BASELINE DESCRIPTION for EPC-19-060

(Deliverable for Subtask 2.1)

February 2021

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

This Baseline Description gives a partial summary of the exploration and definition of the data inputs for modeling of the value of long-duration storage. We recognize the importance of accurate input parameters, but also recognize the high uncertainty of assigning single numbers when actual costs take on a distribution of values. Additionally, there is high uncertainty when extrapolating these into the future.

The data inputs to RESOLVE defined in the Reference System Portfolio (RSP) were carefully reviewed as part of the larger IRP process. After we studied changes that were identified in NREL's ATB and in other documentation, we chose to retain most of the RSP inputs with the following exceptions:

- Use 5-year intervals for defining the periods studied
- Set greenhouse gas targets in 2045 to zero, with a linear pathway to 2045
- Add offshore wind resources
- Modify the Li-battery model, reflecting the 4-hour batteries used in California
- Add additional EV load to reflect the 2020 Executive order accelerating adoption of EVs
- Add additional load for electrolyzers
- Implement baseline with new code under development by E3

Changes made to SWITCH as part of the update process include:

- Change the interest and discount rates from 7% to 5% reflecting the general decrease in interest rates in recent years
- Update capital costs for the different technologies using NREL's ATB 2020
- Update existing generation plants and retirements in the WECC using EIA 860 and 923 forms
- Use the Aggressive EE with Electrification scenario as the baseline
- Use a range of time steps for baseline implementation as described in the Modeling Approach Description

More details are provided in the companion Modeling Approach Description; some details are presented in both.

1. Introduction

This Baseline Description describes the data that will be used for the baseline evaluations. A second report “Modelling Approach Description” describes the modeling approach that will be used with the data inputs. The two reports are complementary.

Modeling of an electricity grid typically includes many – perhaps a million – inputs. We wish to be comprehensive in describing our inputs to the baseline, but we will also place special emphasis on inputs that would affect our conclusions about how long-duration storage will support California’s grid in the future. In general, after much discussion and thought, we have developed a philosophy of retaining the inputs that have been carefully vetted by California processes except in cases where we can point to specific reasons why those should be changed. We document some of our evaluation process to give a flavor for the analysis that we have done (which, in many cases, concluded to keep the current inputs).

Two capacity-expansion models will be used: RESOLVE and SWITCH. An overview of these is given in Table 1.1 describing the data elements of the two models. The rightmost column of Table 1.1 shows how the various elements of the models are organized in the Baseline Description (this document) and the Modelling Approach Description (associated deliverable). In Table 1.1, files for each type of information are indicated in blue.

Table 1. 1 Overview of RESOLVE and SWITCH and guide to document

Category of information	Type of information	RESOLVE	SWITCH	Section
Model details	Identifies modeling selected features	Features are identified as TRUE to select and FALSE to turn off feature_toggles.csv	Scripts that are loaded to the pyomo object are listed in modules.txt. SWITCH version is in SWITCH_inputs_version.txt	Overview in Section 2; details in Modeling Approach Section 2
	Baseline parameters	Modeling numbers that are not varied by the model, but may vary by period, including 11 baseline/scenario costs and five other values (including input carbon price and transmission losses) inputs_passthrough.csv		
	Discount factors	Discount factors and number of years in each period period_discount_factors.tab	Base year, discount rate (5%) and interest rate (5%) financials.csv.	
Time definitions	Periods	Is labeled by the year and is associated with the GHG emissions and renewable energy targets as well as with costs	The investment period is identified by a label and by starting and ending years in periods.csv	Overview in Section 2; details in Modeling Approach Section 3
	Continuous interval	RSP inputs use 24-hour days	timepoints.csv	
	Time step length	Fixed by code to by 1-hour time steps with all timepoints defined in timepoints.tab	A variable time step can be defined in timeseries.csv with Timeseries name, period, duration of timepoint, # of time steps and scaling factor for the period.	
	Selected intervals	RSP chooses 37 days and weights them to represent generation and load profile statistics representing a year day_weights.tab	The timepoints have an id (e.g., 1), a timestamp (e.g., 2025011512) and a timeseries label (e.g., 2020_all) as given in timepoints.csv	
Resource definition	Groups of resources	Includes 25 groups of solar resources and 12 groups of battery resources capacity_groups.tab		Section 3 & 4
	Generation	Generation resources are described by technology (technologies.tab) and zone, and whether they count in various tallies resources.tab The technologies have attributes regarding ramp rates, minimum up and down times, shut-down and start-up costs tech_dispatchable_params.tab and fuel requirements tech_thermal_params.tab	Generation resources are described by technology (non_fuel_energy_sources.csv) and zone. Maximum age, minimum build capacity, scheduled and forced outage rates, type of generation (baseload, variable), energy source and heat rate generation_projects_info.csv	Section 3
	Storage	Storage resources are described by efficiency & minimum duration tech_storage_params.tab		Section 4

Category of information	Type of information	RESOLVE	SWITCH	Section
Resource definition	Costs - fixed	Fixed annual CapEx and O&M costs by vintage (period when resource was built) for generating resource_vintage_params.tab and storage resources resource_vintage_storage_params.tab	Generator overnight cost and fixed O&M costs by build year in gen_build_costs.csv	Section 3 & 4
	Costs - variable	Cost of fuel fuel_prices.tab by fuel type, period and month	Fuel costs are given for each load zone and period in fuel_cost.csv	Section 3 & 4
	Planned builds	Planned builds of each resource reflect existing generators/storage and planned new builds and retirements planned_installed_capacities.tab planned_storage_energy_capacity.tab Minimum cumulative builds may be specified for each resource for each period. For example, in the RSP, Li batteries are required to be built min_cumulative_new_build.tab	Build limits for generation projects in generation_projects_info.csv	Section 3 & 4
	Build limits	Specified maximum cumulative build for each resource for each period. May reflect available sites and/or practical time to market capacity_limits.tab Specified maximum cumulative build for each group of resources (solar and batteries) for each period flexible_params.csv	The predetermined cap for each project and for each year is in Gen_build_predetermined.csv and generation_projects_info.csv	Section 3 & 4
	Details	Demand management program description conventional_dr_period_limits.tab. Solar and wind resources that may be curtailed resource_variable_renewable.tab. Cost associated with being curtailed zone_curtailment_costs.tab.	Project details include technology, zone, connection cost, capacity limit, heat rate, O&M, minimum build, outage rate generation_projects_info.csv	Section 3 & 4
	Hydro details	Expected hydro energy available for each hydro resource for each day with min and max limits hydro_daily_params.tab Ramp time and rate hydro_ramps.tab for CAISO Hydro and any other hydro resources hydro_resources_ramp_limited.tab		Section 3
Regions and transmission	Definition of regions to be modeled	Uses seven zones zones.tab.	Load zones with cost multiplier load_zones.csv. The load zones are linked to a balancing area in zone_balancing_areas.csv	Modeling Approach Description , Section 5

Category of information	**Type of information**	**RESOLVE**	**SWITCH**	**Section**
Regions and transmission	Definition of transmission zones	RSP has 23 transmission zones tx_zones.tab and further subdivides those into 48 resource transmission zones with characteristics resource_tx_zones.tab. Resource transmission zones are assigned to a transmission zone in resource_tx_zone_map.tab. Direction of flow simultaneous_flow_group_lines.tab for simultaneous flow groups simultaneous_flow_groups.tab		
	Transmission	Transmission lines are defined according to which zone they start and end in, the min and max flows, whether more can be built, etc. transmission_lines.tab. Hurdle rates (per MW) are given for transmission between zones for each period hurdle_rates.tab. Flow limits for each period simultaneous_flow_limits.tab	Transmission lines start and end, length, efficiency, & cap Transmission_lines.csv	
Reliability	Reserve margin	Planning reserve margin metrics for each period including a 15% reserve margin, peak load, annual load and planned imports planning_reserve_margin.tab. Penalties and other parameters system_params.tab	balancing_areas.csv gives reserve margins by zone; quick start reserve is 4% of load, spinning reserve is 2% of load	Overview in Section 5; details in Modeling Approach Section 4
	Margins required by timepoint	Reserve margins for each type of ancillary service for each timepoint reserve_timepoint_requirements.tab		
	Eligible resources	Available ancillary services reserve_resources.tab		
	Net qualifying capacity (NQC) fraction	NQC except for wind and solar (see next line). Dependence of the NQC on penetration of batteries is handled by defining multiple batteries and giving decreasing NQC for those built later resource_prm_nqc.tab		
	Electric load carrying capacity (ELCC) for solar and wind	ELCC coefficients for solar and wind as a function of solar and wind penetration elcc_surface.tab. the inclusion of a resource in the count of solar and wind penetration is in resource_variable_renewable_prm.tab		

Category of information	**Type of information**	**RESOLVE**	**SWITCH**	**Section**
Reliability	Maintenance derate values	Specified for each resource and as a function of timepoint without explicitly listing the timepoints flexible_params.csv		
	Generation profile and annual capacity factors	Fractional output (relative to plant rating) for each timepoint for solar and wind shapes.tab. Annual capacity factors for solar and wind resource_variable_renewable_prm.tab	The fractional output (relative to the plant rating) as a function of timepoint for solar and wind variable_capacity_factors.csv.	
Base loads and Policy-driven loads	Load	The load (including efficiency, electrification in general) for each zone and each timepoint zone_timepoint_params.tab	Load for each zone and timepoint loads.csv.	Section 6
	EV Charging efficiency	Charging efficiency for fleets ev_params.tab		Overview in Section 6; details in Modeling Approach Section 6
	EV batteries - Energy	Energy capacity and minimum charge for each fleet of EVs and period ev_period_params.tab		
	EV batteries - Power in and out	Power for drain of EV batteries and power plugged in for each EV fleet and at every time point ev_timepoint_params.tab		
	Hydrogen load definition	Minimum power and total energy for each hydrogen electrolyzer for each period and day hydrogen_electrolysis_daily_params.tab		
Policy Actions	Renewables targets	RPS targets for each period including definition of retail sales and targeted fraction of retail sales. RPS targets 87% of retail sales in 2045 renewable_targets.tab		Overview in Section 7; details in Modeling Approach Section 7
	GHG targets	Targeted tons of CO_2 emitted per year for each period. A credit is also indicated for each period. ghg_targets.tab		
	Emissions rates	Tons of CO_2 emitted per MMBTU for each fuel type fuels.tab Tons of CO_2 emitted per MWh associated with imports and exports as a function of period. RSP set to 0.428 for imports to CAISO, set to 0 for exports from CAISO ghg_import_rates.tab	CO_2 intensity and upstream CO_2 intensity fuels.csv	

1.1 Background - RESOLVE

RESOLVE was chosen as one of the primary models to use for this study because it has been used by California for defining the Reference System Plan (RSP) and various scenarios that, potentially can provide a starting point for this study. We feel it is useful that we will be able to use RESOLVE to express whatever results we obtain with other modeling software.

RESOLVE is a capacity-expansion model designed to inform California's planning for integration of renewable-electricity generation resources. RESOLVE identifies the lowest-cost path to meeting California's renewable energy and greenhouse gas emission targets. It selects investments in new electricity generation resources and optimizes dispatch of those resources over a multi-year period. It currently uses 37 days selected to represent the year.

The current version of RESOLVE was not written with the intent to study long-duration storage. As part of their companion work, E3 is upgrading RESOLVE to have the capabilities needed to study long-duration storage. In parallel with using RESOLVE, we will use other software. An introduction to SWITCH is found in section 1.2. More discussion of the modeling approach is in the companion deliverable entitled "Modeling Approach Description."

This document describes our analysis of the inputs that we will use for RESOLVE for the baseline model. We anticipate updating the inputs for the baseline as more information becomes available related to the effects of the pandemic, additional technological developments, and as the new version of RESOLVE is ready for our use. In particular, it is important to note that when the new version of RESOLVE is completed, it is probable that the inputs will differ from the current inputs. We anticipate shifting to the input files that will align with the new baseline of RESOLVE. We anticipate that those will include both changes to reflect the new structure of the code and updates reflecting changes that have occurred in recent months. Thus, the review that this document provides is most important for the philosophy it conveys and our identification of the inputs that are most important.

The RESOLVE model can be downloaded, complete with a full set of inputs, from the CPUC website.[1] This version was updated on March 23, 2020 and includes the Energy Commission's 2018 Integrated Energy Policy Report (IEPR) for the forecasted loads. Scenario A is labeled "46MMT_20200207_2045_2GWPRM_NOOTCEXT_RSP_PD" reflecting a number of assumptions. We have chosen to use this version as the starting point for our analysis, especially for calculations done with RESOLVE. The CPUC's description of how these RSP inputs were derived as part of the 2019-2020 CPUC IRP can be found online.[2]

This RSP optimizes investment within the CAISO balancing area and optimizes dispatch (but not investment) in six other areas adjacent to CAISO.

---

[1] https://www.cpuc.ca.gov/General.aspx?id=6442464143

[2] https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M331/K772/331772681.PDF

In the creation of the RSP, the concerns tabulated in Table 1.2 were identified as not being fully addressed:[3] In creating our baseline description, we considered these concerns and have described our analysis of how we could best respond.

Table 1. 2 Summary of previous concerns and our analysis of them

Public comment[3]	Our analysis
A common concern was that the cost data for renewable generation utilizes the 2018 National Renewable Energy Laboratory Annual Technology Baseline. A 2019 version has been produced since analysis began in this round of IRP. In addition, there were particular complaints about solar and battery cost assumptions not aligning with market prices, and therefore representing higher costs than parties would have preferred.	Changes in NREL's ATB reflected some small decreases in prices, but we found that these were smaller than the uncertainty in the analysis. We also found that, while in some cases lower prices could be documented, in general, careful study showed that prices in California tend to be higher than the national average documented in NREL's ATB. We plan to analyze the sensitivity to the price inputs. To reduce confusion, we decided to retain the values that are already being used with the distributed version of RESOLVE and then document specific changes to those as part of the later study
A number of parties, including CESA, also lamented the lack of representation of gas/storage or solar/storage hybrid resources in the assumptions.	We will be adding multiple storage resources as part of the study.
TransWest commented that transmission costs need to be updated	It is unclear from this comment what the requested change would be
With respect to battery effective load carrying capability (ELCC) assumptions, CESA, Eagle Crest, and POC all felt that further analysis should be performed to refine the battery ELCC curve before the next IRP cycle analysis.	The ELCC assumptions are complex since they are dependent on the mixture of resources on the grid. We anticipate that some of our studies may be able to provide new information to inform the creation of the ELCC curves.
CESA, SEIA, and Wellhead all also were concerned that hybrid resources should be more directly considered, at the very least in the next IRP cycle.	Yes, we agree that hybrid resources should be included. We hope that E3 will be including these in the next version of RESOLVE, or we will consider adding them.
Numerous parties were also concerned about the reduction in import limits for this IRP cycle.	Our study of WECC with SWITCH should help us better understand the opportunity or lack of opportunity associated with imports.

1.2 Background - SWITCH

SWITCH[4] is an open-source capacity-expansion model[5] similar to RESOLVE in functionality while it differs in the detailed implementation. SWITCH has been jointly developed and maintained by collaborators at multiple institutions including the University of California (UC) Berkeley, the University of Hawaii at Manoa, and the Pontificia Universidad Católica de Chile. SWITCH WECC has been implemented at UC Berkeley and now further developed at UC San

---

[3] https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M331/K772/331772681.PDF page 11.

[4] http://switch-model.org/

[5] Josiah Johnston, Rodrigo Henriquez-Auba, Benjamín Maluenda, Matthias Fripp, "SWITCH 2.0: A modern platform for planning high-renewable power systems," SoftwareX, **10**, 2019, 100251. https://doi.org/10.1016/j.softx.2019.100251. http://www.sciencedirect.com/science/article/pii/S2352711018301547.

Diego and UC Merced. Part of this project included an update to inputs for SWITCH 2.0 WECC and updating of the Python version.

The standard structure of SWITCH is shown in Fig. 1.1. The design is modular; the user may choose which modules to include for each run and/or to add new modules depending on their needs. In Fig. 1.1, blue boxes are subpackages, green boxes are modules.

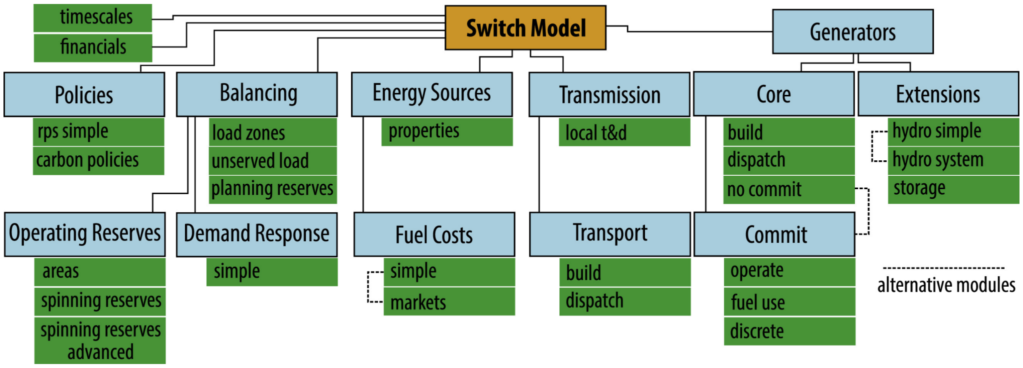


Figure 1. 1 Package and module structure of SWITCH 2.0. From Johnston et al[6]

SWITCH is a long-term power-system capacity-expansion model with high temporal and geographical resolution. As an optimization problem, it is classified as a deterministic linear or mixed integer program. The objective function minimizes the total power system cost: investment and operation costs of generation and transmission. The decision variables of the optimization problem can be summarized in the following sets: capacity investment decisions for each potential new project in each period, capacity investment decisions for each potential new transmission line between any load areas in each period, hourly dispatch decisions for each existing and new generator installed for each period, decisions on hourly transmitted energy through the existing and new transmission lines. The main constraints in the optimization problem are: hourly demand in each load area has to be met by the generation and transmitted energy, capacity limits must be respected for generators and transmission lines, wind and solar generators are limited by their hourly geolocated capacity factors, generation from each hydropower plant is limited by historical monthly availability (minimum, average and maximum generation), biomass and geothermal deployment is limited by the resource availability in the WECC, hourly ramping restrictions for generators depending on their technology, respect yearly maintenance time for each generation technology, lifetime of different technologies must be respected, policy constraints as carbon cap, carbon tax, Renewable Portfolio Standards, among others.

Costs for constructing and operating power systems infrastructure can vary by region. To capture this variation, all costs in the model can be multiplied by a regional economic multiplier derived from normalized average pay for major occupations in United States Metropolitan Statistical Areas (MSAs) (United States Department of Labor 2009). Counties that are not present in the listed MSAs may be given the regional economic multiplier of the nearest MSA. These regional economic multipliers can be assigned to load zones weighted by the population within each county

---

[6] Josiah Johnston, Rodrigo Henriquez-Auba, Benjamín Maluenda, Matthias Fripp, "SWITCH 2.0: A modern platform for planning high-renewable power systems," SoftwareX, **10**, 2019, 100251. https://doi.org/10.1016/j.softx.2019.100251. http://www.sciencedirect.com/science/article/pii/S2352711018301547

located within each load area. Economic multipliers for the US portion of WECC range from 0.88 to 1.18. However, we recognize that these factors are likely to change over the next 25 years and may not be relevant to deployments in the later years. To decrease confusion about the different assumptions, we have decided to omit this calculation, while recognizing that it is available. Data for Canadian and Mexican economic multipliers are estimated at 1.05-1.1 for Canada and 0.85 for Baja California Mexico.

1.3 Comparison of RESOLVE and SWITCH

Geographical resolution: A primary difference between RESOLVE and SWITCH is that SWITCH is configured to be able to study all of WECC. We intend to compare the results of the narrower and wider regions. This is discussed in more detail in Section 5 of the Modeling Approach Description. The comparison is complicated because of the differences in the zone definition. SWITCH defines its data base from the EIA data sets.[7] These data tables indicate the state in which the generator is located, but not the electrical zone or independent system operator. In contrast, RESOLVE is CAISO centric. The CAISO data base of generators is not directly aligned with EIAs.

Temporal resolution: SWITCH was written originally to enable selection of any chosen timepoints, enabling flexibility when studying long-duration storage. RESOLVE will need to be revised to have this feature.

Weather data resources: SWITCH can currently pull from a full year of data. Though it can only run hourly optimizations on a couple of dozen days, it has the possibility of doing 12-hour timesteps on the full year of data. RESOLVE currently uses 37 days selected from 3 years of weather data. E3 is currently in the process of extending those data sets.

Cost assumptions for renewables: In SWITCH, costs for most technologies are assumed to stay constant in real terms through 2050 as these technologies are considered mature. Of the technologies that are most used, CCGT are assumed to be mature, with capital costs and fixed O&M costs held constant throughout the study period. On the other hand, solar, wind, and battery storage technologies are assumed to decline in capital costs and/or fixed O&M costs through 2050. The differences between the RESOLVE and SWITCH costs we have documented in sections 3 and 4 are not easily characterized – sometimes RESOLVE shows a higher cost and sometimes SWITCH shows the higher cost. The effects of these differences will be evaluated later.

Limits on new builds: SWITCH and RESOLVE have set different limits for the possibility of new builds. SWITCH has been more selective on the number of solar plants that can be built while RESOLVE is more conservative on the amount of wind. Again, the differences are difficult to characterize in a systematic way – the details can be found in Sections 3 and 4.

Execution: SWITCH uses a data base from which information is extracted to create a scenario, usually checking data for thousands of generators to construct the desired input files for the optimization. RESOLVE users may use the Scenario tool provided by E3 or may start with the input files and modify them in another way. Typically, RESOLVE requires about 40 input files

---

[7] https://www.eia.gov/electricity/data/eia860/

including multiple Mb of data. While some files may be edited manually, using the Scenario tool or other software is usually required to be able to consistently update all of the input files.

1.4 Data resources

Data are constantly changing. It may be appropriate to update the inputs for the baseline to capture the most accurate data. For example, the U.S. Congress recently extended the Investment Tax Credits. The following data resources are a subset of the documents consulted in developing the input data described in the later sections.

- RESOLVE documentation found at CPUC website[8]
- 2020 Annual Technology Baseline published by NREL[9]
- Technical Assessment of Grid Connected Renewable Energy and Storage Technologies and Strategies, TN228862, published June 27, 2019 by the CEC[10]
- Preliminary Draft Utility Scale Renewable Energy Generation Research Roadmap, TN228863, published June 27, 2019 by the CEC[11]
- Inputs & Assumptions – 2019-2020 Integrated Resource Planning, published February 27, 2020 by the CEC[12]
- Input & Assumptions – CEC SB 100 Joint Agency Report, TN234532, published August 31, 2020 by the CEC[13]
- SB 100 Joint Agency Report, TN235848, published December 3, 2020, by the CEC[14]

The general conclusion of all of the data sources is that prices for solar and wind have decreased impressively. Prices for conventional technologies are much more constant with time. (Fig. 1.2 by the EIA)[15]

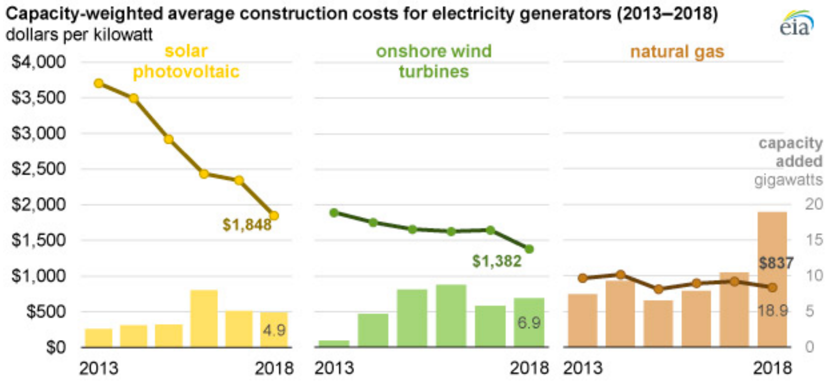


Figure 1. 2. Historical costs for electricity generation (data source: EIA)

---

[8] https://www.cpuc.ca.gov/General.aspx?id=6442464143
[9] https://atb.nrel.gov/electricity/2020/index.php?t=in
[10] https://efiling.energy.ca.gov/getdocument.aspx?tn=228862
[11] https://efiling.energy.ca.gov/getdocument.aspx?tn=228863
[12] https://www.cpuc.ca.gov/General.aspx?id=6442459770
[13] https://efiling.energy.ca.gov/getdocument.aspx?tn=234532
[14] https://efiling.energy.ca.gov/getdocument.aspx?tn=235848
[15] https://www.energyglobal.com/solar/21092020/eia-wind-and-solar-costs-fall-in-us/

2. Model approach

The modeling approach is described in more detail in the Modeling Approach Description. Here we provide a brief overview.

RESOLVE is being modified by E3 to make it suitable for studying long-duration storage. SWITCH is already able to study long-duration storage but has not been used in that way. We will be exploring the time frames to use that will be most effective for modeling in SWITCH. These will also be applied in RESOLVE. We are also using simpler models that neglect transmission to understand the energy balance for different scenarios. These will not provide final answers but give a best-case minimum requirement for storage.

In particular, we will explore decreasing the number of timepoints per day in order to increase the number of contiguous days that can be modeled without overloading the calculation. The timepoints to understand the charging and discharging of storage may be optimally chosen to sample times an hour or so after sunrise and before sunset. We will also explore using 5-year spacing to better understand the transition to zero-emissions grid.

3. Resource definition

RESOLVE uses resource definitions as defined in Table 3.1. By combining similar technologies, RESOLVE simplifies the optimization. For example, solar thermal resources are not differentiated from solar PV. Table 3.1 shows how RESOLVE renewable generators can be grouped into just six resources: Biomass, Geothermal, Small_Hydro, Hydro, Solar, and Wind.

Table 3. 1 Technology definitions for RESOLVE renewable resource descriptions

Technology	Subtechnology	RESOLVE Technology
Biogas	Distributed	Biomass
Biogas		Biomass
Biogas	Pipeline	Other
Biomass	Large	Biomass
Biomass	Distributed	Biomass
Biomass		Biomass
Geothermal		Geothermal
Hydro	Small	Small_Hydro
Hydro		Hydro
Solar PV	Fixed Tilt - 20MW+	Solar
Solar PV	Tracking - 20MW+	Solar
Solar PV	Rooftop	Solar
Solar PV		Solar
Solar Thermal	No Storage	Solar
Various		Other
Wind		Wind

SWITCH retains more differentiation of some of the renewable electricity resources including:

- Bio_Gas
- Bio_Gas_Internal_Combustion_Engine
- Bio_Gas_Internal_Combustion_Engine_Cogen
- Bio_Gas_Steam_Turbine
- Bio_Liquid_Steam_Turbine_Cogen
- Bio_Solid_Steam_Turbine
- Bio_Solid_Steam_Turbine_Cogen
- Central_PV
- Commercial_PV
- CSP_Trough_6h_Storage
- CSP_Trough_No_Storage
- Geothermal
- Hydro_Nonpumped
- Offshore_Wind
- Residential_PV
- Wind

These will be discussed in the sections below.

3.1 Solar

Summary: The rapid decrease in solar costs, coupled with rapidly changing tariffs and incentive programs, have made it difficult to accurately project costs into the future. We find additional confusion arises when the methods for calculating prices change. We carefully reviewed the changes made in NREL's ATB and a range of other resources to identify beneficial changes. We found that the LCOE values for solar dropped in 2020 because of a change in the financing rates rather than because of lower hardware prices. In the end, we propose to make only one change to the solar cost inputs for RESOLVE to reflect the recent Congressional action to extend the Investment Tax Credit (ITC). We include the analysis to provide greater depth for the reader. We also propose to keep the almost unlimited caps on growth and to neglect the anticipated increases in capacity factors.

We document the inputs to SWITCH and compare these with the RESOLVE inputs. There are a number of differences, largely associated with the different ways of grouping the generators into zones.

3.1.1 Solar costs

NREL's ATB projected a decrease in CapEx cost for solar plants from 2018 ($1778/kWdc) to 2019 ($1111/kWdc) of roughly 38%, which is a large decrease for one year. The 2020 ATB CapEx cost increases to $1600/kWac. This increase reflects a change in the way the ATB reported costs, changing from the DC peak watt rating to the AC peak watt rating. However, even accounting for the change in accounting, the CapEx cost increases from the 2019 ATB to the 2020 ATB. The projected LCOE cost decrease is, therefore, more of a reflection of the decrease in financing costs. The general trends are described in Table 3.2.

Table 3. 2 NREL 2020 ATB change from DC to AC ratings

Year	CapEx current cost	Net Capacity factor Los Angeles	Net Capacity factor Daggett	LCOE in Los Angeles	LCOE in Daggett
2018	$1778/kWdc	22%	27%	$55/MWh	$45/MWh
2019	$1111/kWdc	22%	27%	$40/MWh	$33/MWh
2020	$1600/kWac ($1194/kWdc*)	32%	35% (AC) 26% (DC)	$32/MWh	$29/MWh

*calculated assuming an Inverter loading ratio = 1.34, as mentioned in the 2020 ATB notes.

We will use AC ratings throughout the rest of our discussion and analysis.

The RSP for RESOLVE currently uses the same costs for all solar resources except for the Southern Nevada and Arizona resources, which are 2%-3% lower in cost, which is a smaller difference than the variability of the cost. The current RSP costs by vintage for the majority of solar resources are shown in Table 3.3, to be compared with the 2020 NREL ATB data in Table 3.4. The unexpected increase in 2024 reflects the termination of the Investment Tax Credit (ITC), as summarized in Table 3.5. The data from these tables is graphed in Fig. 3.1 to better understand the variations.

Table 3. 3 RESOLVE RSP annualized cost inputs for solar

Build year or Vintage	annual_fixed_cost_by_vintage($/kWac-y)		fixed_o_and_m_dollars_per_kw_yr($/kW-y)	Total Annual Cost** ($/kWac-y)	
	As in RSP input file	Excluding ITC*		Including ITC	Excluding ITC*
2020	66.51	95.01	11.19	77.70	106.2
2021	64.14	91.62	10.42	74.56	102.05
2022	61.30	87.58	10.31	71.61	97.89
2023	59.46	84.95	10.20	69.66	95.14
2024	73.94	82.15	10.08	84.02	92.24
2026	74.75	83.05	9.86	84.61	92.91
2030	72.64	80.71	9.41	82.05	90.12
2045	67.37	74.86	8.19	75.56	83.05

*ITC Calculated using RESOLVE RSP column in Table 3.5.
**Sum of annual fixed cost and fixed O&M cost.

Table 3. 4 2020 NREL ATB cost assumptions utility scale, moderate

Year	Capex Cost ($/kWac)	Annualized Cost ($/kWac-y) (30-y; 4.2%)		Fixed O&M ($/kW-y)	Total Annual Cost** ($/kWac-y)	
		Including ITC*	Excluding ITC		Including ITC*	Excluding ITC
2020	1354	56.14	80.2	16	72.14	96.2
2021	1302	53.99	77.13	15	68.99	92.13
2022	1250	51.8	74.05	15	66.8	89.05
2023	1198	49.68	70.97	14	63.68	84.97
2024	1147	61.16	67.95	13	74.16	80.95
2026	1043	55.62	61.8	12	67.62	73.8
2030	836	44.55	49.5	10	54.55	59.5
2045	725	38.66	42.95	8	46.66	50.95

*ITC Calculated using RESOLVE RSP column in Table 3.5.
**Sum of annual fixed cost and fixed O&M cost.

Table 3. 5 Investment Tax Credit summary

ITC rate	Year of initiation of construction	Date of completion of construction	Vintage used in RESOLVE’S RSP	Revised by Congress in Dec. 2020
30%	2019	Dec. 31, 2023	2021, 2022, 2023	Through 2025
26%	2020	Dec. 31, 2023		
22%	2021	Dec. 31, 2023		
10%	2022	NA	2024 and later	2026 and later

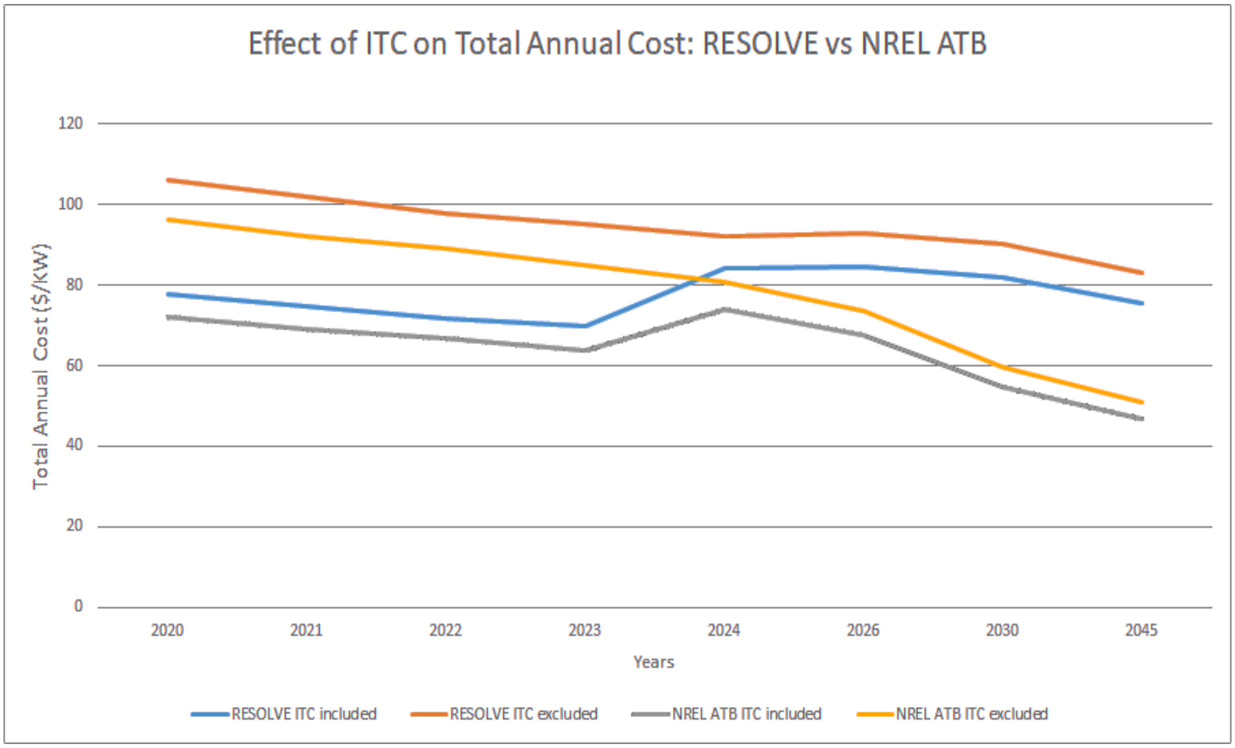


Figure 3. 1 Solar cost data from Tables 3.2 and 3.3 plotted for comparison

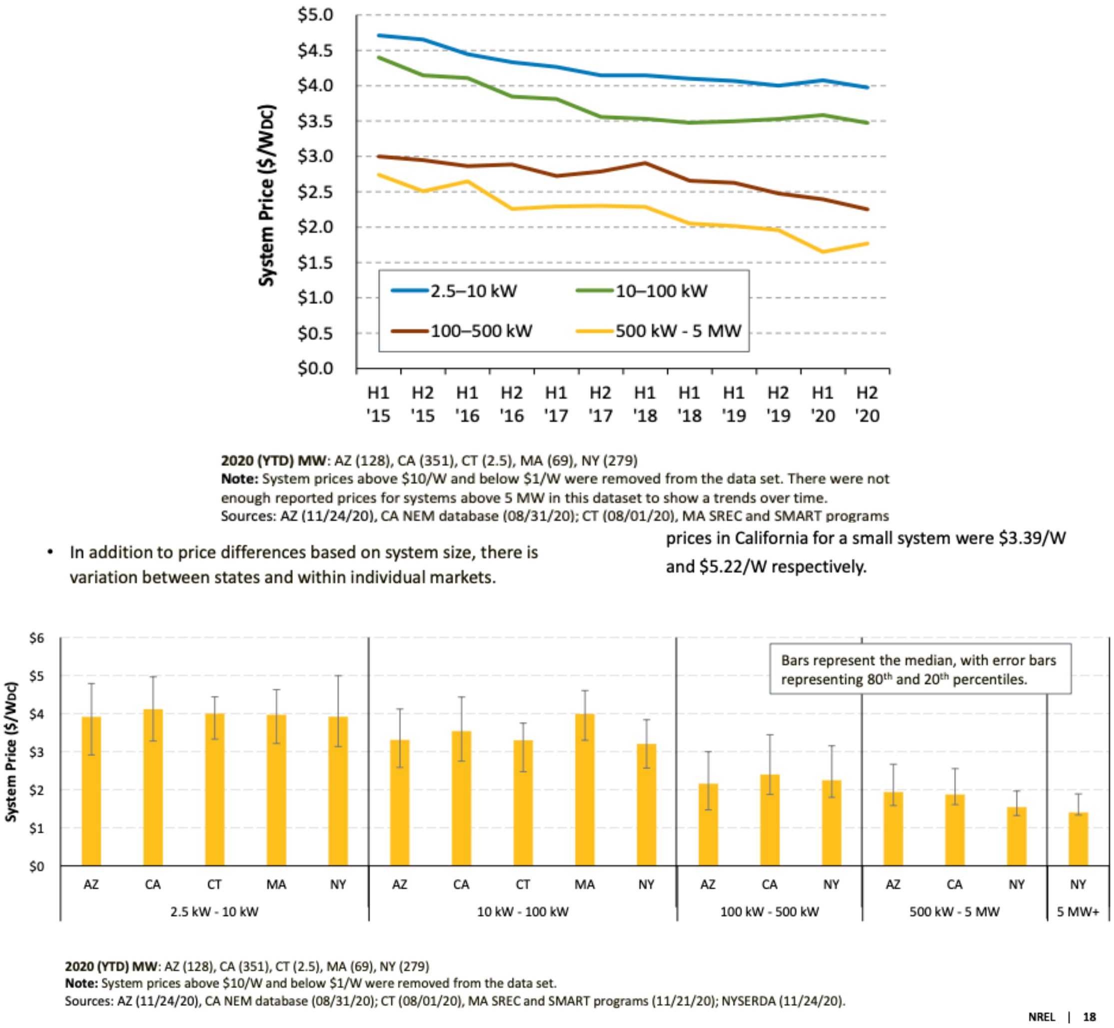
The RESOLVE and NREL ATB prices are fairly similar in the near years. The NREL ATB prices drop more in later years, resulting in a 2045 price that is 62% of what is being used by RESOLVE for 2045. We anticipate that this could make a real difference in simulation results for 2045. We debated whether to modify the RESOLVE inputs to reflect this, but have chosen not to for the baseline.

Actual observed prices for systems in California in 2020 and elsewhere in the United States are shown in Fig. 3.2, taken from an NREL study.[16]

The actual costs for solar plants in California will continue to depend on tariffs and the ITC credit. The tariffs are being constantly debated in court, so are somewhat difficult to predict. The ITC credit can be accessed by some, but not by everyone. Including a partner to take the tax break often adds complexity, cost, and delays to projects, so once the credit is reduced to 10%, we anticipate that the fraction of projects that will use the ITC will be reduced. The ITC was extended by Congress in December 2020 as indicated in Table 3.5 and could be extended again.

---

[16] https://www.nrel.gov/docs/fy21osti/78625.pdf.



2020 (YTD) MW: AZ (128), CA (351), CT (2.5), MA (69), NY (279)
Note: System prices above $10/W and below $1/W were removed from the data set. There were not enough reported prices for systems above 5 MW in this dataset to show a trends over time.
Sources: AZ (11/24/20), CA NEM database (08/31/20); CT (08/01/20), MA SREC and SMART programs

- In addition to price differences based on system size, there is variation between states and within individual markets.

prices in California for a small system were $3.39/W and $5.22/W respectively.

2020 (YTD) MW: AZ (128), CA (351), CT (2.5), MA (69), NY (279)
Note: System prices above $10/W and below $1/W were removed from the data set.
Sources: AZ (11/24/20), CA NEM database (08/31/20); CT (08/01/20), MA SREC and SMART programs (11/21/20); NYSERDA (11/24/20).

NREL | 18

Figure 3. 2 DC solar prices reported by NREL for California and elsewhere

When looking at the importance of solar prices, we make the following notes:

- The difference between NREL's ATB analysis for solar and the reported prices in California is disconcerting, introducing hesitancy about adopting the lower ATB numbers, recognizing that they reflect all of the U.S., not just California.
- The needed large buildout of solar will be mostly driven by California's targets for renewable resources and reduced carbon emissions rather than driven by cost of solar since the cost of solar is already acceptably low and continued use of legacy natural gas plants may be more convenient if a change is not driven by policy.
- Solar penetration is already high enough that addition of substantial new solar will require addition of some sort of storage or load profile change to balance generation with demand. The cost of the storage and uncertainty of the cost of the storage is likely to be greater than the solar cost. So, the cost of the solar may not make a big difference in the modeling results.
- We anticipate that the amount of solar that will be built will cause the simulated cost of reaching zero-carbon emissions to be very dependent on the input price of solar. However,

the amount of solar selected to be built may be relatively independent of the input price. Thus, our conclusions about the cost of the build out should reflect the uncertainty in the cost of solar.

- Given the high uncertainty in the numbers relative to the lack of importance for storage deployment, we would prefer not to change the RESOLVE inputs from the RSP without clear reason. The propose to change the costs for vintage 20205 to reflect the extension of the ITC as shown in Table 3.6.

Table 3. 6 Proposed RESOLVE annual cost inputs for solar

Build year or Vintage	annual_fixed_cost_by_vintage ($/kWac-y)		annual_fixed_cost_by_vintage Excluding ITC* ($/kWac-y)		fixed_o_and_m_dollars per_kw_yr ($/kWac-y)	
	As in RSP Scenario Tool	Proposed	From RSP	Proposed	From RSP	Proposed
2020	66.51	66.51	95.0	95.0	11.19	11.19
2025	74.23	57.75	82.5	82.5	9.97	9.97
2030	72.64	72.64	80.7	80.7	9.41	9.41
2035	71.74	71.74	79.7	79.7	9.02	9.02
2040	70.23	70.23	78.0	78.0	8.63	8.63
2045	67.37	67.37	74.9	74.9	8.19	8.19
2050	64.34	64.34	71.5	71.5	7.75	7.75

*ITC Calculated using RESOLVE RSP column in Table 3.4.

The costs for SWITCH are summarized and compared to costs for RESOLVE in Table 3.7.

Table 3. 7 Proposed SWITCH input costs compared with RESOLVE for solar

Build year or Vintage	Gen_overnight_cost- derived data from SWITCH		Annual_fixed_cost_by_vintage RESOLVE	Gen_fixed_om or planned_capacity_fixed_o_ and_m_dollars_per_wk_yr	
	$/MW (upfront)	$/kW-y (annual)*	From RSP ($/kWac-y)	SWITCH ($/kWac-y)	RESOLVE ($/kWac-y)
2020	1001621	80.37	66.51	15.85	11.19
2025	1094964	87.86	57.75	12.82	9.97
2030	836384	67.11	72.64	9.80	9.41
2035	799236	64.13	71.74	9.36	9.02
2040	762088	61.15	70.23	8.93	8.63
2045	724939	58.17	67.37	8.49	8.19
2050	687791	55.19	64.34	8.05	7.75

* This cost is annualized with 20-year lifetime and 5% discount rate.

Table 3.8 shows assumptions made in SWITCH that affect the calculated annualized costs shown in Table 3.7. SWITCH also includes a connection cost for solar.

Table 3. 8 Assumptions made by SWITCH about solar plants

Fuel	Technology	Construction Time (Yr)	Lifetime (Yr)	Forced Outage Rate (%)	Scheduled Outage Rate (%)	Carbon Emissions (tCO2/MWh)
Solar	Central PV	1	20	0	2	0
Solar	Commercial PV	1	20	0	2	0
Solar	CSP Trough 6h Storage	1	20	6	0	0
Solar	CSP Trough No Storage	1	20	6	0	0
Solar	Residential PV	1	20	0	2	0

3.1.2 Expansion of solar

The RSP for RESOLVE essentially allows unconstrained build of utility-scale solar. Our estimates align with that general assumption that there is adequate space for all of the needed solar deployments in California. We recognize that there will be some local areas that will have a bigger challenge, but within the spatial resolution of the seven zones modeled in the RSP, this is not a concern.

The expansion of residential solar (labeled "Customer PV" in RESOLVE) is not optimized by the model because the model recognizes it as being more expensive than utility solar, reflecting reported data such as that shown in Fig. 3.2. The planned expansion of Customer PV for the RSP is summarized in Table 3.9. The ratio of rooftop solar installations to utility-scale installations is highly uncertain and will affect the cost incurred by the utilities and the community as a whole. This ratio may also affect the use of short-duration storage, especially if the behind-the-meter (BTM) solar is paired with behind-the-meter storage, but we anticipate that these will have smaller effect on the value of long-duration storage.

Table 3. 9 Planned expansion of Customer PV

Period	As in RSP Scenario Tool (GW)	Relative Customer PV
2020	9.83	1.00
2025	15.23	1.55
2030	20.07	2.04
2035	25.18	2.56
2040	30.02	3.05
2045	34.86	3.55
2050	39.70	4.04

The expansion of solar is effectively unlimited for RESOLVE since the amount selected is far less than what is allowed as documented in Table 3.10. The inputs for solar for SWITCH and RESOLVE are compared in Table 3.11. Note that RESOLVE includes solar thermal in their solar and follows different zone differentiation as discussed in the Modeling Approach Description Section 5.

Table 3. 10 PV Expansion selected by RESOLVE for 5-year RSP

Period	CAISO selected operating capacity	CAISO new builds (MW)	CAISO cumulative new builds (MW)	CAISO build limits (MW)
2020	20,310	6,000	6,000	602,076
2025	20,887	0	6,000	596,674
2030	25,691	4,804	10,804	591,838
2035	37,594	11,902	22,706	586,728
2040	58,215	20,621	43,327	581,887
2045	91,793	33,578	76,905	577,046

Table 3. 11 Comparison of Central_PV (SWITCH) and Solar resources (RESOLVE)

Zones for SWITCH*	SWITCH Existing	SWITCH Allowed new***	Resources for RESOLVE*	RESOLVE Existing**	RESOLVE Allowed new
CA_IID	2888 MW	1998 MW	IID_Solar_for_Other & IID_Solar_for_CAISO	166-189 MW	0 MW
CA_LADWP	54 MW	0 MW	LDWP_Solar_for_Other	2411-3460 MW	0 MW
Other CA zones	10753 MW	5884 MW	CAISO_Solar_for_Other & CAISO_Solar_for_CAISO for existing; plus 22 candidates	14310-14887 MW	577046-602076 MW
CA_SMUD	148 MW	933 MW	BANC_Solar_for_Other	2078-3777 MW	0 MW

*The zones used by SWITCH and RESOLVE do not directly map onto each other. These are approximated.
**Ranges reflect 2020 values and planned expansions to 2026.
***Still to be updated.

CAISO reports 14,066 MW as of 1/1/2021.[17]

3.1.3 Solar performance (capacity factors)

NREL's ATB projections suggest that capacity factors for PV plants will continue to increase (Fig. 3.3), especially as bifacial modules are adopted and as DC-to-AC ratios increase. However, RESOLVE is not currently able to include a changing Capacity factor (which should be done by adjusting the DC-to-AC ratio in the PV Watts simulation) and the net result is that neglecting the increasing capacity factors will cause us to calculate that more solar is built than may actually be needed. This should be considered in interpreting the final results, but will have little impact on the conclusions about the value of long-duration storage.

---

[17] http://www.caiso.com/Documents/Key-Statistics-Dec-2020.pdf

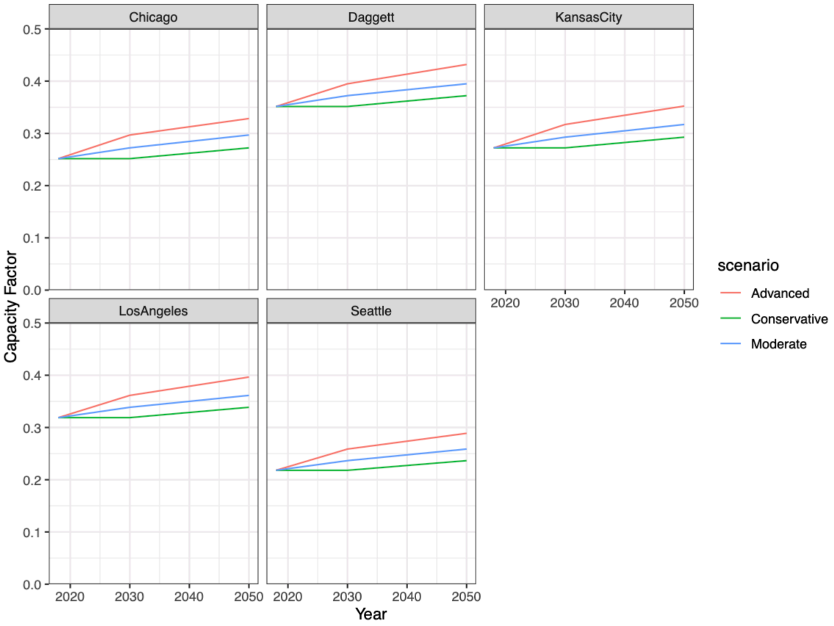


Figure 3. 3 2020 NREL ATB projections of capacity factor for 5 cities

3.1.4 Concentrating solar power (CSP) (Solar thermal)

RESOLVE currently does not include distinction of concentrating solar power (CSP) systems from photovoltaic solar power systems. On a sunny day, the solar thermal (CSP) plant generate 3%-4% of the total solar electricity generation in California. This is a small amount, but solar thermal systems may be able to contribute electricity after sundown, contributing to the long-duration storage need. When comparing the outputs of SWITHC and RESOLVE, we will keep in mind that these are handled differently by the two programs. The size of the difference can be understood from Table 3.12.

Table 3. 12 CSP (solar thermal) plants operating in California

Plant ID	Plant name	Plant operator	Nameplate capacity (MW)
10439	SEGS III	FPL Energy Operating Services Inc - SEGS	34.2
10440	SEGS IV	FPL Energy Operating Services Inc - SEGS	34.2
10441	SEGS V	FPL Energy Operating Services Inc - SEGS	34.2
10442	SEGS VI	FPL Energy Operating Services Inc - SEGS	35.0
10443	SEGS VII	FPL Energy Operating Services Inc - SEGS	35.0
10444	SEGS VIII	Terra-Gen Operating Co-Solar	92.0
10446	SEGS IX	Terra-Gen Operating Co-Solar	92.0
57073	Ivanpah 2	NRG Energy Services	133.4
57074	Ivanpah 1	NRG Energy Services	133.0
57075	Ivanpah 3	NRG Energy Services	133.4
57331	Mojave Solar Project	Mojave Solar LLC	280
57394	Genesis Solar Energy Project	Genesis Solar LLC	250
Total			1286

3.2 Wind

Summary: Similar to solar, the evaluation of changing wind costs is complicated by rapidly changing market dynamics, changing methods of tracking types of wind installations and changing policies. Like solar, we conclude that the only change that should be made to the RESOLVE data inputs is to reflect the recent action by Congress. Unlike solar, for which growth is essentially unconstrained, build out of wind is quite limited in the RSP. SWITCH allows somewhat more wind to be built, but still not a lot. Thus, the selection of land-based wind within California over other technologies will be driven much more by the build limits than by the costs of the technology itself. We discuss these build limits in section 3.2.2. We propose to add offshore wind resources to the baseline of the RESOLVE RSP.

3.2.1 Wind costs

The RESOLVE RSP price inputs for wind are highly dependent on the location of the plant with the lowest prices found for Greater_Imperial_Wind and the highest for Wyoming_Wind, as summarized as an example in Table 3.13.

Table 3. 13 RESOLVE Wind RSP cost input examples

	Greater Imperial		**Humboldt**		**Wyoming**	
Year	**Annualized Cost ($/KW)**	**Fixed O&M ($/KW-y)**	**Annualized Cost ($/KW)**	**Fixed O&M ($/KW-y)**	**Annualized Cost ($/KW)**	**Fixed O&M ($/KW-y)**
2020	71.92	45.11	84.00	42.44	194.67	49.64
2022	89.35	44.47	99.69	41.85	217.47	48.91
2026	111.69	43.17	120.81	40.64	243.91	47.44
2030	112.08	41.89	121.52	39.47	242.14	45.96
2045	115.44	36.95	125.71	34.87	240.18	40.45

The wind production tax credit (PTC) will continue to apply at 60% for any project that begins construction by the end of 2021. The law previously called to reduce the PTC to 40%. The wind PTC is still scheduled to drop to 0% starting in 2022. The new offshore wind ITC allows for a 30% credit on projects that begin construction before 2026.[18]

PTC is included in SWITCH by applying cost reduction factors, which is PTC divided by LCOE of wind power. We will not make any change to reflect Congress' recent action on the PTC. However, we will consider the 30% ITC credit for offshore wind when modeling offshore wind.

The costs for build out of new wind resources used by RESOLVE and SWITCH are compared in Table 3.14. The costs used by SWITCH are less than those used by RESOLVE, even if the comparison is to the lowest cost wind resource used in RESOLVE (Greater Imperial – see Table 3.13). This affects the cost of the build out selected in RESOLVE, but not the build out because the model selects to build almost 100% of what is allowed. (see section 3.2.2). SWITCH allows

---

[18] https://www.reutersevents.com/renewables/wind/us-extends-wind-tax-credits-vestas-expands-development-role?utm_campaign=NEPWIN13JAN21Newsletter&utm_medium=email&utm_source=Eloqua

for build of offshore wind plants using the costs shown in Table 3.15. The offshore wind systems are more expensive, as expected.

Table 3. 14 Proposed SWITCH input costs compared with RESOLVE for wind

Build year (Vintage)	Gen_overnight_cost-derived data from SWITCH		Annual_fixed_cost_by_vintage RESOLVE (Humboldt, as an example)	Gen_fixed_om or planned_capacity_fixed_o_and_m_dollars_per_wk_yr	
	$/MW (upfront)	$/kW-y (annual)*	From RSP ($/kW-y)	SWITCH ($/kW-y)	RESOLVE ($/kW-y)
2020	837300	54.47	84.00	42.50	42.44
2025	1400128	91.08	119.18	40.73	40.93
2030	1226717	79.80	121.52	38.95	39.47
2035	1177137	76.57	123.28	37.49	37.98
2040	1126328	73.27	124.90	36.02	36.45
2045	1074293	69.88	125.71	34.57	34.87
2050	1021030	66.42	126.85	33.11	33.30

* This cost is annualized with 30-year lifetime and 5% discount rate.

Table 3. 15 Proposed SWITCH and RESOLVE input costs for offshore wind

Build year	Gen_overnight_cost-derived data from SWITCH		Annual_fixed_cost_by_vintage RESOLVE (Humboldt, as an example)	Gen_fixed_om or planned_capacity_fixed_o_and_m_dollars_per_wk_yr	
	$/MW (upfront)	$/kW-y (annual)*	From RSP ($/kW-y)	SWITCH ($/kW-y)	RESOLVE ($/kW-y)
2020	3959165	257.55	268	112	94
2030	2744489	178.53	277	112	67
2040	2401870	156.25	194	112	47
2050	2226776	144.86	147	112	34

* This cost is annualized with 30-year lifetime and 5% discount rate.

3.2.2 Expansion of wind

RESOLVE's current RSP limits the model's ability to expand land-based wind quite strongly. It is obvious that many more wind generators could be installed, but it is less obvious whether this should be a priority for California. Addition of wind resources may affect the need for evening storage because wind often increases in the evening just when the sun is setting, as shown in Fig. 3.4. On the other hand, the strength of the wind is inconsistent seasonally as shown by Fig. 3.5.

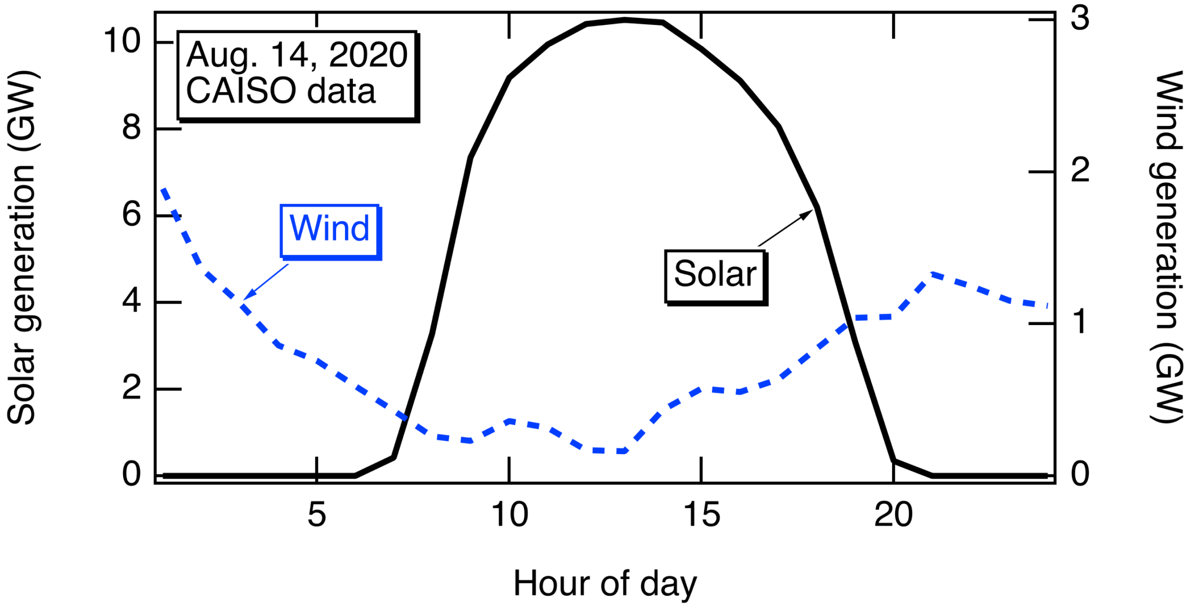


Figure 3. 4 California wind and solar generation as a function of hour of day

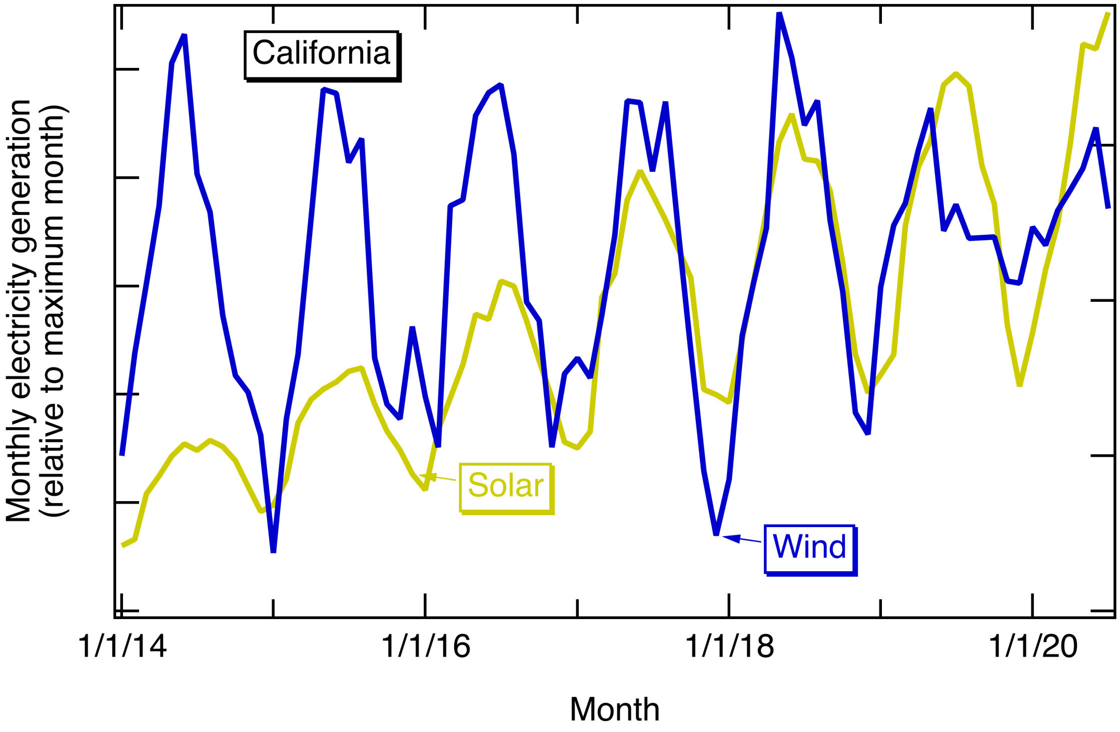


Figure 3. 5 California monthly wind and solar generation (Data: EIA)

The allowed growth of wind in RESOLVE is summarized in Table 3.16. The wind expansion selected by RESOLVE is essentially the same, as shown in Table 3.17. The wind resources in SWITCH are compared with those in RESOLVE in Table 3.18. The accounting used by SWITCH (based on EIA data for California) suggests fewer wind resources currently than used by RESOLVE (which is designed to reflect CAISO, which includes resources outside of California).

Table 3. 16 New builds of wind allowed by RSP

Wind resource	New Build Capacity Limit (MW)	Wind resource	New Build Capacity Limit (MW)
Carrizo_Wind	287	SCADSNV_Wind	-
Central_Valley_North_Los_Banos_Wind	173	Solano_subzone_Wind	18
Greater_Imperial_Wind	-	Solano_Wind	542
Greater_Kramer_Wind	-	Southern_California_Desert_Ex_Wind	-
Humboldt_Wind	34	SW_Ext_Tx_Wind	500
Kern_Greater_Carrizo_Wind	60	Tehachapi_Wind	275
Kramer_Inyokern_Ex_Wind	-	Southern_Nevada_Wind	442
New_Mexico_Wind	1,500	Wyoming_Wind	1,500
Northern_California_Ex_Wind	866	Baja_California_Wind	600
NW_Ext_Tx_Wind	1,500	Total	8297

Table 3. 17 **Wind Expansion selected by RESOLVE for 5-year RSP**

Period	CAISO selected operating capacity	CAISO new builds (MW)	CAISO cumulative new builds	CAISO build limits
2020	7357	0	0	0
2025	9393	1937	1937	5297
2030	11162	1768	3705	8297
2035	15735	4573	8279	8297
2040	15735	0	8279	8297
2045	15735	0	8279	8297

Table 3. 18 Comparison of wind resources

Zones for SWITCH*	SWITCH Existing	SWITCH Allowed new	Resources for RESOLVE*	RESOLVE Existing	RESOLVE Allowed new
CA_IID	46 MW	0 MW	IID_Wind_for_Other & IID_Wind_for_CAISO	0 MW	0 MW
CA_LADWP	0 MW	0 MW	LDWP_Wind_for_Other	5 MW	0 MW
Other CA zones	5815 MW	12066 MW**	CAISO_Wind_for_Other & CAISO_Wind_for_CAISO	7357-7456 MW	5297-8297 MW
CA_SMUD	0 MW	0 MW	BANC_Wind_for_Other	0 MW	0 MW

*The zones used by SWITCH and RESOLVE do not directly map onto each other. These are approximated.
**Includes 3480 MW of offshore wind

CAISO reports 6933 MW of wind installed and operating as of Jan. 1, 2021. This is fairly consistent with the 7357 MW currently used by RESOLVE. The much larger expansion of wind allowed by SWITCH includes 3.5 GW of offshore wind. We propose to add similar offshore wind candidates to the RESOLVE baseline to reflect the probability that the new administration in

Washington will provide permitting opportunities for these. There is already interest from companies to invest in offshore wind for California. The model may select whether these will be economically viable.

The potential offshore wind resource was estimated as part of the SB100 ongoing reviews using data (Table 3.19) from a UC Berkeley study,[19] which identifies offshore wind resources linked to U.S. Bureau of Ocean Energy Management lease areas. The RESOLVE Scenario tool already includes these four resources plus an additional candidate resource called Del_Norte_Offshore_Wind. These numbers are greater than the values currently used by SWITCH, but both have high uncertainty reflecting the challenge of offshore wind in deep water. We have chosen to follow the offshore wind scenario provided by RESOLVE, which is similar to the values in Table 3.19, but replaces the Cape Mendocino resource with Del Norte, with a potential of 6604 MW.

Table 3. 19 Offshore wind resource potential

Offshore wind location	Resource Potential Area (km^2)	Resource Potential (MW)
Cape Mendocino	2,072	6,216 (Full) 1,649 (Limited)
Diablo Canyon	1,441	4,324
Morro Bay	806	2,419
Humboldt Bay	536	1,607
Total	4,855	14,566 (Full) 10,000 (Limited)

3.2.3 Wind performance (Capacity factors and other modeling data)

The capacity factors for wind plants have been increasing slowly as the technology is improved to reduced down time for maintenance events and to increase the time the turbine runs at full power. However, as noted above for solar, RESOLVE is not currently configured to enable increases in capacity factor with time. If we fail to accurately model an increase of the capacity factor of the wind by a couple of percent, the result will be that wind does not contribute to reducing the need for storage as much as it should have. However, we believe that the uncertainty in the build-out limits discussed in section 3.2.2 is greater than the increase in the capacity factor will be.

Our primary question about increases in the observed capacity factors is whether these increases will have a seasonal effect. For example, the addition of Colorado or Wyoming wind will increase generation during the winter, significantly reducing the amount of seasonal long-duration storage needed. We, therefore, have chosen to focus our understanding of changes in capacity factor for wind on the selection of what type of wind resource to model as part of the scenario analysis instead of adding it in the baseline.

Parameters used for calculating the annualized costs for SWITCH are tabulated in Table 3.20.

---

[19] https://laborcenter.berkeley.edu/pdf/2019/CA-Offshore-Wind-Workforce-Impacts-and-Grid-Integration.pdf

Table 3. 20 Parameters used in SWITCH to calculate the annualized cost for wind

Fuel	Technology	Construction Time (Yr)	Lifetime (Yr)	Forced Outage Rate (%)	Scheduled Outage Rate (%)	Carbon Emissions (tCO_2/MWh)
Wind	Offshore Wind	2	30	5	0.6	0
Wind	Wind	2	30	5	0.6	0

3.3 Geothermal

Summary: The costs for geothermal are higher than for solar and wind, but geothermal costs may be lower than for solar or wind coupled with storage. Therefore, geothermal adoption in early years is limited by cost. Then, as California requires more solar electricity coupled with storage, geothermal is better able to compete, but is still limited by the number of candidate sites, since geothermal plants are better built in locations with very hot water available relatively close to the earth's surface. The current RSP for RESOLVE selects to build by 2045 essentially all of the geothermal it is allowed to build. Thus, analyzing the availability of sites may be more important than analyzing the exact cost. Evaluating the data, we find that that the RESOLVE RSP cost is a little higher than is reasonable but that the potential is consistent with the most recent USGS assessment we found.

A scenario in which geothermal plays a consequential role is currently viewed as being high risk, so will not be included in the baseline. MIT published the potential for geothermal to provide all of the electricity that we need.[20] DOE's GeoVision study concluded that the U.S. could increase geothermal electricity generation 26-fold by 2050,[21] which could increase geothermal's electricity contribution to roughly 75% of today's load. Although progress toward this vision has been very slow, engagement by fossil fuel companies with the relevant skills could make a huge difference. The possibility of geothermal being an important player has been gaining more attention.[22] Nevertheless, we select a baseline with little change in geothermal, leaving the enhanced-growth case to an interesting scenario study.

3.3.1 Geothermal costs

The NREL ATB has data for multiple types of geothermal technologies including hydrothermal (the least expensive and most common), enhanced geothermal system (EGS), near-hydrothermal

---

[20] https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf

[21] ***https://www.energy.gov/eere/geothermal/geovision***

[22] https://qz.com/1947017/geothermal-is-the-electricity-combating-climate-change/

field EGS (NF-EGS), and deep EGS, each with a variant of using the flash or the binary approach. The costs from NREL's ATB are shown in Table 3.21. Figure 3.6 shows that all types of geothermal technology are projected by the NREL ATB to reach similar costs in the 2030-2045 timeframe. For simplicity, we will mainly discuss the Hydro-flash costs. Similarly, Figure 3.7 shows the O&M cost projections for the range of technologies.

Table 3. 21 Geothermal Resource and Cost Characteristics from NREL 2020 ATB

		Flash	**Binary**		
	Temp (°C)	**>=200C**	**150-200**	**135-150**	**<135**
Hydrothermal	# identified sites	21	22	17	59
	Total capacity (MW)	15,338	2,991	820	4,759
	Avg OCC ($/kW)	4,175	8,829	9,476	17,757
	Min OCC ($/kW)	3,000	4,397	7,444	11,884
	Max OCC ($/kW)	5,971	38,720	11,781	25,934
	Example Plant OCC ($/kW)	4,522	5,870		
NF-EGS	# sites	12	20		
	Total capacity (MW)	787	596		
	Avg OCC ($/kW)	11,429	27,330		
	Min OCC ($/kW)	9,026	18,974		
	Max OCC ($/kW)	18,797	41,694		
	Example Plant OCC ($/kW)	14,486	32,921		
Deep EGS (3-6 km)	# sites	n/a	n/a		
	Total capacity (MW)	100,000+			
	Avg OCC ($/kW)	28,991	65,081		
	Min OCC ($/kW)	18,733	40,515		
	Max OCC ($/kW)	54,987	96,405		
	Example Plant OCC ($/kW)	14,486	32,921		

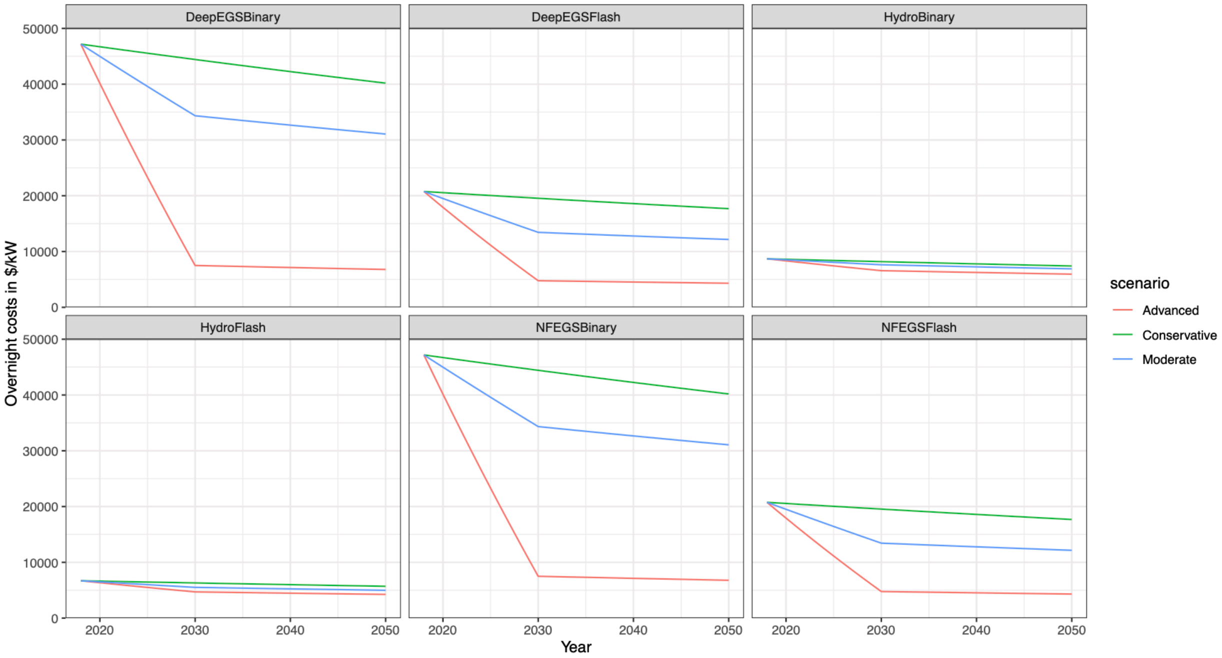


Figure 3. 6 Projected overnight capital costs of geothermal power ($2018) (Data: ATB)

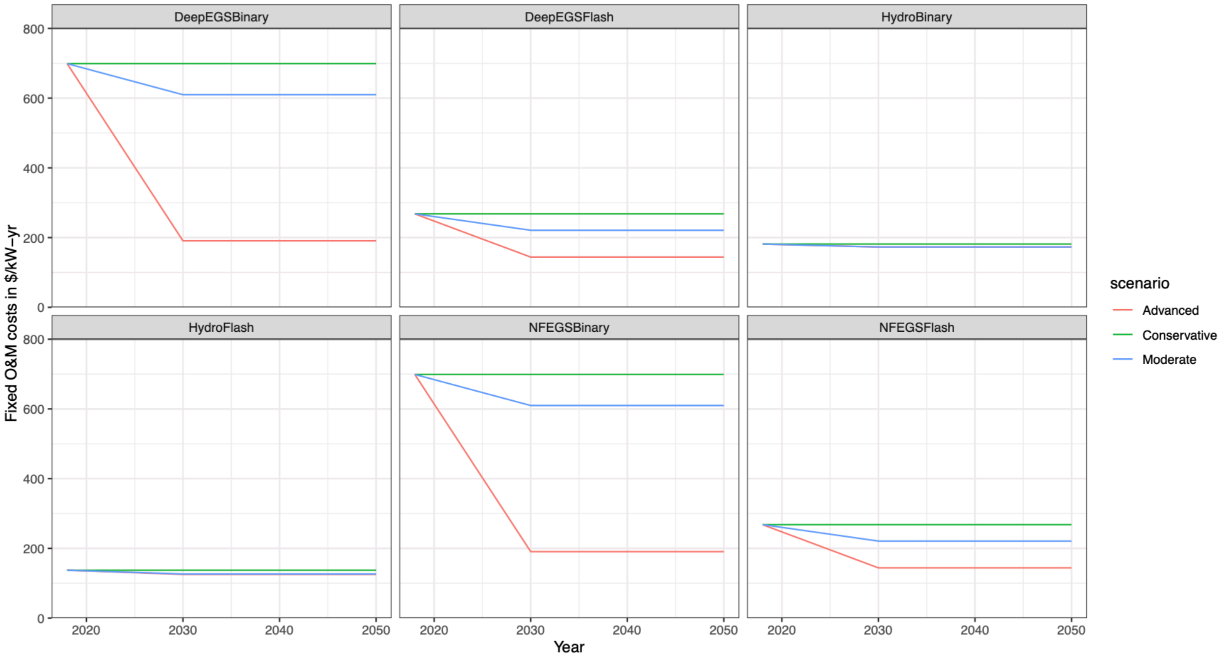


Figure 3. 7 Projections of fixed O&M costs of geothermal power ($2018) (Data: ATB)

The costs from the ATB and from RESOLVE are compared in Table 3.22 and in Fig. 3.8. Specifically, these compare costs for the Greater Imperial Geothermal Resource, which is representative of the different costs used for six Geothermal resources in RESOLVE.

Table 3. 22 Comparison of ATB (Hydro-Flash) moderate and RESOLVE annual costs

	2020 NREL ATB – Hydro-Flash				RESOLVE RSP inputs**		
Period	CapEx cost ($/kW)	Annualized Cost* ($/kW)	Fixed Annual O&M ($/kW)	Total Annual Cost ($/kW)	Fixed Annual Cost ($/kW)	Fixed Annual O&M ($/kW)	Total Annual Cost ($/kW)
2020	6497	413	136	549	477	149	626
2022	6298	400	134	534	479	149	628
2026	5903	375	130	505	542	149	691
2030	5514	351	127	478	561	149	710
2045	5114	325	127	452	555	149	704
	2020 NREL ATB – Hydro-Binary						
2020	8514	541	180	721			
2022	8334	530	179	709			
2026	7978	507	176	683			
2030	7628	485	173	658			
2045	7076	450	173	623			

*Assumptions for the NREL ATB Calculations: Lifetime=30 years & Interest rate=4.8%

**Greater_Imperial

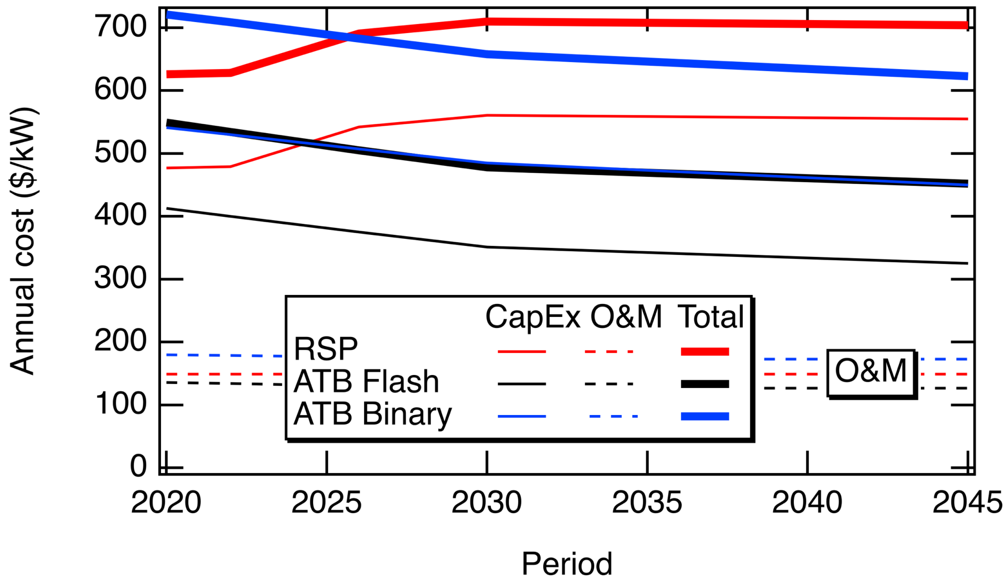


Figure 3. 8 Geothermal costs from the NREL ATB compared with the RESOLVE RSP

The RESOLVE RSP costs are higher than the NREL ATB costs. We compare these numbers to recent power purchase agreements[23] (PPAs) – see Table 3.23. We estimate the annual revenue from the sold electricity based on the reported PPA prices and based on capacity factors that have been observed for geothermal plants in those areas. We find that the annual cost used by the RSP is higher than the revenue that can be expected from such PPAs, suggesting that the RSP annual cost numbers are higher than some projects today. Most of the difference is in the CapEx cost rather than in the O&M cost.

Table 3. 23 Electricity prices for recent geothermal power purchase agreements

Two new plants with recently announced PPAs			
PPA rate ($/kWh)	**Assumed capacity factor**	**Annual (kWh/kW)**	**Annual Revenue ($/kW)**
0.074	90%	7884	583
0.068	80%	7008	477

While the various sources do not exactly agree on the costs we should use for geothermal, they are reasonably consistent. Whether the prices increase or decrease in future years will depend on the types of project executed. Given the large uncertainty, we conclude to use the current RSP cost numbers for RESOLVE.

These are compared with the SWITCH inputs in Table 3.24. The agreement between SWITCH and RESOLVE, especially in the later years, is quite remarkable. The SWITCH costs are slightly higher.

Table 3. 24 Proposed SWITCH input costs compared with RESOLVE for geothermal

Build year or Vintage	**Gen_overnight_cost-derived data from SWITCH**		**Annual_fixed_cost_by_vintage RESOLVE**	**Gen_fixed_om or planned_capacity_fixed_o_and_m_dollars_per_wk_yr**	
	$/MW (upfront)	**$/kW-y (annual*)**	**From RSP ($/kW-y)**	**SWITCH ($/kW-y)**	**RESOLVE ($/kW-y)**
2020	8513624	553.82	477.48	180.01	148.74
2025	8066701	524.75	525.93	176.51	148.74
2030	7628105	496.22	561.46	173.10	148.74
2035	7439300	483.94	562.61	173.10	148.74
2040	7255168	471.96	561.17	173.10	148.74
2045	7075593	460.28	555.22	173.10	148.74
2050	6900464	448.89	548.50	173.10	148.74

* This cost is annualized with 30-year lifetime and 5% discount rate.

3.3.2 Expansion of geothermal

The capacity limits for new builds of geothermal are relatively small so may not affect the role of long-duration storage. Specifically, the RSP limits the Geothermal growth to a total of about 2 GW

---

[23] https://www.latimes.com/environment/story/2020-01-22/california-needs-clean-energy-after-sundown-geothermal-could-be-the-answer

(Tables 3.25 and 3.26), resulting in a total of about 3 GW. If this amount could be doubled or tripled by 2045, it could make a difference in the value of long-duration storage.

Table 3. 25 Summary of build out selected by RESOLVE RSP compared with RSP limits.

Resource	Planned installed capacity (MW)	Capacity limit (MW)	Cumulative new build in 2045 for RSP (MW)	Note
BANC_Geothermal_for_Other	0			No new builds
CAISO_Geothermal_for_Other	38.7			No new builds
IID_Geothermal_for_Other	709.5			No new builds
LDWP_Geothermal_for_Other	0			No new builds
NW_Geothermal_for_Other	132.1			No new builds
SW_Geothermal_for_Other	664.9			No new builds
CAISO_Geothermal_for_CAISO	1812.6			No new builds
IID_Geothermal_for_CAISO	83			No new builds
NW_Geothermal_for_CAISO				No new builds
Greater_Imperial_Geothermal		1352.1	1352.1	
Inyokern_North_Kramer_Geothermal		24	0	
Northern_California_Ex_Geothermal		469	469	
Pacific_Northwest_Geothermal				No new builds
Riverside_Palm_Springs_Geothermal		32	32	
Solano_Geothermal		135	135	
Southern_Nevada_Geothermal		320	320	
Total	3441	2332	2308	

The 2008 USGS report[24] indicates 5.4 GW of identified resources in California, of which 2.7 GW was already in place. The possible geothermal scenarios range from inconsequential additions, as currently allowed in the RSP to many GW (if oil companies used their extensive drilling expertise to explore geothermal). An MIT study in 2006[25] concluded that the U.S. could install 100 GW of geothermal electricity generating capacity by 2050. More recently, DOE's GeoVision study concludes that the U.S. could increase geothermal electricity generation 26-fold by 2050.[26] Such an increase could make a tremendous difference for CAISO, where geothermal currently supplies about 3% of the load. A 26-fold increase would increase that to roughly 75% for today's load. Even if the load in 2050 were to double, geothermal might still have the potential of providing 30%-40% of the electricity, which would have a dramatic effect on the needed storage. The RSP already reflects the most recent USGS projection we found of 5.4 GW. Changes from that will be considered as a scenario varied from the baseline.

---

[24] https://pubs.usgs.gov/fs/2008/3082/pdf/fs2008-3082.pdf

[25] https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf

[26] **https://www.energy.gov/eere/geothermal/geovision**

Table 3. 26 Geothermal Expansion selected by RESOLVE for 5-year RSP

Period	CAISO selected operating capacity	CAISO new builds	CAISO cumulative new builds	CAISO build limits
2020	1851	0	0	0
2025	1851	0	0	2332
2030	1851	0	0	2332
2035	2993	1142	1142	2332
2040	4159	1166	2308	2332
2045	4159	0	2308	2332

The existing and allowed new geothermal resources in SWITCH and RESOLVE are compared in Table 3.27. The totals are fairly similar, while SWITCH places the opportunity for new resources with IID while RESOLVE places that opportunity within CAISO.

Table 3. 27 Comparison of geothermal resources

Zones for SWITCH*	SWITCH Existing	SWITCH Allowed new	Resources for RESOLVE*	RESOLVE Existing	RESOLVE Allowed new
CA_IID	738 MW	2213 MW	IID_Geothermal_for_Other & IID_Geothermal_for_CAISO	782 MW	0 MW
CA_LADWP	0 MW	0 MW	LDWP_Geothermal_for_Other	0 MW	0 MW
Other CA zones	2083 MW	431 MW	CAISO_Geothermal_for_Other & CAISO_Geothermal_for_CAISO	1851 MW	2332 MW
CA_SMUD	0 MW	0 MW	BANC_Geothermal_for_Other	0 MW	0 MW

*The zones used by SWITCH and RESOLVE do not directly map onto each other. These are approximated.

CAISO reports 1421 MW of geothermal as of Jan. 1, 2021.[27]

3.3.3 Geothermal performance

California's geothermal plants currently run in a baseload manner. Turning these into load-following resources would affect the value of long-duration storage. For the small generation that they currently provide, this does not make a big difference. The possibility of turning them into load-following resources can be investigated in a relevant scenario.

The modeling values used by SWITCH are included in Table 3.28.

Table 3. 28 Parameters used in SWITCH to calculate the annualized cost for geothermal

Fuel	Technology	Construction time (y)	Lifetime (y)	Forced-Outage rate (%)	Scheduled outage rate (%)	Carbon emissions (tCO_2/MWh)
Geothermal	Geothermal	3	30	0.7	2.4	0

---

[27] http://www.caiso.com/Documents/Key-Statistics-Dec-2020.pdf

3.4 Biomass/Biogas

Similar to geothermal, assumptions about the role of biomass and biogas have very high uncertainty. A recent report by Lawrence Livermore National Laboratory details how California can achieve its goal of carbon neutrality by 2045 through negative emissions with a key pillar being conversion of biomass to fuels with capture of carbon dioxide.[28]

The cost inputs used by SWITCH and RESOLVE are compared in Table 3.29. Some of the assumptions used for modeling biomass in SWITCH are summarized in Table 3.30. The expansion of biomass allowed and selected by the RESOLVE RSP is shown in Table 3.31 and in Table 3.32, showing how RESOLVE RSP selects to build all of the biomass that is allowed in 2045. Before 2045, biomass is not selected, suggesting that biomass becomes most useful in the final stages of moving toward 100% zero-carbon. The current existing biomass resources in SWITCH and RESOLVE are consistent with the value currently posted by CAISO: 822 MW of biomass as of Jan. 1, 2021.[29] SWITCH allows unlimited installation of biomass plants, but limits their use to the available feedstock, which places a practical limit.

We conclude to keep the RSP baseline for RESOLVE including both the costs and the build limits.

Table 3. 29 Proposed SWITCH biogas input costs compared with RESOLVE for biomass

Build year or Vintage	Gen_overnight_cost-derived data from SWITCH		Annual_fixed_cost_by_vintage RESOLVE	Gen_fixed_om or planned_capacity_fixed_o_and_m_dollars_per_wk_yr	
	$/MW (upfront)	$/kW-y (annual)*	From RSP ($/kW-y)	SWITCH ($/kW-y)	RESOLVE ($/kW-y)
2020	2118354	170.00	631.47	64.38	184.75
2025	2118354	170.00	645.21	64.38	184.75
2030	2118354	170.00	658.83	64.38	184.75
2035	2118354	170.00	658.02	64.38	184.75
2040	2118354	170.00	654.71	64.38	184.75
2045	2118354	170.00	647.96	64.38	184.75
2050	2118354	170.00	636.97	64.38	184.75

* This cost is annualized with 20-year lifetime and 5% discount rate.

---

[28] https://www.llnl.gov/news/new-lab-report-outlines-ways-california-could-reach-goal-becoming-carbon-neutral-2045

[29] http://www.caiso.com/Documents/Key-Statistics-Dec-2020.pdf

Table 3. 30 Parameters used in SWITCH to model the costs for biogas/biomass

Fuel	Technology	Heat Rate (MMBtu/MWh)	Thermal Efficiency, Net (%)	Construction Time (Yr)	Lifetime (Yr)	Forced Outage Rate (%)	Scheduled Outage Rate (%)	Carbon Emissions (tCO_2/MWh)
Bio Gas	Bio Gas	13.5	25.3	1	20	11	4	0
Bio Solid	Biomass IGCC	12.5	27.3	2	40	9	7.6	0
Bio Solid CCS	Biomass IGCC CCS	16.3	20.9	2	40	9	7.6	-1.309

Table 3. 31 Biomass Expansion selected by RESOLVE for 5-year RSP

Period	CAISO selected operating capacity (MW)	CAISO new builds (MW)	CAISO cumulative new builds (MW)	CAISO build limits (MW)
2020	903	0	0	1147
2025	903	0	0	1147
2030	901	0	0	1147
2035	901	0	0	1147
2040	901	0	0	1147
2045	2048	1147	1147	1147

Table 3. 32 Comparison of biogas/biomass resources

Zones for SWITCH*	SWITCH Existing	SWITCH Allowed new	Resources for RESOLVE*	RESOLVE Existing	RESOLVE Allowed new
CA_IID Biosolid	56 MW	**	IID_Biomass_for_Other	77 MW	0 MW
CA_LADWP Biogas	74 MW	**	LDWP_Biomass_for_Other	0 MW	0 MW
Other CA zones	1097 MW	**	CAISO_Biomass_for_Other & CAISO_Biomass_for_CAISO & Instate_Biomass	901 MW	1147 MW
CA_SMUD Biogas	9 MW	**	BANC_Biomass_for_Other	18 MW	0 MW

*The zones used by SWITCH and RESOLVE do not directly map onto each other. These are approximated.
**Capacity is unlimited, but practically is limited by supply of biofuels.

3.5 Hydropower

Inputs for modeling hydropower present different challenges than other generation sources. The availability of hydropower is largely dependent on the rain, and California is known for highly variable amounts of rain.

SWITCH previously used 2015 as its basis for the amount of hydro. However, 2015 was a drought year, so is unrepresentative of typical conditions. For the baseline, the median year for rainfall has been chosen for SWITCH.

Neither SWITCH nor RESOLVE is currently configured to allow build of new hydropower resources as shown in Tables 3.33 and 3.34. CAISO reports 1232 MW of small hydro as of Jan. 1, 2021,[30] which agrees well with the value used in RESOLVE RSP.

Table 3. 33 Comparison of small hydropower resources

Zones for SWITCH*	SWITCH Existing	SWITCH Allowed new	Resources for RESOLVE*	RESOLVE Existing	RESOLVE Allowed new
CA_IID	**	0 MW	IID_Small_Hydro_for_Other	0 MW	0 MW
CA_LADWP	**	0 MW	LDWP_Hydro_for_Other	56 MW	0 MW
Other CA zones	**	0 MW	CAISO_Small_Hydro & CAISO_Small_Hydro_for_Other	974 MW	0 MW
CA_SMUD	**	0 MW	BANC_Small_Hydro_for_Other	0 MW	0 MW

*The zones used by SWITCH and RESOLVE do not directly map onto each other. These are approximated.
**SWITCH does not differentiate large hydro and small hydro, so all are reported in Table 3.34.

Table 3. 34 Comparison of hydropower resources

Zones for SWITCH*	SWITCH Existing**	SWITCH Allowed new	Resources for RESOLVE*	RESOLVE Existing	RESOLVE Allowed new
CA_IID	88 MW	0 MW	IID_Hydro_for_Other	84 MW	0 MW
CA_LADWP	45 MW	0 MW	LDWP_Hydro	234 MW	0 MW
Other CA zones	9573 MW	0 MW	CAISO_Hydro	7070 MW	0 MW
CA_SMUD	212 MW	0 MW	BANC_Hydro	2724 MW	0 MW

*The zones used by SWITCH and RESOLVE do not directly map onto each other. These are approximated.
**SWITCH does not differentiate large hydro and small hydro, so both are reported here.

3.6 Thermal

Summary: The RSP includes an array of thermal resources that are anticipated to be phased out. The primary costs associated with these are the fuel (and operating) costs, so this section emphasizes evaluation of the fuel costs. Projected natural gas prices have a very high uncertainty especially associated with potential policy actions. There is general agreement that prices will increase, but the amount of the increase varies with the chosen scenario. The 2020 losses experienced by the oil and gas industry suggest that investment will slow and the addition of liquified natural gas export terminals may lead to U.S. gas prices drifting upward toward international prices. The high uncertainty is best treated as a scenario analysis, so, we opt to retain

---

[30] http://www.caiso.com/Documents/Key-Statistics-Dec-2020.pdf

the RSP fuel cost inputs for the baseline. The coal and nuclear fuel input costs will have little impact on our results and are only discussed in passing.

The thermal resources available in the RSP are summarized in Table 3.35. Blue and gray highlights guide the plans for nuclear and coal, respectively. The in-state coal is scheduled to be retired by 2025. The in-state nuclear capacity is planned to be about 1 GW in 2045. The green highlights indicate three resources that may be selected to be built.

Table 3. 35 Non-renewable thermal resources planned capacities

Resource Name	2015	2020	2025	2030	2035	2040	2045	2050
CAISO_CHP	2,402	2,296	2,296	2,296	1,148	-	-	-
CAISO_Nuclear	2,935	2,935	635	635	635	635	635	635
CAISO_CCGT1	12,049	12,049	13,333	13,333	13,333	13,333	13,333	13,333
CAISO_CCGT2	2,862	2,928	2,928	2,928	2,928	2,928	2,928	2,928
CAISO_Coal	480	480	-	-	-	-	-	-
CAISO_Peaker1	4,506	4,914	4,914	4,914	4,914	4,914	4,914	4,914
CAISO_Peaker2	3,774	3,683	3,683	3,683	3,683	3,683	3,683	3,683
CAISO_Advanced_CCGT	-	-	-	-	-	-	-	-
CAISO_Aero_CT	-	-	-	-	-	-	-	-
CAISO_Reciprocating_Engine	255	255	255	255	255	255	255	255
CAISO_ST	6,153	3,733	-	-	-	-	-	-
NW_Nuclear	1,170	1,170	1,170	1,757	1,757	1,757	1,757	1,757
NW_Coal	10,665	10,665	8,126	7,364	7,364	7,364	7,364	7,257
NW_CCGT	8,628	9,068	9,573	9,573	9,573	9,573	9,573	8,066
NW_Peaker	2,783	2,993	2,993	2,993	2,993	2,738	2,588	2,358
SW_Nuclear	2,998	2,998	2,998	2,998	2,998	2,998	2,998	-
SW_Coal	9,418	7,168	6,788	6,141	6,141	6,141	6,141	6,141
SW_CCGT	16,030	17,015	17,108	19,741	19,153	18,498	16,157	15,474
SW_Peaker	4,860	5,989	6,808	6,302	6,238	5,482	5,482	5,482
SW_ST	1,606	1,612	1,319	967	825	825	825	825
LDWP_Nuclear	407	407	407	407	407	407	407	-
LDWP_Coal	1,700	1,700	-	-	-	-	-	-
LDWP_CCGT	2,292	2,292	2,292	2,755	2,755	2,755	2,755	2,755
LDWP_Peaker	967	1,545	1,545	1,647	1,647	1,647	1,647	1,647
LDWP_ST	992	992	371	197	197	197	197	197
IID_CCGT	255	255	255	255	255	255	255	255
IID_Peaker	397	397	327	327	327	327	327	277
BANC_CCGT	1,863	1,863	1,863	1,798	1,798	1,798	1,798	1,798
BANC_Peaker	867	867	867	867	867	867	867	867

Natural gas

Three options for the natural gas fuel costs are included in RESOLVE (as "CA", "NW", and "SW"), each of which is based on a WECC burner tip price estimate from the CEC's NAMGas model[31] run posted in April 2019. A new version of the WECC burner tip price estimates was posted in June 2020, but we are not confident that the June 2020 analysis will be more accurate than the 2019 since the effects of the pandemic were being felt, but not yet understood at that time. Costs for each RESOLVE region are aggregated from NAMGas burner tip information using the average of the region of interest. The three options listed in NAMGas model are High Demand/Low Price, Mid Demand, Low Demand/High Price.

Figure 3.9 shows the RSP projected variation of Natural gas fuel price through the period 2020-2045, using data extracted from the RESOLVE Scenario Tool. The data were found in the Sys-Fuels tab, cells M150:AQ152 (Active-Mid scenario). The CA gas price data were increased by the Carbon-cost adder values on line 208 and each data set was multiplied by the average of the monthly adjustments given in cells C40:O42. Note that the NW and CA values are essentially identical before the carbon-cost adder is applied.

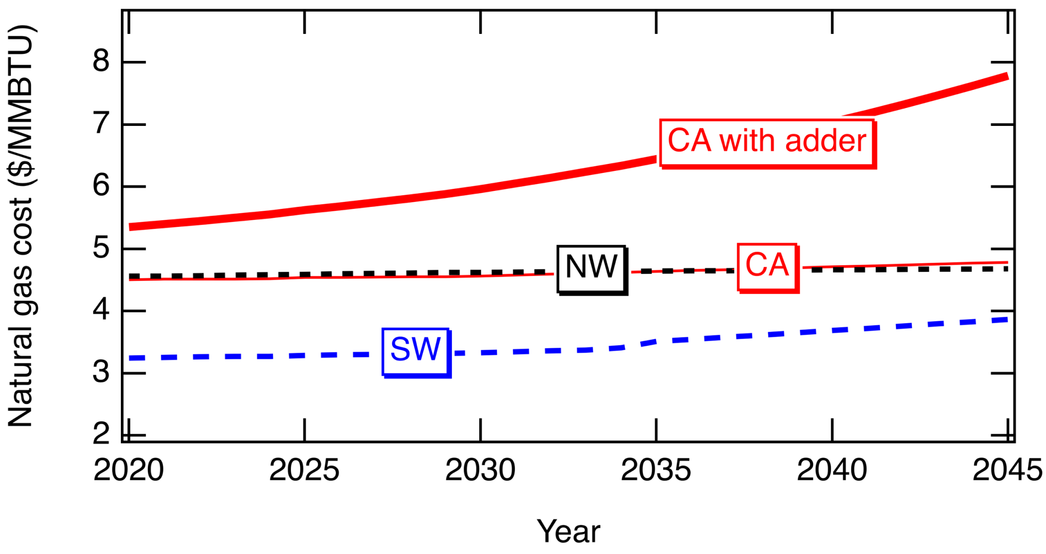


Figure 3. 9 Natural gas costs used in RESOLVE RSP

For comparison, we investigated natural gas price forecasts reported elsewhere. Figure 3.10 summarizes the fuel cost forecast in tables 54, 55, and 56 published in "Inputs & Assumptions: CEC SB100 Joint Agency Report – June 2020."[32]

---

[31] https://www.wecc.org/Administrative/A Dixon CEC_WECC Price Update.pdf

[32] https://efiling.energy.ca.gov/GetDocument.aspx?tn=234532&DocumentContentId=67359

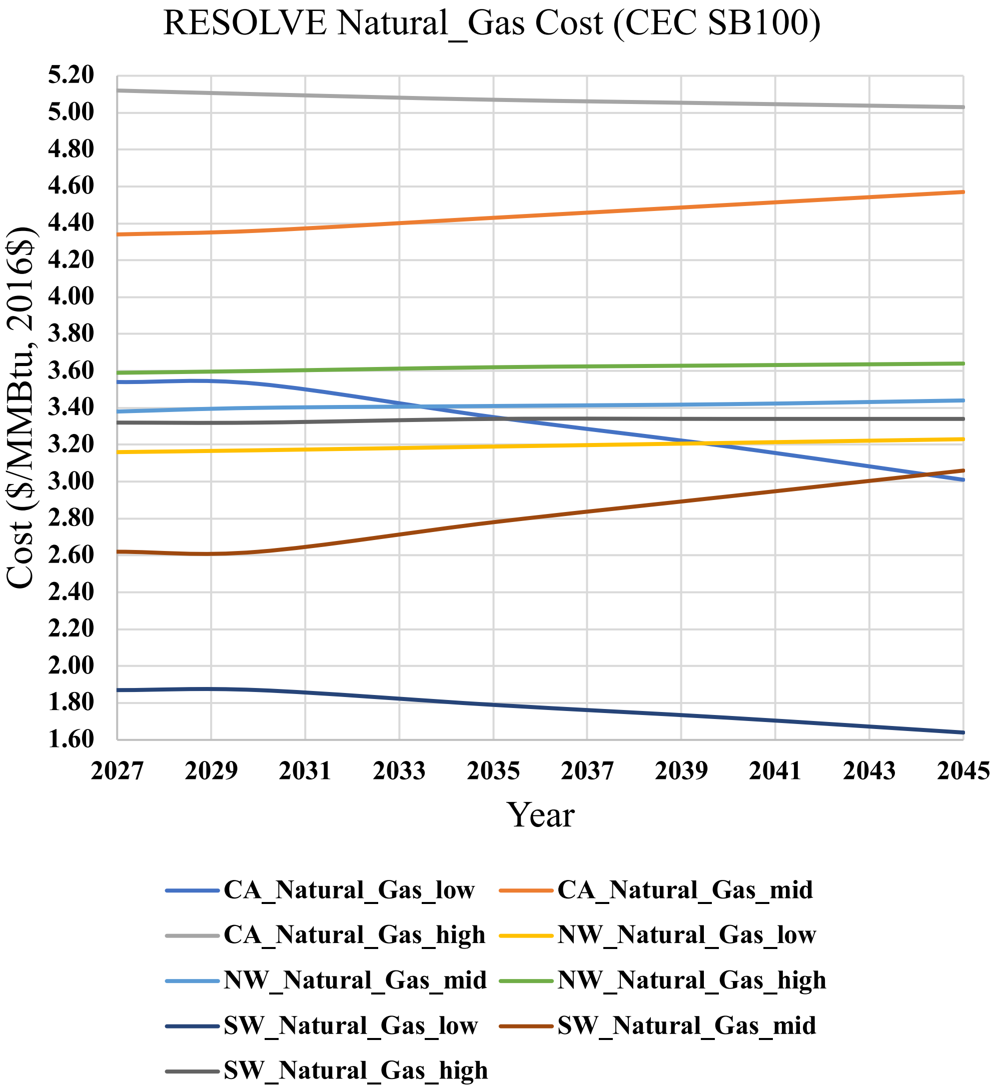


Figure 3. 10 Natural Gas Cost based on CEC SB100

Figure 3.11 shows the variation of Natural Gas costs from EIA[33] and ATB 2020,[34] 2019,[35] and 2018.[36] It is clear that EIA, ATB 2020, ATB 2019-Low, and ATB 2018-Low are close to each other. Also, the EIA and ATB 2020 are almost the same trend with a little shift. We conclude from these data that the possible range in natural gas costs is quite high. This uncertainty is best treated by using scenarios to evaluate the uncertainties in our conclusions. Fortunately, the importance of the natural gas costs will decrease as the emissions from natural gas use are decreased. The natural gas costs will be most important when carbon sequestration is evaluated.

---

[33] https://www.eia.gov/outlooks/aeo/excel/aeotab_13.xlsx

[34] https://atb.nrel.gov/electricity/2020/files/2020-ATB-Data-Mac.xlsm

[35] https://atb.nrel.gov/electricity/2019/data.html

[36] https://data.nrel.gov/system/files/89/2018-ATB-data-interim-geo.xlsm

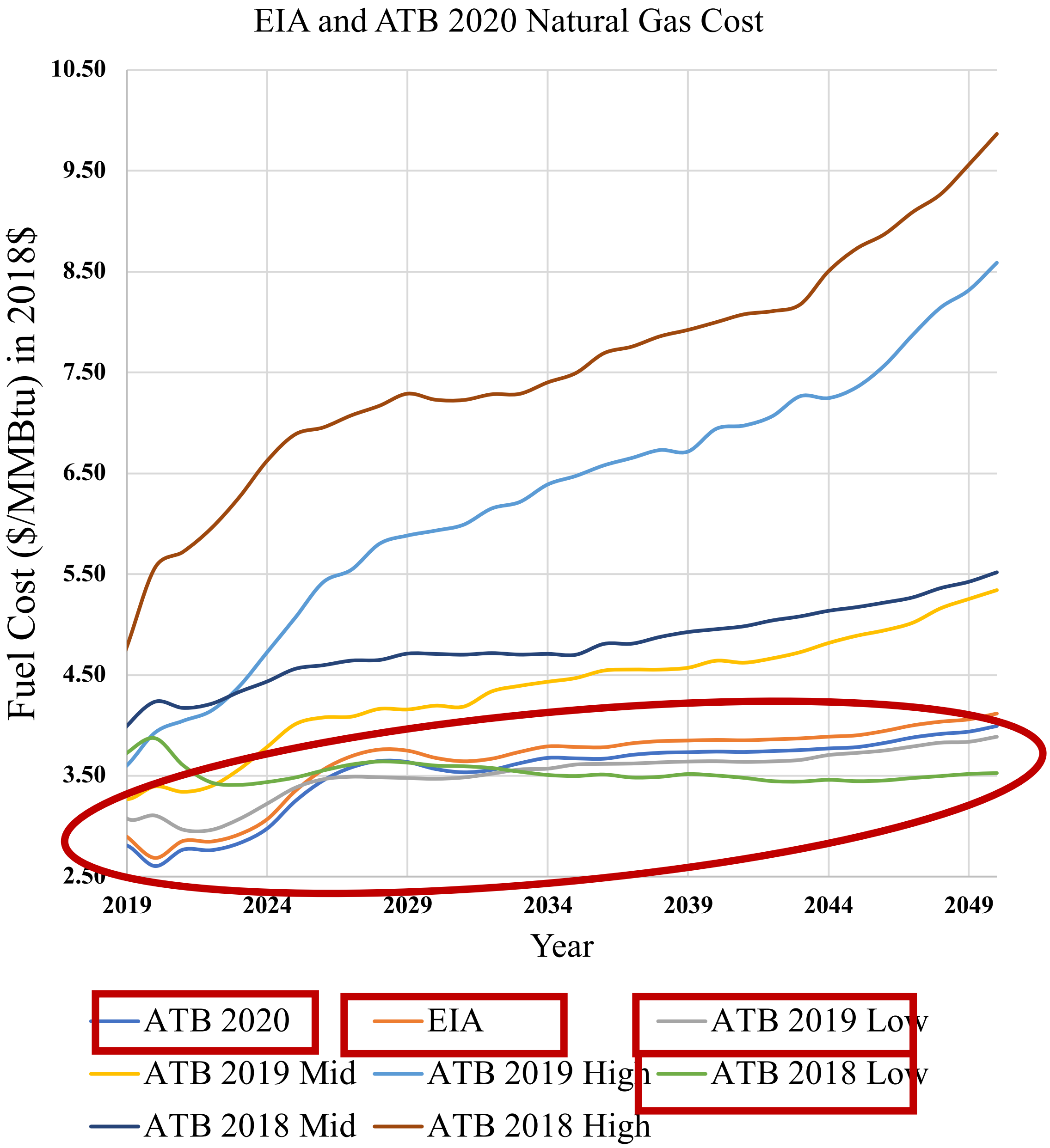


Figure 3. 11 Natural Gas cost based on EIA and ATB

Coal

- The cost of coal was reported to be substantially higher in California than elsewhere. Presumably, this is effectively because of a carbon tax.
- The baseline cost for coal was found to be $2/MMBTU in both RESOLVE and in the NREL 2020 ATB.
- Recognizing that coal is not a major player in California's electricity grid and because the data did not change by year, we have not graphed the data.

Uranium

- The cost of uranium has very little impact on the outputs of the modeling, so are not analyzed here. The more important aspects of nuclear power will depend on coupling of nuclear with hydrogen generation to enable it to become load following. This will be considered in the scenario analysis rather than in the baseline.

Table 3. 36. Parameters used in SWITCH to calculate the annualized cost for conventional

Fuel	Technology	Heat Rate (MMBtu/MWh)	Thermal Efficiency, Net (%)	Construction Time (Yr)	Lifetime (Yr)	Forced Outage Rate (%)	Scheduled Outage Rate (%)	Carbon Emissions (tCO_2/MWh)
Coal	Coal IGCC	7.9	42.9	2	40	8	12	0.759
Coal	Coal Steam Turbine	9.0	37.9	2	40	6	10	0.860
Coal CCS	Coal IGCC CCS	10.4	32.9	2	40	8	12	0.149
Coal CCS	Coal Steam Turbine CCS	12.1	28.2	2	40	6	10	0.173
Gas	CCGT	6.7	50.9	2	20	4	6	0.356
Gas	Compressed Air Energy Storage	4.9	69.5*	6	30	3	4	0.261
Gas	Gas Combustion Turbine	10.4	32.8	2	20	3	5	0.551
Gas CCS	CCGT CCS	10.1	33.9	2	20	4	6	0.080
Uranium	Nuclear	9.7	35.1	6	40	4	6	0

Parameters used by SWITCH to model conventional power generation are summarized in Table 3.36. O&M costs and heat rates are compared for SWITCH, RESOLVE, and NREL's ATB in Table 3.37.

Table 3. 37 O&M costs and heat rates of natural gas-fired power plants (ATB and models)

Items	Units	CT	CC	CC-CCS	RESOLVE(CC)	SWITCH(CC)
Fixed O&M	$/kW-yr	11.4	12.9	27.0	11.5	12.9
Variable O&M	$/MWh	2.16	4.50	5.72	0	4.50
Heat Rate	MMBTu/MWh	9.51	6.40	7.53	-	6.7

4. Resource definition – Storage (Costs and builds)

4.1 Lithium Batteries

Summary: Lithium battery prices have been dropping quickly. The baseline definition of lithium ion batteries will largely determine the competition with other storage technologies, so this is a key element. For the RESOLVE RSP, we select to change the way they are modeled to provide adoption of lithium batteries in a way that reflects how they are being used in California today – as 4-hour batteries. If policy changes, the assumptions would need to change. For SWITCH we select to use the ratio defined by the NREL ATB: the $/kWh will be 1.15 X the $/kW.

The RESOLVE RSP limits the build of the storage resource in two ways. The power capacity is limited explicitly; the energy capacity is equal to or greater than the power capacity multiplied by the minimum duration (12 for pumped hydro, 1 for Li batteries). Thus, the RSP deploys lithium batteries with more than the standard 2- or 4-hour duration, as shown in Tables 4.1 and 4.2.

Table 4. 1 Selected builds in 2045 by RESOLVE for RSP

Resource	New build MW	New build MWh	Ratio (h)
CAISO_Existing_Pumped_Storage	0	0	-
CAISO_New_Pumped_Storage	0	0	-
CAISO_New_Li_Battery	1148.16	16690.01	14.5
CAISO_BTM_Li_Battery	0	0	-
CAISO_New_Li_Battery_2	2186.56	30780.81	14.1
CAISO_New_Li_Battery_3	9020.45	48559.2	5.4
CAISO_New_Li_Battery_4	5917.35	43464.05	7.3
CAISO_New_Li_Battery_5	27123.87	189730.73	7.0

Table 4. 2 Cumulative capacity in 2045 by RESOLVE for RSP

Resource	Cumulative build MW	Cumulative build MWh	Ratio (h)
CAISO_Existing_Pumped_Storage	1599.2*	252821.12*	158*
CAISO_New_Pumped_Storage	973.48	11681.71	12*
CAISO_New_Li_Battery	7801.3**	43302.59	5.6
CAISO_BTM_Li_Battery	1647.06*	4117.66*	2.5*
CAISO_New_Li_Battery_2	6024.12**	35146.77	5.8
CAISO_New_Li_Battery_3	9020.45**	48559.2	5.4
CAISO_New_Li_Battery_4	5917.35**	43464.05	7.3
CAISO_New_Li_Battery_5	27123.87	189730.73	7.0

*Planned values
**Limited growth

Costs for lithium ion batteries typically place more cost associated with the energy than the power rating, but the costs in $/kW and $/kWh are fairly similar as shown in Table 4.3. The ratio of the $/kWh cost to the $/kW costs is about 1.38 for the SB100 reference, 1.9 for the RSP, and 1.15 for the NREL ATB. This substantial variation of the assignment of the costs to the power or energy rating may reflect that the basis of this differentiation is poorly defined for lithium ion batteries.

Table 4. 3 Comparison of prices for lithium-ion batteries.

Year	Power Capital Cost ($/KW)*	Energy Capital Cost ($/KWh)*	Annual Fixed O&M ($/KW)	Annualized Power CAPEX ($/KW)**	Annual Fixed O&M ($/KW)	Annualized Energy CAPEX ($/KWh)**	Annual Energy O&M ($/kWh)	Annualized total for 1-h battery ($/KW)
SB100 CAPITAL COST ASSUMPTION – Mid Case (p. 58-59 Table 42 for later years Table 43 for 2020)								
2020				23	0.35	46	0.69	70
2022				18	0.27	37	0.56	56
2026	Table 42			12	0.18	26	0.39	39
2027	191	265		17.7	0.27	24.6	0.37	63.56
2030	162	224		15.0/10	0.23	20.8/20	0.31	53.8
2035	162	224		15.0	0.23	20.8	0.31	53.8
2040	122	169		15.88	4.365	20.32		40.565
2045	105	145		13.66	3.75	17.44		34.85
RESOLVE RSP – should include ITC								
2020				22.89	0.78	42.07	3.97	69.71
2022				18.08	0.66	33.86	3.36	55.95
2026				12.27	0.49	23.69	2.53	38.98
2030				10.34	0.42	20.06	2.18	33.00
2045				8.84	0.36	17.16	1.86	28.22
NREL ATB moderate as written (using the 4-h battery O&M and 15-year life) excludes ITC								
2020	260	299		28.55	36.37*	32.82	0	97.74
2022	228	262		25.03	31.86*	28.77	0	85.66
2026	173	198		18.99	24.17*	21.74	0	64.90
2030	146	168		16.04	20.43*	18.45	0	54.92
2045	119	136		13.03	16.60*	14.93	0	44.56
NREL ATB moderate with 10-year life and lower (RSP) O&M Excludes ITC								
2020	260	299		37.02	0.78	42.57	3.97	84.34
2022	228	262		32.46	0.66	37.30	3.36	73.78
2026	173	198		24.63	0.49	28.19	2.53	55.84
2030	146	168		20.79	0.42	23.92	2.18	47.31
2045	119	136		16.94	0.36	19.36	1.86	38.52

* overnight prices

** annualized using the assumptions: ITC of 30% in 2020 and 10% after 2022 for best value. The SB100 calculations assumed lifetime=20 years, after-tax WACC=6.77% in 2030, fixed O&M=1.5%. The NREL ATB calculations assumed: lifetime=15 yrs, discount rate=7%, fixed O&M=2.5% of the 4-h duration total capex, and 2018$.

Testing the sensitivity of the RSP results to the distribution of costs, the RSP lithium ion battery costs were replaced with $0/kW and with the sum of the $/kW+$/kWh for the $kWh cost, forcing expansion beyond one hour to bear the full Capex cost of a 1-hour battery (though the O&M costs were left as in the RSP). The modified RSP results are compared in Tables 4.4 and 4.5, duplicating the data in 4.1 and 4.2 for easy comparison. Key changes are that

- an additional 3 GW of pumped storage are built (with the required 12 hours of storage)

- an additional 7 GW of flow batteries are built
- an additional 11 GW of lithium ion batteries are built
- the lithium ion batteries have about 100 GWh less storage capacity
- the 100 GWh less storage for the lithium ion batteries is replaced by a similar amount of pumped hydro (36 GWh) and flow batteries (59 GWh)
- the energy-to-power ratio for the lithium ion batteries are now pinned at 4 h

Table 4. 4 Selected builds in 2045 by RESOLVE for RSP with modified cost inputs

	RSP			**Modified RSP**		
Resource	**New build MW**	**New build MWh**	**Ratio**	**New build MW**	**New build MWh**	**Ratio**
Existing_Pumped_Storage	0	0	-			
New_Pumped_Storage	0	0	-	**0**	**0**	
New_Flow_Battery	0	0	-	**0**	**22835**	**n/a**
New_Flow_Battery_2	0	0	-	**0**	**8543**	**n/a**
New_Li_Battery	1148	16690	14.5	**263**	**1052**	**4.0**
BTM_Li_Battery	0	0	-	**0**	**0**	
New_Li_Battery_2	2187	30781	14.1	**5498**	**23570**	**4.3**
New_Li_Battery_3	9020	48559	5.4	**9020**	**36082**	**4.0**
New_Li_Battery_4	5917	43464	7.3	**5917**	**23669**	**4.0**
New_Li_Battery_5	27124	189731	7.0	**38716**	**154864**	**4.0**

Table 4. 5 Cumulative capacity in 2045 by RESOLVE for RSP and modified RSP

	RSP			**Modified RSP**		
Resource	**Cum. build MW**	**Cum. build MWh**	**Ratio**	**Cum. build MW**	**Cum. build MWh**	**Ratio**
Existing_Pumped_Storage	1599*	252821*	158*	**1599***	**252821***	**158***
New_Pumped_Storage	973	11681	12*	**4000**	**48000**	**12***
New_Flow_Battery	0	0	-	**5036**	**42978**	**8.5**
New_Flow_Battery_2	0	0	-	**1875**	**16044**	**8.6**
New_Li_Battery	7801**	43303	5.6	**6916**	**27665**	**4.0**
BTM_Li_Battery	1647*	4118*	2.5*	**1647***	**4118***	**2.5***
New_Li_Battery_2	6024**	35147	5.8	**6024****	**24096**	**4.0**
New_Li_Battery_3	9020**	48559	5.4	**9020****	**36082**	**4.0**
New_Li_Battery_4	5917**	43464	7.3	**5917****	**23669**	**4.0**
New_Li_Battery_5	27124	189731	7.0	**38716**	**154864**	**4.0**
Total for Li Batteries	57533	364322	6.3	**68240**	**266376**	**3.9**
Total ALL storage	60105	628824		**80750**	**626219**	

*Planned values
**Limited growth

We propose to compare the modeling using NREL ATB ratio of split costs to the requirement that lithium batteries be built to a minimum of 4 hours while placing all of the cost on the energy cost, which will discourage building beyond 4 hours. This has some risk as it is technically feasible to install 1-hour lithium battery resources. But, by making different choices for the two models, we will be able to ascertain whether it causes a significant difference. We also will run each both ways for comparative purposes. The proposed data are summarized in Tables 4.6 and 4.7. Additional parameters used by SWITCH are summarized in Table 4.8.

Table 4. 6 Proposed energy-related SWITCH and RSP RESOLVE costs for batteries

Build year or Vintage	Gen_overnight_cost-derived data from SWITCH		Energy_storage_cost_dollars_per_kwh_yr RESOLVE	new_energy_capacity_fixed_o_and_m_dollars_per_kwh_yr	
	$/MWh (upfront)	$/kWh-y (annual)*	From RSP ($/kWh-y)	SWITCH ($/kWh-y)	RESOLVE ($/kWh-y)
2020	306678	39.72	64.96	0	3.97
2025	211720	27.42	38.23	0	2.69
2030	172299	22.31	30.40	0	2.18
2035	161555	20.92	28.41	0	2.05
2040	150811	19.53	27.21	0	1.95
2045	139988	18.13	26.00	0	1.86
2050	129244	16.74	24.69	0	1.77

* This cost is annualized with 10-year lifetime and 5% discount rate.

Table 4. 7 Proposed power-related SWITCH and RSP RESOLVE costs for batteries

Build year or Vintage	Gen_overnight_cost-derived data from SWITCH		Annual_fixed_cost_by_vintage RESOLVE	Gen_fixed_om or fixed_o_and_m_dollars_per_kw_yr	
	$/MW (upfront)	$/kW-y (annual)*	From RSP ($/kW-y)	SWITCH ($/kW-y)	RESOLVE ($/kW-y)
2020	267020	34.58	0	32.04	0.78
2025	184307	23.87	0	25.19	0.52
2030	150021	19.43	0	20.43	0.42
2035	140620	18.21	0	19.15	0.40
2040	131298	17.00	0	17.88	0.38
2045	121897	15.79	0	16.60	0.36
2050	112496	14.57	0	15.32	0.35

* This cost is annualized with 10-year lifetime and 5% discount rate.

The very high fixed O&M costs included in the NREL ATB arise because of assuming capacity additions will be used to counter degradation.[37] The graph (reproduced in Fig. 4.1) in Fig. 7 top right in NREL Report #75385 shows how the reported O&M costs may vary by a full order of magnitude. Some of the highest values are taken from 2017 and imply that the batteries must

---

[37] https://www.nrel.gov/docs/fy20osti/75385.pdf

effectively be replaced something like every 3-4 years, inconsistent with the concept of a 15-year battery. For SWITCH, consistent with the above, we will follow the NREL ATB. For RESOLVE, we will use the lower O&M values, consistent with the RESOLVE RSP, as tabulated in Tables 4.6 and 4.7.

Table 4. 8 Parameters used in SWITCH to calculate the annualized cost for batteries

Fuel	Technology	Construction time (y)	Lifetime (y)	Forced-Outage rate (%)	Scheduled outage rate (%)	Carbon emissions (tCO_2/MWh)
Storage	Battery Storage	3	10	2	0.5	0

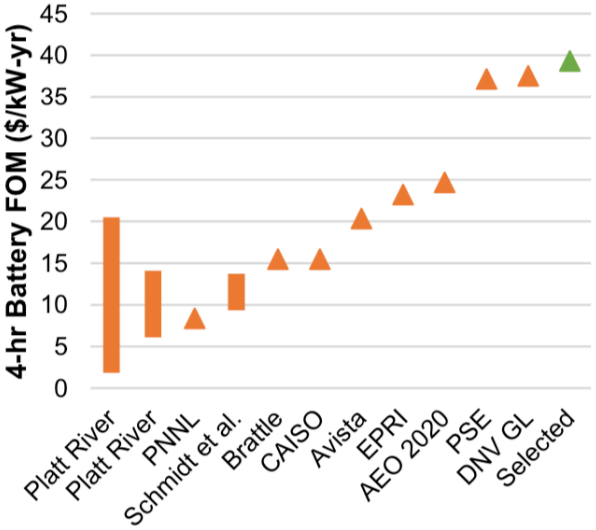


Figure 4. 1 Battery fixed O&M cost (Source: NREL)

4.2 Pumped Hydro

CAISO currently has 1599 MW of pumped hydro storage capacity with a total of 253 GWh of energy storage capacity. These numbers represent 5 existing systems that are aggregated into a single resource. The largest of these is Helms with roughly 75% of the total (power) capacity. The pumped hydro storage provides 40% of the energy storage capacity calculated for 2045 by the current RSP. The inputs in the RSP for new pumped hydro are shown in Table 4.9 and result is only an additional 2% of pumped hydro capacity being built.

More recently, as part of the SB100 analysis,[38] the cost inputs for Pumped hydro were revisited and the results are shown in the rightmost column of Table 4.9. The minimum duration for the new pumped hydro is specified to be 12 hours. The “Total for 12 h duration” column enables direct comparison with the SB100 total.

---

[38] https://efiling.energy.ca.gov/getdocument.aspx?tn=234532

The following assumptions were made in the SB100 Joint Agency Report.

- Financing lifetime of 50 years
- Fixed O&M of $25/kW-yr with an annual escalation of 2%
- No variable O&M costs
- After-tax WACC of 7.24% (in 2030).

Table 4. 9 Summary of inputs for new Pumped Hydro resources in RESOLVE RSP

Period	Annualized Power Capex ($/kW-y)	Annual Power O&M ($/kW-y)	Annualized Energy Capex ($/kWh-y)	Annual Energy O&M ($/kWh-y)	Total for 12 h duration ($/kW-y)	SB100 total ($/kW-y)
2020	117.22	13.89	10.78	0	260.47	
2021	109.84	13.83	10.1	0	244.87	
2022	104.26	13.81	9.59	0	233.15	
2023	92.46	13.71	8.5	0	208.17	
2024	92.48	13.76	8.5	0	208.24	
2026	93.37	13.87	8.59	0	210.32	
2027						190
2030	95.02	14.03	8.74	0	213.93	192
2035			8.96			197
2040			9.09			199
2045	99.69	14.06	12.15	0	259.55	200

While multiple groups are working on new pumped hydro plants, many of these projects (Eagle Mountain and Cat Creek) have taken years. There can be opposition and construction barriers to overcome. Pumped hydro is the largest storage technology available today and it has been proposed[39] that pumped hydro could meet all of our storage needs by doing projects that are off river. Although this vision is quite attractive, we have found little evidence that it is on the verge of becoming a reality. Thus, rather than including a larger buildout of pumped hydro as part of the baseline, we will consider it as a scenario.

RESOLVE allows build out of pumped hydro plants using the cost assumptions in Tables 4.10 and 4.11. The resulting buildout, compared with the build limits, is shown in Table 4.12. We observe that the model selects to build only a fraction of the allowed build. This reflects that the annualized cost of the pumped hydro is substantially higher than the cost of the lithium batteries. The comparison of pumped hydro with battery technologies is difficult because a pumped hydro project may have an enormous upfront investment that provides benefit for decades (or even centuries). In contrast, the batteries last only 10 or 15 years. As discussed above, modeling the batteries to account for their degradation can be done in multiple ways.

Pumped hydro also has the disadvantage that there is no large business pushing for it and environmental groups pushing against it.

---

[39] Lu, Bin, et al. "Geographic information system algorithms to locate prospective sites for pumped hydro energy storage." *Applied energy* 222 (2018): 300-312.

Table 4. 10 Proposed energy-related RESOLVE costs for pumped hydro

Build year or Vintage	Gen_overnight_cost-derived data from SWITCH		Annual_fixed_cost_by_vintage RESOLVE	O&M Costs	
	$/MWh (upfront)	$/kWh-y (annual)	From RSP ($/kWh-y)	SWITCH ($/kWh-y)	RESOLVE ($/kWh-y)
2020	*	*	10.78	*	0
2025	*	*	8.53	*	0
2030	*	*	8.74	*	0
2035	*	*	8.96	*	0
2040	*	*	9.09	*	0
2045	*	*	12.1480752	*	0
2050	*	*	12.1480752	*	0

*SWITCH does not allow building of new pumped hydro

Table 4. 11 Proposed power-related RESOLVE costs for pumped hydro

Build year or Vintage	Gen_overnight_cost-derived data from SWITCH		Annual_fixed_cost_by_vintage RESOLVE	O&M Costs	
	$/MW (upfront)	$/kW-y (annual)	From RSP ($/kW-y)	SWITCH ($/kW-y)	RESOLVE ($/kW-y)
2020	*	*	117.22	*	13.89
2025	*	*	92.72	*	13.80
2030	*	*	95.02	*	14.03
2035	*	*	97.44	*	14.05
2040	*	*	98.80	*	14.05
2045	*	*	99.69	*	14.06
2050	*	*	99.71	*	14.06

*SWITCH does not allow building of new pumped hydro

Table 4. 12 Pumped hydro Expansion selected by RESOLVE for 5-year RSP

Period	CAISO selected operating capacity (MW)	CAISO new builds (MW)	CAISO cumulative new builds (MW)	CAISO build limits (MW)
2020	1599	0	0	0
2025	1599	0	0	0
2030	2057	458	458	4000
2035	2687	630	1088	4000
2040	2687	0	1088	4000
2045	2687	0	1088	4000

4.3 Carbon capture from natural gas plants

The possibility of using carbon sequestration to enable natural gas plants to effectively operate in a zero-emissions mode has attracted a lot of attention. The approach is not a favorite of many clean-energy advocates because of the ongoing risk of methane leaks and related environmental impacts. However, there is a growing movement toward investing in carbon sequestration for the purpose of reducing the current level of carbon dioxide even if additional emissions could be eliminated. Carbon sequestration will first be used for processes that result in high carbon dioxide concentrations. The development and maturation of carbon capture technology and of the associated infrastructure for sequestering the carbon dioxide is likely to result in a reduction in cost.

There are two key developments that will affect the adoption of carbon sequestration for the power sector:

1. The reduction of cost as investment in carbon sequestration increases, and
2. The need for reliability as we reach 80%, 90%, and finally 100% reduction in emissions.

The first development is beginning to unfold, but will be very difficult to project because of the highly political nature of the investment. The strong desire of the oil companies to continue with their current business model may enable both policies and technological investment to accelerate carbon sequestration efforts.

On the other hand, the probable competitor of carbon sequestration plus natural gas is blue or green hydrogen. The investment of converting our current infrastructure from handling massive amounts of natural gas to handling massive amounts of hydrogen will not be easy, but is already being explored.

Because the pathway to using carbon sequestration (coupling it with natural gas or as blue hydrogen) is not clear, we opt to consider carbon sequestration as part of the scenario analysis and not as part of the baseline.

5. Resource adequacy

Our study requires both a full understanding of what will be required to maintain resource adequacy as well as the ramifications of that maintenance on the use of the resources. Notably, providing resources that will be adequate in the worst year might cause investment in resources that are only used in those worst years.

Thus, we intend to develop full-year data sets for multiple years. Our understanding is that E3 is also working on this task and we do not wish to duplicate their work. The creation of solar generation profiles for 30 years is quite straightforward using tools that are readily available.

More details of our approach are given in the Modeling Approach Description, Section 4.

6. Loads

Load profiles need to reflect the weather as well as be dependent on the location. For a historical year, these can be presented as reported, but modeling the future is more difficult. The IEPR process studies population growth, energy efficiency trends and many other factors to provide the best forecasts.

We will leverage previous work done in developing both RESOLVE and SWITCH to identify load profiles that are relevant to the study, recognizing that these have high uncertainties and must be varied as part of our sensitivity analysis.

See section 6 in the Modeling Approach Description for more detail.

7. Policy actions

California Senate Bill 100 sets a target of zero-carbon emissions in 2045 and Senate Bill 350

The meaning of the SB100 targets is sometimes debated. The spirit of the law suggests that no carbon emissions should be associated with the direct operation of the grid. However, the phrase "retail sales" has sometimes been interpreted to suggest that carbon emissions may be acceptable for the small amount of electricity that does not reach the retail customer because it is dissipated in the transmission lines.

The greenhouse gas targets implemented by the Scenario tool for 5-year periods are shown in Table 7.1 along with a proposed set of targets that would reach 0 in 2045.

Table 7. 1 GHG Targets in RESOLVE RSP and proposed

Period	ghg_emissions_target _tco2_per_year	Proposed ghg_emissions_target _tco2_per_year
2020	52,512,420	52,512,420
2025	45,206,210	42,009,936
2030	37,900,000	31,507,452
2035	29,350,488	21,004,968
2040	20,800,975	10,502,484
2045	12,251,463	0

We choose to set the carbon emissions target in 2045 to zero for the baseline in order to explore the ramifications of meeting the tougher target. However, we note that the study may be viewed as how to reach the zero-carbon target. Our model of 2040 may look very much like the 2045 results in the RSP.

The targets that have been used in SWITCH and that we propose are shown in Table 7.2.

Table 7. 2 GHG Targets in SWITCH

PERIOD	WECC carbon_cap_tco2 _per_yr	CA carbon_cap_tco2 _per_yr_CA	WECC Proposed carbon_cap_tco2 _per_yr	CA Proposed carbon_cap_tco2 _per_yr_CA
2020	284,800,000	49,000,000	225,875,000	58,925,000
2025	244,453,238	39,200,000	195,990,738	48,462,500
2030	184,106,762	29,400,000	146,106,762	38,000,000
2035	148,760,000	23,887,500	123,426,667	25,333,333
2040	113,413,238	18,375,000	100,746,572	12,666,667
2045	78,066,762	12,862,500	78,066,762	0

8. Bibliography

- Black and Veatch, 2012, Cost and performance data for power generation technologies. Overland Park, KS, 2012; [http://bv.com/docs/reports-studies/nrel-cost-report.pdf]
- Bloomberg NEF, March 2020, Hydrogen Economy Outlook [https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf]
- California Energy Commission, June 2020, Input & Assumptions - CEC SB 100 Joint Agency Report [https://efiling.energy.ca.gov/GetDocument.aspx?tn=234532&DocumentContentId=67359]
- California Energy Commission, 2021, Draft 2020 Integrated Energy Policy Report (IEPR) Update, Volume I [https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2020-integrated-energy-policy-report-update-0]
- California Public Utility Commission, March 2020, 2019-2020 Electric Resource Portfolios to Inform Integrated Resource Plans and Transmission Planning [https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M331/K772/331772681.PDF]
- Center for Climate Energy and Solutions, State Climate Policy Maps [https://www.c2es.org/content/state-climate-policy/]
- Clean Energy States Alliance (CESA), 2020, 100% Clean Energy Collaborative - Table of 100% Clean Energy States [https://www.cesa.org/projects/100-clean-energy-collaborative/table-of-100-clean-energy-states/]
- Cole, W. and A.W. Frazier, June 2020, Cost Projections for Utility-Scale Battery Storage: 2020 Update
- Cole, Wesley, and A. Will Frazier, June 2019, Cost Projections for Utility-Scale Battery Storage
- Eichman, Josh, Mariya Koleva, Omar J. Guerra, and Brady McLaughlin, March 2020, Optimizing an Integrated Renewable Electrolysis System [https://www.nrel.gov/docs/fy20osti/75635.pdf]
- Energy and Environmental Economics, June 2020, "Hydrogen Opportunities in a Low-Carbon Future" [https://www.ethree.com/wp-content/uploads/2020/07/E3_MHPS_Hydrogen-in-the-West-Report_Final_June2020.pdf]
- European Commission, March 2020, Commercialisation of Energy Storage in Europe [https://www.fch.europa.eu/sites/default/files/CommercializationofEnergyStorageFinal_3.pdf]
- Fu, Ran, Timothy Remo, and Robert Margolis, November 2018, 2018 U.S. Utility-Scale Photovoltaics Plus-Energy Storage System Costs Benchmark
- Fuel Cell and Hydrogen Energy Association (FCHEA), "Road Map to a US Hydrogen Economy" [http://www.fchea.org/us-hydrogen-study]
- Klein, J., 2007, Comparative costs of California central station electricity generation technologies: cost of generation model. California Energy Commission, Sacramento, CA, 2007; [http://www.energy.ca.gov/2007publications/CEC-200-2007-011/CEC-200-2007-011-SD.PDF]
- Lazard, November 2019, Lazard's Levelized Cost of Storage Analysis - version 5.0

- McGowin, C., 2007, Renewable Energy Technical Assessment Guide. TAG-RE:2007. Palo Alto, CA: Electric Power Research Institute.
- Mileva, A., et al. 2016, Power system balancing for deep decarbonization of the electric power sector. Applied Energy, 162, 1001-1009
- National Renewable Energy Laboratory (NREL), 2018 Annual Technology Baseline (ATB) [https://data.nrel.gov/system/files/89/2018-ATB-data-interim-geo.xlsm]
- National Renewable Energy Laboratory (NREL), 2019 Annual Technology Baseline (ATB) [https://data.nrel.gov/system/files/115/2019-ATB-data.xlsm]
- National Renewable Energy Laboratory (NREL), 2020 Annual Technology Baseline (ATB) [https://atb.nrel.gov/electricity/2020/files/2020-ATB-Data.xlsm]
- pv magazine, August 2020, Power-to-gas facility in Canada could pay back in just under three years [https://www.pv-magazine.com/2020/08/11/power-to-gas-facility-in-canada-could-pay-back-in-just-under-three-years/]
- pv magazine, December 2020, PV trends of 2020: Part 5 [https://www.pv-magazine.com/2020/12/30/pv-trends-of-2020-part-5/]
- RESOLVE Scenario Tool for creating the input files for RESOLVE [ftp://ftp.cpuc.ca.gov/energy/modeling/RESOLVE_Scenario Tool 2020-05-27_inputs_for_pyomo_5-6-9.xlsb]
- Strategen, December 2020, Long Duration Energy Storage for California’s Clean, Reliable Grid [https://www.strategen.com/strategen-blog/long-duration-energy-storage-for-californias-clean-reliable-grid]
- United States Energy Information Administration, 2007a, Form EIA-860 database annual electric generator report. Washington, DC, 2007.
- United States Department of Labor, 2009, Occupational pay comparisons among metropolitan areas. Bureau of Labor Statistics, Washington, DC, 2009.
- United States Energy Information Administration, 2012, Annual energy outlook 2012. Washington, DC, 2012.
- U.S. Department of Energy, July 2020, Battery Storage in the United States: An update on market trends [https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage.pdf]
- U.S. Energy Information Administration, Annual Energy Outlook 2020 (Table 13. Natural Gas Supply, Disposition, and Prices) [https://www.eia.gov/outlooks/aeo/excel/aeotab_13.xlsx]