RESOLVE Model Documentation

Technical Appendix to CAISO SB350 Study

March 28, 2016

Energy+Environmental Economics

RESOLVE Model Documentation

Technical Appendix to CAISO SB350 Study

March 28, 2016

Energy and Environmental Economics, Inc.
101 Montgomery Street, Suite 1600
San Francisco, CA 94104
415.391.5100
www.ethree.com

Table of Contents

1 RESOLVE Model Methodology

1.1 Introduction

The Renewable Integration Solutions model (RESOLVE) is an optimal investment and operational model designed to inform long-term planning questions around renewables integration in California and other systems with high penetration levels of renewable energy. RESOLVE co-optimizes investment and dispatch over a multi-year horizon with one-hour dispatch resolution for a study area, in this case the California Independent System Operator (ISO) footprint. The model incorporates a geographically coarse representation of neighboring regions in the West in order to characterize and constrain flows into and out of the ISO. RESOLVE solves 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, a capacity adequacy constraint to maintain reliability, constraints on operations that are based on a linearized version of the classic zonal unit commitment problem as well as feedback from ISO, and scenario-specific constraints on the ability to develop specific renewable resources.

The RESOLVE model is one of a growing number of models designed to answer planning and operational questions related to renewable resource integration. In general, these models fall along a spectrum from planning-oriented models with enough treatment of operations to characterize the value of resources in a traditional power system to detailed operational models that include full characterization of renewable integration challenges on multiple time scales but treat planning decisions as exogenous. The PSO model utilized by Brattle as part of this SB 350 analysis is an example of a detailed production simulation dispatch model which takes the renewable resource procurement decisions as exogenous inputs. For this reason, the RESOLVE model is used to develop the renewable resources portfolios that populate the PSO model in the SB 350 study. Below, we provide a description of the RESOLVE model.

1.2 Theory

One economic lens that can be used to evaluate various integration solutions is to consider the consequences of failing to secure the solutions. This is similar to the avoided cost framework, which has been applied broadly to cost-effectiveness questions in the electricity sector and other areas. In a flexibility-constrained system, the default consequence of failing to secure enough operational flexibility to deliver all of the available renewable energy is to curtail some amount of production in the time periods in which the system becomes constrained. In a jurisdiction with a binding renewable energy target, however, this curtailment may jeopardize the utility's ability to comply with the renewable energy target. In such a system a utility may need to procure enough renewables to produce in excess of the energy target in anticipation of curtailment events to ensure compliance. This "renewable overbuild" carries with it additional costs to the system. In these systems, the value of an integration solution, like energy storage, can be conceptualized as the renewable overbuild cost that can be avoided by using the solution to deliver a larger share of the available renewable energy. Cost effectiveness for an integration solution under these conditions may be established when the avoided renewable overbuild cost exceeds the cost of the integration solution.

Beyond cost effectiveness, this framework also allows for the determination of an optimal by examining the costs and benefits of increasing levels of investment in integration solutions. If a single integration solution is available to the system, the optimal investment in that solution is the investment level at which the marginal cost of the solution is equal to the marginal benefit in terms of avoided renewable overbuild of the solution. However, as described above, many different strategies can be pursued and the value of each solution will depend on its individual performance characteristics as well as the rest of the solution portfolio. RESOLVE provides a single optimization model to explicitly treat the cost and behavior of specific solutions as well as the interactions between solutions.

1.3 Methodology

The RESOLVE model co-optimizes investment and operational decisions over several years in order to identify least-cost portfolios for meeting renewable energy targets. This section describes the RESOLVE model in terms of its temporal and geographical resolution, characterization of system operations, and investment decisions. Particular attention is placed on topics that are unique to an investment model that seeks to examine renewable integration challenges, including: renewables selection; reserve requirements; energy storage; flexible loads; and day selection and weighting for operational modeling.

1.3.1 TEMPORAL SCOPE AND RESOLUTION

In this analysis, investment decisions are made with 5-year resolution between 2015 and 2030. Operational decisions are made with hourly resolution on a subset of independent days modeled within each investment year. Modeled days are selected to best reflect the long run distributions of key variables like load, wind, solar, and hydro availability. The day selection and weighting methodology is described in more detail below.

For each year, the user defines the portfolio of resources (including conventional, renewable, and storage) that are available to the system without incurring additional fixed costs – these include existing resources, resources that have already been approved, and contracted resources, net of planned retirements. In addition to these resources, the model may be given the option to select additional resources or retrofit existing resources in each year in order to meet an RPS requirement, fulfill a resource adequacy need, or to reduce the total cost. Fixed costs for selected resources are annualized using technology-specific financing assumptions and costs are incurred for new investments over the remaining duration of the simulation. The objective function reflects the net present value of all fixed and operating costs over the simulation horizon, plus an additional N years, where the N years following the last year in the simulation are assumed to have the same annual costs as the last simulated year, T. When the investment decision resolution is coarser than one year, the weights applied to each modeled year in the objective function are determined by approximating the fixed and operating costs in un-modeled years using linear interpolations of the costs in the surrounding modeled years.

1.3.1.1 Operating Day Selection and Weighting

To reduce the problem size, it is necessary to select a subset of days for which operations can be modeled. In order to accurately characterize economic relationships between operational and investment decisions, the selected days and the weights applied to their cost terms in the objective function must reflect the distributions of key variables. In the analysis described here, distributions of the following parameters were specifically of interest: hourly load, hourly wind, hourly solar, hourly net load, and daily hydropower availability. In addition, the selection of the modeled days sought to accurately characterize: the number of days per month, average monthly hydropower availability, and site-specific annual capacity factors for key renewable resources. To select and weight the days according to these criteria or target parameters, an optimization problem was constructed. To construct the problem, a vector, b, was created that contained all of the target parameter values and described each target parameter distribution with a set of elements, each of which represents the probability that the parameter falls within a discrete bin. The target values can be constructed from the full set of days that the problem may select or from an even longer historical record if data is available.

For each of the days that can be selected, a vector, a, is produced to represent the contribution of the conditions on that day to each of the target parameters. For example, if b_i represents the number of hours in a year in which the load is anticipated to fall within a specified range, a_{ij} will represent the number of hours in day j that the load falls within that range. The target parameters vector, b, may therefore be represented by a linear combination of the day-specific vectors, a_j, and the day weights can be determined with an optimization problem that minimizes the sum of the square errors of this linear combination. An additional term is included in the objective function to reduce the number of days selected with very small weights and a coefficient, c, was applied to this term to tune the number of days for which the selected weight exceeded a threshold. The optimization problem was formulated as follows:

$$\begin{aligned} &\mathit{minimize} \quad \sum_i \left[\left(\sum_j a_{ij} w_j \right) - b_i \right]^2 - c \sum_j w_j^2 \\ &\mathit{subject\ to} \quad \sum_j w_j = 365 \end{aligned}$$

The resulting weights can then be filtered based on the chosen threshold to yield a representative subset of days. This method can be modified based on the specific needs of the problem. For example, in this analysis, while the hourly net load distribution was included in the target parameter vector, cross-correlations between variables were not explicitly treated. These could be incorporated into future studies, as could several other parameters of interest in characterizing the likelihood of various system states.

1.3.2 GEOGRAPHIC SCOPE AND RESOLUTION

While RESOLVE selects investment decisions only for the region of interest, in this case the ISO, operations in a highly interconnected region are influenced by circumstances outside the region. For example, the conditions in the Northwest, Southwest, and Los Angeles Department of Water and Power (LADWP) regions influence the ISO dispatch via economic imports and exports. To capture these effects, RESOLVE includes a zonal dispatch topology with interactions between the zones characterized by a linear transport model. Both the magnitudes of the flows and the ramps in flows over various durations can be constrained based on the scenario. Hurdle rates can also be applied to represent friction between balancing areas. Simultaneous flow constraints can also be applied over collections of interties to constrain interactions with neighboring regions.

The zonal topology for the analysis is shown in Figure 1 – the ISO footprint is the primary zone and the Northwest and Southwest regions and LADWP balancing area are the secondary zones. The flow constraints applied in this analysis are summarized in Table 1.

Figure 1. Zonal topology

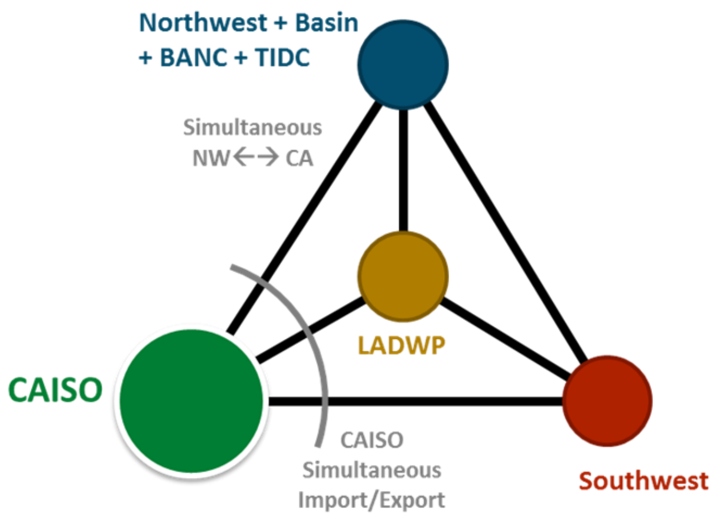

Table 1. Flow constraints between zones and simultaneous flow constraints

Path	Minimum Flow (MW)	Maximum Flow (MW)
SW → ISO	-7,250	6,785
NW → ISO	-5,171	6,364
LADWP → ISO	-2,045	4,186
LADWP → NW	-,2826	2,963
SW → LADWP	-3,373	3,373
NW → SW	-1,480	1,465
Simultaneous NW → CA	-7,934	9,390
ISO Simultaneous Import	-8,000 to -2,000	10,068

1.3.3 INVESTMENT DECISIONS

1.3.3.1 Renewable Resources

The RESOLVE model was designed primarily to investigate investment driven by a renewable energy target. This constraint, which is applied based on the policy goal in each year, ensures that the procured renewable energy net of any renewable energy curtailed in operations exceeds a MWh target based on the load or retail sales in that year. RESOLVE allows the user to specify a set of resources that must be built in each modeled year as well as additional renewable resources that may be selected by the optimization. These options allow for the design of portfolios that take into consideration factors such as environmental or institutional barriers to development.

While a traditional capacity-expansion model might take into consideration the technology cost, transmission cost, capacity factor of candidate renewable resources, RESOLVE also considers the energy value through avoided operational costs, capacity value through avoided resource adequacy build, and the integration value through avoided renewable resource overbuild. These three factors depend on the timing and variability of the renewable resource availability as well as the operational capabilities of the rest of the system. To account for all of these factors, each candidate resource is characterized by its hourly capacity factor over the subset of modeled days, installed cost on a per kW basis, location within a set of transmission development zones, and maximum resource potential, in MW.

Transmission development zones are characterized by a threshold total renewable build, above which a $/MW-yr cost is applied to incremental renewable build to reflect the annualized cost of additional transmission build to support interconnecting renewables on to the high-voltage transmission system. Multiple renewable resources may be assigned to the same transmission development zone (for example some zones may have both solar and wind resources that can be developed) and the selection of resources within each zone will depend on their relative net cost and the combined impact of resource build on incurred transmission development costs.

1.3.3.2 Integration Solutions

RESOLVE is also given the option to invest in various renewables integration solutions such as different types of energy storage or gas resources. Renewable curtailment occurs when the system is not capable of accommodating all of the procured renewable energy in hourly operations. While there is no explicit cost penalty applied to the curtailment observed in the system dispatch, the implicit cost is the cost of overbuilding renewable resources to replace the curtailed energy and ensure compliance with the renewable energy target. This renewable overbuild cost is the primary renewable integration cost experienced by the system and may be reduced by investment in integration solutions.

1.3.3.3 Resource Portfolios in Secondary Zones

RESOLVE selects investment decisions only for the primary zone, in the case the ISO. The resource portfolios for the secondary zones, in this case the Northwest, Southwest and LADWP, must be designed to ensure resource adequacy and renewable policy compliance outside of RESOLVE. These decisions, which are exogenous from the planner's perspective in the primary zone are also exogenous to the model. For each year of the simulation, each secondary zone is characterized by the hourly load, hourly renewable availability, hydro availability, and conventional resource stack. Because the model only selects investment decisions for the primary zone, the resource portfolios for the secondary zones must be designed to ensure resource adequacy and renewable policy compliance outside of RESOLVE. These decisions, which are exogenous from the planner's perspective in the primary zone are also exogenous to the model. For the SB 350 project, renewable resources were hand-selected selected for the California municipal utilities to ensure compliance with a 50% RPS by 2030 for these regions.

1.3.4 SYSTEM OPERATIONAL CONSTRAINTS

1.3.4.1 General

RESOLVE requires that sufficient generation is dispatched to meet load in each hour in each modeled zone. In addition, dispatch in each zone is subject to a number of constraints related to the technical capabilities of the fleets of generators within the zone, which are described in detail below. In general, dispatch in each zone must satisfy

$$\sum_{i \in I_z} x_h^{it} + w_h^{zt} + \sum_{\omega \in Z} \sum_{j \in J_{z\omega}} (R_{jt}^{tot} r_h^j - q_h^{jt}) + \sum_{k \in K_z^{in}} f_h^{kt} - \sum_{k \in K_z^{out}} f_h^{kt}$$

$$+x_h^{dzt} - x_h^{czt} + u_h^{zt} - o_h^{zt} = l_h^{zt}$$

where l_h^{zt} is the load in zone *z*, year *t*, and hour *h*; x_h^{it} is the generation from thermal resource *i*; I_z is the set of all thermal resources in zone *z*; R_{jt}^{tot} is the total installed capacity of renewable resource *j*; q_h^{jt} is the curtailment of renewable resource j; $J_{z\omega}$ is the set of all renewable resources located in zone *z* and contracted to zone ω; w_h^{zt} is hydr o generation in zone *z*; x_h^{dzt} and x_h^{czt} are the energy discharged from energy storage and energy extracted from the grid to charge energy storage respectively; u_h^{zt} is the undergeneration and o_h^{zt} is othe overgeneration in zone *z*; f_h^{kt} is the flow over line k, K_z^{in} and K_z^{out} are the sets of all transmission lines flowing into and out of zone *z*, respectively.

1.3.4.2 Reserve Requirements and Provision

RESOLVE requires upward and downward load following reserves to be held in each hour in order to ensure that the system has adequate flexibility to meet subhourly fluctuations and to accommodate forecast errors. In real systems, reserve requirements depend non-linearly on the composition of the renewable portfolio and the renewable output in each hour. To avoid additional computational complexity, RESOLVE requires the user to specify the hourly reserve requirements for each scenario. In the ISO example, the methodology described in NREL the Eastern Wind Integration and Transmission Study (EWITS)[1] was used to derive hourly reserve requirements associated with today's renewable portfolio, a 33% RPS portfolio in 2020, and two potential 50% RPS portfolios in 2030 – one dominated by solar resources and one with a more diverse mix of solar, wind, and geothermal resources. For each scenario, the user selects which set of reserve requirements to use for 2020 and 2030 and the reserve requirements in each year are approximated via linear interpolation.

The user specifies whether each technology is capable of providing flexibility reserves, and the reserve provisions available from each technology are described above. Upward flexibility reserve violations are penalized at a very high cost to ensure adequate commitment of resources to meet upward flexibility challenges within the hour. However, downward reserve shortages are not penalized as operating violations. RESOLVE assumes that a portion of downward reserve needs – 50% in the cases analyzed for this study – can be managed via real-time curtailment of renewable resources. This behavior is approximated in RESOLVE through a parameterization of the subhourly imbalances similar to that implemented in E3's REFLEX model.[2] Subhourly curtailment in RESOLVE is a function of the reserve provisions held, as described in Hargreaves et al (2014). If the entire downward reserve requirement is held, then it is anticipated that the system will experience no additional renewable curtailment in real-time to

---

[1] National Renewable Energy Laboratory, "Eastern Wind Integration and Transmission Study," Revised February 2011. Available at: **http://www.nrel.gov/docs/fy11osti/47078.pdf**

[2] Hargreaves, J., E. Hart, R. Jones, A. Olson, "REFLEX: An Adapted Production Simulation Methodology for Flexible Capacity Planning," IEEE Transactions of Power Systems, Volume:PP, Issue: 99, September 2014, pp 1 – 10.

manage subhourly imbalances. If the downward reserve requirement cannot be met, then the expected real-time curtailment can be approximated.

This formulation allows the dispatch model to directly trade-off between the cost of holding additional reserves (including the cost of committing additional units and operating these units at less efficient set points) against the cost of experiencing some amount of expected subhourly renewable curtailment by shorting the downward reserve provision. Just as with curtailment experienced on the hourly level, expected subhourly curtailment is not directly penalized in the objective function, but does result in additional cost to the system by requiring additional renewable overbuild for policy compliance.

In addition, RESOLVE allows the user to constrain the absolute amount of observed subhourly curtailment in each hour to reflect potential limits in the participation of renewable resources in real-time markets or real-time dispatch decisions. These limits are typically set as a fixed fraction of the available energy from curtailable renewable resources in each hour. Finally, RESOLVE allows the user to apply a minimum constraint on the fraction of the downward reserve requirement held with conventional units. This constraint reflects a level of conservativism on the part of the system operator. While full participation of renewable resources in real-time markets may be the lowest cost approach to managing downward flexibility challenges, a system operator may seek to keep some downward flexibility across the conventional fleet as a backstop in case the full response from renewable resources does not materialize in real-time. While operating knowledge on this subject is limited at present, it is anticipated that with improved participation of renewable resources in markets over the next several years, additional data can be brought to bear on this question of renewable responsiveness at the subhourly level and the extent to which system operators can rely on it when scheduling conventional resources.

1.3.4.3 Other requirements

Additional operational constraints are imposed based on specific system needs. For example, for this SB 350 project, additional constraints were designed for consistency with modeling efforts by the ISO for the California Long-Term Procurement Plan. These include: a frequency response requirement of 775MW in each hour, half of which can met upward capability on hydro resources and the other half of which can be met with other dispatchable units on the system including energy storage resources.

1.3.4.4 Capacity Adequacy

In addition to hourly operational constraints, RESOLVE enforces an annual capacity adequacy constraint based on a parameterization of resource adequacy needs to maintain reliability. The parametrization was developed based on simulations of loss of load probability (LOLP) in the CAISO system under high-solar and diverse renewable portfolio scenarios and takes into account the expected load-carrying capability (ELCC) of the renewable portfolio. The constraint requires that sufficient conventional capacity is available to meet net load plus a certain percentage above net load. In this study, the capacity adequacy constraint is not binding and does not cause procurement of conventional capacity.

1.3.5 RESOURCE OPERATIONAL CONSTRAINTS

1.3.5.1 Thermal Resources

For large systems such as the CAISO's, thermal resources are aggregated into homogenous fleet of units that share a common unit size, heat rate curve, minimum stable level, minimum up and down time, maximum ramp rate, and ability to provide reserves. In each hour, dispatch decisions are made for both the number of committed units and the aggregate set point of the committed units in the fleet. For sufficiently large systems, such as the ISO, commitment decisions are represented as continuous variables. For smaller systems, specific units may be modeled with integer commitment variables. For the continuous commitment problem, reserve requirements ensure differentiation between the committed capacity of each fleet and its aggregated set point. The ability of each fleet to provide upward reserves, $\overline{x}_h^{it}$, is:

$$x_h^{it} + \overline{x}_h^{it} \leq n_h^{it} x_{max}^i \quad \forall i, t, h$$

where n_h^{it} is the number of committed units and x_{max}^i is the unit size. Downward reserve provision is limited by:

$$x_h^{it} - \underline{x}_h^{it} \geq n_h^{it} x_{min}^i \quad \forall i, t, h$$

where x_{min}^i is the minimum stable level of each unit.

Upward reserve requirements are imposed as firm constraints to maintain reliable operations, but downward reserve shortages may be experienced by the system with implications for renewable curtailment (See section 1.3.4.2). The primary impact of holding generators at set points that accommodate reserve provisions is the increased fuel burn associated with operating at less efficient set points. This impact is approximated in RESOLVE through a linear fuel burn function that depends on both the number of committed units and the aggregate set point of the fleet:

$$g_h^{it} = e_i^1 x_h^{it} + e_i^0 n_h^{it}$$

where g_h^{it} is the fuel burn and e_i^1 and e_i^0 are technology-specific parameters.

Minimum up and down time constraints are approximated for fleets of resources. In addition, startup and shutdown costs are incurred as the number of committed units changes from hour to hour, and constraints to approximate minimum up and down times for thermal generator types are imposed.

Must-run resources are modeled with flat hourly output based on the installed capacity and a de-rate factor applied to each modeled day based on user-defined maintenance schedules. Maintenance schedules for must-run units are designed to overlap with periods of the highest anticipated oversupply conditions so that must run resources may avoid further exacerbating oversupply conditions in these times of year. Maintenance and forced outages may be treated for any fleet through the daily de-rate factor. However in the analysis presented here, maintenance schedules for dispatchable resources were not explicitly modeled – it was instead assumed that maintenance on these systems could be scheduled around the utilization patterns identified by the dispatch solution.

1.3.5.2 Hydro Resources

Hydro resources are dispatched in the model at no variable cost, subject to: an equality constraint on the daily hydro energy; daily minimum and maximum outputs constraints; and multi-hour ramping constraints. These constraints are intended to reflect seasonal environmental and other constraints placed on the hydro system that are unrelated to power generation. The daily energy, minimum, and maximum constraints are derived from historical data from the specific modeled days. Ramping constraints, if imposed, can be derived based on a percentile of ramping events observed over a long historical record. Hydro resources may contribute to both upward and downward flexibility reserve requirements.

1.3.5.3 Energy Storage

Each storage technology is characterized by a round-trip efficiency, per unit discharging capacity cost ($/kW), per unit energy storage reservoir or maximum state of charge cost ($/kWh), and for some resources, maximum available capacity. Energy storage investment decisions are made separately for discharging capacity and reservoir capacity or maximum state of charge. Dispatch from each energy storage resource is modeled by explicitly tracking the hourly charging rate, discharging rate, and state-of-charge of energy storage systems based on technology-specific parameters and constraints. Reserves can be provided from storage devices over the full range of maximum charging to maximum discharging. This assumption is consistent with the capabilities of battery systems, but overstates the flexibility of pumped storage systems, which can only provide reserves in pumping mode if variable speed pumps are installed, typically cannot switch between pumping and generating on the time scales required for reserve products, and are subject to minimum pumping and minimum generating constraints that effectively impose a deadband on the resource operational range.

An adjustment to the state of charge is assumed that represents the cumulative impact of providing flexibility reserves with the device over the course of the hour. For example, if a storage device provides upward reserves throughout the hour, it is anticipated that over the course of hour the storage device will be called upon to increase its discharge rate and/or decrease its charge rate to help balance the grid. These subhourly dispatch adjustments will decrease the state of charge at the end of the hour. Similarly, providing downward reserves will lead to an increase in the state of charge at the end of the hour. Little is known about how energy storage resources will be dispatched on subhourly timescales in highly renewable systems – this behavior will depend on storage device bidding strategies and technical considerations like degradation. Rather than model these factors explicitly, RESOLVE approximates the impact of subhourly dispatch with a tuning parameter, which represents the average deviation from hourly schedules experienced as a fraction of the energy storage reserve provision.