utilized the RESOLVE model developed for the CPUC's 2017-2018 Integrated Resource Planning proceeding (R.16-02-007) in preparation of this report. With data inputs from Castle Wind, E3 has made specific modifications to the CPUC RESOLVE model for the purpose of conducting the analysis described herein. The modifications are summarized in the tables below.

E3 does not endorse any specific policy or regulatory measures as a result of this analysis.

E3 and Castle Wind are solely responsible for the contents of this report, and for the data, assumptions, methodologies, and results described herein.

Summary of Modifications Made to the CPUC 2018 IRP RESOLVE model[1]

Modification	Purpose
Generic California offshore wind resource added to renewable supply curve	To evaluate the buildout and potential cost savings associated with offshore wind as a resource option
Solar, wind, and battery storage resource costs modified	To provide more up-to-date points of comparison when modeling offshore wind avoided costs in the future

[1] Detailed tables of data modifications are provided in Section 6.2 Key Model Inputs and Modifications Made to the CPUC 2018 IRP RESOLVE Model.

1 Introduction

California's ambitious clean energy and climate goals – namely its targets to use 100% zero-emission energy sources for its electricity by 2045 and to reduce GHG emissions by 40% from 1990 levels by 2030 and 80% by 2050 – have made the state one of the biggest renewable energy markets in the U.S. Over the past decade, California's Renewable Portfolio Standard (RPS) and its economy-wide cap-and-trade program, two central pillars in the state's environmental agenda, have led to a major increase in renewable energy capacity and corresponding decrease in emissions associated with fossil-fueled generation. Solar PV and onshore wind capacity, in particular, have grown rapidly under the state's RPS regime. But conclusions in California Energy Commission (CEC) and CPUC studies indicate that the state will require two to six times more renewable capacity by 2050 than is installed today in order to meet the current policies.[2]

Meeting California's long-term goals will require a scale of renewable development and integration that has not been approached anywhere in the world to date. In order to chart the most economic and politically feasible path to its high-renewable future, California must consider all resources at its disposal. But California's policies and planning processes have only recently begun to explicitly consider offshore wind as a future supply option for GHG-free energy.

With global installed capacity having grown rapidly over the past decade, offshore wind is becoming an important part of the electric generation portfolio in many regions due to rapidly declining costs and policies favoring emissions-free renewable energy. Globally, the market now tops 22 gigawatts in capacity, more than ten times the capacity a decade ago, with around 20% of that installed in 2018 alone.[3] In the

[2] Future renewable capacity needs vary primarily by the type of renewables deployed (e.g., a megawatt of offshore wind at 50% capacity factor generates twice as much energy as a megawatt of solar at 25% capacity factor) and by the future demand growth driven by electrification. CEC PATHWAYS study, CPUC IRP results

[3] https://renewablesnow.com/news/global-offshore-wind-capacity-hits-22-gw-in-2018-645662/
https://www.windpoweroffshore.com/article/1525116/europe-adds-265gw-offshore-2018

U.S., several Northeast states have made offshore wind a cornerstone of their future clean energy portfolios, with more than 20 gigawatts (GW) of new offshore wind capacity mandated by 2035.

California differs from the Northeast U.S. in that its deep coastal waters require a different type of offshore wind technology: floating turbines. This technology has been successfully demonstrated in multiple jurisdictions worldwide, with larger-scale commercial projects being planned and contracted for deployment in the near future. While the cost of floating offshore wind today is higher than fixed-bottom offshore wind, the technology is well understood and is expected to decline rapidly in cost with commercialization and greater scale of deployment.

For this study, **Castle Wind retained E3 to model the long-term economics of floating offshore wind and its potential as a least-cost option for meeting California's policy goals**. E3 has deep expertise in resource planning analyses and has regularly supported state and utility integrated resource planning (IRP) efforts throughout North America using its suite of modeling tools, such as RESOLVE (a long-term resource planning and renewable integration model) and RECAP (a reliability planning tool), and other proprietary in-house analytics.

In this study, E3 relied on the latest public version of the RESOLVE capacity expansion tool, which was used by the CPUC its 2017-18 IRP cycle, and added offshore wind as a new resource option to test its overall value to the California grid. Castle Wind provided E3 with recent industry assumptions regarding the cost and performance of offshore wind, which were then run through the RESOLVE model to identify the optimal buildout of offshore wind and the associated long-term cost savings for the California Independent System Operator (CAISO) system. The study's underlying assumptions, modeling approach, and findings are presented in the remaining sections of this report.

1.1 Current Climate Policy and Long-Term Energy Goals in California

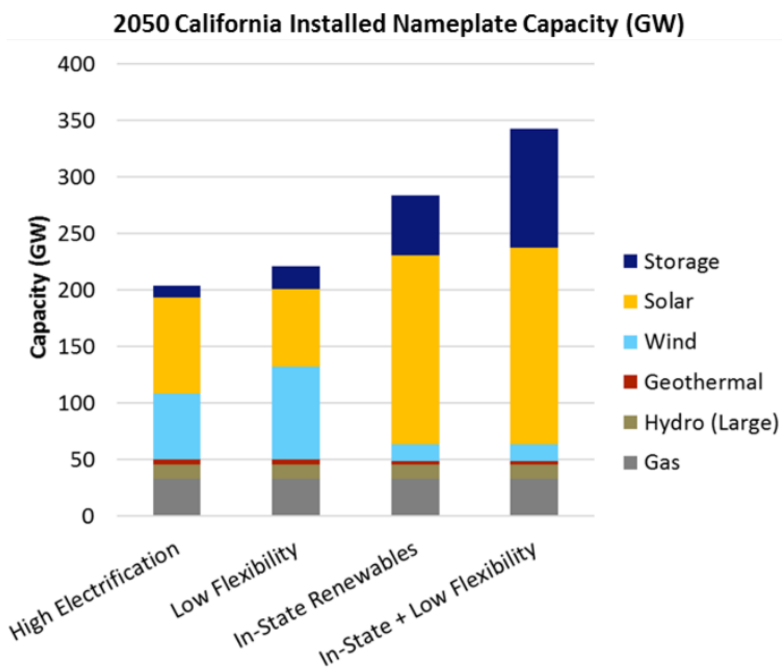
California's two environmental policies that most directly impact power markets and demand for renewable energy are the RPS mandate and the pricing of carbon emissions. California's Renewable Portfolio Standard (RPS) policies date back to 2002 and have since been revised several times to incorporate increasingly stringent targets for renewable energy supply. An important consequence of California's RPS program is that its market support for new technologies helped drive down early-stage costs to enable cheaper, fully commercialized deployment. For example, solar power purchase agreements (PPAs) signed before 2010 were priced as high as $200 per megawatt-hour (MWh), whereas the Los Angeles Department of Water and Power (LADWP) recently signed a solar PPA at $19.97/MWh, marking a 90% cost reduction for the same resource in the same state just a decade later.[4] Onshore wind PPAs have followed a similar trajectory, declining in cost from over $100/MWh to below $40/MWh today.[5] SB 100, passed in 2018, increased California's targets to 60% renewable energy supply by 2030 and 100% GHG-free power supply by 2045.[6] Compliance with SB100 alone will require the state to approximately double its existing renewable energy capacity by 2030, adding at least another 20 GW.

California's GHG policies offer an even more comprehensive mandate for combatting climate change. Under AB32 and Executive Order S-03-05, the state has committed to reduce its GHG emissions to 40% and 80% below 1990 levels by 2030 and 2050, respectively. These goals require a much broader reimagining of California's energy economy, including significant reductions of emissions from the transportation and building sectors in addition to the electric grid. According to E3's 2018 report for the California Energy Commission, the **total new renewable capacity needed to meet California's 2050 GHG goals could range from 100 to 150 GW.**[7] The amount of renewable capacity needed will depend upon the type of resources used to reduce GHG emissions in the power sector (e.g., solar versus wind power) and

[4] https://www.greentechmedia.com/articles/read/ladwp-plans-to-break-new-low-price-records-with-massive-solar-battery-proje#gs.nnvsol
[5] Level10 Q4 2019 PPA Price Index report
[6] For reference, California's current power supply is approximately 30% renewable and 55% GHG-free; see https://www.energy.ca.gov/almanac/electricity_data/total_system_power.html
[7] "Deep Decarbonization in a High Renewables Future" https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012-1.pdf

the amount of emissions reductions attributable to the power sector versus mitigation efforts in other parts of the economy (e.g., switching to electric vehicles for transportation).

Figure 1: California 2050 Generation Portfolios Under Differing GHG Reduction Compliance Pathways[8]

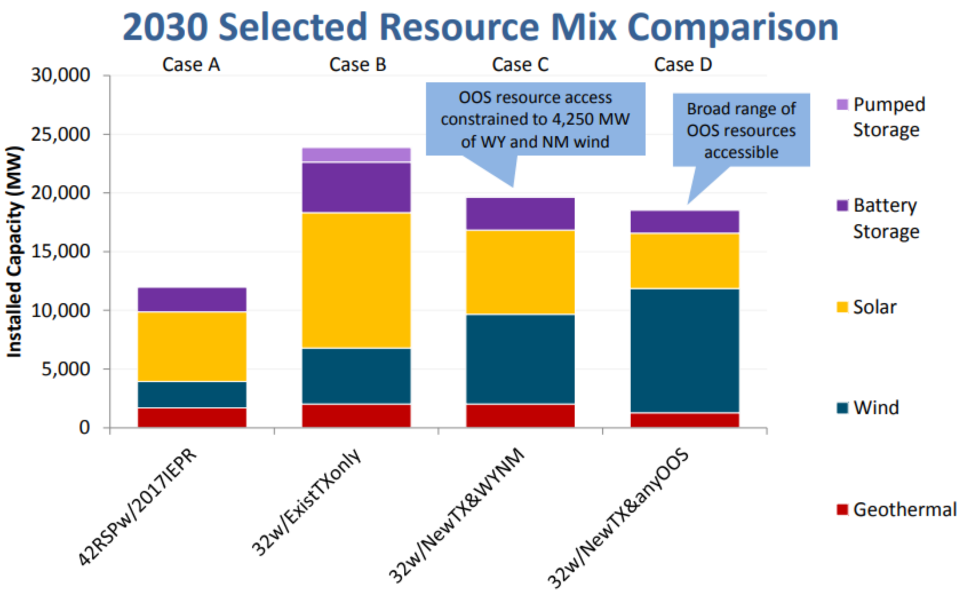


As shown in the above chart from the CEC's 2018 *Deep Decarbonization in a High Renewables Future* study, California's current resource scenarios for reducing GHG emissions by 2050 lean heavily upon just three types of resources: solar PV, onshore wind, and energy storage. This is consistent with the CPUC's IRP process, which earlier this year recommended four different 2030 resource portfolios to inform the California Independent System Operator's (CAISO's) Transmission Planning Process (TPP).[9] All portfolios, from both, CEC and CPUC, focused primarily on identifying the best mix of solar, wind, and battery storage to meet the state's long-term GHG and RPS goals in four plausible future scenarios related to GHG policy targets and the ability to rely on out-of-state resources.

[8] CEC, *Deep Decarbonization in a High Renewables Future* (2018), available at **https://efiling.energy.ca.gov/GetDocument.aspx?tn=223785**

[9] Certain aspects of resource planning for load-serving entities (LSEs) in the CAISO market is subject to CPUC jurisdiction. The CAISO market includes the three large investor-owned utilities in California (Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric) as well as other LSEs that together represent approximately 80% of the state's electric load.

Figure 2: Proposed 2030 Generation Portfolios from CPUC IRP 2017-18 Planning Cycle



These long-term planning studies, which inform the state's energy procurement, transmission investment, and associated policy decisions, have yet to formally model offshore wind as a future supply option for GHG-free energy. This study seeks to close a longstanding information gap by investigating the potential role of offshore wind to help meet California's long-term policy goals.

1.2 Compliance Programs to Implement California's Policy Goals

1.2.1 RPS: RENEWABLE ENERGY CERTIFICATES (RECS)

The RPS program incentivizes new renewable energy development by putting a market premium on energy generated from renewable resources. Effectively, renewable energy generators are granted RECs for every unit of energy produced. Electricity suppliers such as investor-owned utilities (IOUs) and community choice aggregators (CCAs) are required to obtain an increasing number of RECs over time, which creates a market for RECs and a price signal for project developers.

E3 models California's RPS program as a constraint within RESOLVE that ensures that future resource portfolios comply in each year with SB100 requirements (i.e., 60% renewable energy by 2030 and 100%

carbon-free energy by 2045). RESOLVE effectively identifies the REC price needed to incent development of new renewable generation until the target number of RECs are generated. If renewable energy is cost competitive in a given year without any REC market support (i.e., the state exceeds its RPS targets without needing a subsidy for renewables), then the REC "shadow price" in the model is zero.

1.2.2 GHG PRICING: CAP-AND-TRADE PROGRAM

The most comprehensive climate policy in California is the cap-and-trade program instituted under AB32, which is used to price carbon emissions in the state. The cap-and-trade program is an economy-wide mechanism for implementing the state's goal to reduce GHGs emissions 40% by 2030 and 80% by 2050 (relative to 1990 levels). These goals are enforced through the program's cap on emissions, which declines by a fixed percentage each year. Emitting sources covered by the program include large power plants, industrial sources, and fossil fuel distributors; entities must acquire allowances for their emissions, with the sum of allowances in any year equaling the program cap for that year. Carbon pricing is also applied to electricity imports from outside of California to account for out-of-state emissions and create a level playing field in wholesale power markets.

Recent California carbon prices have been in the range of $15/metric ton CO2e.[10] For a typical combined cycle gas plant, carbon pricing at this level increases marginal costs of generation by approximately $5/MWh. Carbon costs at all fossil-fueled generators thus appear in wholesale market bids and the resulting power market prices experienced in CAISO.

Based on E3's modeling for this study, **California's GHG-reduction goals by 2030 appear to supersede its renewable energy goals under SB100 by 2030.** In other words, to meet the state's long-term GHG-reduction goals, by 2030 the power sector will need to exceed the pace of clean energy adoption mandated under SB100.

This policy dynamic will be translated to power markets through an **increasing carbon price and deteriorating REC price**. Under a carbon cap that becomes more stringent over time, carbon prices will

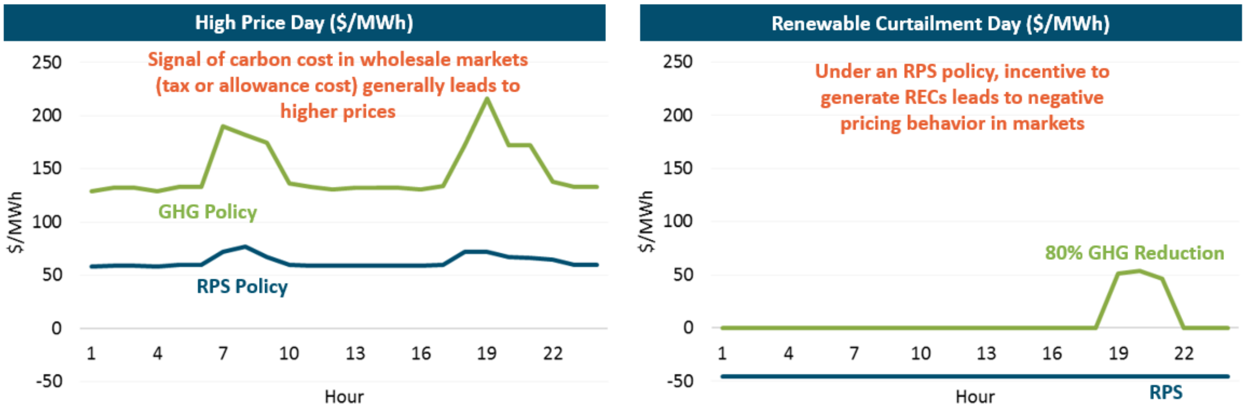
[10] http://calcarbondash.org/

generally increase to reflect the increasing marginal cost of carbon reductions. For the power sector, this means that carbon prices will rise to the level needed to incentivize switching to less carbon-intensive power; for example, higher carbon prices will make wind power more competitive relative to gas-fired power, which will incentivize investment in new wind projects. At the same time, renewable energy procurement to meet carbon policy requirements may exceed the amount needed for SB100 compliance, which will reduce the marginal cost of RECs.

The shift from California's historical, RPS-focused market regime to a future, more GHG-focused market regime will have significant implications for energy market prices and investment decisions. Unlike the RECs used to track RPS compliance, carbon prices provide a more granular time-varying market signal throughout each day. This is because carbon prices are passed through to energy prices on a real-time basis that directly correlates with carbon intensity. In the evening hours when peak electricity demand occurs, the CAISO must fire up its most costly and least efficient generators to supply the grid. The marginal "peaker" plants in these hours emit significantly more carbon per MWh of electricity generated, meaning they must pay a higher carbon price that gets passed through to energy markets. Looked at another way, the value per MWh of replacing fossil generation with clean generation is highest in these peak hours, which generally occur in the evening.

The difference between energy prices in an RPS-driven regime and carbon-price-driven regime is illustrated below.

Figure 3: Differing Impact of RPS and Carbon Pricing Policies on Energy Markets



Carbon-driven market trends are particularly relevant for valuing investments in future renewable resources, such as offshore wind, because they capture the time-dependent carbon reduction value of intermittent resources and their associated generation profiles (e.g., solar generation that peaks at midday vs. wind generation that correlates with evening hours). The RESOLVE model used in this study dynamically models carbon prices and their impact on hourly emissions and energy value. The optimal least-cost resource mix for meeting annual carbon caps and the associated shadow price for carbon are two of the model's primary outputs.

1.3 Technical, Cultural, and Economic Challenges to Achieving California's Climate Goals

The growing contribution of intermittent renewable energy to California's grid has already produced unique technical challenges, such as the diurnal "duck curve" pattern due to large-scale deployment of solar in the state. The continued integration of renewable energy will present new challenges over time as the state's best resources are developed and the economy as a whole evolves to meet state GHG targets. California will face a number of challenges in meeting its future clean energy goals, including:

+ **Serving increasing load while reducing emissions**. Over the past decade, California's retail electricity load has remained more or less flat. This is expected to change in the next decade, however, with the rapid growth of electric vehicles that is required by the state's GHG policy goals. This will simultaneously increase power demand while requiring reductions in total emissions.
+ **Maintaining clean, reliable power in all hours of the day.** California's growing solar capacity has begun to saturate the grid in midday hours, leaving the remaining evening and morning hours with the highest energy prices, GHG emissions, and peak capacity needs. Maintaining a reliable grid while reducing reliance on dispatchable fossil resources like gas-fired plants during these non-solar hours will be a central challenge in the implementation of the state's GHG policy. Resources that generate clean energy during hours of peak demand, such as the 6 p.m. to 10 p.m. period after solar generation ramps down, will be most valuable in this regard.

- **Siting of new renewable energy projects around local opposition**. Local constituencies have frequently resisted development of new energy projects in their backyards, whether that energy is renewable or not. For example, San Bernardino County, the largest county in California (and in the U.S.), recently restricted the development of utility-scale solar projects.[11] If the best available sites for renewable energy development face new restrictions in the future, the state's goals will become more difficult and more expensive to attain.
- **Transmission of power from remote clean energy sources to concentrated areas of demand,** such as coastal "load centers" like the L.A. Basin and Greater Bay Area. Some of the best wind resources in the Western U.S. are located in Wyoming and eastern New Mexico, but energy from these potential resources cannot currently be delivered to California without major new transmission projects that require lengthy siting and permitting processes across multiple state jurisdictions. Building new transmission capacity to deliver power the final mile in urban environments is also difficult and expensive, as evidenced by the $130 million Scattergood-Olympic project in Los Angeles (which LADWP completed, in 2018, at a cost of over $11 million per mile for the 11.4-mile line).[12] New onshore transmission lines can either be built overhead (and potentially draw local opposition) or can be undergrounded (at significantly higher cost).

The current mix of renewable resources on the California grid is a relatively diverse mix of solar, wind, geothermal, small hydro, and biomass. Resource diversity provides value as a hedge against rapidly changing technology costs and offers portfolio effects from generation at different hours of the day in different locations at different times of the year. Going forward, however, California's resource planning trajectory as is currently envisioned for 2030 features a heavy reliance on solar PV and lithium-ion battery storage, due to the rapid price declines experienced by both technologies. Solar and energy storage have each become cheap enough in recent years that they can be deployed together to offer "shaped" energy, whereby solar is stored during the day and injected into the grid during more valuable evening hours. While the cost-effectiveness of this combination is becoming clear, there are technical limits to grid reliability when relying on energy storage to serve peak load. Other E3 studies in various jurisdictions have found that storage offers diminishing reliability value as its share of grid capacity increases.[13] Achieving

[11] https://pv-magazine-usa.com/2019/03/01/san-bernardino-county-bans-large-scale-solar-wind-in-some-areas/
[12] https://www.ladwpnews.com/ladwp-completes-construction-of-the-largest-underground-transmission-line-in-the-city-of-los-angeles/
[13] https://www.utilitydive.com/news/moving-beyond-rules-of-thumb-for-smart-cost-effective-storage-deployment/553674/

the state's long-term policy goals will require a comprehensive planning approach that accounts for the challenges described herein and offers flexible future paths to compliance.

1.4 Potential Role of Offshore Wind in Achieving Climate Goals

Though offshore wind has not been featured in California's resource planning analyses to date, it offers several attributes that could be helpful in addressing the challenges discussed in the previous section. As a potential resource, offshore wind offers the following unique characteristics:

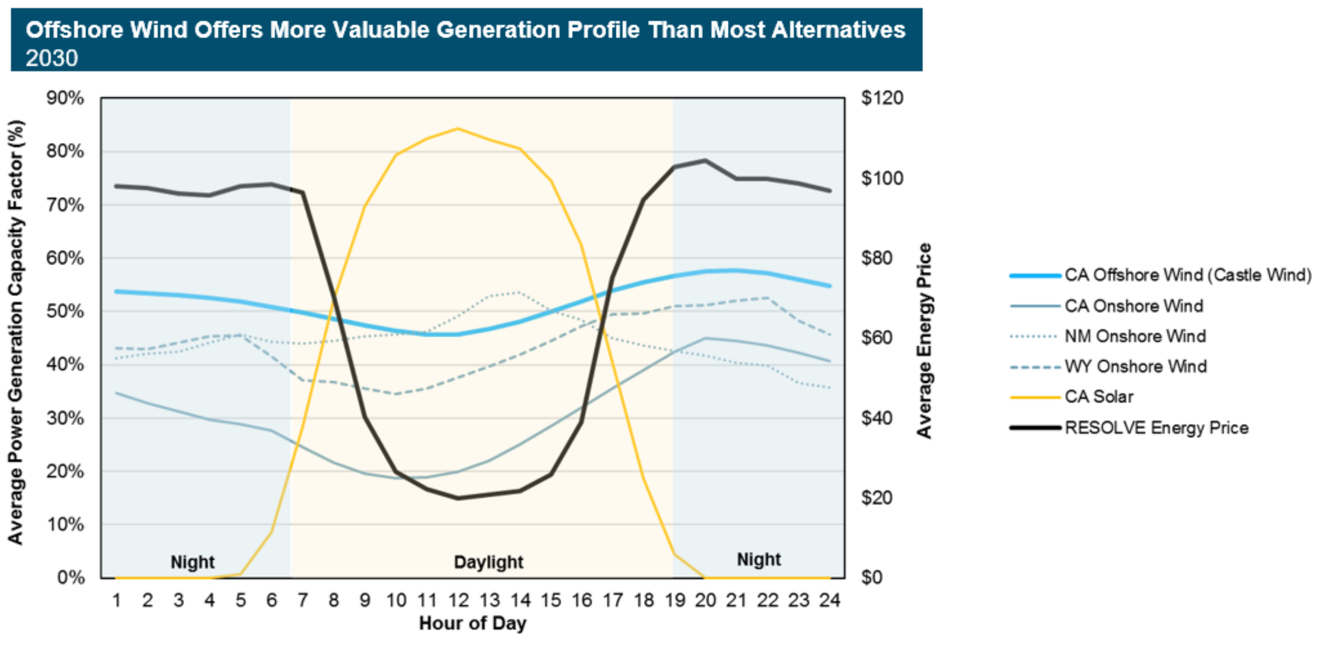
+ **Large and highly scalable.** California faces diminishing resource potential for onshore wind, as the best sites have already been developed. Offshore wind could unlock an untapped resource at a larger scale than that of many of today's remaining onshore resources. Offshore wind projects in the Northeastern U.S., such as the projects ranging from over 800 MW to 1.1 GW recently procured by Massachusetts, New Jersey and New York, are being built at a scale several times larger than most of California's current wind projects.[14] Given the scale of the state's future clean energy goals, the opportunity to build at the gigawatt scale may be a key to meeting its long-term needs.
+ **Less constrained by land use issues.** While offshore wind is subject to novel siting concerns (e.g., the Department of Defense's exclusion zones, fisheries, and ocean shipping lanes), it may face less community resistance because offshore wind turbines can be placed beyond the visible horizon from shore. This makes offshore wind a useful alternative to onshore resources if protecting local viewsheds is a priority or a legal necessity.
+ **Deliverable directly to coastal load centers.** Compared to other renewable technologies, offshore wind faces considerably fewer obstacles to delivering power to the areas where it is needed most. Offshore wind power can be routed directly into coastal load pockets via undersea cables and can provide a second life for existing transmission infrastructure at coastal power plants that are slated for retirement.[15] For example, the expected retirement

[14] https://www.utilitydive.com/news/new-jersey-taps-rsteds-11-gw-offshore-wind-project-in-countrys-largest/557443/; https://www.utilitydive.com/news/new-york-awards-record-1700-mw-offshore-wind-contracts/559091/
[15] In this study, E3 did not evaluate the cost of undersea transmission cables needed for delivery into coastal load pockets or the local capacity value associated with interconnection of offshore wind in a capacity-constrained zone.

by 2025 of the Diablo Canyon nuclear plant will free up multiple gigawatts in transmission capacity. Likewise, several coastal power plants from Morro Bay to Los Angeles are scheduled to retire or have already shut down, leaving behind valuable transmission infrastructure that can be utilized as a point of interconnection for offshore wind.[16]

+ **Generates more output in valuable, carbon-intensive evening hours.** Delivering clean, reliable power in evening hours will require investment in both energy storage, to shift excess solar power to the time of day when it is needed most, and renewable resources that continue to generate energy once the sun goes down. Offshore wind fulfills the latter need by generating most of its energy during valuable and higher-emission evening hours, which may also reduce the state's future reliance on grid-scale lithium-ion battery storage.

Figure 4: Projected Average Renewable Resource Hourly Generation Profiles vs. 2030 Average Energy Prices in Model



Each of these attributes may make offshore wind a valuable tool in achieving California's climate goals. **This study attempts to quantify the approximate value of offshore wind to the grid for each of these**

[16] For example, the Scattergood plant in Los Angeles, which was the subject of LADWP's recent transmission upgrade, is slated to close by 2025, leaving behind a high-voltage transmission line that may become underutilized unless a new generation source is connected at the site of the coastal plant.

attributes by using a standard system planning tool, RESOLVE, that simultaneously accounts and optimizes for these different factors.

1.5 Rationale for Study of Economic Value of Offshore Wind Power

California has ambitious climate goals that will require major changes in the state's future energy supply portfolio. In particular, the state's RPS program and GHG reduction targets will demand investment in renewable energy at a scale well beyond current levels. However, several technical, cultural, and economic challenges must be overcome in order to achieve these climate goals. Renewable energy deployment at the required scales will lead to difficult decisions regarding where the state sources its power and whose backyards are impacted by new generation and transmission development. Offshore wind power off the coast of California has a unique set of potentially beneficial characteristics, as detailed in Section 1.4, that may have a role in achieving the state's long-term goals.

As the state continues to plan for a future decarbonized economy, it will be valuable for decisionmakers and planners to consider all resources that could reduce the state's emissions most effectively at the least cost and to better understand the potential role of offshore wind in meeting these long-term goals. For this reason, Castle Wind has asked E3 to study the economic value of offshore wind in meeting California's policy goals and to determine the potential market size and systemwide cost savings if offshore wind were to be deployed at scale.

2 Description of the Study

2.1 Purpose of Study

Castle Wind asked E3 to study the economic value of offshore wind power in California and to determine the potential market size and total electric system savings if this technology were to be deployed at scale. To do so, E3 used a public version of its RESOLVE model to estimate the total system costs of meeting California's clean energy policies both with and without offshore wind as a future resource option. This study focuses on the time horizon through 2040 and uses the policy milestone years of 2030 and 2040 as key points of reference.

2.2 RESOLVE Model

E3 has created proprietary versions of the RESOLVE model to support numerous IRP efforts across North America. The analysis in this study was performed in the latest public version of the RESOLVE model that supports the CPUC's Integrated Resource Planning (IRP) process. Using this model allowed the study to analyze the potential role of offshore wind under similar assumptions to the ones underlying the state's current long-term planning and procurement regime. The domain of this model is the California Independent System Operator (CAISO) grid, which serves approximately 80% of the electricity demand in California and includes both the major wholesale market participants over which the state has regulatory authority (i.e., Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric) and the growing number of Community Choice Aggregators (CCAs) that procure power in wholesale markets. Through its use in the CPUC IRP, the RESOLVE model helps to determine the optimal portfolio of resources that the above-mentioned load-serving entities (LSEs) should target in their procurement efforts through 2030. This study uses the CPUC RESOLVE Model with 2017 Integrated Energy Policy Report (IEPR) released

April 23, 2018 as a starting point, and updates several of the assumptions based on inputs provided by Castle Wind.[17]

The CPUC RESOLVE model was modified in two key ways for this study: 1) offshore wind was introduced as a new resource option for possible selection by the model; and 2) costs for solar PV, onshore wind, and lithium-ion battery storage were updated to more current values in certain scenarios to reflect recent cost declines that are not captured in the default CPUC model assumptions. The details of these modifications and the input data themselves are provided in the Appendix of this report.

2.3 Key Scenarios and Model Assumptions

E3 modeled several different scenarios as part of this study to test the results' sensitivity to varying GHG policy, resource cost, and out-of-state resource availability assumptions. Other model inputs were left at the default values in the 2017-18 IRP RESOLVE model for consistency with prior California resource planning efforts. Key scenarios and assumptions are described in detail below.

2.3.1 COST SCENARIOS

For this study, one focus area and key set of assumptions concerned the model's new resource options and their associated costs. In particular, the model was highly sensitive to the costs of new offshore wind, solar, and battery storage capacity, which each serve as close substitutes in future resource selection. (In other words, the cheaper a resource is, the more likely the model is to select it.) Resource costs were modeled under two different scenarios: a "Reference Costs" scenario that inserts offshore wind into the 2017-18 IRP model with minimal modifications to other assumptions; and an "Industry Estimate Costs" scenario that reflects more current assumptions regarding current resource costs, including offshore wind costs provided by Castle Wind:

[17] Publicly available on the CPUC website at **https://www.cpuc.ca.gov/General.aspx?id=6442457210**

1. **Reference Costs:** existing costs in the 2018 IRP RESOLVE model, plus offshore wind at the 2018 National Renewable Energy Laboratory Annual Technology Baseline (NREL ATB) cost forecast. This scenario illustrates the potential findings if offshore wind had been included in the 2017-18 IRP process at the cost levels assumed by NREL's latest annual ATB report. *Note: During the preparation of this study, NREL released its 2019 ATB report which forecasts significantly lower costs for floating offshore wind than in the 2018 ATB report. NREL's latest cost projections are more closely aligned with the assumptions provided by Castle Wind in the Industry Estimate Costs scenario, which suggests that offshore wind may decline in cost faster than previously assumed.*

2. **Industry Estimate Costs:** updated capital, fixed operations and maintenance (FO&M), and variable operations and maintenance (VO&M) costs for wind, solar, and storage based on the 2018 NREL ATB, Lazard Levelized Cost of Storage Analysis – Version 4.0 (LCOS 4.0), and cost recommendations for offshore wind from Castle Wind. This scenario represents the most current set of widely accepted public cost assumptions available for solar, wind, and battery storage costs, per E3's view, plus Castle Wind's estimates of floating offshore wind costs in California.

Resource performance assumptions such as hourly and seasonal generation profiles and annual capacity factors (CF) for wind and solar were held the same in each scenario.[18] Key cost components in the two scenarios are summarized in Figure 5 below.

[18] Capacity factor is a measure of power plant energy generation divided by maximum possible generation output over a period of time. For example, if a plant runs at maximum capacity for 12 hours and has zero output for 12 hours, its capacity factor would be 50% over the total 24-hour period.

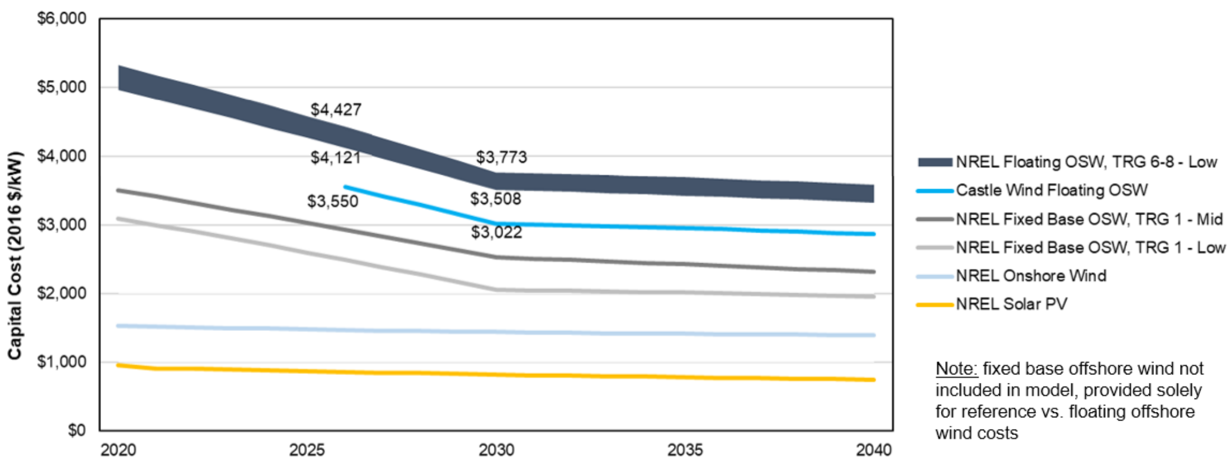
Figure 5: Renewable Resource 2030 Cost Input Summary Under Study Scenarios[19]

Resource Cost Scenario	2030 CA Resource Costs			
	Offshore wind	Solar PV	Onshore wind	Li-ion storage (4-hr duration)
Reference Costs Offshore Wind: 2018 NREL ATB TRG 8 – Low Case Other Resources: 2018 CPUC IRP RESOLVE	Capex: $3,773/kW[20] FO&M: $128/kW-yr CF: 52%	Capex: $1,892/kW FO&M: $26/kW-yr CF: varies, most 29% to 34%	Capex: $2,117/kW FO&M: $33/kW-yr VO&M: $3/MWh CF: varies, most 30%-36%	Capex: $1,407/kW FO&M: $14/kW-yr[21] CF: n/a
Industry Estimate Costs Offshore Wind: Castle Wind provided Other Resources: E3 updated based on 2018 NREL ATB, Lazard LCOS 4.0, and other public data	Capex: $3,022/kW FO&M: $55/kW-yr CF: 52%	Capex: $1,135/kW FO&M: $9/kW-yr CF: varies, most 29% to 34%	Capex: $1,454/kW FO&M: $46/kW-yr CF: varies, most 30%-36%[22]	Capex: $608/kW FO&M: $43/kW-yr CF: n/a

Another key assumption regarding resource costs is their evolution over time. For the purpose of this study, E3 assumed that the offshore wind cost quote provided by Castle Wind would relate to a 2026 commercial operations date (COD), then offshore wind costs would decline thereafter by the same percentage as assumed in the 2018 NREL ATB cost forecasts. The future capital cost trajectories for floating offshore wind from NREL and Castle Wind, as well as bottom-fixed offshore wind, solar, and onshore wind for reference, are shown in Figure 6.

[19] Onshore wind O&M in the 2017-18 IRP is split between fixed and variable costs, with the total representing approximately a similar total as in the Industry Estimate Costs scenario.
[20] Capital cost assumptions for floating offshore wind from the 2018 NREL ATB include $730/kW in grid connection costs that represent the cost of a spur line to connect offshore wind generation to onshore transmission. This study does not evaluate the cost of onshore transmission upgrades, which may vary by location and cost recovery provisions.
[21] FO&M in the 2018 IRP RESOLVE scenario is represented as a percent of capex. The Industry Estimate Costs scenario reflects a more current understanding of storage costs including capex declines but higher opex that includes extended warranty and storage system augmentation costs.
[22] Small amount of wind potential (<500 MW) with CF of over 36% is available in RESOLVE, but majority of resource is 36% CF or lower. Likewise, a small amount of solar potential is available at CFs above 33%, but a majority of the resource is modeled at a 33% CF or lower.

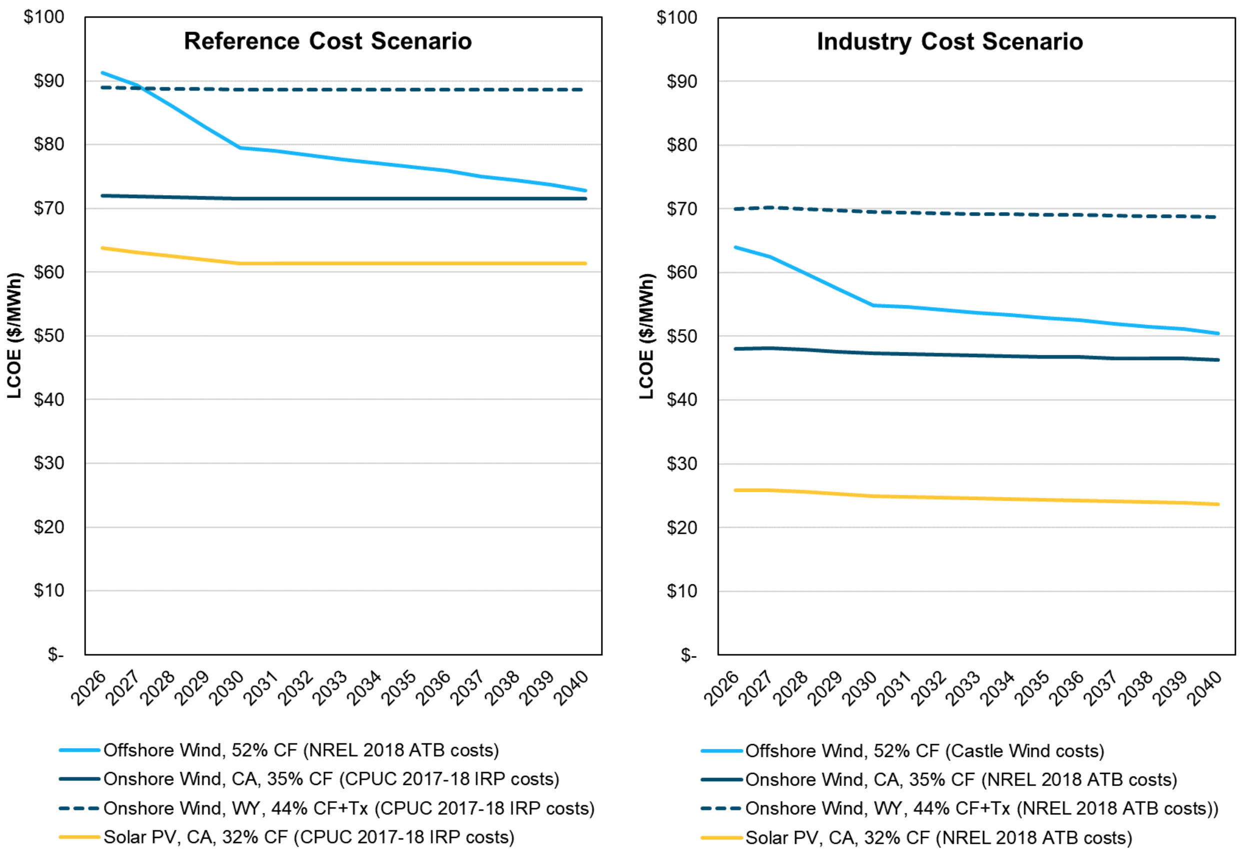
Figure 6: Renewable Resource Capital Cost Assumptions Over Time



The operating lifetime for an offshore wind project in E3's financial model is assumed to be 30 years, with financing via 20-year debt at a 70%/30% debt/equity ratio and a project weighted average cost of capital (WACC) that declines over time in line with the 2018 NREL ATB's financing cost assumptions as the technology becomes more commercially mature.[23] **Calculating levelized costs using representative California production assumptions of 52% capacity factor for offshore wind, 35% for onshore wind, and 32% for utility-scale solar PV yields a picture where offshore wind declines substantially in levelized cost of energy (LCOE) and begins to approach comparability with onshore wind at around $50/MWh by 2040,** as shown in Figure 7. While this range of levelized costs for floating offshore wind is lower than that predicted by NREL, it aligns with projections from WindEurope which forecast LCOEs of 40-60 €/MWh ($45-$68/MWh) for floating offshore wind by 2030.[24] It is important to note that LCOE is not the sole driver of the model's resource selection, as the relative valuation of different resources also depends upon their hours of generation and relative ability to meet peak load needs.

[23] Castle Wind estimates that the first floating projects will feature a 60%/40% debt/equity ratio. E3's assumption of a 70%/30% debt/equity ratio is associated with likely financing in the long term once floating offshore wind technology is more widely commercialized.
[24] https://windeurope.org/wp-content/uploads/files/policy/position-papers/Floating-offshore-wind-energy-a-policy-blueprint-for-Europe.pdf

Figure 7: Example 2026-2040 LCOEs for California Renewable Resources Under Study Assumptions



As a modeling simplification, the offshore wind costs in this study were fixed by COD, which is how all other resource costs are treated. Effectively, offshore wind is assumed to decline in price on a fixed schedule over time, which correlates with growing industry experience from commercial deployment in other jurisdictions. One factor that is not considered in this model is the effect of local scale on offshore wind costs. For example, a single 800-MW offshore wind project in California would be more costly on a $/MW basis than 5,000 MW of offshore wind due to the spreading of supply chain costs over a smaller amount of capacity. Instead of scaling costs over a growing base of installed capacity, which would require a much more detailed cost study and model, this RESOLVE analysis assumes a fixed cost profile per MW that is more reflective of a mature future offshore wind industry on the West Coast.

As with costs, the performance of offshore wind is also modeled using a single representative project profile rather than a more granular supply curve that represents multiple offshore sites. For simplicity, the RESOLVE model analyzes the demand for a single generic class of offshore wind based on measured wind speeds, simulated generation from a 12-MW turbine, and estimated project costs in the Morro Bay area provided by Castle Wind based on initial industry quotes. To the extent that better offshore wind resources or complementary onshore resources that offer diversity benefits might exist elsewhere, the model may have underestimated the total system value of offshore wind due to its reliance on a single representative location. Lastly, this model did not consider transmission and ocean usage constraints on the available capacity of offshore wind. Effectively, the model was given an unlimited amount of offshore wind potential in order to estimate the optimal capacity without regard to any existing limitations.[25]

2.3.2 POLICY SCENARIOS

Another central assumption in this model is the amount of power sector emissions reductions required by the state's GHG policy. While the state has set economy-wide GHG targets for 2030 and 2050, there is still uncertainty as to how much each sector of the California economy must reduce its emissions. In 2017, the California Air Resources Board (CARB) Scoping Plan identified a 2030 emissions target range of 30-53 million metric tons (MMT) for the power sector, reflecting a reduction of 51% to 72% below 1990 levels.[26] The CPUC then identified two policy scenarios for modeling caps on 2030 power sector carbon emissions for the 2017-18 IRP process: a 42 MMT case and 30 MMT case. In the CPUC's words:

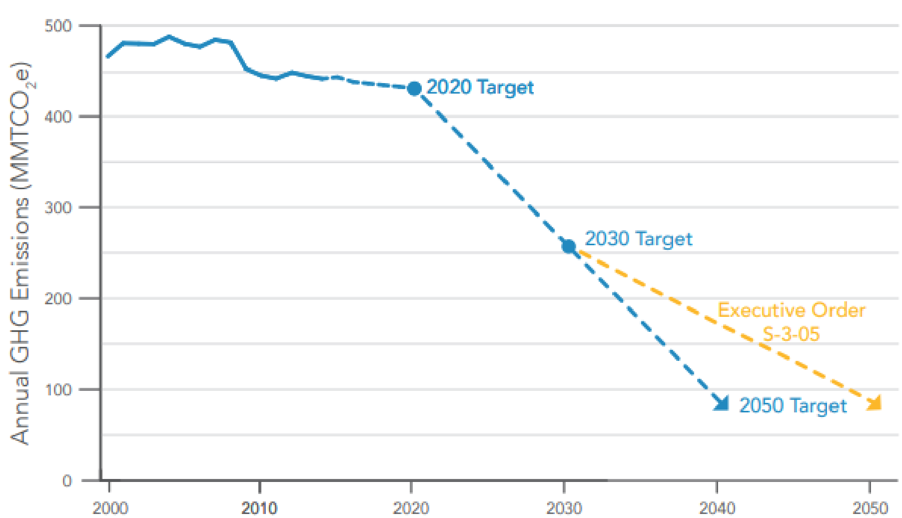
> The 42 MMT case reflects the "low end of estimated range for [the] electric sector in [the] CARB scoping plan; [and] reflects [a] scenario in which the state GHG reduction goal is achieved with 40-85 MT of reductions from unknown measures." The 30 MMT case reflects "electric sector emissions in [a] CARB scenario in which [the] state GHG reduction goal is achieved with known measures."[27]

[25] The amount of solar and onshore wind potential was left at the default finite values specified in the CPUC RESOLVE model. Onshore solar and wind potential in the model are composed of discrete location-specific resources with differing profiles for cost, performance, and transmission needs.
[26] https://ww3.arb.ca.gov/cc/scopingplan/scoping_plan_2017.pdf
[27] https://www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/ElectPowerProcurementGeneration/irp/AttachmentA.CPUC_IRP_Proposed_Ref_System_Plan_2017_09_18.pdf

The CPUC GHG targets use a slightly different accounting than the CARB scoping plan; CARB's plan would add another 4 MMT for behind-the-meter cogeneration emissions not considered by the CPUC. This means that the CPUC's 42 and 30 MMT metrics translate to 46 and 34 MMT by CARB's accounting, both of which still lie within the CARB Scoping Plan range. For the CPUC IRP, the 42 MMT planning target was selected as the baseline for the 2017-18 planning cycle, but the 30 MMT scenario was also run for a point of comparison. In neither case did the CPUC or CARB establish a follow-on 2050 target for power sector emissions.

E3 modeled the two existing planning scenarios for power-sector GHG emissions in California: the 42 MMT reference case and 30 MMT alternative case specified in the 2017-18 CPUC IRP to align with the CARB 2017 Scoping Plan. While these assumptions align with state planning targets for the 2030 timeframe, there is not yet a formal target for power sector emissions in 2050. The CARB Scoping Plan noted that, if 2030 targets are achieved, multiple paths may exist that lead to compliance with 80% by 2050 goals, as shown in Figure 8.

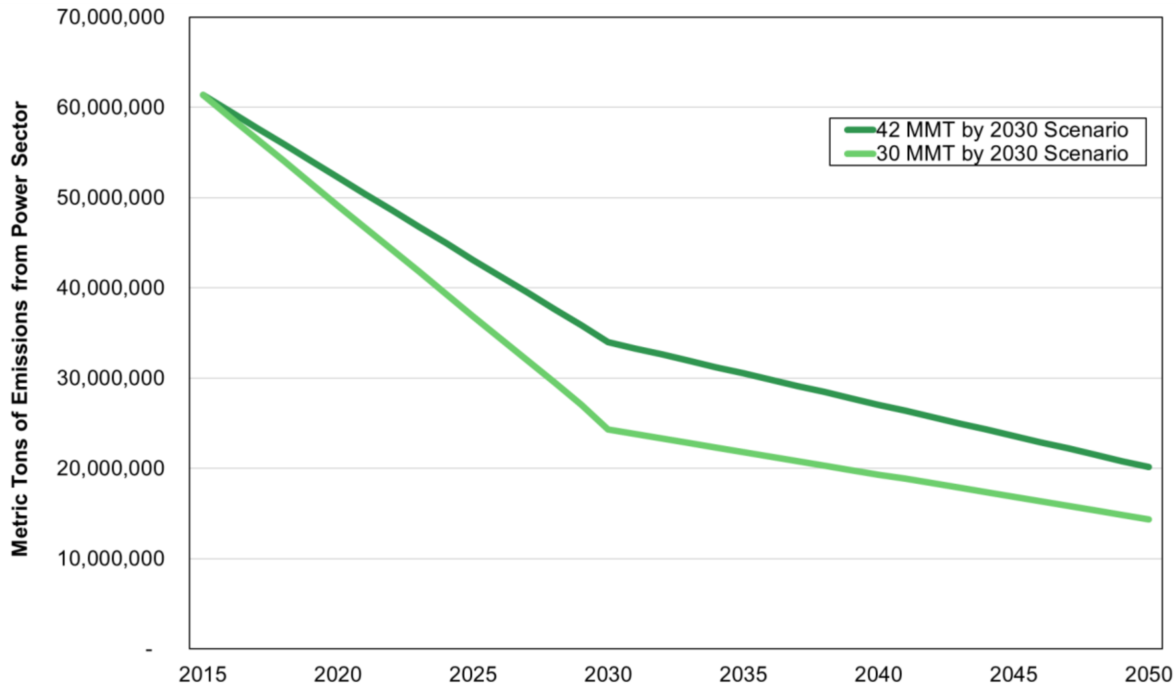
Figure 8: CARB Scoping Plan Figure Showing Potential Post-2030 GHG Emissions Trajectories[28]



[28] CARB 2017 Scoping Plan, https://ww3.arb.ca.gov/cc/scopingplan/scoping_plan_2017.pdf

This study analyzed the two default GHG trajectories included in the CPUC IRP RESOLVE model, which are depicted in Figure 9 below.

Figure 9: Power Sector GHG Cap Scenarios Modeled in RESOLVE



2.3.3 RESOURCE OPTION SCENARIOS

The study also considered alternative scenarios for out-of-state resource availability to serve California's clean energy demand. In the base case scenario, out-of-state resources are limited to delivery via existing transmission lines (e.g., limited amounts of Pacific Northwest wind or Southern Nevada geothermal can be selected by the model). In the alternative scenario, new transmission is allowed as an option to deliver up to 4,250 MW of out-of-state wind resources from New Mexico and Wyoming. Costs associated with firm transmission of out-of-state wind are assumed to be $120 and $125/kW-yr for NM and WY respectively, as defined in the CPUC 2017-18 IRP, which translate to an LCOE adder of approximately $30/MWh for energy delivered to California.

All in-state resource options were held fixed at the default values specified in the 2017-18 CPUC IRP RESOLVE model for consistency with prior state resource planning efforts. The in-state resources reflect a diverse set of onshore renewable sites with varying performance, cost, and transmission characteristics. As the RESOLVE model identifies optimal future portfolios, it first selects the most valuable sites and, when those are exhausted in capacity, moves to the next most valuable sites. E3 did not consider cases where onshore solar or wind potential might be more limited than the default values due to future restrictions in land use, transmission access, or from other onshore development challenges.

2.3.4 LOAD GROWTH AND ELECTRIFICATION ASSUMPTIONS

Another major input that was not considered in detail in this study was future load growth from electric vehicles and building electrification, both of which may be necessary to meet the state's GHG goals. These inputs were left at the default values assumed in the CPUC 2018 IRP process, which were based on the CEC's 2017 Integrated Energy Policy report (IEPR) released in March 2017.[29] To the extent that the state's current electrification goals exceed the 2017 CEC projections, the model will likely underestimate the total demand for clean energy and thus offshore wind. For example, the CEC's 2017 IEPR forecast for electric vehicle (EV) adoption is 3.3 million light-duty vehicles by 2030, which is now superseded by the state's goal of 5 million EVs by 2030.[30] Such an increase in EVs would likely increase the state's annual electricity consumption by approximately 2.5% in 2030. Long-term demand driven by building and transportation electrification may be even higher, potentially adding nearly 30% to the state's baseline electric load by 2045.[31] In these higher demand scenarios where California meets its long-term GHG-reduction goals via electrification, the need for offshore wind may be significantly larger.

[29] https://ww2.energy.ca.gov/2017_energypolicy/
[30] https://efiling.energy.ca.gov/getdocument.aspx?tn=223205 and https://www.cpuc.ca.gov/zev/
[31] E3 CEC PATHWAYS RESOLVE model

3 Study Results

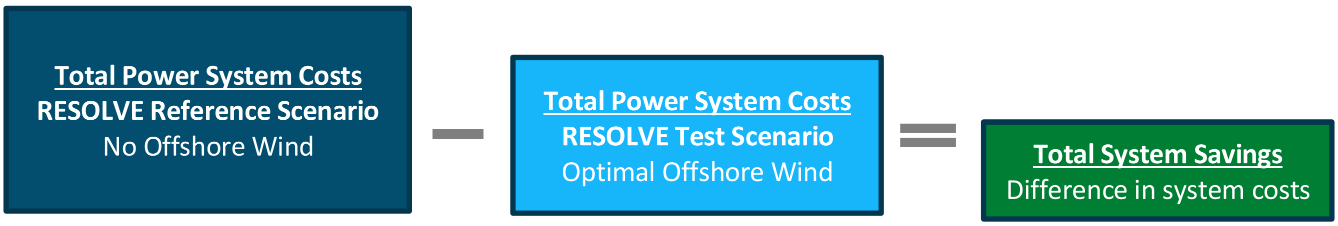
The study results are presented in terms of two model outputs that vary over the model forecast horizon:

1. **Total Offshore Wind Capacity (MW)**: the RESOLVE model identifies the optimal mix of future investments needed to serve forecasted electricity demand on an hourly basis while meeting the state's clean energy goals. The amount of offshore wind selected as part of this "least-cost portfolio" of resources reflects the optimal buildout in a given year, subject to the provided assumptions for resource costs and performance over time.

2. **Total Electric System Costs ($)**: the RESOLVE model optimizes the amount of offshore wind and other future resource investments subject to total system costs, which include both fixed and variable costs of operating the grid, such as fuel costs, operations and maintenance costs (O&M), capital costs for constructing and financing new resources, transmission costs for interconnecting new resources, and any applicable taxes and/or tax credits. This summary metric reflects the total costs charged to ratepayers and thus the net bill impacts of the modeled scenarios.

To quantify the economic value of offshore wind, this study compares the total system costs both with and without offshore wind made available as a future resource option in the RESOLVE model. **Modeling results across all scenarios found that offshore wind was a least-cost resource option for which demand increases over time, and that including 7-9 GW of offshore wind capacity in the state's energy mix by 2040 would produce ratepayer savings of approximately $1 to $2 billion** on a net present value (NPV) basis, or an average of 25 cents per month in residential energy bill savings. For context, 7 GW of capacity would supply over 10% of the state's energy needs, which is enough energy to power over 4 million homes.

Figure 10: Methodology for Calculating Total System Value of Offshore Wind



While a number of input sensitivities were modeled, this report focuses on the results for four core scenarios. These scenarios reflect each of the combinations between the resource cost and GHG policy sensitivities modeled by E3, as shown in the figure below.

Figure 11: Four Core Scenarios Reflect Combination of GHG Policy and Resource Cost Sensitivities

	Policy Scenario	
Resource Cost Scenario	SB 100 42 Mt GHG Target	SB 100 30 Mt GHG Target
Reference Costs Offshore Wind: 2018 NREL ATB Low Scenario Other Resources: 2018 CPUC IRP RESOLVE defaults	✓	✓
Industry Estimate Costs Offshore Wind: Castle Wind provided Other Resources: E3 update based on 2018 NREL ATB, Lazard LCOS 4.0, and other public data	✓	✓

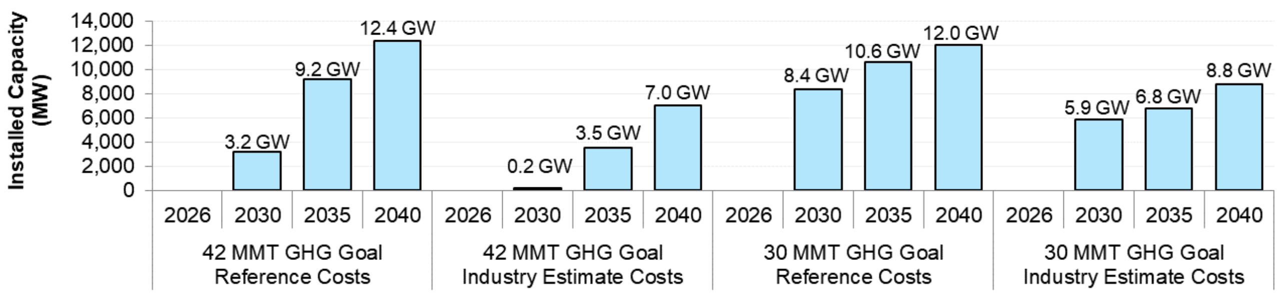
Because the high transmission costs associated with out-of-state wind prevent that resource from being selected over offshore wind in any of the out-of-state resource scenarios, the results for those scenarios are nearly identical to the results for the four scenarios presented here.

3.1 Optimal Offshore Wind Capacity by Year

Two clear trends emerge in the resource buildout results across all four focus scenarios. The first is a clear increase in demand for offshore wind over time: in all cases, the amount of offshore wind increases in every model year from 2030 through 2040. The second trend is that the optimal amount of offshore wind demand is larger in every year when the GHG policy target is set at 30 MMT versus 42 MMT. This is an intuitive finding that reflects the increasing value of offshore wind's ability to offset carbon emissions under a more stringent GHG cap.

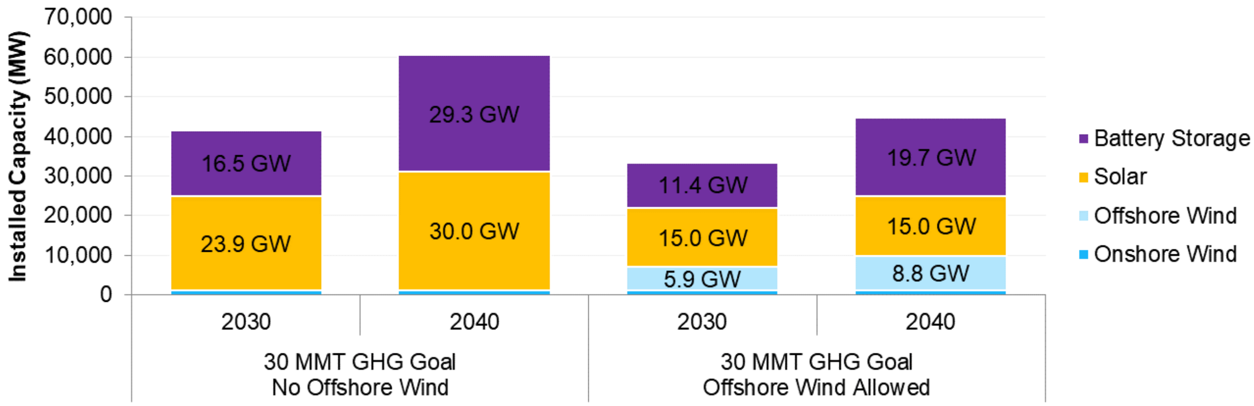
The optimal amount of offshore wind capacity selected by the model in each year ranges from 7 to 12+ GW by 2040, with at least 3.5 GW of offshore wind appearing by 2035 in all four core scenarios.

Figure 12: Cumulative Offshore Wind Capacity in RESOLVE by Modeled Year for Focus Scenarios (MW)



Another trend worth highlighting in the capacity built is that capacities are lower across the board in the Industry Estimate Costs scenarios. This is due to the significantly lower solar and battery storage costs in these scenarios, which reflect updates from the outdated solar and battery storage cost assumptions that are defaults in the 2017-18 IRP RESOLVE model (i.e., the Reference Cost scenario costs). The costs of solar and battery storage are particularly relevant to model outcomes because these are the resources that are most competitive with offshore wind. In fact, the amount of offshore wind capacity built in the model directly offsets a proportional amount of solar and battery storage capacity in each scenario, as illustrated in the following chart.

Figure 13: Cumulative Resource Capacity Selected by RESOLVE with and without Offshore Wind Included



This dynamic is a key finding of the study: offshore wind can save ratepayers by greatly offsetting total solar and battery storage needs in the future, particularly as GHG emissions caps become more constraining over time. In 2040 in the 30 MMT emission cap scenario, every 1 MW of offshore wind offsets 1.70 MW of solar PV and 1.09 MW of battery storage capacity, which significantly decreases total capacity needs as seen in Figure 13. This is a primary driver of the cost savings offered by offshore wind.

3.2 System Cost Savings for CAISO Ratepayers

The potential systemwide cost savings from offshore wind development can be quantified on both an annual basis and a total NPV basis across all future years. In general, the cost savings from offshore wind parallel the trends observed in the capacity buildout of offshore wind, with increasing value over time that reflects the value of offshore wind in offsetting increasingly costly GHG emissions. The total cost savings from offshore wind in the Industry Estimate Cost scenarios illustrate a general correlation over time with the depth of GHG reductions required, appearing higher in the 30 MMT GHG scenario and in more distant model years.

Figure 14: Annual Cost Savings from Offshore Wind and NPV of Total Future Cost Savings ($ millions)

GHG Target Scenario	2026	2030	2035	2040	2019 NPV of Savings
Industry Cost Estimates, 42 MMT GHG Cap in 2030	$2	-$9	$39	$149	$881
Industry Cost Estimates, 30 MMT GHG Cap in 2030	-$22	$216	$164	$193	$1,964

The total cost savings in both the 42 MMT and 30 MMT scenarios approach $150 to $190 million per year by 2040. In fact, once the CAISO system GHG emissions cap falls below about 30 MMT, which occurs by 2030 in the 30 MMT case and 2040 in the 42 MMT case, the systemwide savings from offshore wind increase to at least $149 million per year. This appears to be the GHG cap threshold beyond which cost savings from offshore wind grow significantly.

4 Conclusions

When envisioning a power system with large amounts of variable renewable energy, system planners must include information on the least-cost manner of reliably operating that system, in both the present and future. Full consideration of all resource options is important when planning for a future grid with different technical needs and economic considerations than the grid of today. Based on this study, **offshore wind could be a valuable and significant resource for meeting the state's long-term policy goals in the least-cost manner**.

The latest cost estimates for floating-base offshore wind suggest that it could play a major role as an economic renewable resource under California's clean energy and GHG reduction policies, with at least 3.5 GW of offshore wind by 2035 and a total of 7–9 GW by 2040 across all scenarios studied. If developed at this scale, offshore wind has the potential to save ratepayers approximately $1 to $2 billion on an NPV basis. Savings would increase over time to approximately $150 to $190 million per year in 2040.[32]

Offshore wind development would directly offset the state's projected reliance on solar PV and battery storage, with each megawatt of offshore wind replacing the need for approximately 1.7 MW of solar and 1.1 MW of storage. In the low GHG scenario (30 MMT case) modeled, 8.8 GW of offshore wind installed by 2040 would offset the need for 14.9 GW of solar generation plus 9.6 GW of battery storage.

The addition of offshore wind would therefore help diversify the state's future energy mix. Given the unpredictable nature of resource costs in the future (e.g., see solar PV module tariffs or the volatile prices of oil and gas), offshore wind appears to be a valuable and significant resource that warrants further consideration for its ability to help meet California's long-term decarbonization goals in the most cost-effective way possible while diversifying the state's energy supply and mitigating risks from heavy reliance

[32] Savings do not consider cost or timing of bulk transmission upgrades needed for delivery of full wind capacity built in RESOLVE model

on two specific technologies (i.e., solar PV and battery storage). If existing challenges associated with onshore renewable energy and transmission development persist or grow more restrictive in the future, offshore wind may provide the scalable resource option California needs to stay on track towards its 2050 goals.

5 Areas for Future Research

This study outlines some of the economic considerations around the optimal timing of offshore wind deployment in California and the total future demand for offshore wind capacity. In this study, E3 did not consider limits to resource potential or development timelines due to offshore permitting and transmission constraints, both of which are critical path items to any future commercial development of offshore wind. This study also did not account for Local Resource Adequacy value, which could benefit offshore wind that is interconnected in coastal load pockets such as the L.A. Basin. Such site-specific considerations will require further study to test the economics of future offshore wind development on a project-by-project basis.

Further work is necessary on many fronts to better understand the challenges involved with California's ambitious climate goals and to realize the potential opportunities presented by offshore wind, including:

+ **Identification of areas available for offshore wind development.** This study did not consider the relative merits of specific sites for offshore wind development, but instead modeled a generic offshore wind profile representative of California's offshore resources. The available capacity of this offshore wind resource was unbounded and limited only by economic potential. However, the ideal siting of future offshore wind development is a key question for the state's system planners that requires further in-depth study and must be answered before this resource's value can be realized.

+ **Transmission costs and available capacity at points of interconnection** must be identified. Such a process would include assessments of how much offshore wind can be delivered into existing transmission infrastructure, design studies on potential upgrades required to facilitate offshore wind development at a greater scale, as well as assesments of coastal load pockets where offshore wind interconnections could help displace gas generation needed for local capacity. For example, offshore wind would require transmission lines, potentially undersea cables, for delivery into San

Francisco or Los Angeles. Locational variations in transmission upgrade costs can be a key factor in determining where and at what scale offshore wind development is most economical.

+ **Cost forecasting for floating-base offshore wind systems**, both for actual commercial projects and forecasted for future technologies. There is limited public data available regarding both capital costs and O&M costs for floating offshore wind. Development of commercial-scale projects and more detailed costing studies will help generate the necessary cost data to facilitate more precise modeling of the economic opportunities and potential value presented by offshore wind.

+ **Additional offshore wind generation data for floating turbines,** whether real or simulated, will add certainty to the production estimates used when modeling this technology. The capacity factors and generation from offshore wind depend on wind speed, floating offshore wind system technology, degradation rates, maintenance outages, and other operating constraints. Additional research on and operational data from floating offshore wind systems will add certainty regarding the capacity factors to expect from floating offshore wind and the associated cost savings from this resource.

+ **Future load growth**, especially from electric vehicles and building electrification, both of which may be necessary to meet the state's GHG goals. California's goal of 5 million EVs by 2030 is likely to increase the state's annual electricity consumption by approximately 2.5% in 2030. Long-term demand driven by building and transportation electrification may be even higher, potentially adding nearly 30% to the state's baseline electric load by 2045. In these higher demand scenarios where California meets its long-term GHG-reduction goals via electrification, the need for offshore wind may be significantly larger.

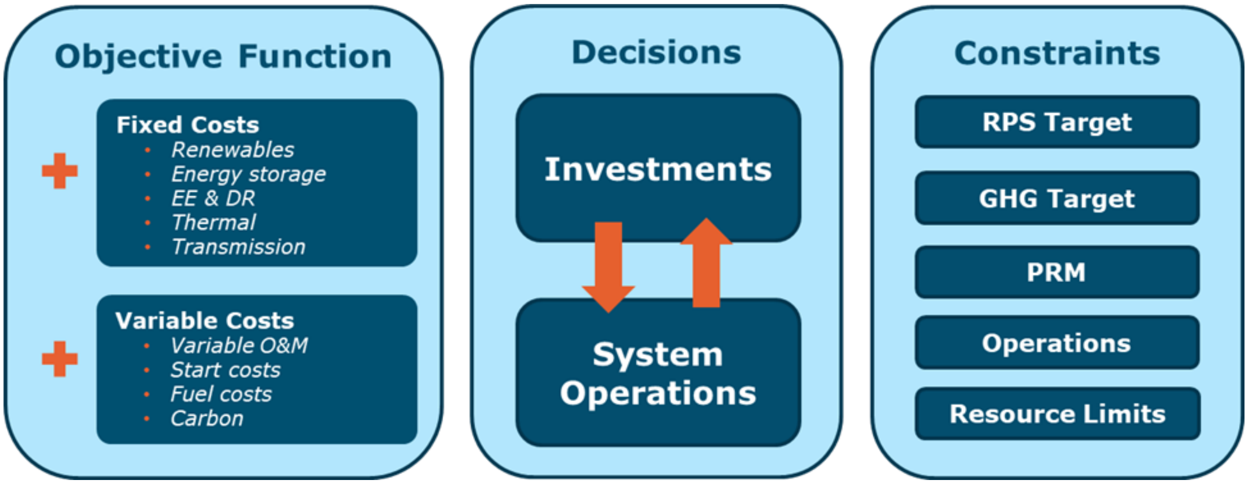
6 Appendix: RESOLVE Model Background and Detailed Model Assumptions

This appendix contains a detailed summary of key inputs and assumptions in the RESOLVE model used in this study.

6.1 RESOLVE Model Overview and Current Uses

RESOLVE is a capacity expansion model that uses linear programming to identify optimal long-term generation and transmission investments in an electric system, subject to reliability, technical, and policy constraints. Designed specifically to address capacity expansion questions for systems seeking to integrate large quantities of variable resources, RESOLVE layers a capacity expansion logic on top of a reduced-form production cost model to determine the least-cost investment plan, accounting for both the up-front capital costs of new resources and the variable costs to operate the grid reliably over time. In an environment where most new investments in the electric system have fixed costs significantly larger than their variable operating costs, this type of model provides a strong foundation to identify potential investment benefits associated with alternative scenarios.

Figure 15. RESOLVE Modeling Methodology



RESOLVE's optimization capabilities allow it to select from among a wide range of potential new resources. The full range of resource options considered by RESOLVE in this study is shown in Figure 16 below.

Figure 16. Resource Options Considered in RESOLVE

Resource Option	Examples of Available Options	Capabilities
Natural Gas Generation	• Simple cycle gas turbines • Combined cycle gas turbines • Reciprocating engines • Repowered CCGTs	• Dispatches economically based on heat rate, subject to operational constraints • Contributes to ramping & reserve needs • Provides large capacity value
Renewable Generation	• Geothermal • Hydro Upgrades • Solar PV • Onshore wind • Offshore wind	• Curtailable when needed to balance load • Provides partial capacity value based on ELCC
Energy Storage	• Batteries (>1 hr) • Pumped Storage (>12 hr)	• Balances variability of renewable generation by storing excess for later use • Contributes to ramping needs
Energy Efficiency	• HVAC • Lighting • Dryer, refrigeration, etc.	• Reduces load, retail sales, planning reserve margin need
Demand Response	• Interruptible tariff (ag) • DLC: space & water heating (res)	• Contributes to planning reserve margin needs

To identify optimal investments in the electric sector, maintaining a robust representation of prospective resources' impact on system operations is fundamental to ensuring that the value each resource provides to the system is captured accurately. At the same time, adding investment decisions across multiple periods to a traditional unit commitment problem increases its computational complexity significantly. RESOLVE's simulation of operations has therefore been carefully designed to simplify a traditional unit commitment problem where possible while maintaining a level of detail sufficient to provide a reasonable valuation of potential new resources. The key attributes of RESOLVE's operational simulation are enumerated below:

+ **Hourly chronological simulation of operations:** RESOLVE's representation of system operations uses an hourly resolution to capture the intraday variability of load and renewable generation. This level of resolution is necessary in a planning-level study to capture the intermittency of potential new wind and solar resources, which are not available at all times of day to meet demand and must be supplemented with other resources.

- **Planning reserve margin requirement:** When making investment decisions, RESOLVE requires the portfolio to include enough firm capacity to meet coincident system peak plus additional 15% of planning reserve margin (PRM) requirement. The contribution of each resource type towards this requirement depends on its attributes and varies by type; for instance, variable renewables are discounted compared to thermal generators because of limitations on their availability to produce energy during peak hours.
- **Greenhouse gas cap:** RESOLVE also allows users to specify and enforce a greenhouse gas constraint on the resource portfolio for a region. As the name suggests, the emissions cap requires that annual emission generated in the entire system to be less than or equal to the designed maximum emission cap. As it designs future portfolios, RESOLVE chooses both (1) how to dispatch new and existing resources to meet the goal (e.g., displacing output from existing coal plants with increased natural gas generation); and (2) what additional investments are needed to further reduce carbon in the system.

6.1.1 MODEL MECHANICS: INPUTS AND OUTPUTS

RESOLVE relies on a wide range of inputs and assumptions to carry out analyses. The key categories of these inputs and assumptions are summarized in Figure 15 below.

Figure 17. Summary of Core Inputs and Assumptions for RESOLVE

Input Category	Description
Policy constraints	Annual percentage of renewable energy credits (RECs) required and cap on GHG emissions
Demand forecast	Annual demand and peak forecast for the CAISO system
Existing resources	Capacity, commission dates, retirement dates and operating characteristics for all existing and planned resources within the CAISO system
New resources	Costs and performance for candidate resources considered in the portfolio optimization
Hourly profiles	Hourly profiles for all the components of demand; hourly generation profiles for solar and wind resources; hourly profiles for all other chronological hourly dispatch resources like EE
Fuel price forecasts	Fuel price forecast data for all thermal resources
NW and SW market representation	Load and resource assumptions for external zones connected to CAISO service territory

RESOLVE produces a wide range of useful output data for resource planning purposes. A few of the key results metrics include:

+ **Resource additions in each investment period (MW).** The cumulative total capacity of new resources added throughout the modeled period by RESOLVE as a result of its optimization.
+ **Annual generation by resource (GWh).** The generation by all the resources in the portfolio (existing and additional) in each of the modeled years.
+ **Annual renewable curtailment (%).** The level of curtailment experienced in each modeled year due to the imbalance between variable resource availability and hourly demand.
+ **Annual RPS level reached (%).** The level of renewable penetration achieved in each scenario expressed as a percentage of annual retail sales.
+ **Ongoing fixed O&M costs ($MM).** The ongoing cost for operating and maintaining existing resources.
+ **All-in fixed costs ($MM).** The costs associated with all the additional new resources in the portfolio.
+ **Variable & fuel costs ($MM).** The cost of generation for all resources.

- **Net cost (or revenue) ($MM)**. Associated with purchases (or sales) from external zones.

6.2 Key Model Inputs and Modifications Made to the CPUC 2018 IRP RESOLVE Model

Detailed model inputs related to candidate resource costs in the RESOLVE model under both the Reference Cost and Industry Estimate Cost scenarios can be found in the following tables.

Resource Capex ($/kW)

Scenario	Reference	Industry Estimate	Reference	Industry Estimate	Reference	Industry Estimate	Reference	Reference	Industry Estimate	Industry Estimate
Source	NREL 2018 ATB	Castle Wind	CPUC 2017-18 IRP	NREL 2018 ATB	CPUC 2017-18 IRP	NREL 2018 ATB	CPUC 2017-18 IRP	CPUC 2017-18 IRP	Lazard LCOS 4.0	Lazard LCOS 4.0
Year	Offshore wind	Offshore wind	Solar PV, tracking	Solar PV, tracking	Onshore wind	Onshore wind	Li-ion Battery Storage (capacity, $/kW)	Li-ion Battery Storage (energy, $/kWh)	Li-ion Battery Storage (capacity, $/kW)	Li-ion Battery Storage (energy, $/kWh)
2025	$4,584	$3,550	$1,798	$873	$1,566	$1,391	$290	$313	$34	$179
2026	$4,427	$3,550	$1,780	$862	$1,562	$1,377	$280	$302	$32	$169
2027	$4,267	$3,421	$1,756	$852	$1,559	$1,363	$272	$293	$31	$161
2028	$4,106	$3,290	$1,733	$842	$1,556	$1,350	$267	$288	$29	$154
2029	$3,940	$3,157	$1,712	$831	$1,553	$1,338	$265	$286	$28	$149
2030	$3,773	$3,022	$1,692	$821	$1,553	$1,327	$265	$286	$28	$145
2031	$3,759	$3,009	$1,692	$814	$1,553	$1,316	$265	$286	$27	$142
2032	$3,743	$2,996	$1,692	$807	$1,553	$1,306	$265	$286	$27	$141
2033	$3,726	$2,982	$1,692	$800	$1,553	$1,297	$265	$286	$27	$140
2034	$3,708	$2,967	$1,692	$793	$1,553	$1,288	$265	$286	$26	$138
2035	$3,690	$2,951	$1,692	$786	$1,553	$1,280	$265	$286	$26	$137
2036	$3,670	$2,936	$1,692	$779	$1,553	$1,273	$265	$286	$26	$136
2037	$3,649	$2,919	$1,692	$771	$1,553	$1,267	$265	$286	$26	$134
2038	$3,627	$2,901	$1,692	$764	$1,553	$1,261	$265	$286	$25	$133
2039	$3,606	$2,883	$1,692	$757	$1,553	$1,256	$265	$286	$25	$131
2040	$3,582	$2,864	$1,692	$750	$1,553	$1,251	$265	$286	$25	$130

Total Fixed O&M Cost by Model Year ($/kW-yr)

Scenario	Reference	Industry Estimate	Reference	Industry Estimate	Reference	Industry Estimate	Reference	Reference	Industry Estimate	Industry Estimate
Source	NREL 2018 ATB	Castle Wind	CPUC 2017-18 IRP	NREL 2018 ATB	CPUC 2017-18 IRP	NREL 2018 ATB	CPUC 2017-18 IRP	CPUC 2017-18 IRP	Lazard LCOS 4.0	Lazard LCOS 4.0
Year	Offshore wind	Offshore wind	Solar PV, tracking	Solar PV, tracking	Onshore wind	Onshore wind	Li-ion Battery Storage (capacity, $/kW)	Li-ion Battery Storage (energy, $/kWh)	Li-ion Battery Storage (capacity, $/kW)	Li-ion Battery Storage (energy, $/kWh)
2025	$111	$47	$26	$10	$33	$48	$3	$13	$1	$8
2026	$110	$47	$26	$10	$33	$48	$3	$13	$1	$8
2027	$110	$46	$26	$10	$33	$47	$3	$13	$1	$7
2028	$109	$46	$26	$9	$33	$47	$3	$12	$1	$7
2029	$108	$46	$26	$9	$33	$47	$3	$12	$1	$7
2030	$108	$46	$26	$9	$33	$46	$3	$12	$1	$7
2031	$107	$46	$26	$9	$33	$46	$3	$12	$1	$6
2032	$107	$46	$26	$9	$33	$45	$3	$12	$1	$6
2033	$106	$46	$26	$9	$33	$45	$3	$12	$1	$6
2034	$105	$46	$26	$9	$33	$45	$3	$12	$1	$6
2035	$105	$46	$26	$9	$33	$44	$3	$12	$1	$6
2036	$104	$46	$26	$9	$33	$44	$3	$12	$1	$6
2037	$103	$46	$26	$9	$33	$44	$3	$12	$1	$6
2038	$103	$46	$26	$9	$33	$43	$3	$12	$1	$6
2039	$102	$46	$26	$9	$33	$43	$3	$12	$1	$6
2040	$101	$46	$26	$8	$33	$42	$3	$12	$1	$6

Total Levelized Fixed Cost by Model Year ($/kW-yr)*

Scenario	Reference	Industry Estimate	Reference	Industry Estimate	Reference	Industry Estimate	All	All	Reference	Reference	Industry Estimate	Industry Estimate
Source	NREL 2018 ATB	Castle Wind	CPUC 2017-18 IRP	NREL 2018 ATB	CPUC 2017-18 IRP	NREL 2018 ATB	CPUC 2017-18 IRP	CPUC 2017-18 IRP	CPUC 2017-18 IRP	CPUC 2017-18 IRP	Lazard LCOS 4.0	Lazard LCOS 4.0
Year	Offshore wind	Offshore wind	Solar PV, tracking	Solar PV, tracking	Onshore wind	Onshore wind	NM wind Tx	WY wind Tx	Li-ion Battery Storage (capacity, $/kW)	Li-ion Battery Storage (capacity, $/kW)	Li-ion Battery Storage (energy, $/kWh)	Li-ion Battery Storage (energy, $/kWh)
2025	$464.27	$288.57	$182.28	$72.11	$221.03	$146.46	$120.14	$125.20	$30.18	$41.27	$3.80	$23.46
2026	$453.08	$291.27	$180.86	$72.36	$220.71	$147.12	$120.14	$125.20	$29.10	$39.79	$3.58	$21.98
2027	$441.60	$284.66	$178.89	$72.56	$220.38	$147.74	$120.14	$125.20	$28.31	$38.71	$3.39	$20.77
2028	$423.23	$273.11	$177.15	$71.71	$220.05	$146.91	$120.14	$125.20	$27.80	$38.02	$3.23	$19.76
2029	$405.45	$261.44	$175.52	$70.72	$219.72	$145.96	$120.14	$125.20	$27.55	$37.67	$3.08	$18.95
2030	$387.53	$250.01	$174.00	$69.78	$219.40	$145.08	$120.14	$125.20	$27.55	$37.67	$2.99	$18.36
2031	$383.38	$248.57	$174.00	$69.58	$219.40	$144.82	$120.14	$125.20	$27.55	$37.67	$2.94	$18.00
2032	$379.66	$246.59	$174.00	$69.22	$219.40	$144.36	$120.14	$125.20	$27.55	$37.67	$2.90	$17.75
2033	$375.89	$244.53	$174.00	$68.84	$219.40	$143.93	$120.14	$125.20	$27.55	$37.67	$2.87	$17.49
2034	$371.69	$242.86	$174.00	$68.61	$219.40	$143.72	$120.14	$125.20	$27.55	$37.67	$2.84	$17.29
2035	$367.50	$241.09	$174.00	$68.33	$219.40	$143.48	$120.14	$125.20	$27.55	$37.67	$2.80	$17.08
2036	$363.18	$239.30	$174.00	$68.04	$219.40	$143.28	$120.14	$125.20	$27.55	$37.67	$2.79	$16.92
2037	$359.61	$236.75	$174.00	$67.54	$219.40	$142.82	$120.14	$125.20	$27.55	$37.67	$2.75	$16.73
2038	$355.32	$234.81	$174.00	$67.24	$219.40	$142.66	$120.14	$125.20	$27.55	$37.67	$2.73	$16.60
2039	$351.06	$232.82	$174.00	$66.95	$219.40	$142.57	$120.14	$125.20	$27.55	$37.67	$2.72	$16.44
2040	$346.84	$229.91	$174.00	$66.35	$219.40	$142.07	$120.14	$125.20	$27.55	$37.67	$2.69	$16.26

*Total levelized fixed costs represents the total levelized cost of capital, financing, and fixed O&M. For renewable resources without variable cost of operations, such as wind and solar, these costs represent the total levelized costs of a new plant and can be converted to levelized cost of energy (LCOE) using an assumed capacity factor.