RESOLVE Documentation: CPUC 2017 IRP

Inputs & Assumptions (DRAFT)

July 2017

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Energy+Environmental Economics

RESOLVE Model Documentation

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1 Introduction

1.1 Overview

RESOLVE is an optimal investment and operational model designed to inform long-term planning questions around renewables integration in systems with high penetration levels of renewable energy. The model is formulated as a linear optimization problem. RESOLVE co-optimizes investment and dispatch for a selected set of days over a multi-year horizon in order to identify least-cost portfolios for meeting renewable energy targets and other system goals. RESOLVE also incorporates a representation of neighboring regions in order to characterize transmission flows into and out of a main zone of interest endogenously. RESOLVE can solve for the optimal investments in renewable resources, various energy storage technologies, new gas plants, and gas plant retrofits subject to an annual constraint on delivered renewable energy that reflects the RPS policy, an annual constraint on greenhouse gas emissions, a capacity adequacy constraint to maintain reliability, constraints on operations that are based on a linearized version of the unit commitment problem, as well as constraints on the ability to develop specific renewable resources.

For the purposes of the CPUC's Integrated Resource Plan, E3 has developed inputs and assumptions for RESOLVE to create optimal portfolios for the CAISO electric system under a range of different forecasts of load growth, technology costs, fuel costs, and policy constraints. RESOLVE optimizes the buildout of new resources twenty years into the future, representing the fixed costs of new investments and the costs of operating the CAISO system within the broader footprint of the WECC electricity system.

This document summarizes key inputs and assumptions to the RESOLVE model under development for the California Public Utility Commission's (CPUC) 2017 Integrated Resource Plan (IRP). It is intended to accompany the Excel-based RESOLVE User Interface to provide parties with documentation of the inputs and assumptions contained within that spreadsheet.

1.2 Contents of User Interface

The Excel-based RESOLVE User Interface contains the complete set of inputs and assumptions needed to run a RESOLVE scenario spread across many worksheets. The tabs in the User Interface are grouped into several categories:

- **System inputs (SYS):** inputs that broadly define the electric system;
- **Load inputs (LOADS):** assumptions related to current and future loads;
- **Renewable inputs (REN):** assumptions related to both existing and potential future renewable resources;
- **Conventional generator inputs (CONV):** assumptions related to both existing and potential future gas, coal, and nuclear generators;
- **Hydro generation inputs (HYD):** assumptions on the hydroelectric fleet;
- **Storage-related inputs (STOR):** assumptions defining existing and future storage resource potential;
- **DR-related inputs (DR):** assumptions defining existing and future demand response resource potential; and
- **Resource costing module (COSTS):** a module used to calculate levelized costs of future generation resources based on assumed capital, O&M, and fuel costs.

The classification of each tab among these categories is indicated by its prefix. Subsequent sections of this document discuss the sourcing and development of information contained on these tabs; for completeness, a comprehensive inventory of the contents of the User Interface is presented in Table 1.

Table 1. RESOLVE User Interface table of contents

Tab	Description
SYS_Fuel_Costs	This worksheet provides all input data and calculations on fuel costs, including the carbon cost.
SYS_Planning_Reserve	This worksheet provides all input data and calculations regarding planning reserve margin and resource adequacy.
SYS_Local_Needs	This worksheet provides all input data and calculations regarding local capacity needs.
SYS_RPS_GHG_Targets	This worksheet includes all input data and calculations regarding the RPS and GHG targets in the CAISO system.
SYS_Regional_Settings	This worksheet contains all data and calculations regarding zonal transmission constraints, hurdle rates between zones, carbon adders for transmission into California, and simultaneous flow constraints (such as NW to California).
SYS_Reserves	This worksheet contains all data and calculations regarding reserve requirements (upward and downward), and the sub-hourly deployment of load-following down (which dictates how much sub-hourly curtailment occurs when renewables provide load-following down).
SYS_Baseline_Costs	This worksheet includes all the "Baseline" costs used to contextualize the resulting costs from RESOLVE. These costs are not direct inputs to the RESOLVE optimization, but are shown to place the total cost output of RESOLVE in the context of total electric sector costs.
LOADS_Forecast	This worksheet contains all data and calculations regarding the load forecast, such as the baseline consumption, EV forecast, behind-the-meter PV forecast, energy efficiency forecast etc. The data is both provided in terms of annual load (GWh) and contribution to peak load (MW).
LOADS_Hydrogen	This worksheet contains a forecast of future hydrogen production loads (set to zero by default in all scenarios).
LOADS_EV_Char	This worksheet contains all data and calculations regarding the operating characteristics of the EV fleet, such as workplace charging availability, EV charging flexibility, EV charging demand shapes, etc. When none of the EV charging is flexible, the EV shape is defined by the shape provided in the LOADS_Profiles worksheet. The EV driving demand shape is only used for the fraction of EV charging that is flexible, and coincides with the driving times (i.e. it peaks in the morning and evening). Note that the actual EV demand forecast is provided through the LOADS_Forecast worksheet.
LOADS_Profiles	This worksheet contains all data and calculations regarding the load shapes. For all non-CAISO zones, this is simply a normalized load shape for that entire zone. For the CAISO zone, the load shape is built up by combining a baseline consumption shape (no behind-the-meter PV, electric vehicles, energy efficiency, or time-of-use adjustments), an electric vehicle shape, an energy efficiency shape, and a time-of-use load modifier shape.

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REN_Baseline	This worksheet contains all data and calculations regarding planned renewable resources for each of the modeled zones (CAISO, NW, SW, LDWP, BANC, IID). For each zone and for each type of resource, the planned GWh of generation by year is drawn from the REN_Existing_Resources worksheet, which contains a list of all the planned renewable resources. Since RESOLVE works with MW of installed capacity rather than GWh of annual generation, the annual generation for each resource is converted to a MW number, using the RESOLVE capacity factor assumed for that resource. If the RESOLVE capacity factor does not match the actual capacity factor, this will result in a different installed capacity number (MW). This is acceptable since the model will still match the annual generation, but it could confuse some users.
REN_Candidate	This worksheet contains all data and calculations regarding the candidate renewable resource, i.e. the renewable resources that RESOLVE can pick from to optimize the buildout incremental to planned (baseline) renewables. The worksheet contains the renewable potential by RESOLVE resource (drawn from the REN_Supply_Curve worksheet), the forced renewable build (candidate resources that the user can force to be built), and the annualized fixed costs per kW of installed capacity for each of these resources, including transmission costs if applicable. Please note that for biomass, small hydro, and geothermal, the annualized fixed costs are adjusted upwards to take into account that RESOLVE models these resources to have a 100% capacity factor, while in reality capacity factors range from 53% to 88%.
REN_Supply_Curve	This worksheet contains a list of the total renewable supply curve, which is synced with the latest RPS calculator version. It is used to calculate the total potential by RESOLVE resource, as well as the average capacity factor and cost. The latter is dependent on which of the cost settings is chosen in the Dashboard tab (a macro needs to be rerun to update these costs).
REN_Tx_Costs	This worksheet contains all data and calculations regarding transmission costs. It contains the transmission cost for out-of-state (OOS) renewable resources, as well as full capacity deliverability status (FCDS) capacity limits and costs, and energy only (EO) capacity for each of the transmission zones. Last, it contains the mapping of Super CREZ/WREZ to RESOLVE zone, which is used to determine the potential by RESOLVE zone from the renewable supply curve.
REN_Profiles	This worksheet contains all data and calculations regarding the renewable profiles. It contains hourly shapes for the 37 modeled days for each of the candidate renewable resources, as well as the planned (baseline) resources.
REN_Existing_Resources	This worksheet is a list of all existing and committed (i.e. planned projects with permits and CPUC-approved contracts) renewable resources. It is used in the REN_Baseline worksheet to calculate the total amount of planned renewables by zone and type.
CONV_Baseline	This worksheet contains the installed capacity by year for each conventional resource for each of the RESOLVE zones. For the CAISO zone, these numbers are based on the data in the CONV_CAISO_Gen_List worksheet. For the other zones, these

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	are hardcoded values based on the 2026 Common Case.
CONV_Candidate	This worksheet contains the annualized fixed costs for the conventional candidate resources, i.e. the thermal resources that RESOLVE can decide to build. These are pulled from the tables in the COSTS_Costs_Table worksheet.
CONV_OpChar	This worksheet contains all data and calculations regarding the operating characteristics of the conventional fleet of each RESOLVE zone. For computational reasons, the thermal fleet is represented as a limited set of units that represent the weighted average for each generator class. For the CAISO generators, most of the data is pulled from the CONV_CAISO_Gen_List worksheet.
CONV_CAISO_Gen_List	This worksheet contains a list of all CAISO generators, including operating characteristics such as heat rate and Pmin. It is based on the CAISO NQC list and the CAISO Master Generating Capability List.
HYD_OpChar	This worksheet contains hydro operating characteristics for each of the RESOLVE zones. For each of the 37 modeled days, it specifies a daily hydro budget, a minimum generation constraint, and a maximum generation constraint.
STOR_Inputs	This worksheet contains all data and calculations regarding storage inputs. It contains the round-trip efficiency, minimum duration, planned storage build, and resource potential. It also contains the annualized fixed costs for the candidate storage resources for both the energy part of storage (e.g. pumped storage reservoir, Li-cells, flow battery tanks) and the capacity part (e.g. pumped storage turbine, Li-ion inverter and power electronics). These costs are pulled from the tables in the COSTS_Costs_Table worksheet.
DR_Shed	This worksheet contains all data and calculations regarding the existing shed demand response programs, broken out by utility. It also includes the assumed supply curve for new shed DR.
DR_Shift	This worksheet contains all data and calculations regarding shift demand response resources modeled in RESOLVE
COSTS_Cost_Table	This worksheet contains a list of tables with calculated costs for each of the resource types as defined in the COSTS_Resource_Char worksheet. The numbers in these tables are entered by a macro that loops over each of the resource types in the COSTS_Resource_Char worksheet and calculates annual levelized fixed costs using pro forma calculations (note that this button activates the same macro as the button on the *COSTS_Resource_Char* tab). To refresh these costs, press the “Refresh Levelized Costs” macro button at the top left.
COSTS_Resource_Char	This worksheet contains all data and calculations regarding resource costs. A list of inputs is provided in the yellow-shaded cells. The costs can be recalculated by pressing the “Refresh All Levelized Costs” macro button at the top left (note that this button activates the same macro as the button on the *COSTS_Cost_Table* tab). This will spit out a list of numbers (blue font) in the green-shaded cells, as well as fill out the tables in the COSTS_Costs_Table worksheet.

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Tab	Description
COSTS_Pro_Forma	This worksheet contains the pro forma calculations used to determine annual levelized fixed costs for each of the resources. When the "Refresh All Levelized Fixed Costs" button is clicked, the resource pro forma will be evaluated for each resource for each year of interest and the final output will be pasted in the COSTS_Cost_Table worksheet and the COSTS_Resource_Char worksheet.

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1.3 Conventions

The following conventions are used in RESOLVE and/or in this documentation:

- All costs are reported in **2016 dollars**.
- All levelized costs are assumed to be **levelized in real terms** (i.e., a stream of payments over the lifetime of the contract that is constant in real dollars).
- Within RESOLVE and throughout this document, the term **"Baseline Resources"** is used to designate the portion of the portfolio that is exogenous, generally reflecting either existing resources and future resources planned by the utilities; the term **"Selected Resources"** refers to those resources that are chosen by RESOLVE as part of the portfolio optimization.

1.4 Document Contents

The remainder of this document is organized as follows:

- **Section 2 (Load Forecast)** documents the assumptions and corresponding sources used to derive the forecast of load in CAISO and the WECC, including the impacts of demand-side programs, load modifiers, and the impacts of electrification;
- **Section 3 (Baseline Resources)** summarizes RESOLVE's assumptions on "baseline" resources—resources that are treated as exogenous to RESOLVE;
- **Section 4 (Candidate Resources)** discusses assumptions used to characterize the candidate resources that RESOLVE can select for inclusion in the optimized, least-cost portfolio;
- **Section 5 (Operating Assumptions)** presents the assumptions used to characterize the operations of each of the resources represented in RESOLVE's internal hourly production simulation model;
- **Section 6 (Resource Adequacy Requirements)** discusses the constraints imposed on the RESOLVE portfolio to ensure system and local reliability needs are met, as well as assumptions regarding the contribution of each resource towards these requirements;

+ **Section 7 (Greenhouse Gas Constraint)** discusses assumptions used in RESOLVE to characterize constraints on portfolio greenhouse gas emissions.

2 Load Forecast

2.1 CAISO Zone

Within CAISO, the annual load forecast is explicitly represented as a forecast of “Baseline Consumption” with a series of “demand-side modifiers.” These modifiers include:

+ Electric vehicles;
+ Building electrification;
+ Behind-the-meter PV;
+ Non-PV self-generation;
+ Energy efficiency; and
+ TOU rate impacts.

The CAISO load forecast is decomposed into these components so that the distinct hourly profile of each of these factors can be represented explicitly in RESOLVE. The profiles used to represent each component of the forecast are discussed in Section 5.2.1.

The primary source for load forecast inputs in RESOLVE is the CEC’s 2016 Integrated Energy Policy Report (IEPR) Demand Forecast.[1] For several of the demand-side modifiers, alternative levels of achievement can be selected as alternative scenario settings within RESOLVE; where this functionality exists, the sources of alternative assumptions are discussed.

All demand forecasts presented in this section reflect demands at the customer meter. Within RESOLVE, these demand forecasts are subsequently grossed up for assumed transmission & distribution losses of

[1] Most inputs to RESOLVE were extracted from Forms 1.1c, 1.5a, 1.5b, and 1.2.

7.3%, based on the average losses across the CAISO footprint assumed in the CEC's 2016 IEPR Demand Forecast.

2.1.1 BASELINE CONSUMPTION

Within RESOLVE, the term "Baseline Consumption" is used to refer to a counterfactual forecast of the consumption of electricity, capturing forecast economic and demographic changes in California, in the absence of load modifiers. The Baseline Consumption used in RESOLVE is derived from the retail sales reported in the CEC's 2016 IEPR Demand Forecast along with accompanying information on the magnitude of embedded load modifiers. The derivation of this Baseline Consumption from the retail sales forecast is shown in Table 2.

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Table 2. Derivation of "Baseline Consumption" from CEC 2016 IEPR Demand Forecast (GWh)

Component	2018	2022	2026	2030
CEC 2016 IEPR Retail Sales	209,522	208,903	207,748	*(last year of CEC 2016 IEPR Demand Forecast is 2027)*
+ Mid AAEE	+5,652	+11,829	+17,990	
+ Non-PV Self Generation	+13,516	+13,857	+14,058	
+ Behind-the-Meter PV	+10,226	+13,983	+20,191	
- Electric Vehicles	-1,123	-2,808	-5,626	
- Building Electrification	-187	-575	-917	
Baseline Consumption	**237,605**	**245,189**	**253,444**	***261,760***

Values shown in italics are extrapolated based on the 5-year compound average growth rate between 2022-2027

2.1.2 ELECTRIC VEHICLES

RESOLVE includes three options for forecasts of the future load impact of vehicle electrification. The first forecast is based directly on the embedded assumptions of the CEC 2016 IEPR Mid Demand forecast. The second two options capture forecasts of transportation electrification included in CARB's 2016 Scoping Plan[2]: (1) the "SP" option reflects CARB's adopted Scoping Plan scenario, which includes 3.6 million light duty electric vehicles in California by 2030; and (2) the "Alt1" option represents CARB's Alternative 1 scenario, which includes a total of 4 million light duty vehicles by 2030. Both of CARB's

[2] CARB's 2016 Scoping Plan is available for download here: **https://www.arb.ca.gov/cc/scopingplan/scopingplan.htm**

scenarios also include some electrification of the medium- and heavy-duty vehicle fleets. These three alternative forecasts are shown in Table 3.

Table 3. Electric vehicle forecast options (GWh)

RESOLVE Scenario Setting	2018	2022	2026	2030
CEC 2016 IEPR	1,123	2,808	5,626	*8,552*
CARB Scoping Plan – SP	716	1,997	4,931	8,483
CARB Scoping Plan – Alt1	713	1,960	5,069	9,039

Values shown in italics are extrapolated based on the 5-year linear growth rate between 2022-2027 (IEPR) and 2025-2030 (Scoping Plan)

In addition to electric vehicles, ARB's Scoping Plan also assumes adoption of hydrogen fuel cell vehicles. Because of the uncertainty associated with the development of hydrogen infrastructure to supply fuel for these vehicles, electric loads for associated hydrogen production are not included in this analysis.

2.1.3 BUILDING ELECTRIFICATION

As with electric vehicles, RESOLVE includes three options for forecasts of the future load impact of building electrification: one based on the forecast embedded in the CEC 2016 IEPR and two based on CARB's 2016 Scoping Plan scenarios. CARB's "SP" scenario includes no incremental building electrification measures and so is assumed to be identical to the CEC 2016 IEPR forecast. CARB's "Alt1" scenario assumes some incremental electrification in residential cooking, residential and commercial HVAC, and residential and commercial water heating. These forecasts are shown in Table 4.

Table 4. Building electrification forecast options (GWh)

RESOLVE Scenario Setting	2018	2022	2026	2030
CEC 2016 IEPR[3]	187	575	917	*1,232*
CARB Scoping Plan – SP	187	575	917	*1,232*

[3] Based on correspondence with the CEC, the forecast of building electrification loads is assumed not to have changed since the 2015 IEPR. The level of building electrification load embedded in the 2015 Demand Forecast is based on "CAISO Load Modifiers Mid Baseline-Mid AAEE," available at: http://docketpublic.energy.ca.gov/PublicDocuments/15-IEPR-03/TN209995_20160127T095507_CAISO_Load_Modifiers_Mid_BaselineMid_AAEE.xlsx.

CARB Scoping Plan – Alt1	187	575	3,874	*13,183*

Values shown in italics are extrapolated based on the 5-year linear growth rate between 2022-2027 (IEPR) and 2025-2030 (Scoping Plan)

2.1.4 BEHIND-THE-METER PV

RESOLVE includes three options for behind-the-meter PV adoption, each of which is based on the CEC's 2016 IEPR Demand Forecast. These options—Low, Mid, and High[4]—correspond to installed capacities of behind-the-meter PV of 9,300 MW, 15,900 MW, and 20,100 MW among CAISO LSEs by 2030, respectively. These forecasts are shown in Table 5.

Table 5. Behind-the-meter PV forecast options (GWh)

RESOLVE Scenario Setting	2018	2022	2026	2030
CEC 2016 IEPR – Low PV	9,741	11,163	13,297	*15,627*
CEC 2016 IEPR – Mid PV	10,226	13,983	20,191	*26,819*
CEC 2016 IEPR – High PV	10,480	15,733	24,470	*33,801*

Values shown in italics are extrapolated based on the average linear growth rate between 2022 and 2027.

2.1.5 NON-PV SELF GENERATION

The forecast of non-PV self-generation (i.e., on-site combined heat & power) is based on the CEC 2016 IEPR Demand Forecast. This assumption is shown in Table 6. Alternative levels of on-site CHP adoption are not considered in RESOLVE.

Table 6. Forecast of non-PV on-site self-generation (GWh)

Scenario Setting	2018	2022	2026	2030
CEC 2016 IEPR	13,516	13,857	14,058	*14,096*

Values shown in italics are assumed to remain constant at the level forecast in 2027.

[4] RESOLVE's Low PV forecast is based on the IEPR High Demand forecast; the High PV forecast is based on the IEPR Low Demand forecast. The naming of the IEPR forecasts corresponds to the relative level of retail load in each of the forecasts (higher amounts of customer PV yields lower retail load).

2.1.6 ENERGY EFFICIENCY

RESOLVE includes four options for varying levels of energy efficiency achievement among CAISO load-serving entities:

+ **CEC 2016 IEPR – No AAEE:** Based on the CEC's 2016 IEPR Demand Forecast, this forecast assumes no achievement of the "Additional Achievable Energy Efficiency" (AAEE) beyond current committed programs.
+ **CEC 2016 IEPR – Mid AAEE:** Based on the CEC's 2016 IEPR Demand Forecast, this forecast assumes that utilities continue to procure all cost-effective energy efficiency as identified under current programs.
+ **CEC 2016 IEPR – Mid AAEE + AB802:** In addition to including the load impact of the Mid AAEE, this option includes additional load reduction measures associated with savings enabled by AB802, which allows utilities to claim savings for programs that bring existing buildings up to code. The potential savings associated with such programs were identified by Navigant in a 2016 report funded by the CPUC.[5]
+ **SB350 – Mid AAEE x2:** In addition to the including the load impact of the Mid AAEE, this option includes additional savings that would achieve the 2030 SB350 goal of a doubling of energy efficiency. The incremental efficiency savings included in this option is derived from the RPS Calculator v.6.2, which includes load scenarios that reflect both the Mid AAEE and its doubling. To date, no analysis has identified the specific programs or measures that might be included in this wedge.

The assumed reductions in retail load corresponding to each of these levels of achievement are shown in Table 7.

Table 7. Energy efficiency forecast options (GWh)

RESOLVE Scenario Setting	2018	2022	2026	2030
CEC 2016 IEPR – No AAEE	—	—	—	—

[5] *AB802 Technical Analysis: Potential Savings Analysis.* Available at: http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=11189.

CEC 2016 IEPR – Mid AAEE	5,652	11,829	17,990	24,006
CEC 2016 IEPR – Mid AAEE + AB802	6,974	15,574	24,130	32,570
SB350 – Mid AAEE x2	6,098	16,431	30,540	39,535

2.1.7 TIME-OF-USE RATE IMPACTS

RESOLVE includes four options representing differing impacts of residential time-of-use (TOU) rate implementation on retail load:

+ **None:** assumes no change in load shape.
+ **Low (Christensen Scenario 3):** based on the results of *Statewide Time-of-Use Scenario Modeling for 2015 California Energy Commission Integrated Energy Policy Report*, a study conducted by Christensen Associates. In this study, "Scenario 3" assumes 30% residential participation in TOU rates by 2025.
+ **Mid (MRW Scenario 4):** based on the results of *Potential Load Impacts of Residential Time of Use Rates in California*, a study conducted by MRW & Associates. In this study, "Scenario 4" assumes 80% residential participation in TOU rates by 2025.
+ **High (MRW Scenario 4 x1.5):** in this scenario, the load impacts from the "Mid" case are multiplied by a factor of 1.5. This scenario is intended to capture the potential impacts of even more aggressive TOU pricing patterns than the "Mid" case.

The two studies referenced above are summarized in the *Joint Agency Staff Paper on Time-of-Use Load Impacts*.[6] The load impacts are summarized in Table 8. Because TOU rates primarily impact the timing of consumption, rather than the absolute total amount of energy consumed, the aggregate load impacts shown in Table 8 are small. The corresponding impacts upon the load shape are discussed in Section 5.2.1.4.

[6] Available at: http://docketpublic.energy.ca.gov/PublicDocuments/15-IEPR-03/TN210253_20160209T152348_Joint_Agency_Staff_Paper_on_TimeofUse_Load_Impacts.pdf

Table 8. Residential TOU rate implementation load impacts (GWh)

RESOLVE Scenario Setting	2018	2022	2026	2030
None	—	—	—	—
Low (Christensen Scenario 3)	-31	-31	-31	-31
Mid (MRW Scenario 4)	-66	-66	-67	-67
High (MRW Scenario 4 x1.5)	-99	-99	-100	-100

2.2 Other Zones

Demand forecasts for other zones in RESOLVE are developed from two sources. The CEC's 2016 IEPR Demand Forecast is used for each of the other zones within California (LADWP, BANC, and IID).[7] For the external load areas (the Pacific Northwest and the Southwest), TEPPC's 2026 Common Case[8] is used as the basis for load projections. The load forecasts for each external zone, shown in Table 9, have been grossed up for transmission & distribution losses.

Table 9. Demand forecasts for external regions in RESOLVE (GWh)

Region	2018	2022	2026	2030
BANC	18,768	19,255	19,943	*20,646*
IID	3,891	4,226	4,587	*4,965*
LADWP	28,045	28,235	29,161	*30,142*
NW	243,947	253,078	262,551	*272,378*
SW	154,196	161,004	168,114	*175,537*

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[7] See Table 33 for detail on the zonal topology used in RESOLVE

[8] This analysis relies on Version 1.5 of TEPPC's 2026 Common Case, posted October 21, 2016 and available here: **https://www.wecc.biz/Reliability/WECC_2026CC_V1.5%20Package.zip**

3 Baseline Resources

Within RESOLVE, a portion of the generation fleet is specified exogenously, representing the resources that are assumed to be existing over the course of the analysis; these **"Baseline Resources"** are included by default in the portfolio optimized by RESOLVE. The set of Baseline Resources generally includes (1) existing generators, net of expected future retirements; (2) specific future generation resources with sufficient likelihood to include for planning purposes; and (3) generic future resources needed to meet policy and reliability targets outside of CAISO.

3.1 Conventional Generation

Any non-renewable, thermal resource is referred to as conventional generation. For computational reasons, the thermal fleet in RESOLVE is represented by a limited set of resource classes by zone that represent the weighted average for each resource class in that zone. For each zone, the following 5 resource classes are present: Nuclear, Coal, CHP, CCGT, and Peaker. To more accurately reflect different classes of gas generators in the CAISO zone, CAISO's gas generators are further divided into subcategories:

+ The **"CHP"** category represents non-dispatchable cogeneration facilities, which are modeled as must-run baseload resources within RESOLVE.[9]
+ CCGT generators are divided into two subcategories: a low heat rate type (**"CAISO_CCGT1"**) and a high heat rate type (**"CAISO_CCGT2"**).
+ Peaker generator are divided into two subcategories: a low heat rate type (**"CAISO_Peaker1"**) and a high heat rate type (**"CAISO_Peaker2"**).

[9] Within RESOLVE, cogeneration units that are flexible and assumed to dispatch in response to market conditions are classified under other categories (e.g. CCGT or peaker) depending on their characteristics. "CHP" is used only to represent non-dispatchable, baseload CHP resources in RESOLVE.

- The **"CAISO_ST"** class is used to represent the existing fleet of steam turbines, most of which are scheduled to retire by 2020 to achieve compliance with the State Water Board's Once-Through-Cooling regulations.
- **"CAISO_Reciprocating_Engine"** represents the existing reciprocating engines on the CAISO system.

Two additional categories of gas generation, **"CAISO_Aero_CT"** and **"CAISO_Advanced_CCGT,"** are represented in RESOLVE but are used only to represent candidate resources and are not used to reflect the capabilities of the existing fleet.

3.1.1 CAISO

The Baseline Conventional Resources included in the portfolio of the CAISO load serving entities is derived from the preliminary 2017 CAISO NQC List[10], as shown on the CONV_CAISO_Gen_List worksheet. The data from the NQC list is supplemented with additional information from the CAISO Master Generating Capability List[11], the TEPPC 2026 Common Case, and the CARB Scoping Plan. These data sources are further supplemented by information from CPUC proceedings and decisions authorizing new procurement, including A.14-11-018, D.15-11-04, and D.15-11-041. E3 manually assigned the appropriate thermal generator type to each of the entries in the NQC list. The resulting annual installed capacity by resource class is shown in Table 10.

By default, RESOLVE assumes that thermal generators will remain online in perpetuity unless they have formally announced intentions to retire, which results in the Baseline thermal fleet remaining relatively stable over time (with the exception of the retirement of the aging once-through-cooling steam generators in 2020). However, RESOLVE also includes functionality to accelerate retirements of the thermal fleet according to assumptions of the economic useful lifetime. Users may select an assumed plant lifetime of 20, 25, or 30 years; this assumption is applied to all flexible gas generators and can be used to model accelerated retirements as shown in Table 10. Note that where an announced retirement conflicts with an assumed plant lifetime, the announced retirement date is assumed to take precedence.

[10] The preliminary 2017 CAISO NQC list was posted August 26, 2016, and is available here: http://www.caiso.com/Documents/2017NetQualifyingCapacity-ResourceAdequacyResources.html

[11] The CAISO Master Generating Capability List used in this analysis represents known CAISO resource information as of November 2, 2016.

Deleted: http://www.caiso.com/Documents/2017NetQualifyingCapacity-ResourceAdequacyResources.html

Table 10. Baseline Conventional Resources in the CAISO balancing area (MW)

Scenario Setting	Resource Class	2018	2022	2026	2030
Default	CHP*	1,685	1,685	1,685	1,685
	Nuclear**	2,922	2,922	622	622
	CCGT1	12,419	13,703	13,703	13,703
	CCGT2	2,974	2,974	2,974	2,974
	Peaker1	5,195	5,555	5,555	5,555
	Peaker2	2,859	2,729	2,729	2,729
	Advanced_CCGT	—	—	—	—
	Aero_CT	—	—	—	—
	Reciprocating_Engine	263	263	263	263
	ST	6,416	652	652	652
	Total	**34,734**	**30,484**	**28,184**	**28,184**
Accelerated Gas Retirements *(based on 25-yr economic lifetime)*	CHP*	1,685	1,685	1,685	1,685
	Nuclear**	2,922	2,922	622	622
	CCGT1	12,419	13,507	11,835	5,995
	CCGT2	2,974	2,974	2,815	2,003
	Peaker1	5,195	4,706	4,530	4,171
	Peaker2	2,859	1,841	1,459	744
	Advanced_CCGT	—	—	—	—
	Aero_CT	—	—	—	—
	Reciprocating_Engine	263	255	163	163
	ST	6,416	12	—	—
	Total	**34,734**	**27,903**	**23,108**	**15,108**
Accelerated CHP Retirements *(based on 25-yr economic lifetime)*	CHP*	1,685	73	28	28
	Nuclear**	2,922	2,922	622	622
	CCGT1	12,419	13,703	13,703	13,703
	CCGT2	2,974	2,974	2,974	2,974
	Peaker1	5,195	5,555	5,555	5,555
	Peaker2	2,859	2,729	2,729	2,729
	Advanced_CCGT	—	—	—	—
	Aero_CT	—	—	—	—
	Reciprocating_Engine	263	263	263	263

Scenario Setting	Resource Class	2018	2022	2026	2030
	ST	6,416	652	652	652
	Total	**34,733**	**28,871**	**26,526**	**26,526**

** CHP, which represents the non-dispatchable cogeneration units on the CAISO system, is modeled based on its NQC rather than its nameplate capacity, as large portions of these resources are typically used to meet on-site loads and are not exported to the grid.*

***Diablo Canyon is assumed to retire between 2024 & 2025. The remaining nuclear capacity shown thereafter represents the share of Palo Verde contracted to CAISO LSEs, which is modeled as located within CAISO in RESOLVE.*

In the Dashboard tab of the RESOLVE User Interface, one of the scenario toggles allows the user to enforce early retirement of the thermal fleet. A second toggle lets the user specify how many years after the commercial operations date (as specified in the CAISO_Gen_List worksheet) thermal plants are forced to retire. Existing thermal resources in an accelerated retirement scenario have their early retirement date set to occur no earlier than 2019.

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3.1.2 OTHER ZONES

For external zones, the assumed committed thermal generation fleet is based on the assumptions of the TEPPC 2026 Common Case. The Common Case is used to characterize the existing fleet in each region as well as anticipated future changes, including announced retirements of coal generators and near-term planned additions included in utility integrated resource plans. These assumptions are summarized in Table 11. To ensure resource adequacy in each region in spite of significant retirements in the coal fleet, RESOLVE assumes that CCGTs are added in each region such that the total installed capacity of the thermal fleet does not decrease below its present level.

Table 11. Baseline conventional resources in external zones (MW)

Zone	Resource Class	2018	2022	2026	2030
NW	Nuclear	1,170	1,170	1,170	1,170
	Coal	10,765	8,896	8,226	8,226
	CCGT	9,594	11,133	12,133	12,218
	Peaker	3,327	3,657	3,327	3,243
	Subtotal, NW	**24,856**	**24,856**	**24,856**	**24,856**
SW	Nuclear*	2,858	2,858	2,858	2,858
	Coal	9,101	8,097	7,449	7,449

Zone	Resource Class	2018	2022	2026	2030
	CCGT	19,863	20,571	20,887	21,276
	Peaker	8,586	9,197	10,759	10,371
	Subtotal, SW	**40,408**	**40,723**	**41,953**	**41,953**
LDWP	Nuclear*	457	457	457	457
	Coal	1,800	1,800	1,800	—
	CCGT	1,936	1,969	2,413	4,213
	Peaker	2,759	2,727	2,283	2,283
	Subtotal, LDWP	**6,952**	**6,952**	**6,952**	**6,952**
IID	CCGT	255	255	255	255
	Peaker	634	814	814	814
	Subtotal, IID	**889**	**1,069**	**1,069**	**1,069**
BANC	CCGT	1,874	1,874	1,874	1,874
	Peaker	891	891	891	891
	Subtotal, BANC	**2,765**	**2,765**	**2,765**	**2,765**

** In RESOLVE, Palo Verde is split up and modeled in zones according to its contractual ownership shares. This results in portions of the plant being modeled in the Southwest (72.6%), CAISO (15.8%), and LDWP (11.6%).*

3.2 Renewables

3.2.1 CAISO

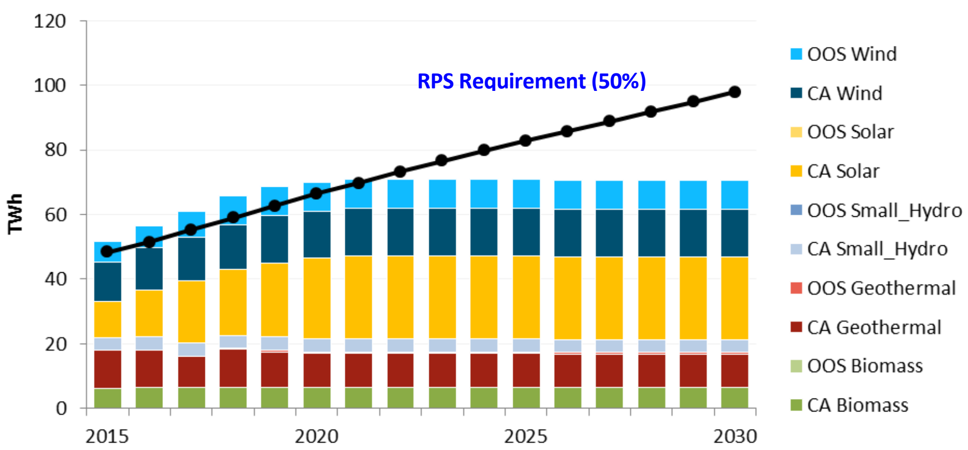
The Baseline Renewable Resources included in the portfolio of the CAISO load serving entities includes both (1) existing resources under contract to CAISO LSEs, and (2) resources under development with CPUC-approved contracts to the three investor-owned utilities. This information is compiled from multiple sources:

- **CPUC IOU Contract Database:** The CPUC maintains a database of all of the IOUs' active and past contracting activities for renewable generation. Utilities submit monthly updates to this database with changes in contracting activities; the IRP relies on information submitted to the contract database by the utilities in October 2016.

- **CEC POU Contract reports:** Publicly owned utilities submit annual updates to the CEC summarizing their renewable contracting activities. These reports provide detail on the facilities under contract to each POU and the expected duration of those contracts.
- **CEC Statewide Renewable Net Short spreadsheet:** The CEC tracks the total renewable generation in California, as well as out-of-state resources under contract to California entities, in an effort to quantify the total statewide renewable net short. The generator-specific information in this spreadsheet, including annual historical generation figures (MWh), is used as a supplemental source and a check to ensure that the combined portfolios of the California entities reflects the appropriate total amount of existing renewable generation.

The composition of the portfolio of Baseline Renewable Resources is shown in Figure 1.

Figure 1. Composition of Baseline Resources in renewable portfolios for CAISO LSEs.



3.2.2 OTHER ZONES

3.2.2.1 Other California LSEs

RESOLVE assumes that LSEs in each of the non-CAISO balancing authorities comply with the current RPS statute (50% RPS by 2030). Portfolios of resources for each of these entities are specified exogenously

and are based on the existing resource portfolios of each of these entities and assumptions regarding the types of resources that will be used to satisfy the remaining net short for each utility. The existing resources included in each entity's renewable portfolio are derived primarily from the CEC's Statewide Renewable Net Short spreadsheet and contract reports provided by the POUs. Future resources needed to continue compliance with the increasing RPS requirements are based on existing integrated resource plans where available; where such information is unavailable, local solar resources are assumed to fill the renewable net short.

Figure 2. Renewable portfolio for LSEs in BANC

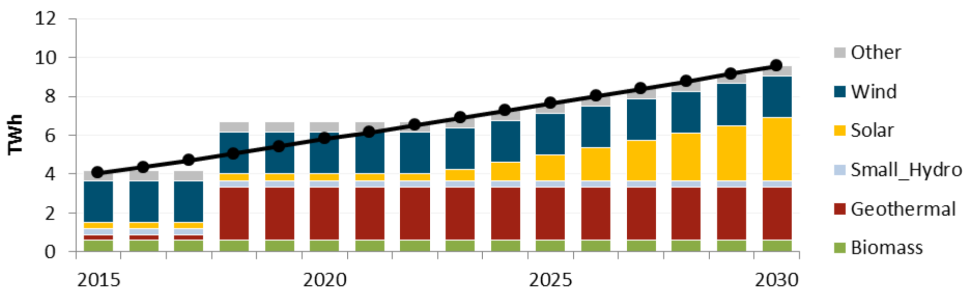


Figure 3. Renewable portfolio for LSEs in IID

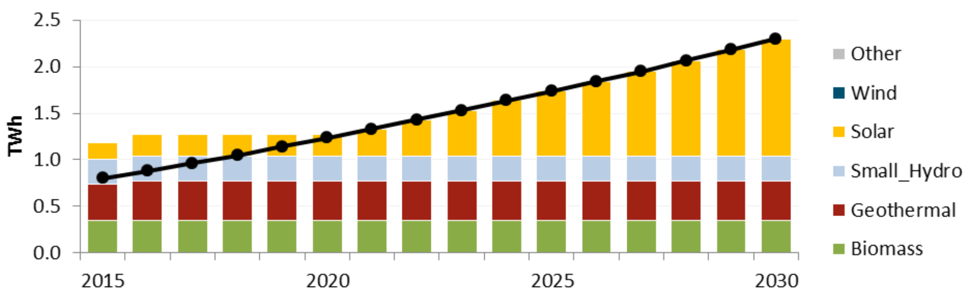
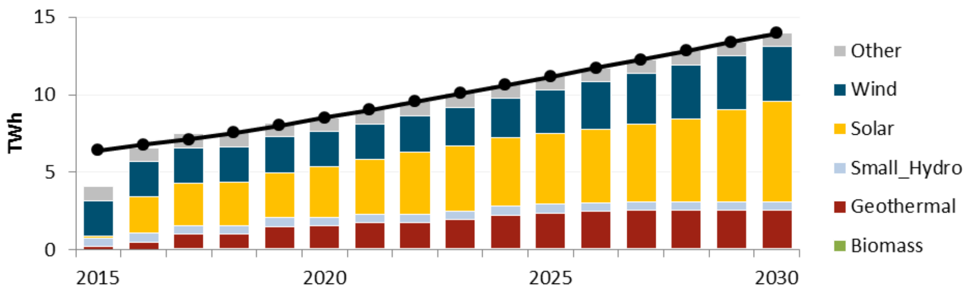


Figure 4. Renewable portfolio for LSEs in LADWP



3.2.2.2 Non-California LSEs

RESOLVE assumes that neighboring states outside of California comply with their applicable RPS statutes. The portfolios of resources procured to meet each state's goals are based on TEPPC's 2026 Common Case, developed by WECC staff with input from stakeholders.

Beyond 2026, renewable resources are added in the Northwest and Southwest to maintain the same level of penetration reached in 2026 across the region. In the Northwest, these generic resources are assumed to be new wind generation; in the Southwest, new generic resources beyond 2026 are assumed to be solar PV.

The renewable portfolios for the Northwest and Southwest are shown in Figure 5 and Figure 6, respectively.

Figure 5. Renewable portfolio for LSEs in the Northwest, based on 2026 Common Case.

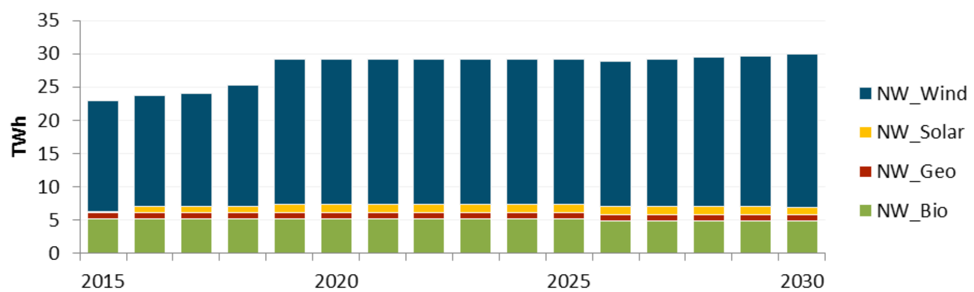
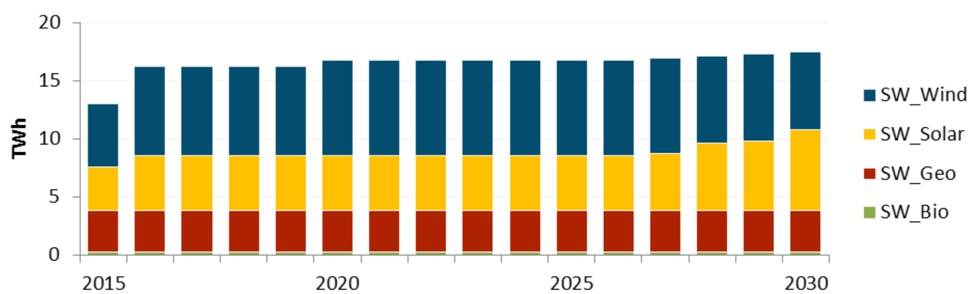


Figure 6. Renewable portfolio for LSEs in the Southwest, based on 2026 Common Case.



Some of the resources in the TEPPC Common Case located outside of California represent resources under long-term contract to California LSEs. Since these resources are captured in the portfolios of CAISO and other California LSEs, they are removed from the set of resources assumed to meet the policy goals of the non-California LSEs. The list of resources located outside of California but excluded for this reason is based on information and spreadsheets provided by WECC staff and stakeholders is shown in Table 12.

Table 12. TEPPC 2026 Common Case renewable plants outside of CA attributed to California loads.

TEPPC ID	MW	TEPPC ID	MW	TEPPC ID	MW	TEPPC ID	MW
Ajo Solar	132	EnelCoveFort1-1	16	MesquiteSolar111	16	RpsCA-0059	150
Amercian Falls Solar II	140	EnelCoveFort1-2	16	MesquiteSolar112	16	RpsCA-0067	116
American Falls Solar I	140	Foothills Solar 1	116	MesquiteSolar12	16	RpsCA-0068	50

TEPPC ID	MW	TEPPC ID	MW	TEPPC ID	MW	TEPPC ID	MW
ArlingtonValleyPV1	127	Foothills Solar 2	116	MesquiteSolar13	10	Sand Ranch	100
ArlingtonValleyPV2	127	Four Corners	10	MesquiteSolar14	16	Sand Ridge	9
ArlingtonWind	103	Four Mile Canyon	10	MesquiteSolar15	16	Sandstone Solar	11
Avalon Solar II	1	Ft. Huachuca	4	MesquiteSolar16	8	Simco Solar	140
Benson Creek Wind (OR)	40	Gila Bend	174	MesquiteSolar17	16	South_Hurlburt3	145
BigHorn1	200	GlacierWind1	107	MesquiteSolar18	12	South_Hurlburt4	145
BigHorn2	50	GlacierWind2	104	MesquiteSolar19	16	Springerville Expansion	3
BlackspringRidge	300	Goodnoe_Hills1	94	MilfordWind1-1	145	Star_Point	99
Boise City Solar	140	Goodnoe_Hills2	34	MilfordWind1-2	59	Stateline	100
CaithDixiVally1	19	Goshen2-JollyHills-1	90	MilfordWind2	102	TGP_1	130
CaithDixiVally2	19	Goshen2-JollyHills-2	39	Moapa Southern Paiute Solar	9	ThermoNo1-2	14
CaithDixiVally3	19	Grand View PV Solar Two	140	Mountain Home Solar	140	Three Mile Canyon	100
CaithnessDixieValley	50	Graycliff Wind Prime	10	Murphy Flat Power	140	Thunderegg Solar	140
Clark Solar 1	140	GREEN RIDGE POWER (JACKSON)	55	Musselshell Wind Two	107	TietonDamHydroUNIT1	7
Clark Solar 2	140	Grove Solar Center LLC	140	NorthHurlburt1	133	TietonDamHydroUNIT2	7
Clark Solar 3	140	Halkirk1	76	NorthHurlburt2	133	Torch Red Horse	10
Clark Solar 4	140	Halkirk2	74	NRG Solar- Avra Valley	3	Tucannon River Wind	9
Comanche Solar	9	Hooper Solar	9	Open Range Solar (OR)	140	Tuolumne1	68
CopperMtnPV2_1	30	Huerfano River Wind	152	Orchard Ranch Solar	140	Tuolumne2	68
CopperMtnPV2_2	30	Hyder II	132	Pacific Canyon	100	Vale Solar (OR)	140
CopperMtnPV2_3	34	Hyline Solar Center	140	Patua1A1	16	Vantage	96
CopperMtnPV2_4	30	Jett Creek Wind (OR)	40	Patua1A2	16	Wild_Rose	25
CopperMtnPV2_5	30	Kingman PPA	3	Patua1A3	16	Willow Creek	78
CopperMtnPV48_2	8	KlondikeWind3_1	224	Patua1A4	16	WillowCreekEC	72
CopperMtnPV48_3	10	KlondikeWind3_2	77	Patua1A5	16	WindyFlats1	202
CopperMtnPV48_4	10	LeaningJunipr1	101	Patua1A6	16	WindyFlats2	60
CopperMtnPV48_5	10	Limon III	100	PebbleSprings	99	WindyFlats3	99
CopperMtnPV48_6	10	LindenWind	50	Pocatello Solar 1	140	Wolverine Creek	19
Durbin Creek Wind (OR)	40	Meadowlake Solar PV	4	Prospector Wind (OR)	40	WyomingWindGE15	144
Echanis_Wind	104	MesquiteSolar11	16	Railroad Solar Center	140		
Elkhorn_Valley	100	MesquiteSolar110	12	RimRockEnergy	189		

3.3 Large Hydro

The existing large hydro resources in each region of the analysis are assumed to remain unchanged over the timeline of the analysis. The total installed capacity of large hydro and pumped storage resources in each region are shown in Table 13. The large hydro resources as shown in this table represent the resources physically located in each region with the exception of Hoover, which is split among the CAISO, LADWP, and SW regions in proportion to its ownership shares.

Table 13. Assumed large hydro resources in RESOLVE (MW)

Region	Non-Hoover Resources (MW)	Hoover Share (MW)	Total (MW)
BANC	2,742	—	2,742
CAISO*	7,047	797	7,844
IID	85	—	85
LADWP*	1,572	366	1,939
NW	34,379	—	34,379
SW*	3,073	917	3,991

** Each of these regions include a share of Hoover's total generating capability (2,080 MW) in proportion to their ownership shares: CAISO (38.3%), LADWP (17.6%), and SW (44.1%)*

3.4 Energy Storage

3.4.1 PUMPED STORAGE

The existing pumped storage resources in CAISO are based on the CAISO 2017 NQC list; the storage capability of each facility, in MWh, is based on input assumptions in CAISO's 2014 LTPP PLEXOS database. Note that although this number is large, the capability to store energy beyond 12 hours is not directly captured in RESOLVE given the dispatch window of one day at a time. The existing pumped storage resources in CAISO are summarized in Table 14.

Table 14. Existing pumped storage resources in CAISO

Unit	Capacity (MW)	Storage (MWh)
Eastwood	200	5,000
Helms	1,216	184,500
Lake Hodges	40	125
San Luis	374	100,000
Total	**1,832**	**289,625**

3.4.2 STORAGE MANDATE

RESOLVE includes multiple options for assumptions on the Baseline Resources for energy storage. These options, shown Table 15, allow the user to model three different levels of storage penetration (in each case, RESOLVE will add additional storage resources if it finds it is cost-effective to do so).

Table 15. Options for planned storage resources in RESOLVE (MW)

Scenario Setting	2018	2022	2026	2030
No Mandate	470	470	470	470
1,325 MW by 2020	835	1,325	1,325	1,325
1,325 MW by 2020 + 500 MW	1,135	1,825	1,825	1,825

The storage resources included as Baseline Resources in RESOLVE are, by default, assumed to have an average duration of four hours.

3.5 Demand Response

RESOLVE treats the IOUs' existing shed demand response programs as Baseline Resources; the assumed peak load impact for each utility's programs are based on each utility's proposed demand response programs in the 2018-2022 funding cycle. Two options for assumptions on existing shed demand response programs are available:

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+ **Reliability & Economic Programs** assumes that the current suite of reliability and economic demand response programs are continued indefinitely at current levels of load impact; and
+ **Reliability Programs Only** assumes that economic demand response programs are discontinued after the current funding cycle (2018-2022), resulting in a reduction in the amount of Baseline DR resources after 2022.

The load impacts associated with each of these scenario settings are shown in Table 16.

Table 16. Forecast load impact of IOU demand response programs (MW)

Scenario Setting	Region	2018	2022	2026	2030
Reliability & Economic Programs	PG&E	541	541	*541*	*541*
	SCE	1,019	1,019	*1,019*	*1,019*
	SDG&E	56	56	*56*	*56*
	Total	**1,617**	**1,617**	***1,617***	***1,617***
	Total, w/ losses	**1,752**	**1,752**	***1,752***	***1,752***
Reliability Programs Only	PG&E	541	541	*330*	*330*
	SCE	1,019	1,019	*696*	*696*
	SDG&E	56	56	*7*	*7*
	Total	**1,617**	**1,617**	***1,033***	***1,033***
	Total, w/ losses	**1,752**	**1,752**	***1,119***	***1,119***

DR load impacts shown in italics represent assumed load impacts beyond current funding cycle (2018-2022).

RESOLVE also treats existing load-modifying DR as a baseline resource. The peak impact of load-modifying DR is reproduced from the non-coincident capacity values and coincidence factors in the 2016 IEPR Demand Forecast. Load-modifying DR is represented as a reduction in peak demand, not as a generating resource.

4 Candidate Resources

"Candidate resources" represent the menu of options from which RESOLVE can select to create an optimal portfolio. RESOLVE can add multiple different types of resources, including natural gas generation, renewables, energy storage, and demand response. The optimal mix is a function of the relative costs and characteristics of the candidate resources and the constraints that the portfolio must meet.

4.1 Natural Gas

RESOLVE includes multiple technology options for new natural gas generation of varying costs and efficiencies. The natural gas resource classes available to the model and their respective all-in fixed costs, derived from E3's 2014 review of capital costs for WECC, *Capital Cost Review of Power Generation Technologies*,[12] are shown in table below. This cost includes all costs, except variable O&M and fuel costs.

Operational assumptions for these plants are summarized in Section 5.3.1.

Table 17. All-in fixed costs for candidate natural gas resources ($/kW-yr)

Resource Class	Capital Cost ($/kW)	Fixed O&M Cost ($/kW-yr)	All-In Fixed Cost ($/kW-yr)
CAISO_Advanced_CCGT	$1,300	$10	$202
CAISO_Aero_CT	$1,250	$12	$197
CAISO_Reciprocating_Engine	$1,250	$12	$197

[12] Available at: https://www.wecc.biz/Reliability/2014_TEPPC_Generation_CapCost_Report_E3.pdf

4.2 Renewables

4.2.1 POTENTIAL

Assumptions on the cost, performance, and potential of candidate renewable resources are based on data developed by Black & Veatch for the CPUC's RPS Calculator v.6.3.[13] Black & Veatch used geospatial analysis to identify potential sites for renewable development in California and throughout the Western Interconnection. For input into RESOLVE, the detailed geospatial dataset developed by Black & Veatch is aggregated into "transmission zones." Within California, transmission zones are groupings of Competitive Renewable Energy Zones (CREZs). These groupings are shown in Figure 7.

The raw technical potential estimates developed by Black & Veatch are filtered through a set of environmental screens to produce the potential assumed available to RESOLVE. RESOLVE includes several options for environmental screens, which were original developed for the RPS Calculator:

+ **Base:** includes RETI Category 1 exclusions only
+ **Environmental Baseline (EnvBase):** includes RETI Category 1 and 2 exclusions
+ **NGO1:** first screen developed by environmental NGOs
+ **NGO1&2:** second screen developed by environmental NGOs
+ **DRECP/SJV:** includes RETI Categories 1 and 2 plus preferred development areas only in the DRECP and SJV
+ **Minimum:** represents the minimum available potential across all screens

The associated potential for each of these environmental screens is summarized in Table 18.

[13] Black & Veatch, *RPS Calculator V6.3 Data Updates*. Available at: http://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Energy_Programs/Electric_Power_Procurement_and_Generation/LTPP/RPSCalc_CostPotentialUpdate_2016.pdf. Note that although the data was developed with the intention of incorporating it into a new version of the RPS Calculator, no version 6.3 has been developed. This is because the IRP system plan development process is anticipated to replace the function previously served by the RPS Calculator.

Figure 7. In-state transmission zones in RESOLVE.

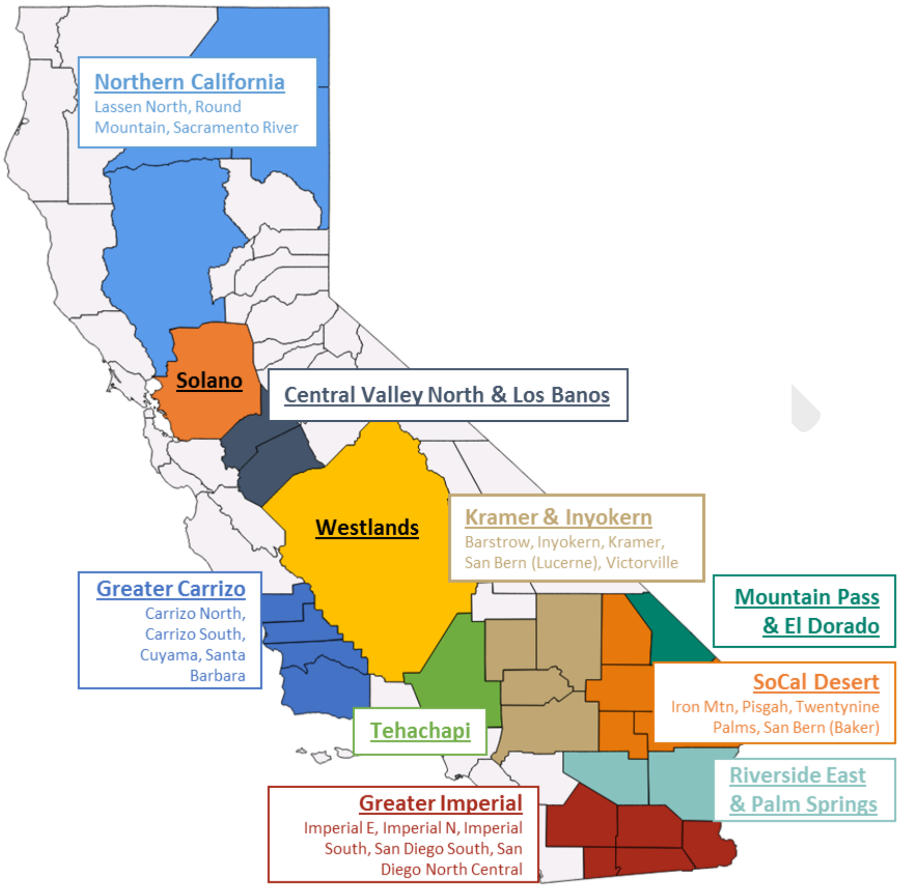

Table 18. California renewable potential under various environmental screens.

Type	Resource	Renewable Potential (MW)					
		Base	Env Base	NGO1	NGO1&2	DRECP/SJV	Minimum
Biomass	InState	1,293	1,293	1,293	1,293	1,293	1,293
Geothermal	Greater Imperial	1,384	1,384	1,384	1,384	1,384	1,384
	Northern California	424	424	424	424	424	424

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	Subtotal, Geothermal	**1,808**	**1,808**	**1,808**	**1,808**	**1,808**	**1,808**
Solar	Central Valley North Los Banos	3,988	3,021	3,901	2,477	1,264	1,264
	Distributed	36,605	36,605	36,605	36,605	36,605	36,605
	Greater Carrizo	4,572	3,787	4,540	2,734	3,805	2,734
	Greater Imperial	7,797	5,155	7,702	4,928	9,143	3,953
	Mountain Pass El Dorado	288	15	288	10	62	10
	Northern California	29,319	19,572	28,715	16,192	19,649	16,192
	Riverside East Palm Springs	4,172	2,289	4,145	2,198	14,339	1,420
	Solano	6,147	3,624	5,925	2,937	3,729	2,937
	Southern California Desert	3,283	1,084	3,246	1,043	12,096	448
	Tehachapi	4,535	3,493	4,464	3,446	1,073	1,073
	Westlands	13,147	11,310	12,661	9,317	15,750	7,643
	Subtotal, Solar	**113,853**	**89,954**	**112,190**	**81,886**	**117,515**	**74,278**
Wind	Central Valley North Los Banos	170	146	126	69	146	69
	Distributed	253	253	253	253	253	253
	Greater Carrizo	1,276	1,096	1,267	908	1,095	908
	Greater Imperial	922	83	919	83	—	—
	Kramer Inyokern	1,381	283	1,314	283	—	—
	Northern California*	—	—	—	—	—	—
	Riverside East Palm Springs	544	42	527	42	42	42
	Solano	1,629	642	1,520	567	643	567
	Southern California Desert	124	48	124	48	-	-
	Tehachapi	934	715	923	704	407	405
	Subtotal, Wind	**7,233**	**3,307**	**6,973**	**2,957**	**2,586**	**2,244**

** Renewable potential for Northern California wind is set to zero across all screens due to both the unproven nature of the resource and expected obstacles in resource permitting*

A small amount of the in-state renewable potential is assumed to be developed by California entities outside of CAISO to meet their 50% RPS needs and is therefore assumed to be unavailable to CAISO LSEs for development. Where available, these assumptions are based on information from utility IRPs; in the absence of procurement plans, solar PV was assumed as a backstop resource. The total resource potential that is excluded from the California potential in RESOLVE for this reason is shown in Table 19.

Table 19. California renewable potential allocated to non-CAISO LSEs.

Type	Resource
Biomass	—
Geothermal	108

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Deleted: 592
Deleted: 8,807
Deleted: 617
Deleted: 4,693
Deleted: 2,170
Deleted: 4,471
Deleted: 1,483
Deleted: 2,275
Deleted: 1,483
Deleted: —
Deleted: —
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Deleted: —
Deleted: 8,533
Deleted: —
Deleted: 108,780
Deleted: 87,081
Deleted: 107,156
Deleted: 79,054
Deleted: 112,162
Deleted: 72,041
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Type	Resource
Solar	1,981
Wind	254

The available potential for out-of-state resources is also based primarily on Black & Veatch's assessment of renewable resource potential that identifies high-quality resources in Western Renewable Energy Zones (WREZs), which are aggregated to regional bundles. These high-quality resources are assumed to require investments in new transmission to interconnect and deliver to California loads. These estimates of resource potential are supplemented with assumptions regarding the availability of lower-quality renewables that may be interconnected on the existing transmission system.

RESOLVE includes three "screens" for out-of-state resources available in the model's scenario settings:

+ **None:** no out-of-state resources are included in the optimization;
+ **Existing Tx Only:** only resources that can be interconnected on the existing transmission system and delivered to California are included in the optimization; and
+ **Existing & New Tx:** all out-of-state resources, including those requiring major investments in new transmission, are included in the optimization.

The amount of renewable potential included under each screen is summarized in Table 20; all estimates of potential shown in this table—with the exception of resources assumed to interconnect to the existing transmission system—are based on Black & Veatch's potential assessment.

Table 20. Out-of-state renewable potential under various scenario settings.

Type	Resource	Renewable Potential (MW)		
		None	Existing Tx Only	Existing & New Tx
Geothermal	Pacific Northwest	—	—	832
	Southern Nevada	—	—	320
	Subtotal, Geothermal	**—**	**—**	**1,152**
Solar	Arizona	—	—	19,270
	New Mexico	—	—	166
	Southern Nevada	—	—	37,176
	Utah	—	—	14,414
	Subtotal, Solar	**—**	**—**	**71,026**
Wind	Arizona	—	—	2,900

	Idaho	—	—	6,869
	New Mexico (Existing Tx)	—	500	500
	New Mexico	—	—	34,580
	Pacific Northwest (Existing Tx)	—	1,500	1,500
	Pacific Northwest	—	—	11,072
	Southern Nevada	—	—	442
	Utah	—	—	5,033
	Wyoming	—	—	33,862
	Subtotal, Wind	**—**	**2,000**	**96,758**

4.2.2 COST & PERFORMANCE

The primary source for cost & performance assumptions of renewable generation was developed by Black & Veatch for the RPS Calculator v.6.3 in early 2013.[13] This information has been supplemented by an additional analysis conducted by E3 on the cost and performance of new generation resources for the Western Electricity Coordinating Council (WECC). In particular, because market data suggests a notable reduction in the cost of solar PV since Black & Veatch's assessment, E3's WECC study has been used to update the assumed cost of solar PV resources. The assumptions for renewable resources used in RESOLVE are shown in Table 21 and Table 20 for in-state and out-of-state resources, respectively. The input to RESOLVE is an assumed levelized fixed cost ($/kW-yr) for each resource; this is translated into the levelized cost of energy ($/MWh) in Table 21 and Table 20 for comparability with typical Power Purchase Agreements (PPA) entered into between utilities and third-party developers.

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Several conventions and assumptions are worth noting to clarify the assumptions highlighted in these two tables:

+ Note that the increase in the implied levelized cost for wind and solar, notwithstanding the reductions in capital costs assumed between 2018 and 2030, are a result of the expiration of the federal Production Tax Credit (wind), federal Investment Tax Credit (solar), and state property tax exclusion (solar).
+ The capital costs reported in Table 21 reflect AC capital costs for all technologies. For solar PV, an inverter loading ratio of 1.3 is assumed, which implies that DC capital costs are $1.74 and $1.57 per watt in 2018 and 2030, respectively.

Table 21. California renewable resource cost & performance assumptions.

Type	Resource	Capacity Factor	Capital Cost (2016 $/kW)				Implied Levelized Cost of Energy (2016 $/MWh)			
			2018	2022	2026	2030	2018	2022	2026	2030
Biomass	InState	86%	$6,231	$6,231	$6,231	$6,231	$161	$161	$161	$161
Geothermal	Greater Imperial	88%	$5,349	$5,349	$5,349	$5,349	$92	$92	$92	$92
	Northern California	80%	$5,011	$5,011	$5,011	$5,011	$89	$89	$89	$89
Solar *(solar capital costs shown in $/kW-ac)*	Central Valley North Los Banos	30%	$1,908	$1,841	$1,788	$1,699	$53	$52	$69	$67
	Distributed	23%	$3,269	$3,040	$2,886	$2,725	$104	$99	$126	$120
	Greater Carrizo	32%	$1,908	$1,841	$1,788	$1,699	$49	$48	$64	$62
	Greater Imperial	34%	$1,908	$1,841	$1,788	$1,699	$47	$46	$61	$58
	Mountain Pass El Dorado	34%	$1,908	$1,841	$1,788	$1,699	$46	$45	$59	$57
	Northern California	30%	$1,908	$1,841	$1,788	$1,699	$53	$52	$69	$66
	Riverside East Palm Springs	34%	$1,908	$1,841	$1,788	$1,699	$46	$45	$60	$58
	Solano	29%	$1,908	$1,841	$1,788	$1,699	$54	$53	$70	$67
	Southern California Desert	35%	$1,908	$1,841	$1,788	$1,699	$46	$45	$60	$57
	Tehachapi	35%	$1,908	$1,841	$1,788	$1,699	$45	$44	$58	$56
	Westlands	30%	$1,908	$1,841	$1,788	$1,699	$52	$51	$67	$65
Wind	Central Valley North Los Banos	31%	$2,019	$2,004	$1,989	$1,974	$57	$70	$78	$77
	Distributed	28%	$2,499	$2,480	$2,462	$2,443	$88	$100	$108	$107
	Greater Carrizo	31%	$2,063	$2,048	$2,033	$2,018	$60	$73	$80	$80
	Greater Imperial	31%	$2,032	$2,017	$2,002	$1,987	$52	$65	$73	$73
	Kramer Inyokern	32%	$2,028	$2,012	$1,997	$1,983	$61	$73	$81	$81
	Northern California	29%	$2,000	$1,985	$1,970	$1,955	$66	$78	$85	$85
	Riverside East Palm Springs	33%	$2,018	$2,003	$1,988	$1,974	$59	$71	$79	$79
	Solano	30%	$2,022	$2,007	$1,992	$1,977	$61	$73	$81	$81
	Southern California Desert	27%	$2,010	$1,995	$1,980	$1,965	$66	$79	$87	$86
	Tehachapi	33%	$2,119	$2,103	$2,087	$2,072	$55	$67	$75	$75

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Table 22. Out-of-state renewable resource cost & performance assumptions

Type	Resource	Capacity Factor	Capital Cost (2016 $/kW)				Implied Levelized Cost of Energy (2016 $/MWh)			
			2018	2022	2026	2030	2018	2022	2026	2030
Geothermal	Pacific Northwest	84%	$4,952	$4,952	$4,952	$4,952	$82	$82	$82	$82
	Southern Nevada	80%	$6,259	$6,259	$6,259	$6,259	$104	$104	$104	$104
Solar *(solar capital costs shown in $/kW-ac)*	Arizona	34%	$1,750	$1,689	$1,640	$1,558	$39	$38	$53	$51
	New Mexico	33%	$1,754	$1,692	$1,644	$1,562	$39	$38	$54	$52
	Southern Nevada	32%	$1,850	$1,784	$1,733	$1,647	$47	$45	$62	$59
	Utah	30%	$1,793	$1,730	$1,680	$1,597	$46	$45	$62	$60
Wind	Arizona	29%	$1,824	$1,810	$1,797	$1,784	$58	$71	$79	$78
	Idaho	32%	$1,916	$1,901	$1,887	$1,873	$56	$68	$76	$76
	New Mexico (Existing Tx)	36%	$1,843	$1,830	$1,816	$1,803	$44	$56	$65	$64
	New Mexico	44%	$1,846	$1,832	$1,819	$1,805	$31	$44	$53	$53
	Pacific Northwest (Existing Tx)	30%	$2,188	$2,171	$2,155	$2,139	$69	$81	$89	$88
	Pacific Northwest	32%	$2,101	$2,085	$2,069	$2,054	$63	$75	$83	$82
	Southern Nevada	28%	$2,164	$2,148	$2,132	$2,116	$80	$91	$98	$98
	Utah	31%	$1,902	$1,888	$1,874	$1,860	$60	$72	$80	$80
	Wyoming	44%	$1,757	$1,744	$1,731	$1,718	$28	$41	$50	$50

For solar PV, the capital cost reductions shown in Table 21 reflect the default assumptions used in RESOLVE, but RESOLVE includes scenario settings for both low and high cost as alternatives. The three options for future capital cost reductions for solar PV are shown in Table 23.

Table 23. Alternative cost reduction trajectories for solar PV (% of 2016 capital cost).

RESOLVE Scenario Setting	2018	2022	2026	2030
Low	100%	100%	100%	100%
Mid	98%	94%	91%	87%
High	88%	77%	72%	68%

Beyond 2030, capital costs are assumed to remain constant in real terms.

4.2.3 TRANSMISSION COST & AVAILABILITY

Candidate renewable resources in RESOLVE may be selected for the portfolio either as **fully deliverable (FCDS)** resources or **energy only (EO)** resources, each representing a different classification of deliverability status by CAISO; the deliverability status assigned to each resource has implications for the transmission system as well as upon the value the resource provides to the system. The primary tradeoff between fully deliverable and energy only resources is the relative cost of transmission upgrades and the value of capacity provided by the resource: full deliverability allows a resource to count towards a utility's resource adequacy requirement but may require costly Deliverability Network Upgrades (DNUs); whereas energy only resources cannot be counted for capacity but do not require transmission upgrades for interconnection.

In each transmission zone, RESOLVE selects resources in three categories:

+ **FCDS resources on the existing system.** Each transmission zone is characterized by the amount of new capacity that can be installed on the existing system while still receiving full capacity deliverability status.
+ **EO resources on the existing system.** Each transmission zone is also characterized by the amount of incremental energy-only capacity that can be installed beyond the FCDS limits (i.e. this quantity is additive to the FCDS limit).
+ **FCDS resources on new transmission.** Resources in excess of the limits of the existing system may be installed but require investment in new transmission. This may occur (1) if both the FCDS

and EO limits are reached; or (2) if the FCDS limit is reached and the value of new capacity exceeds the cost of the new transmission investment.

Assumptions on the cost and availability of transmission for renewable resources are derived from information that is provided annually by CAISO staff to CPUC staff as part of a 2010 memorandum of understanding on transmission planning.[14] Previous iterations of this information were incorporated into the RPS Calculator.[15] Each transmission zone within the model is characterized by several assumptions, summarized in Table 24. Most of these input assumptions are provided by CAISO; where CAISO has not studied costs of transmission system upgrades, generic cost estimates from the RPS Calculator are used to supplement (indicated by * in the table).

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Table 24. Transmission availability & cost in California

Transmission Zone	Existing Transmission, FCDS (MW)	Existing Transmission, EO (MW)	New Transmission Cost ($/kW-yr)
Central Valley North Los Banos	700	—	$28
Greater Carrizo	40	160	$89*
Greater Imperial	1,200	1,900	$60
Kramer Inyokern	1,000	1,000	$54
Mountain Pass El Dorado	800	2,200	$34
Northern California	668	4,232	$52*
Riverside East Palm Springs	2,950	2,550	$60
Solano	—	700	$13
Southern California Desert	—	—	$82*
Tehachapi	5,000	800	$13
Westlands	1,500	700	$11
Total	**13,858**	**14,242**	

[14] http://www.caiso.com/Documents/100517DecisiononRevisedTransmissionPlanningProcess-CPUCMOU.pdf

[15] For example, see pages B22-B25 of the RPS Calculator 6.2 User Guide, available at: http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=10349

New out-of-state resources are attributed an additional transmission cost, representing either the cost to wheel power across adjacent utilities' electric systems (for resources delivered on existing transmission) or the cost of developing a new transmission line (for resources delivered on new transmission). Wheeling costs on the existing system are derived from utilities' Open Access Transmission Tariffs; the cost of new transmission lines is based on assumptions developed for the CPUC's RPS Calculator v.6.2. These assumptions are shown in Table 25.

Table 25. Transmission cost assumptions for out-of-state resources

Zone	Existing Transmission Cost ($/kW-yr)	New Transmission Cost ($/kW-yr)
Arizona	—	$26
Idaho	—	$113
New Mexico	$72	$120
Northwest	$34	$86
Southern Nevada	—	$76
Utah	—	$60
Wyoming	—	$125

4.3 Energy Storage

In this section, the assumptions regarding costs and available potential (if applicable) regarding energy storage in RESOLVE are detailed.

Note that costs are broken down into power costs and energy costs. The power cost refers to all costs that scale with the rated installed power (kW) while the energy costs refers to all costs that scale with the duration/energy of the storage resource (kWh). For pumped storage, power costs are the largest fraction of total costs and relate to the costs of the turbines, the penstocks, the interconnection, etc., while energy costs are small and mainly cover the costs of digging a reservoir. For li-ion batteries, the power costs mainly relate to the cost of an inverter and other power electronics for the interconnection, while the energy costs relate to the actual Li-ion battery cells. For flow batteries, the power costs relate to the cost of an inverter and other power electronics, as well as the ion exchange membrane and fluids pumps, while the energy costs mainly relate to the tanks and the electrolyte. As a result, the power component of flow battery costs is higher than that of Li-ion, while the energy component is lower.

4.3.1 PUMPED STORAGE

The capital costs of candidate pumped storage resources, shown in Table 26 below, are based on *Lazard's Levelized Cost of Storage 2.0* (2016)[16]. Pumped storage costs are assumed to remain constant in real terms.

Table 26. Capital costs for candidate pumped storage resources

Cost Component	All Years
Capital Cost - Power ($/kW)	$1,307
Capital Cost - Energy ($/kWh)	$131
Fixed O&M Cost ($/kW-yr)	$24

These capital costs are fed into a pro forma model to estimate levelized fixed costs, using the following assumptions: financing lifetime of 25 years, fixed O&M of $24/kW-yr with annual escalation of 2%, no variable O&M costs, and after-tax WACC of 7.71%. The resulting all-in levelized fixed costs are shown in Table 27 below.

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Table 27. All-in levelized fixed costs ($/kW-yr and $/kWh-yr) for candidate pumped storage resources

Cost Component	All Years
Levelized Power Cost ($/kW)	$146
Levelized Energy Cost ($/kWh)	$12

The pumped storage resource potential assumptions are shown in Table 28 below.

Table 28. Available potential by year (MW) for candidate pumped storage resources.

Resource Class	2018	2022	2026	2030
Potential (MW)	—	2,000	4,000	4,000

[16] Available at: https://www.lazard.com/perspective/levelized-cost-of-storage-analysis-20/. E3 used the average of the range provided in p. 31 of the Appendix. For the breakout of power to energy cost, E3 used the specified duration (8-hours) and assumed energy costs per kWh are 1/10th of the power costs per kW.

4.3.2 BATTERY STORAGE

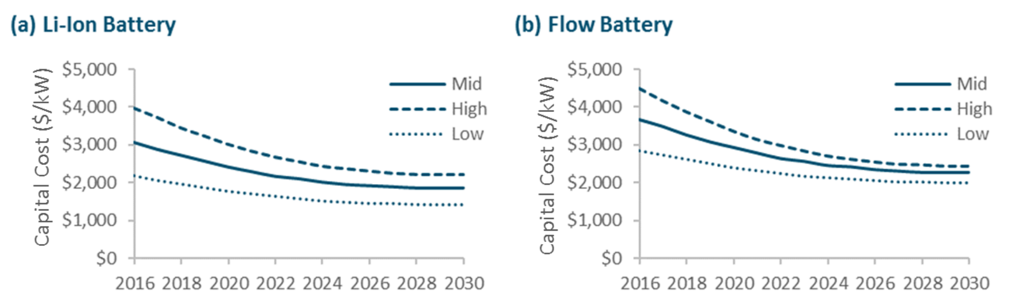
RESOLVE includes three options for candidate battery costs, each of which is based on *Lazard's Levelized Cost of Storage 2.0* (2016)[17]. The capital costs for each of these options - Mid, Low, and High – are shown in Table 29 below, along with fixed O&M costs expressed as a percentage of capital costs. Note that these include installation and interconnection costs.

Table 29. Capital cost assumptions for candidate battery resources.

Resource	Cost Component	Case	2018	2022	2026	2030
Li-Ion Battery	Capital Cost – Power ($/kW)	Low	$208	$172	$154	$150
		Mid	$248	$197	$172	$166
		High	$285	$218	$186	$179
	Capital Cost – Energy ($/kWh)	Low	$491	$406	$363	$352
		Mid	$689	$548	$479	$462
		High	$878	$672	$574	$550
	Fixed O&M (%)	All	1.0%	1.0%	1.0%	1.0%
Flow Battery	Capital Cost – Power ($/kW)	Low	$1,710	$1,470	$1,345	$1,313
		Mid	$2,120	$1,720	$1,521	$1,471
		High	$2,501	$1,913	$1,635	$1,567
	Capital Cost – Energy ($/kWh)	Low	$229	$197	$180	$176
		Mid	$292	$237	$210	$203
		High	$352	$269	$230	$220
	Fixed O&M (%)	All	2.5%	2.5%	2.5%	2.5%

[17] For flow batteries, the Peaker Replacement and Transmission cost tables in the Appendix are used, while for Li-ion the Frequency Regulation cost table was used. By using both the Peaker Replacement and Transmission cost table for flow batteries, E3 interpolated the membrane costs and other costs that scale with power but are not included in Lazard's AC costs. The Mid Case represents the average of Lazard's range, while the Low and High Case represent resp. the low end and the high end of the range. Cost trajectories are estimated based on Lazard's Capital Cost Outlook (p. 19). We assume that costs no longer go down after 2030 (in real terms).

Figure 8. Battery capital cost trajectories (4-hr duration)



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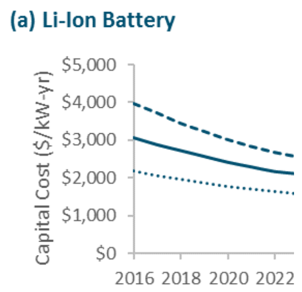

These capital costs are then fed into a pro forma model to estimate levelized fixed costs, using the following assumptions: financing lifetime of 20 years and after-tax WACC of 7.58%. For Li-ion, we assumed replacement of the battery cells at year 10 at the projected cost of the energy component of the Li-battery in the year of replacement (e.g. the replacement cost of a Li-ion system built in 2020 would be the 2030 energy cost, which is $462/kWh in the Mid Case). The resulting all-in levelized fixed costs are shown in Table 30 below.

Table 30. All-in levelized fixed costs ($/kW-yr and $/kWh-yr) for candidate battery resources

Resource	Cost Component	Case	2018	2022	2026	2030
Li-Ion Battery	Levelized Fixed Cost – Power ($/kW-yr)	Low	$24	$20	$18	$17
		Mid	$29	$23	$21	$20
		High	$34	$27	$23	$22
	Levelized Fixed Cost – Energy ($/kWh-yr)	Low	$59	$50	$44	$43
		Mid	$91	$72	$64	$62
		High	$122	$95	$82	$79
Flow Battery	Levelized Fixed Cost – Power ($/kW-yr)	Low	$203	$175	$160	$155
		Mid	$251	$203	$180	$175
		High	$296	$228	$197	$186
	Levelized Fixed Cost – Energy ($/kWh-yr)	Low	$27	$23	$21	$21
		Mid	$35	$28	$25	$24
		High	$42	$32	$27	$26

The default RESOLVE assumptions do not limit the available potential for candidate battery storage resources.

4.4 Demand Response

4.4.1 SHED DEMAND RESPONSE

Assumptions on the cost, performance, and potential of candidate new shed demand response resources are based on Lawrence Berkeley National Laboratory's report for the CPUC: *2015 California Demand Response Potential Study: Final Report on Phase 2 Results* (2016)[18]. The resource potential supply curve is based on data outputs from LBNL's DRPATH model, with the scenario assumptions outlined below in

Table 31.

Table 31. Scenario assumptions for DRPATH model used to generate supply curve data

Category	Assumption
Base year	2020
DR Availability Scenario	Medium
Weather	1 in 2 weather year

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Category

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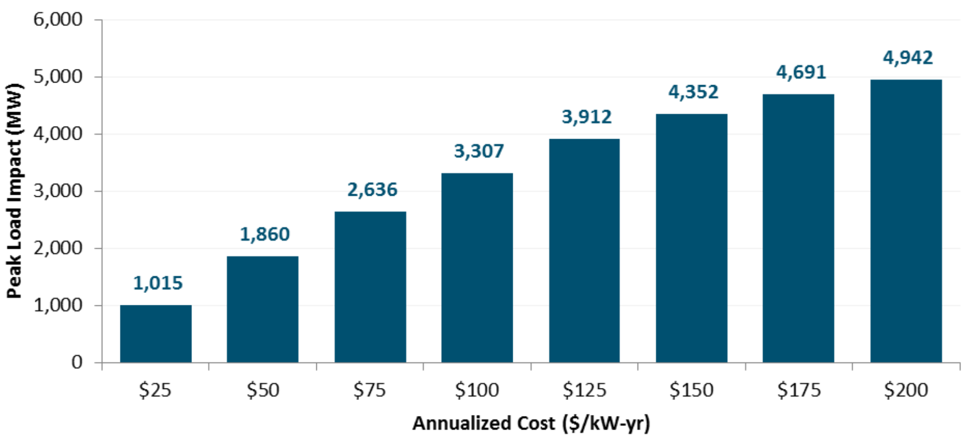
[18] Lawrence Berkeley National Laboratory, *2015 California Demand Response Potential Study: Final Report on Phase 2 Results.* 2016. Available at: http://www.cpuc.ca.gov/General.aspx?id=10622http://www.cpuc.ca.gov/General.aspx?id=10622

Energy Efficiency Scenario	midAAEE
Rate Scenario	Rate Mix 1—TOU and CPP (as defined by LBNL report)
Cost Framework	Gross

The resulting supply curve is shown below in Figure 9.

Figure 9. Conventional DR supply curve.



4.4.2 SHIFT DEMAND RESPONSE

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Assumptions on the cost, performance, and potential of candidate advanced demand response resources—also referred to as "flexible loads"—are based on Lawrence Berkeley National Laboratory's report for the CPUC: *2015 California Demand Response Potential Study: Final Report on Phase 2 Results* (2016)[19]. The resource potential supply curve is based on data outputs from LBNL's DRPATH model, with the scenario assumptions outlined below in Table 32.

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[19] Lawrence Berkeley National Laboratory, *2015 California Demand Response Potential Study: Final Report on Phase 2 Results.* 2016. Available at: http://www.cpuc.ca.gov/General.aspx?id=10622**http://www.cpuc.ca.gov/General.aspx?id=10622**

Table 32. Scenario assumptions for DRPATH model used to generate supply curve data

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Category	Assumption
Base year	2020
DR Availability Scenario	Medium
Weather	1 in 2 weather year
Energy Efficiency Scenario	midAAEE
Rate Scenario	Rate Mix 1—TOU and CPP (as defined by LBNL report)
Cost Framework	Gross

Moved up [2]: Table 31. Scenario assumptions for DRPATH model used to generate supply curve data¶
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The resulting supply curve is shown in Figure 10 below. Quantity of shift demand response is reported in units of (MWh/day)-yr, which is the available *daily* energy budget for a given year. As this is based on the "Shift" resource, end-use energy consumption in the model can be shifted, for example, from on-peak hours to off-peak hours; the maximum amount of energy shifted in one day is the daily energy budget. RESOLVE includes an additional constraint that sets a maximum quantity of energy that can be shifted in one hour. A majority of this resource is based on weather-independent industrial process loads, so it is currently assumed that the full daily energy budget is available on every day of the year. It is also assumed that there is no efficiency loss penalty incurred by shifting loads to other times of the day.

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Figure 10. Shift demand response: total annual costs vs potential daily energy budget

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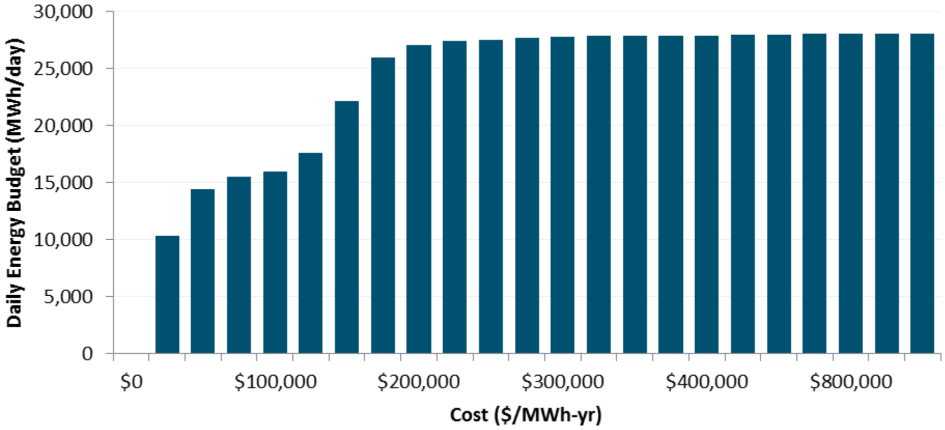


5 Operating Assumptions

5.1 Overview

RESOLVE's objective function includes the annual cost to operate the electric system across RESOLVE's footprint; this cost is quantified using a linear production cost model.

+ **Zonal transmission topology:** RESOLVE uses a zonal transmission topology to simulate flows among the various regions in the Western Interconnection. RESOLVE includes six zones: four zones capturing California balancing authorities and two zones that represent regional aggregations of out-of-state balancing authorities. The constituent balancing authorities included in each RESOLVE zone are shown in Table 33.

Table 33. Constituent balancing authorities in each RESOLVE zone.

RESOLVE Zone	Balancing Authorities
BANC	Balancing Authority of Northern California (BANC) Turlock Irrigation District (TIDC)
CAISO	California Independent System Operator (CAISO)
LADWP	Los Angeles Department of Water and Power (LADWP)
IID	Imperial Irrigation District (IID)
NW	Avista Corporation (AVA) Bonneville Power Administration (BPA) Chelan County Public Utility District (CHPD) Douglas County Public Utility District (DOPD) Grant County Public Utility District (GCPD) Idaho Power Company (IPC) NorthWestern Energy (NWMT) Pacificorp East (PACE) Pacificorp West (PACW) Portland General Electric Company (PGE) Puget Sound Energy (PSE)

RESOLVE Zone	Balancing Authorities
	Seattle City Light (SCL) Sierra Pacific Power (SPP) Tacoma Power (TPWR) WAPA – Upper Wyoming (WAUW)
SW	Arizona Public Service Company (APS) El Paso Electric Company (EPE) Nevada Power Company (NEVP) Public Service Company of New Mexico (PNM) Salt River Project (SRP) Tucson Electric Power Company (TEP) WAPA – Lower Colorado (WALC)
Excluded	*Alberta Electric System Operator (AESO)* *British Columbia Hydro Authority (BCHA)* *Comision Federal de Electricidad (CFE)* *Public Service Company of Colorado (PSCO)* *WAPA – Colorado-Missouri (WACM)*

+ **Aggregated generation classes:** rather than modeling each generator within the study footprint independently, generators in each region are grouped together into categories with other plants whose operational characteristics are similar (e.g. nuclear, coal, gas CCGT, gas CT). Grouping like plants together for the purpose of simulation reduces the computational complexity of the problem without significantly impacting the underlying economics of power system operations.

+ **Linearized unit commitment:** RESOLVE includes a linear version of a traditional production simulation model. In RESOLVE's implementation, this means that the commitment variable for each class of generators is a continuous variable rather than an integer variable. Additional constraints on operations (e.g. Pmin, Pmax, ramp rate limits, minimum up & down time) further limit the flexibility of each class' operations.

+ **Co-optimization of energy & ancillary services:** RESOLVE dispatches generation to meet load across the Western Interconnection while simultaneous reserving flexible capacity within CAISO to meet the contingency and flexibility reserve needs of the CAISO balancing authority.

+ **Smart sampling of days:** whereas production cost models are commonly used to simulate an entire calendar year (or multiple years) of operations, RESOLVE simulates the operations of the WECC system for 37 independent days. Load, wind, and solar profiles for these 37 days, sampled

from the historical meteorological record of the period 2007-2009, are selected and assigned weights so that taken in aggregate, they produce a reasonable representation of complete distributions of potential conditions; daily hydro conditions are sampled separately from low (2008), medium (2009), and high (2011) hydro years to provide a complete distribution of potential hydro conditions.[20] This allows RESOLVE to approximate annual operating costs and dynamics while simulating operations for only the 37 days. The 37 days sampled are summarized in Table 34.

Table 34. RESOLVE's 37 days and associated weights.

Index	Weather Date	Hydro Condition	Day Weight	Index	Weather Date	Hydro Date	Day Weight
1	1/1/07	High	14.250	20	5/7/08	High	5.808
2	1/2/07	Mid	5.908	21	5/19/08	Low	15.361
3	2/12/07	High	28.022	22	6/2/08	Low	17.733
4	3/6/07	High	14.341	23	8/3/08	Mid	20.807
5	3/20/07	Low	6.699	24	10/28/08	Low	1.167
6	4/2/07	High	0.495	25	11/5/08	Mid	12.447
7	4/8/07	Low	2.197	26	12/20/08	High	33.401
8	4/15/07	Low	1.133	27	1/6/09	Mid	0.881
9	5/5/07	Mid	5.384	28	1/21/09	Mid	7.922
10	5/29/07	High	3.902	29	3/26/09	High	8.913
11	6/2/07	High	9.228	30	4/4/09	Low	3.381
12	6/16/07	High	1.631	31	4/17/09	High	9.045
13	7/17/07	Mid	31.789	32	4/24/09	High	5.718
14	8/7/07	High	4.542	33	4/25/09	Low	4.810
15	9/2/07	High	13.817	34	4/25/09	High	0.903
16	9/26/07	Low	16.348	35	6/24/09	High	1.748
17	11/27/07	High	19.042	36	8/17/09	Low	5.811
18	1/28/08	Mid	0.664	37	10/6/09	High	28.928

[20] An optimization algorithm is used to select the days and identify the weight for each day such that distributions of load, net load, wind, and solar generation match long-run distributions.

Index	Weather Date	Hydro Condition	Day Weight	Index	Weather Date	Hydro Date	Day Weight
19	4/4/08	High	0.822	**Total**			**365.000**

5.2 Load & Renewable Profiles

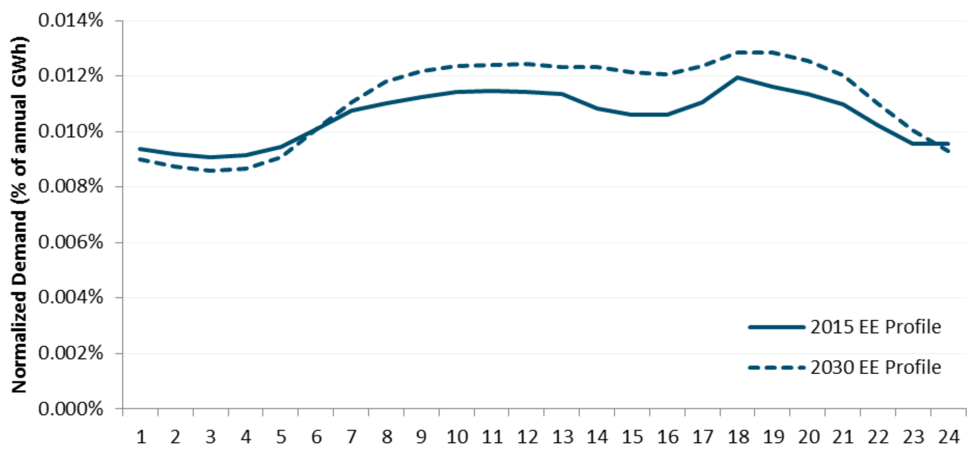
5.2.1 LOAD PROFILES

Load profiles are based on historical loads for the zones of interest as reported by the Western Electricity Coordinating Council (WECC) for 2007-2009. Since there were virtually no behind-the-meter PV, electric vehicles, additional energy efficiency, or time-of-use rate impacts at that time, these profiles are assumed to reflect the baseline profile. For the non-CAISO zones, these profiles are used "as is", whereas for the CAISO zone, the final load profile is obtained by adding appropriate shapes for behind-the-meter PV, electric vehicles, energy efficiency, and time-of-use rate impacts to the baseline profile. The baseline profiles and the adjustments can be found in the LOADS_profiles worksheet of the User Interface spreadsheet.

5.2.1.1 Energy Efficiency Profiles

The EE profiles used by RESOLVE for 2015 and 2030 are shown Figure 11 below. As can be seen, the profiles roughly follow the load profile. For years in between 2015 and 2030, a linear interpolation of both profiles is used. For years beyond 2030, the 2030 profile is used. These profiles are based on the hourly profiles developed by the CEC to represent the load impact of Additional Achievable Energy Efficiency in the 2015 IEPR Demand Forecast.

Figure 11. Energy efficiency profile (January representative day)



5.2.1.2 Electric Vehicle Load Profiles

EV load profiles are created using an EV charging model developed by E3. The charging model is based on the 2009 National Household Transportation Survey ("NHTS"), a dataset on personal travel behavior[21]. The model translates travel behavior into aggregate EV load shapes by weekday/weekend-day, charging strategy, and charging location availability. The weekend/weekday shapes are aggregated and normalized into month-hour shapes by charging location availability. A blend is created by assuming a certain fraction of drivers have charging infrastructure available both at home and their workplace, while the rest of the drivers only have charging infrastructure available at home. There are three predefined settings available for the fraction of drivers that have workplace charging available, as shown in Table 35 below.

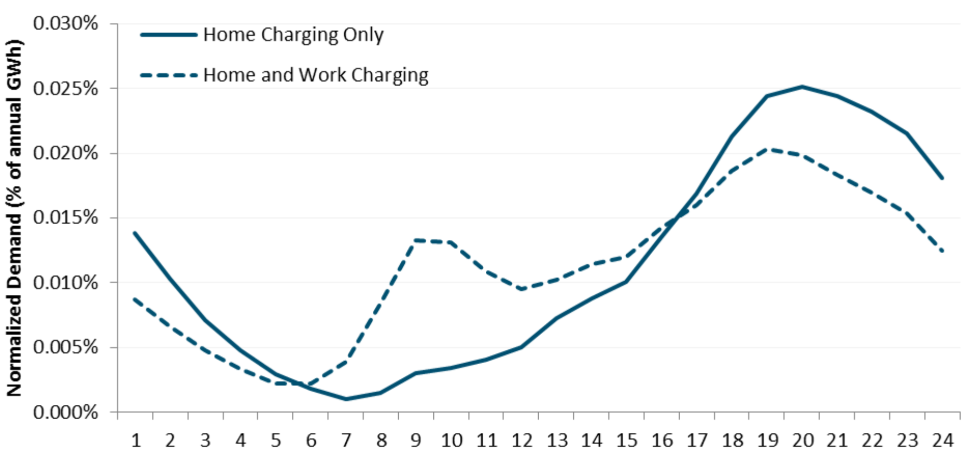
Table 35. Workplace charger availability by scenario.

Scenario Setting	2018	2022	2026	2030

[21] Available at: http://nhts.ornl.gov/introduction.shtml

Low	2%	5%	7%	10%
Mid	6%	14%	22%	30%
High	16%	37%	59%	80%

Figure 12. Electric vehicle charging shape for January by charger availability.



RESOLVE also has the option to have flexible EV charging, which lets the RESOLVE model dynamically optimize the charging shape. There are three predefined settings available for the fraction of EV load that is flexible, as shown in Table 36 below. Note that the default assumption is to have no flexible EV charging ("Low" scenario).

Table 36. Fraction of flexible electric vehicle charging by scenario.

Scenario Setting	2018	2022	2026	2030
Low	0%	0%	0%	0%
Mid	4%	9%	15%	20%
High	10%	23%	37%	50%

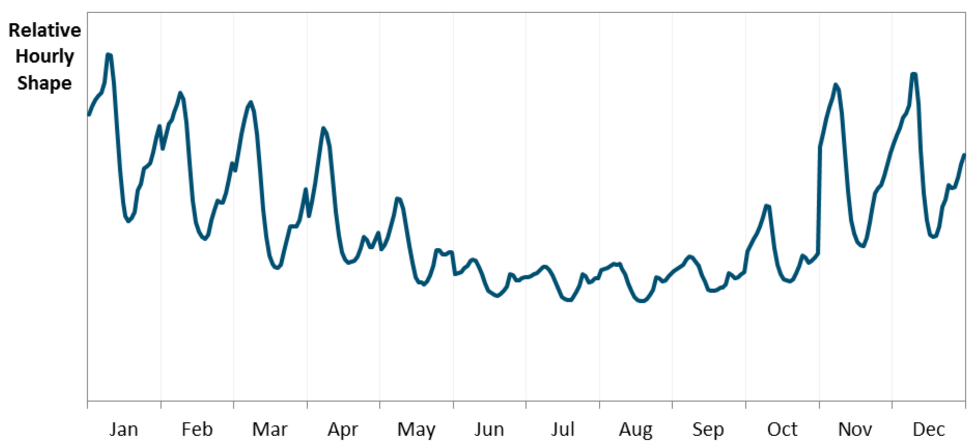
For the vehicles that have flexible charging, the optimal charging shape is constrained by the amount of vehicles that is plugged in, which defines how much charge capacity is available, and the instantaneous driving demand for that hour, which affects the state-of-charge of the fleet.

5.2.1.3 Building Electrification Profiles

The load profiles used to represent incremental building electrification are based on the end-use load shapes used in E3's PATHWAYS model, used in the development of CARB's Scoping Plan. The profile included in RESOLVE is a composite of shapes associated with the following end uses: (1) residential cooking, (2) residential space heating, (3) residential water heating, (4) commercial space heating, and (5) commercial water heating. In the composite shape for building electrification, each of these end uses is weighted in proportion to the relative amount of incremental electrification observed by 2030 in CARB's Alternative 1 scenario.

Within RESOLVE, the shape for building electrification is input as a representative hourly shape for each month. The representative hourly shape for each month is shown in Figure 13. As illustrated in this figure, building electrification loads are more concentrated in the winter due to the electrification of space heating and water heating end uses.

Figure 13. Building electrification load shape by month



5.2.1.4 Time-of-Use Rates Adjustment Profiles

Time-of-use rate profile impacts are based on a 2015 study by Christensen Associates (2015)[22]. E3 applied the 2025 TOU load impacts from this study to the relevant periods of the 37 modeled days (summer peak, summer off-peak, winter peak, etc.) to obtain the TOU shape for 2025. For all other years, the TOU adjustment was scaled based on the ratio of the load (net of EE) of that year vs. the load in 2025. The 2025 profile and the scalars for each year can be found in the LOADS_profiles worksheet of the User Interface spreadsheet. As can be seen, the TOU adjustments are relatively small, maxing out at a reduction of about 150 MW for the year 2025.

5.2.2 SOLAR PV PROFILES

Solar profiles for RESOLVE are created using a python-based solar simulation tool made by E3. The tool uses standard solar modeling principles as laid out by Sandia's PV Performance Modeling Collaborative[23] to simulate PV production based on weather data from the National Solar Radiation Database (NSRDB).[24]

For each of the resources modeled in RESOLVE, NSRDB data for five to twenty representative lat-lon coordinates (more for larger regions) is collected for the years 2007-2009. PV production profiles for each of these locations are then simulated for a fixed-tilt configuration, a single-axis tracking configuration, and a behind-the-meter rooftop configuration. The inverter loading ratio is assumed to be 1.3 for utility-scale systems, and 1.1 for behind-the-meter systems. Next, aggregate profiles for each resource and configuration (fixed-tilt, single-axis tracking, behind-the-meter) are obtained by taking the average of the representative locations. For utility scale resources (everything but behind-the-meter PV), one last step involves aggregating the utility scale profiles, assuming 25% is fixed tilt and 75% is tracking.

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[22] *Statewide Time-of-Use Scenario Modeling for 2015 California Energy Commission Integrated Energy Policy Report.* Available at: **http://docketpublic.energy.ca.gov/PublicDocuments/15-IEPR-03/TN207031_20151215T151300_Statewide_TimeofUse_Scenario_Modeling_for_2015_California_Energ.pdf**

[23] Available at: **https://pvpmc.sandia.gov/** The modeling framework and assumptions on this website are very similar to what is used in NREL's PVWatts tool and NREL's System Advisor Model.

[24] See: **https://nsrdb.nrel.gov/current-version**

Before the solar profiles can be used in RESOLVE, they are scaled such that the weighted capacity factor of the 37 modeled days matches the capacity factor derived from the CPUC's RPS Calculator (Version 6.2) Supply Curve. For out-of-state resources, the target capacity factors are based on data from the 2026 WECC Common Case. The reshaping is done by linearly scaling the shape up or down until the target capacity factor is met. When scaling up, the maximum normalized output is capped to 100% to ensure that a profile's hourly production does not exceed its rated installed capacity. This essentially mimics increasing/decreasing the inverter loading ratio.

The final capacity factors are shown in Table 37 below. The final shapes can be found in the REN_Profiles worksheet.

Table 37. Solar capacity factors in RESOLVE (%)

Category	Resource	Capacity Factor
Baseline Resources	CAISO_Solar_for_CAISO	30%
	CAISO_Solar_for_Other	28%
	IID_Solar_for_CAISO	29%
	NW_Solar_for_Other	24%
	SW_Solar_for_CAISO	32%
	SW_Solar_for_Other	27%
	Customer_PV*	19%
Candidate Resources	Northern_California_Solar	30%
	Solano_Solar	29%
	Central_Valley_North_Los_Banos_Solar	30%
	Westlands_Solar	30%
	Greater_Carrizo_Solar	32%
	Tehachapi_Solar	35%
	Kramer_Inyokern_Solar	36%
	Mountain_Pass_El_Dorado_Solar	35%
	Southern_California_Desert_Solar	35%
	Riverside_East_Palm_Springs_Solar	34%
	Greater_Imperial_Solar	34%
	Distributed_Solar	23%
	Baja_California_Solar	35%
	Utah_Solar	30%
	Southern_Nevada_Northwest_Arizona_Solar	32%

	Arizona_Solar	34%
	New_Mexico_Solar	33%

** Customer_PV profile represents all behind-the-meter solar PV installations*

5.2.3 WIND PROFILES

Hourly shapes for wind resources are obtained from NREL's Wind Integration National Dataset ("WIND") Toolkit.[25] For each of the wind resources modeled in RESOLVE, wind production profiles for a set of representative locations is collected for the years 2007-2009. The profiles are then adjusted using a filter such that such that the weighted capacity factor of the 37 modeled days matches the capacity factor derived from the CPUC's RPS Calculator v.6.3 supply curve.[13] For out-of-state resources, the target capacity factors are based on data from the 2026 WECC Common Case. The filter is set up such that outputs at lower level are affected more (to represent better/worse turbine technology), while hourly ramps are preserved.

The final capacity factors are shown in Table 38 below. The final shapes can be found in the REN_Profiles worksheet.

Table 38. Wind capacity factors in RESOLVE (%)

Category	Resource	Capacity Factor
Baseline Resources	Contracted_NW_Wind	32%
	CAISO_Wind_for_CAISO	28%
	CAISO_Wind_for_Other	28%
	SW_Wind_for_CAISO	44%
	NW_Wind_for_Other	29%
	SW_Wind_for_Other	44%
Candidate Resources	Northern_California_Wind	29%
	Solano_Wind	30%
	Central_Valley_North_Los_Banos_Wind	31%
	Greater_Carrizo_Wind	31%
	Tehachapi_Wind	33%

[25] See: https://www.nrel.gov/grid/wind-toolkit.html

Category	Resource	Capacity Factor
	Kramer_Inyokern_Wind	32%
	Southern_California_Desert_Wind	27%
	Riverside_East_Palm_Springs_Wind	33%
	Greater_Imperial_Wind	31%
	Distributed_Wind	28%
	Baja_California_Wind	36%
	Pacific_Northwest_Wind	32%
	Idaho_Wind	32%
	Utah_Wind	31%
	Wyoming_Wind	44%
	Southern_Nevada_Northwest_Arizona_Wind	28%
	Arizona_Wind	29%
	New_Mexico_Wind	44%

5.3 Operating Characteristics

5.3.1 CONVENTIONAL

As discussed in Sections 3.1, the thermal fleet in RESOLVE is represented by a limited set of resource classes by zone that represent the capacity-weighted average for each resource class in that zone. The operating characteristics (Pmax, Pmin, heat rate etc.) for each resource class are compiled from the 2026 TEPPC Common Case. For the CAISO zone, these operating characteristics are matched with the NQC list and shown explicitly in the CAISO_Gen_List worksheet, after which they are aggregated by resource class in the CONV_OpChar worksheet. For all other zones, the aggregation is done as separate pre-processing step, and only the final, aggregated results are shown. Operating parameters for each resource class are based on a capacity-weighted average of individual plant operating characteristics, most of which are gathered from the TEPPC 2026 Common Case. Several plant types are modeled using operational information from other sources:

+ The CAISO_Aero_CT and CAISO_Advanced_CCGT operating characteristics are based on manufacturer specifications of the latest available models of these class.

+ The CAISO_CHP plant type is modeled as a must-run resource at its full NQC capacity with an assumed net heat rate of 7,600 Btu/kWh, based on CARB's Scoping Plan assumptions for cogeneration.

The operating characteristics for each of the generator classes in RESOLVE are shown below in Table 39.

Table 39. Main operating characteristics of the conventional generator fleet in RESOLVE

Resource	Zone	Must Run	Pmax (MW)	Pmin (MW)	Max Ramp Rate (%Pmax/hr)	Heat Rate at Pmax (Btu/MWh)	Heat Rate at Pmin (Btu/MWh)	Min Up/Down Time (hrs)	Startup Cost ($/MW)
CAISO_CHP	CAISO	TRUE	20	20	0%	7.606	7.606	24	$62
CAISO_Nuclear	CAISO	TRUE	584	423	18%	12.554	13.008	24	$113
CAISO_CCGT1	CAISO		484	291	64%	6.865	7.280	6	$93
CAISO_CCGT2	CAISO		248	129	54%	7.381	7.996	6	$85
CAISO_Peaker1	CAISO		62	29	378%	9.308	12.904	1	$86
CAISO_Peaker2	CAISO		46	22	338%	12.110	15.182	1	$49
CAISO_Advanced_CCGT	CAISO		600	120	100%	6.833	10.167	1	$50
CAISO_Aero_CT	CAISO		100	30	100%	9.572	17.632	—	$10
CAISO_Reciprocating_Engine	CAISO		5	1	1495%	9.151	10.893	—	$7
CAISO_ST	CAISO		337	27	102%	9.663	17.117	6	$78
CAISO_CCGT_Retrofit	CAISO		484	97	64%	6.865	7.280	2	$93
Conventional_DR	CAISO		1	0	100%			—	—
NW_Nuclear	NW	TRUE	1,170	1,170	20%	10.907	10.907	24	—
NW_Coal	NW		305	129	66%	10.609	11.259	24	$16
NW_CCGT	NW		337	178	57%	7.141	7.721	6	$15
NW_Peaker	NW		28	10	322%	10.591	12.500	1	$714
SW_Nuclear	SW	TRUE	1,403	1,403	19%	10.544	10.544	24	—
SW_Coal	SW		414	174	57%	10.374	11.211	24	$12
SW_CCGT	SW		372	205	55%	7.143	7.667	6	13
SW_Peaker	SW		71	26	249%	10.554	14.269	1	$282
LDWP_Nuclear	LDWP	TRUE	152	152	19%	10.544	10.544	24	—
LDWP_Coal	LDWP		900	328	54%	9.608	10.289	24	$6
LDWP_CCGT	LDWP		215	123	110%	6.995	7.095	6	$23
LDWP_Peaker	LDWP		74	36	201%	9.042	10.532	1	$272
IID_CCGT	IID		128	61	72%	7.905	9.209	6	$85
IID_Peaker	IID		41	14	429%	12.140	16.208	1	$49
BANC_CCGT	BANC		234	124	75%	7.677	8.037	6	$85
BANC_Peaker	BANC		40	16	292%	10.392	12.121	1	$49

For must-run generators, the assumptions regarding availability by month are shown in Table 40 below.

Table 40. Monthly availability by generator type (% of nameplate)

Resource	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NW_Nuclear	100%	100%	100%	100%	50%	50%	100%	100%	100%	100%	100%	100%
SW_Nuclear	100%	100%	100%	75%	75%	100%	100%	100%	75%	75%	100%	100%
LDWP_Nuclear	100%	100%	100%	75%	75%	100%	100%	100%	75%	75%	100%	100%
CAISO_Nuclear	100%	100%	100%	75%	75%	100%	100%	100%	75%	75%	100%	100%
NW_Coal	95%	95%	95%	95%	50%	50%	95%	95%	95%	95%	95%	95%
SW_Coal	95%	95%	95%	50%	50%	95%	95%	95%	95%	95%	95%	95%
LDWP_Coal	95%	95%	95%	50%	50%	95%	95%	95%	95%	95%	95%	95%

Monthly derates for each plant reflect assumptions regarding the timing of annual maintenance requirements. Nuclear maintenance and refueling is assumed to be split between the spring (April & May) and the fall (September & October) so that the plants can be available to meet summer and winter peaks. Annual maintenance of the coal fleets in the WECC is assumed to occur during the spring months, when wholesale market economics tend to suppress coal capacity factors due to high hydro availability and low loads.

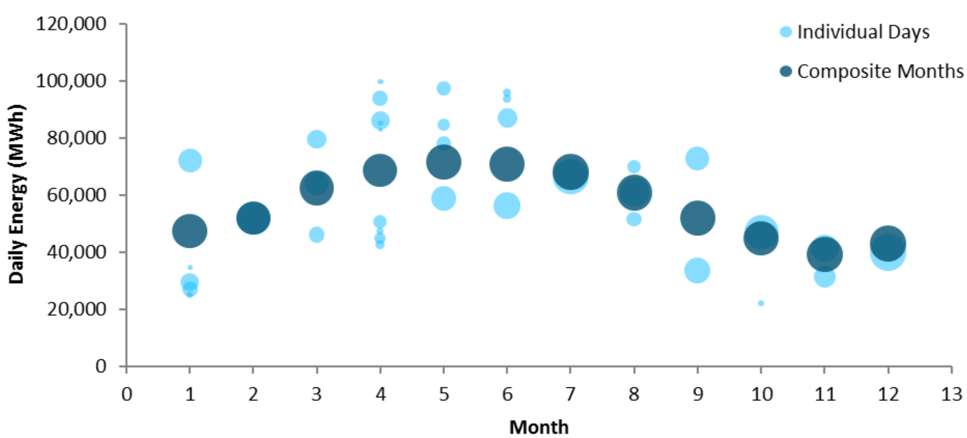
5.3.2 HYDRO

The operations of the hydro fleets in each region are constrained on each day by three constraints:

+ **Daily energy budget:** the total amount of energy, in MWh, to be dispatched throughout the day; and
+ **Daily maximum and maximum output:** upper and lower limits, in MW, for power production intended to capture limits on the flexibility of the regional hydro system due to hydrological, biological, and other technical factors; and
+ **Ramping capability:** within CAISO, the ramping capability of the fleet it further constrained by hourly and multi-hour ramp limitations (up to four hours), which are derived from historical CAISO hydro operations.

In the CAISO, these constraints are drawn from the actual historical record: the daily budget and minimum/maximum output are based on actual CAISO operations on the day of the year from the appropriate hydrological year (low = 2008, mid = 2009, high = 2011) that matches the canonical day used for load, wind, and solar conditions (e.g., as presented in Table 34, day 3 uses February 12, 2007 for load, wind, and solar conditions and uses 2011 hydro conditions; therefore, the daily budget and operational range is based on actual CAISO daily operations on February 12, 2011). Figure 14 summarizes the daily energy budgets for each of the 37 days modeled in RESOLVE.

Figure 14. Daily energy budgets for CAISO hydro fleet



In the chart above, each of the 37 days is shown as a light blue point according to its calendar month. The size of the bubble in the diagram above represents the weight assigned to that day in RESOLVE. The dark blue points represent the average hydro budget for all days in that month.

Outside CAISO, where daily operational data was not available, assumed daily energy budgets are derived from monthly historical hydro generation as reported in EIA Form 906/923 (e.g., in the example discussed above for Day 3, the daily energy budgets for other regions is based on average conditions in February 2011). Minimum and maximum output for regions outside CAISO are based on functional relationships between daily energy budgets and the observed operable range of the hydro fleet derived from historical data gathered from WECC.

5.3.3 ENERGY STORAGE

The efficiency and minimum duration for each of the storage technologies modeled in RESOLVE is shown in Table 41 below.

Table 41. Assumptions for new energy storage resources

Technology	Round-Trip Efficiency	Minimum Duration (hours)
Li_Battery	85%	1
Flow_Battery	70%	1
Pumped_Hydro	81%	12

For all storage devices, we assume that they have no minimum generation or minimum "discharging" constraint, allowing them to charge or discharge over a continuous range. For pumped storage, this is a simplification, as pumps and generators typically have a somewhat limited operating range. We also don't specify ramp rates for storage devices, implicitly assuming that they can ramp over their full operable range almost instantly.

5.4 Reserve Requirements

RESOLVE models the following reserve products for the CAISO main zone:

Table 42. Reserve types modeled in RESOLVE

Product	Description	RESOLVE Requirement	Operating Limits
Frequency Response	Aside from system inertia, this is the fastest reserve type and is operated through governor response. In RESOLVE, it is assumed that storage devices can provide these services as well.	The default assumption in RESOLVE is to hold 770 MW, of which half is held by non-modeled resources, which results in a remaining requirement of 385 MW.	For thermal generators, we assume that they can contribute 8% of their committed capacity. For storage devices, we assume that they can provide all their available headroom.
Regulation Up/Down	This is the second fastest reserve product modeled (5 min – 4 sec). This reserve	The default assumption is 1% of the hourly CAISO load both for regulation up and	We assume that thermal generators can provide all their available

Product	Description	RESOLVE Requirement	Operating Limits
	product ensures that the system's frequency, which can deviate due to real-time swings in the load/generation balance, stays within a defined band. In practice, this is controlled by generators on Automated Generator Control (AGC), which get sent a signal based on the frequency deviations of the system.	regulation down.	headroom/footroom[26], limited by their 10-min ramp rate. Storage systems are only constrained by their available headroom/footroom.
Load Following Up/Down	This reserve product ensures that sub-hourly variations from the load forecast, as well as lumpy blocks of imports/exports/generator commitments, are dealt with by the system in real-time.	RESOLVE uses an hourly requirement based on subhourly analysis that was done for one 33% and two 50% RPS cases in the CAISO system. This analysis parameterized the hourly load following requirements for each of the 37 RESOLVE model days based on the renewable penetration and diversity (high solar vs. diverse).	We assume that thermal generators can provide all their available headroom/footroom, limited by their 10-min ramp rate. Storage systems are only constrained by their available headroom/footroom.
Spinning Reserve	This contingency reserve ensures that there are enough generators online in case of an outage or other contingency.	The default assumption is 3% of the hourly CAISO load.	We assume that thermal generators can provide all their available headroom, limited by their 10-min ramp rate. Storage systems are only constrained by their available headroom. RESOLVE ensures that storage has enough state-of-charge available to provide spinning reserves, but deployment (which would reduce the state-of-charge) is not explicitly modeled.

Deleted: Storage systems.

Deleted: both for regulation up and regulation down.

Deleted: /footroom

Deleted: We assume a CAISO spinning reserve requirement of 3% of the hourly load.

Deleted: /footroom

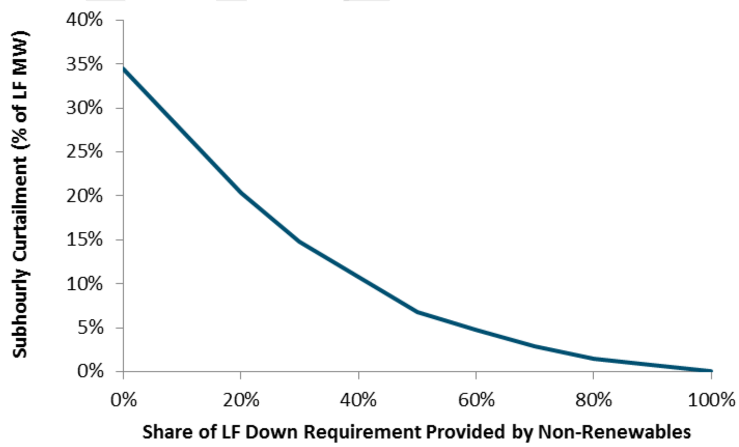
[26] For generators, headroom and footroom are defined as the difference between the current operating level and the maximum and minimum generation output, respectively. For storage devices, headroom and footroom are defined as the difference between the current operating level and resp. the maximum discharge capacity, and maximum charge capacity, e.g. a 100 MW battery charging at 50 MW has a headroom of 150 MW (100 – (-50)) and a footroom of 50 MW.

Non-spinning reserves are not modeled in RESOLVE. Also, reserves are not modeled in any of the non-CAISO zones.

Deployment of reserves is only modeled for storage devices, and only for regulation and load following (not for spinning reserve and primary frequency response). The default assumption for deployment for these services is 20%. In other words, for every MW of regulation or load following up provided in a certain hour, we assume that the storage device is discharged 0.2 MWh (and vice versa for regulation / load following down).

In the base case, we assume that renewables can provide load following down, but only up to 50% of the load following down requirement. This allows renewables to be curtailed on the subhourly level to provide reserves. The amount of subhourly curtailment (i.e. the deployment) is parametrized by a "Reflex Surface" in the SYS_Reserves worksheet. Figure 15 shows the amount of subhourly curtailment this results in. For instance, when all load following down is met by renewables, this surface indicates that the amount of subhourly curtailment that would occur would be equal to 34% of the hourly downward load following requirement across the hour (i.e. "deployed"). Note that for storage devices providing load following down (or up), we assume a flat 20% deployment.

Figure 15. Anticipated subhourly renewable curtailment as a function of load following met by renewables.



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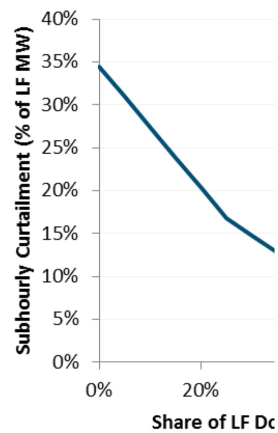


5.5 Transmission Topology

The zonal transmission topology assumed in RESOLVE is shown in Figure 16. This topology is based on compiled information from a number of public data sources. Where possible, transfer capability between zones is tied to rated WECC paths, per the WECC 2016 Path Catalog In instances where rating in one direction (e.g., West-to-East) is not defined, it is assumed to be symmetric with the opposite direction. WECC path ratings are complemented by other available data, including scheduling total transfer capacity provided on the OASIS sites of certain utilities and transmission owners. Where path data is not available, the sum of thermal ratings on lines connecting neighboring zones in WECC's nodal TEPPC cases has been used to allocate or provide information. This data is supplemented by other documents identified in past public filings online, as well as conversations with transmission engineers, to approximate actual operations to the extent possible.

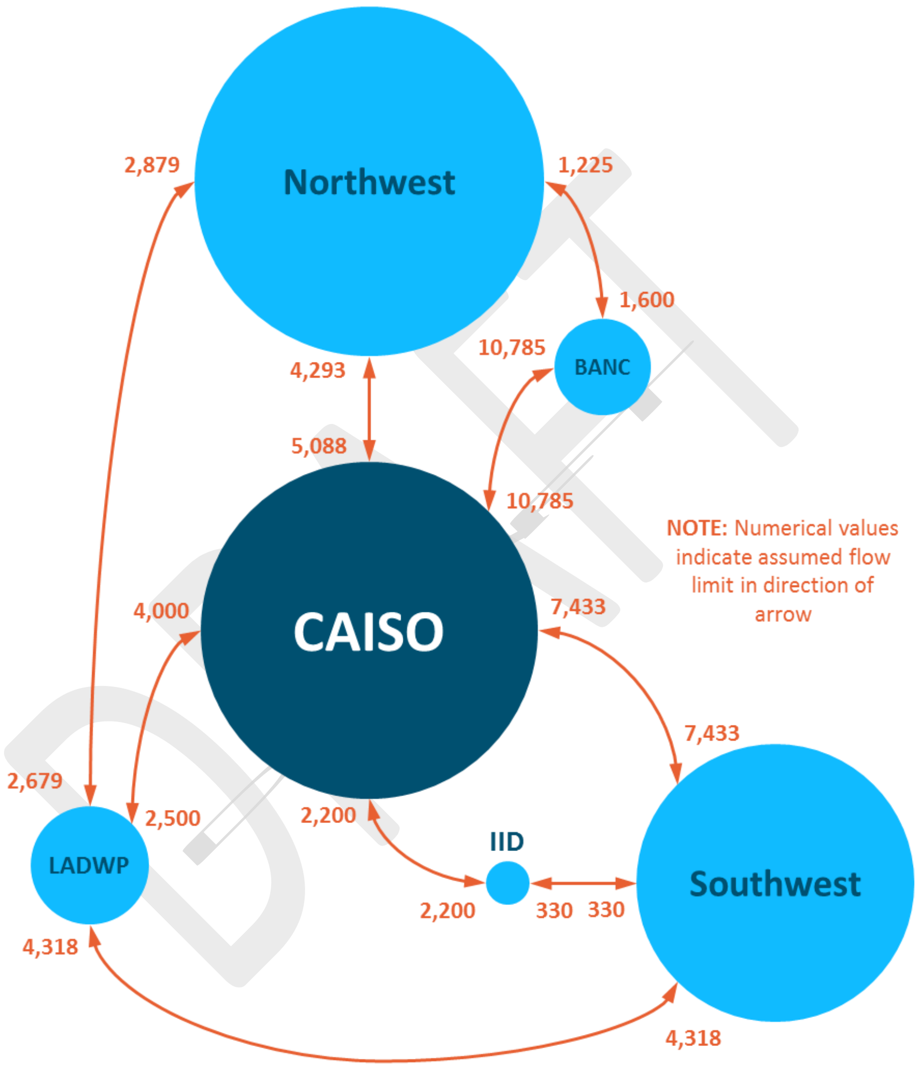
RESOLVE also incorporates hurdle rates for transfers between zones; these hurdle rates are intended to capture the transactional friction to trade energy across neighboring transmission systems. The hurdle rates, shown in Table 43, are based on CAISO's 2014 LTPP PLEXOS Case, and are tied to the zone of export (e.g., sending power from CAISO to the NW, or any other zone, incurs a hurdle rate of $9.96/MWh).

Table 43. Hurdle rates in RESOLVE ($/MWh)

Export Zone	Hurdle Rate ($/MWh)
From BANC	$2.47
From CAISO	$9.96
From IID	$4.07
From LDWP	$5.71
From NW	$3.89
From SW	$3.86

In addition to these cost-based hurdle rates, an additional cost is attributed to all imports to California reflecting the cost to import unspecified power into California under CARB's cap and trade program; this cost is calculated based on the relevant year's carbon cost (see Table 48) and a deemed rate of 0.43 tons/MWh.

Figure 16. Transmission topology used in RESOLVE (transfer limits shown in MW).



In addition to the physical underlying transmission topology shown above, RESOLVE also includes a constraint on the simultaneous net exports from CAISO. This constraint is included to capture explicitly

the uncertainty in the size of the future potential market for California's exports of surplus renewable power. RESOLVE includes three options for the export constraint from California, shown in Table 44.

Table 44. Assumed CAISO net export limits (MW)

Scenario Setting	2018	2022	2026	2030
Low	2,000	2,000	2,000	2,000
Mid	2,000	3,000	4,000	5,000
High	2,000	4,000	6,000	8,000

5.6 Fuel Costs

RESOLVE includes three options for fuel costs, each of which is based on a WECC burner tip price estimate using CEC's 2015 IEPR Demand Forecast[27]. Prices for each region were calculated using the average of the region of interest, and were adjusted for inflation (2%/yr.) to reflect 2016 dollars. These forecasts – Low, Mid, High – are shown in Table 45, Table 46, and Table 47.

Table 45. Fuel Cost Forecast – Low ($/MMBtu, 2016$).

Fuel Type	2018	2022	2026	2030
CA_Natural_Gas	$3.86	$4.21	$4.57	*$4.39*
NW_Natural_Gas	$3.28	$3.54	$3.87	*$3.76*
SW_Natural_Gas	$3.57	$3.85	$4.18	*$4.02*
CA_Coal	$2.00	$2.00	$2.00	*$2.00*
Coal	$2.00	$2.00	$2.00	*$2.00*
Uranium	$0.70	$0.70	$0.70	*$0.70*

Values shown in italics are extrapolated based on the average linear growth rate between 2021 and 2026.

[27] Available here: http://docketpublic.energy.ca.gov/PublicDocuments/15-IEPR-03/TN209537_20160126T084035_WECC_Gas_Hub_Burner_Tip_Price_Estimates_using_2015_IEPR_Natural.xlsx

Table 46. Fuel Cost Forecast – Mid ($/MMBtu, 2016$).

Fuel Type	2018	2022	2026	2030
CA_Natural_Gas	$4.50	$5.24	$5.50	*$5.33*
NW_Natural_Gas	$3.92	$4.57	$4.80	*$4.70*
SW_Natural_Gas	$4.21	$4.88	$5.11	*$4.96*
CA_Coal	$2.00	$2.00	$2.00	*$2.00*
Coal	$2.00	$2.00	$2.00	*$2.00*
Uranium	$0.70	$0.70	$0.70	*$0.70*

Values shown in italics are extrapolated based on the average linear growth rate between 2021 and 2026.

Table 47. Fuel Cost Forecast – High ($/MMBtu, 2016$).

Fuel Type	2018	2022	2026	2030
CA_Natural_Gas	$5.70	$6.59	$7.17	*$7.06*
NW_Natural_Gas	$5.12	$5.93	$6.46	*$6.42*
SW_Natural_Gas	$5.41	$6.23	$6.77	*$6.68*
CA_Coal	$2.00	$2.00	$2.00	*$2.00*
Coal	$2.00	$2.00	$2.00	*$2.00*
Uranium	$0.70	$0.70	$0.70	*$0.70*

Values shown in italics are extrapolated based on the average linear growth rate between 2021 and 2026.

RESOLVE includes four options for carbon costs, each of which is based on the preliminary 2015 IEPR Nominal Carbon Price Projections. This forecast projects a 5% year-over-year increase of the carbon price, plus annual inflation. Nominal prices were brought back to 2016 dollars assuming a constant 2% inflation rate. These forecasts – Low, Mid, High, Zero – are shown in Table 48. The model's default assumption is to only apply these carbon prices to resources in California, as well as generation imported to California.

Table 48. Carbon Cost Forecast Options ($/tCO2, 2016$).

Fuel Type	2018	2022	2026	2030
Low	$ 15.17	$ 18.86	$ 23.44	$ 29.28
Mid	$ 15.17	$ 28.29	$ 35.16	$ 43.92

High	$ 45.52	$ 56.59	$ 70.31	$ 87.83
Zero	—	—	—	—

Values shown in italics are extrapolated based on the average linear growth rate between 2026 and 2030.

6 Resource Adequacy Requirements

6.1 System Resource Adequacy

To ensure that the optimized generation fleet is sufficient to meet resource adequacy needs throughout the year, RESOLVE includes a planning reserve margin constraint that requires the total available generation plus available imports in each year to meet or exceed a 15% margin above the annual 1-in-2 peak demand. The contribution of each type of generation resource to this requirement depends on its performance characteristics and availability to produce power during the most constrained periods of the year; the treatment of each type of resource in the planning reserve margin constraint is discussed below.

6.1.1 CONVENTIONAL

The contribution of thermal generators to resource adequacy is based on the CAISO's Net Qualifying Capacity list. For each type of thermal generation, this list is used to derive an assumed NQC, expressed as a percentage of nameplate capability; this percentage is used to calculate the NQC contribution of existing and new resources towards the planning reserve margin. For most thermal generation, these percentages are relatively close to 100%. These assumptions are summarized in Table 49.

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Table 49. Assumed Net Qualifying Capacity (NQC) for thermal generators (% of maximum capability)

Resource Class	NQC (% of max)
CHP*	100%
Nuclear	99%
CCGT1	95%
CCGT2	98%
Peaker1	98%
Peaker2	98%

Advanced_CCGT	95%
Aero_CT	95%
Reciprocating_Engine	100%
ST	100%

** The NQC of CHP of 100% is a result of the modeling convention used for CHP, in which CHP resources are modeled as baseload resources that produce power at their NQC capacity throughout the year.*

6.1.2 HYDRO

The NQC of existing hydroelectric resources is based on the CAISO's current net qualifying capacity list.

6.1.3 DEMAND RESPONSE

The contribution of demand response resources to the resource adequacy requirement, including new shed DR resources selected by RESOLVE, is assumed to be equal to the 1-in-2 ex ante peak load impact. This forecast is discussed in Section 3.5. Shift demand response selected by RESOLVE are not currently assumed to have an impact on the planning reserve margin.

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6.1.4 RENEWABLES

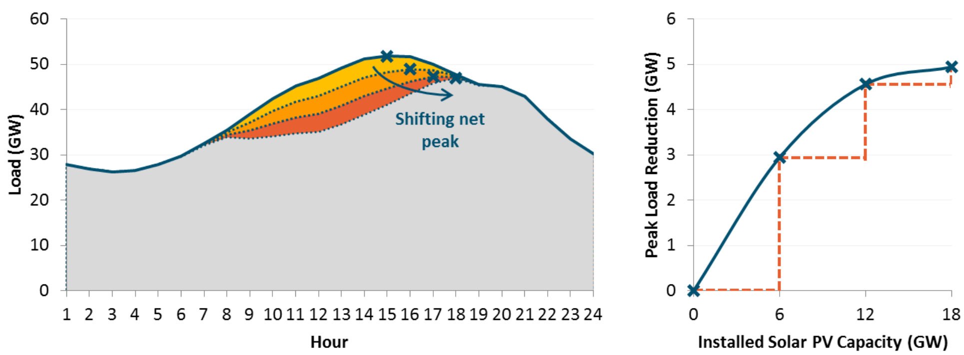
Renewable resources with full deliverability capacity status (FCDS) are assumed to contribute to system resource adequacy requirements. Within RESOLVE, these resources fall into two categories: (1) baseload, which includes all biomass, geothermal, and small hydro; and (2) variable resources, which includes both solar and wind resources. The treatment of each category reflects the differences in their intermittency.

For baseload renewables, each resources' contribution to resource adequacy is assumed to be equivalent to its average annual capacity factor (i.e., a geothermal resource with an 80% capacity factor is also assumed to have an 80% net qualifying capacity). This assumption reflects the characteristic of baseload resources that they tend to produce energy throughout the year with a relatively flat profile, and thereby their contribution to peak needs is not materially different from their average levels of production throughout the year.

To measure the contribution of variable renewable resources to system resource adequacy needs, RESOLVE uses the concept of "Effective Load Carrying Capability" (ELCC), defined as the incremental flat load that may be met when that resource is added to a system while preserving the same level of

reliability. The contribution of wind and solar PV resources to resource adequacy needs depends not only on the coincidence of the resource with peak loads, but also on the characteristics of the other variable resources on the system as well. This relationship is perhaps best illustrated by the phenomenon of the declining marginal capacity value of solar resources as the "net" peak demand shifts away from periods of peak solar production, as illustrated in Figure 17. Because of this phenomenon, correctly accounting for the capacity contribution of variable renewable resources requires a methodology that accounts for the ELCC of the collective portfolio of intermittent resources on the system.

Figure 17. Illustrative example of the declining ELCC of solar PV with increasing penetration.



To approximate the cumulative ELCC of the CAISO's wind & solar generators within RESOLVE, RESOLVE incorporates a three-dimensional ELCC surface much like the one derived for the CPUC's RPS Calculator v.6.0. The surface expresses the total ELCC of a portfolio of wind and solar resources as a function of the penetration of each of those two resources; each point on the surface is the result of a single model run of E3's Renewable Energy Capacity Planning (RECAP) model. To incorporate the results into RESOLVE, the surface is translated into a multivariable linear piecewise function, in which each facet of the surface is expressed as a linear function of two variables: (1) solar penetration, and (2) wind penetration. The surface is normalized by load, such that the ELCC of a portfolio of resources will adjust with increases or decreases in load.

6.1.5 ENERGY STORAGE

For energy storage, a use-limited resource, the contribution to the planning reserve margin is a function of both the capacity and the duration of the storage device. To align with resource adequacy accounting

protocols, RESOLVE assumes a resource with four hours of duration may count its full capacity towards the planning reserve margin. For resources with durations under four hours, the capacity contribution is derated in proportion to the duration relative to a four-hour storage device (e.g. a 2-hour energy storage resource receives half the capacity credit of a 4-hour resource). This logic is applied to all committed and candidate storage resources.

6.1.6 IMPORTS

The contribution of imports to the resource adequacy requirement is based on the CAISO's 2017 allocation of import capability for resource adequacy, which identifies 11,310 MW of import capability available for resource adequacy in CAISO.[28] Because CAISO's contractual shares of both Palo Verde and Hoover are modeled within CAISO in RESOLVE, the capacity of these resources is deducted from the import capability to determine the contribution of imports to the Planning Reserve Margin. These assumptions are shown in Table 50.

Table 50. Assumed import capability for resource adequacy.

	Capacity (MW)
2016 Maximum Import Capability	11,310
Adjustment for CAISO Share of Palo Verde	-622
Adjustment for CAISO Share of Hoover	-797
RESOLVE Import Capacity for Resource Adequacy	**9,891**

6.2 Local Resource Adequacy

RESOLVE also includes a constraint that requires that sufficient new generation capacity must be added to meet the local needs in specific Local Capacity Resource (LCR) areas. To characterize these local capacity needs, RESOLVE relies predominantly on the CAISO's Transmission Planning Process (TPP).

[28] CAISO, "Step 6 – 2017 Assigned & Unassigned RA Import Capability on Branch Groups." Available at: http://www.caiso.com/Documents/Step6-2017AssignedandUnassignedRAImportCapabilityonBranchGroups.pdf.

Since, in its 2016-'17 TPP, CAISO identified no local areas with expected shortfalls in 2021 or 2026,[29] RESOLVE does not include any local capacity needs in this version.

[29] CAISO 2016-'17 Transmission Plan, Appendix D: Local Capacity Technical Analysis, available at: https://www.caiso.com/Documents/AppendixD_RevisedDraft_2016-2017TransmissionPlan.pdf

7 Greenhouse Gas Constraint

7.1 Greenhouse Gas Cap

RESOLVE includes optionality to enforce a greenhouse gas constraint on the CAISO generation fleet. The current version of RESOLVE includes a single option for a greenhouse gas constraint, based on CARB's Scoping Plan Alternative 1 scenario. The statewide emissions of the electricity sector in this scenario has been multiplied by 81%—the share of ARB's forecasted 2030 allocation of emissions allowances to distribution utilities within the CAISO footprint[30]—to yield a target for CAISO LSEs. This target is shown in Table 51.

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Table 51. Options for GHG constraints (million metric tons)

Scenario Setting	2018	2022	2026	2030
None	—	—	—	—
62 MMT	59.2	56.2	53.2	50.2
52 MMT	57.5	52.4	47.3	42.1
42 MMT	55.9	48.6	41.3	34.0
30 MMT	54.0	44.2	34.4	24.3

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7.2 Greenhouse Gas Accounting

RESOLVE tracks the greenhouse gas emissions attributed to entities within the CAISO footprint using a method consistent with the California Air Resources Board's (CARB) regulation of the electric sector under California's cap & trade program.

[30] CARB's allowance allocation to distribution utilities from 2021-2030 is available here: **https://www.arb.ca.gov/regact/2016/capandtrade16/attach10.xlsx**

7.2.1 CAISO GENERATORS

The annual emissions of generators within the CAISO is calculated in RESOLVE based on (1) the annual fuel consumed by each generator—evaluated endogenously within RESOLVE as part of the dispatch simulation; and (2) an assumed carbon content for the corresponding fuel. Within CAISO, the only fossil fuel consumed by generation resources is natural gas; this fuel is assumed to have a carbon content of 117 lbs per MMBtu.

7.2.2 IMPORTS TO CAISO

RESOLVE also attributes emissions to generation that is imported to CAISO based on the deemed emissions rate for unspecified imports as determined by CARB. The assumed carbon content of imports based on this deemed rate is 0.432 metric tons per MWh—a rate slightly higher than the emissions rate of a combined cycle gas turbine.

The attribution of the deemed rate to imports assumes that imported generation is, in fact, unspecified; in reality, a number of entities outside of California have either specified resources or received asset-controlling supplier status, allowing a lower emissions rate to be applied to power that they schedule to California. Because RESOLVE's dispatch module cannot directly account for these specified and/or portfolio resources, RESOLVE includes an offset to the total emissions to account for the fact that some of the specified generation imported to CAISO will have a lower carbon content than the rate for unspecified power. This amount is equal to 2.8 million metric tons.[31]

[31] This quantity is based on the amount of specified hydro imported to California assumed in CARB's PATHWAYS modeling (8.02 TWh per year), adjusted by the unspecified emissions rate (0.427 tons per MWh) and derated by CAISO's load-ratio share of state load (82%)