RESOLVE Model Documentation

User Manual (DRAFT)

July 2017

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Energy+Environmental Economics

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The core of the RESOLVE model is written in the Python scripting language. This model was created by E3 and was adapted for use in the CPUC's Integrated Resource Planning proceeding under the administration of CPUC's Energy Division. The E3 RESOLVE Model is free software under the terms of the GNU Affero General Public License as published by the Free Software Foundation, either version 3 of the License, or (at your option) any later version.

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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.

The purpose of this document is to provide users with the guidance needed to set up and run RESOLVE and to analyze the results of scenarios once they have been completed. RESOLVE is a linear program written in Python with Excel-based interfaces for scenario development and results processing; a schematic of the RESOLVE environment is shown in Figure 1. While users may wish to review the raw input and output files and Python scripts that constitute the core of RESOLVE, the RESOLVE package is designed to allow users to run scenarios and analyze results using only the Excel-based user interfaces for developing scenarios and viewing results.

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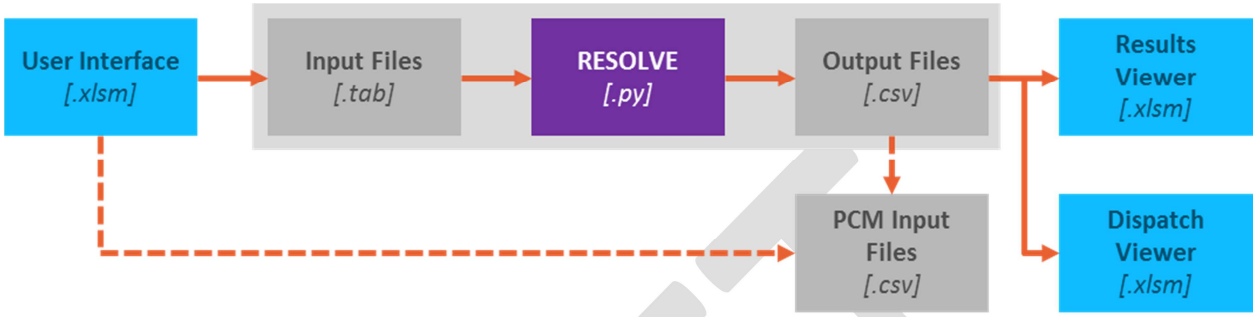
Figure 1. Schematic of RESOLVE modeling environment.



The individual components of the RESOLVE modeling environment are described below:

- RESOLVE's **User Interface** ("UI") is an Excel workbook that includes a scenario management dashboard and additional worksheets with key inputs to the model. The User Interface provides users with a simple interface to develop and run scenarios through RESOLVE. After setting up RESOLVE (see Section 2), users can begin running scenarios directly from the User Interface.
- When a scenario is run from the User Interface, RESOLVE will first create a set of **Input Files** in .tab format. While RESOLVE users need not manipulate or review these files directly, the contents of these files are described in Section 3.2 for users interested in reviewing these files.
- Next, the Input Files will be read into **RESOLVE**, a linear program written in the Python programming language. Based on the assumptions specified in the User Interface, RESOLVE will identify an optimal portfolio of investments across the time horizon of the analysis.
- After solving the linear program, RESOLVE writes outputs to a series of raw **Output Files** in .csv format.
- The **Results Viewer**, an Excel workbook, is the main interface through which users may review results of a completed RESOLVE run. This workbook can be used to import and view summaries of the raw Output Files for a specific model. Section 3.2 provides a summary of functionality included in the Results Viewer.

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- Additionally, the **Dispatch Viewer**, also in Excel, is a supplementary tool that can be used to examine the results of RESOLVE's internal production simulation model in detail. Because of the size of raw output files related to hourly dispatch modeling, this workbook is separate from the main Results Viewer. Section 3.3 provides an overview of how to use the Dispatch Viewer to examine dispatch results.
- With each model run, RESOLVE also produces a set of **PCM Input Files** in .csv format. These summary files, which include both input assumptions and RESOLVE outputs, are intended to facilitate the transfer of a complete RESOLVE case to other production simulation modeling platforms such as PLEXOS, AURORAxmp, or GridView. The contents of the PCM Input Files are described in Section 5.

If the user is merely interested in reviewing inputs and outputs to the pre-built RESOLVE scenarios, the User Interface, Results Viewer, and Dispatch Viewer provide can be used directly in Excel without installing Python or setting up RESOLVE.

1.2 Contents

The remainder of this document is organized as follows.

- **Section 2 (RESOLVE Set-Up)** is a prerequisite for anyone planning to run RESOLVE. It describes the system requirements for running RESOLVE and the set-up process.
- **Section** Error! Reference source not found. **(Running Scenarios in RESOLVE)** provides a quick overview of the Excel-based User Interface and Results Viewers. For users seeking only to run RESOLVE cases and view model outputs, this section provides the necessary background to do so.
- For RESOLVE users wishing to review and/or examine the core of RESOLVE (text-based input & output files and Python-based linear program), **Section** Error! Reference source not found. **(RESOLVE Model Detail)** provides a summary of the contents of the raw inputs and outputs as well as the scripts that make up RESOLVE.

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- For users seeking to adapt RESOLVE results to other modeling platforms for additional analysis, **Section 5 (Using RESOLVE Outputs in Other Models)** describes the contents of RESOLVE's PCM Input Files package.

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2 RESOLVE Set-Up

2.1 System Requirements

Operating System: RESOLVE has been tested on both Windows and Ubuntu. It is likely that Mac OS X will also be able to run RESOLVE.

Python: install **Anaconda** or another Python distribution. RESOLVE is currently written in Python version 2.x (as opposed to Python 3.x). E3 currently uses Python version 2.7.9 (64-bit). Compatibility with Python version 3.x has not been verified. Installing a stand-alone version of Python (as opposed to installing Anaconda or similar distribution) is not recommended because Resolve depends on other libraries that are installed with Anaconda.

Pyomo: Pyomo can be installed on the command line by opening `cmd.exe` from the Start Menu and running `pip install pyomo`. E3 currently uses Pyomo version 4.3 or 5.1.1. The version of Pyomo installed on your system can be found by running on the command line `pyomo --version`.

Solver: **CBC** (a free, open-source solver) can be installed on any platform. A 64-bit version of CBC should be installed.

For CBC on Windows, the **64-bit version of CBC** is available as a stand-alone executable on the **AMPL website**. Download cbc-win64.zip, unzip, and move the executable (cbc.exe) to a folder of your choosing.

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The final step is to add the folder in which cbc.exe resides to your PATH system variable, which can be done by following **these instructions**. E3 has tested CBC version 2.9.7 (64-bit) on Windows 7.

For CBC on Linux or Mac OS X, install the latest version of the **COIN-OR Optimization Suite**.

If the user has a license, RESOLVE can also employ many common commercially available solvers, many of which may give faster solution times than CBC. The solver Gurobi has been extensively tested by E3.

2.2 RESOLVE Set-Up

Once you have downloaded the RESOLVE code, you should see the following directories and files in `yourdirectory`:

- `inputs`: directory that contains scenario directories with input files for each scenario
- `resolve_code`: directory that contains the RESOLVE python scripts
- `.gitignore`: text file with directories and files to be ignored by Git (version control software)
- `results`: directory containing results directories for each scenario – will be created automatically upon running RESOLVE.
- `results_summaries`: directory containing results summaries for each scenario – will be created automatically when loading up results in the Results Viewer.
- `prod_cost_inputs`: directory containing an output package to facilitate adaptation of RESOLVE results in other production simulation models.

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3 Running Scenarios in RESOLVE

3.1 User Interface

The user interface (UI) is an Excel tool that allows users to create RESOLVE inputs for specific scenarios and run RESOLVE for these scenarios. The Dashboard is the main worksheet that the user interacts with. It allows the user to:

- Run a pre-defined scenario;
- Create a new scenario and run it; and
- Run a batch of RESOLVE scenarios (pre-defined and/or user-defined).

Unless the user wants to change the raw input data behind any of the scenario toggles, this is the only worksheet that the user should interact with. The other worksheets could still be useful to have a look at the underlying data, but regular users are discouraged to change any of the underlying data itself. If the user wants to see what data is used for a certain scenario toggle in the Dashboard, the user can go to the appropriate data worksheet to find the associated inputs for each setting[1]. Note that the calculation settings are set to manual by default, so the user should press F9 (calculate) to ensure that the formulas and tables correctly reflect the current settings.

[1] If unclear which worksheets are affected by the toggle, the "trace dependents" option in Excel might be useful

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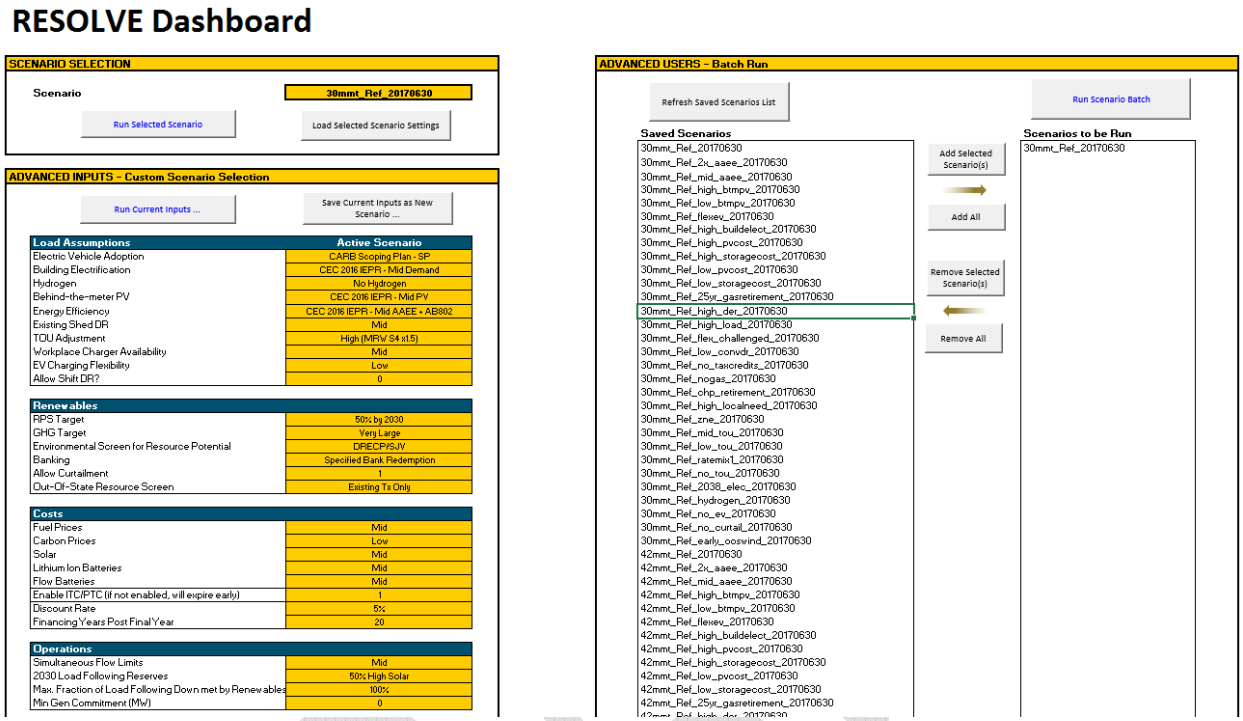

Figure 2. Screenshot of the Dashboard of the User Interface

3.1.1 RUNNING A PRE-DEFINED SCENARIO

The RESOLVE model comes with a set of pre-defined scenarios. The dropdown menu in cell D6 of the Dashboard lists all pre-defined scenarios. Each scenario represents a combination of scenario settings, shown in the Scenario Settings worksheet of the User Interface. The settings can also be loaded to the Dashboard (see below).

The user can load and run a pre-defined using the following steps:

1. Select a scenario of interest in cell D6.

2. [*Optional*] Load the scenario settings for the selected scenario by pressing **"Load Selected Scenario Settings"**. This macro will look up the relevant scenario settings from the Scenario Settings worksheet, and copy paste them into the settings shown on the Dashboard. This step allows the user to review the settings before running the scenario. The user can decide to skip this step and simply run the model directly after selecting the scenario (see below).

3. Run the RESOLVE model for the selected scenario by pressing **"Run Selected Scenario"**. This macro will run the RESOLVE model for the selected scenario. Note that before running RESOLVE, this macro will save a set of RESOLVE input files (.tab) in a subdirectory of the inputs directory, named after the scenario name. This requires recalculation of the spreadsheet and rerunning the capital cost macro, which could take several minutes and slow down the user's computer. Once the input files are made, an external command prompt window will pop up through which the model is run. Once the command window pops open, a RESOLVE run can take anywhere from 20 minutes to a few hours, depending on the specific scenario being run and which solver is being used.

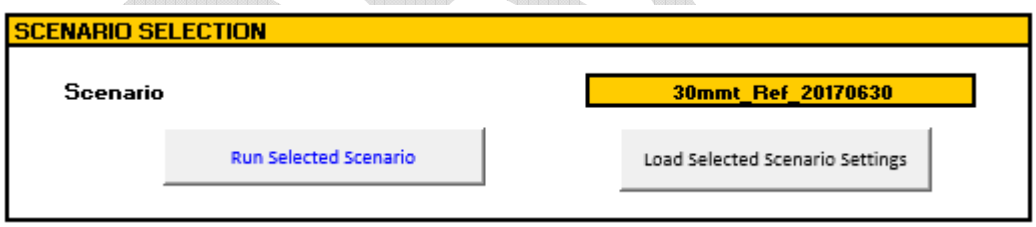

Figure 3. Dashboard options for running a pre-defined scenario.

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3.1.2 CREATING A NEW SCENARIO

Advanced users may wish to create and run new scenarios, rather than running pre-defined scenarios. This can be done by interacting with the Scenario Settings section of the Dashboard. The steps are as follows:

1. Select and load a scenario of interest (for instructions, see above)

2. Customize the input toggles in the Advanced Inputs section using the available drop down menus. Note that some inputs don't have drop downs, but rather require the user to input a number (e.g. the discount rate).

3. [*Optional*] Save the new custom scenario by pressing **"Save Current Inputs as New Scenario…"**. This macro prompts the user to enter a new scenario name, and saves the current toggle settings to this user-defined scenario name. After saving the custom scenario, it will now show up in the dropdown menu of pre-defined scenarios. Saved scenarios and their associated settings are also shown in the "Scenario Settings" worksheet.

4. Run the new custom scenario by pressing **"Run Current Inputs…"**. This macro first saves the new custom scenario through a user-prompt (see step 3), and then runs RESOLVE for this custom scenario. Note that before running RESOLVE, this macro will save a set of RESOLVE input files (.tab) in a subdirectory of the inputs directory, named after the scenario name. This requires recalculation of the spreadsheet and rerunning the capital cost macro, which could take several minutes, and might slow down the user's computer. Once the input files are made, an external command prompt window will pop up through which the model is run.

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ADVANCED INPUTS – Custom Scenario Selection

Run Current Inputs ...

Save Current Inputs as New Scenario ...

Load Assumptions	Active Scenario
Electric Vehicle Adoption	CARB Scoping Plan - SP
Building Electrification	CEC 2016 IEPR - Mid Demand
Hydrogen	No Hydrogen
Behind-the-meter PV	CEC 2016 IEPR - Mid PV
Energy Efficiency	CEC 2016 IEPR - Mid AAEE + AB802
Existing Shed DR	Mid
TOU Adjustment	High (MRW S4 x1.5)
Workplace Charger Availability	Mid
EV Charging Flexibility	Low
Allow Shift DR?	0

Renewables	
RPS Target	50% by 2030
GHG Target	Very Large
Environmental Screen for Resource Potential	DRECP/SJV
Banking	Specified Bank Redemption
Allow Curtailment	1
Out-Of-State Resource Screen	Existing Tx Only

Costs	
Fuel Prices	Mid
Carbon Prices	Low
Solar	Mid
Lithium Ion Batteries	Mid
Flow Batteries	Mid
Enable ITC/PTC (if not enabled, will expire early)	1
Discount Rate	5%
Financing Years Post Final Year	20

Operations	
Simultaneous Flow Limits	Mid
2030 Load Following Reserves	50% High Solar
Max. Fraction of Load Following Down met by Renewables	100%
Min Gen Commitment (MW)	0

Other Sensitivities	
Local Capacity Needs	Low
Coal Flexibility	Dispatchable
Storage Mandate Case	1325 MW by 2024
Allow Pumped Storage Build	1
Allow Battery Storage Build	1
Allow New Gas Build	1
Retirement Date Diablo Unit 1	12/31/2024
Retirement Date Diablo Unit 2	12/31/2025
Gas Retirement (excl. CHP)	No early retirement
CHP Retirement	No early retirement

Figure 4. Dashboard options for creating and running a customer scenario.

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Table 1. Summary of scenario settings on RESOLVE dashboard

Scenario Setting	Options	Notes
Load Assumptions		
Electric Vehicle Forecast	CEC 2016 IEPR – Mid Demand	This dropdown varies the Electric Vehicle (EV) demand forecast.
	CARB Scoping Plan – SP	
	CARB Scoping Plan – Alt1	
Building Electrification Forecast	CEC 2016 IEPR – Mid Demand	This dropdown varies the electrification demand forecast.
	CARB Scoping Plan – SP	
	CARB Scoping Plan – Alt1	
Hydrogen	No Hydrogen	This dropdown varies the hydrogen demand forecast. Hydrogen loads are assumed to be fully flexible, with an installed capacity that is 4 times the average demand.
	CARB Scoping Plan – Alt1	
Behind-the-Meter PV Forecast	No Addt'l PV	This dropdown varies the BTM PV forecast.
	CEC 2016 IEPR – Low PV	
	CEC 2016 IEPR – Mid PV	
	CEC 2016 IEPR –High PV	
	Very High	
Energy Efficiency Forecast	CEC 2016 IEPR – No AAEE	This dropdown varies the energy efficiency forecast.
	CEC 2016 IEPR – Mid AAEE	
	CEC 2016 IEPR – Mid AAEE + AB802	
	SB350 – Mid AAEE x2	
Existing Shed DR	Mid	This dropdown varies the existing Shed DR forecast.
	Low	
TOU Adjustment	None	This toggle varies the TOU adjustment. TOU adjustments are small additions/subtractions to the hourly CAISO load that are forecasted to take place due to the introduction of time-of-use rates.
	Low (Christensen S3)	
	Mid (MRW S4)	
	High (MRW S4x1.5)	
	Rate Mix 1	
Workplace Charger Availability	Low	This dropdown varies the workplace EV charging availability. The inflexible EV shape is composed of 2 shapes: a shape for EV owners that can charge at work, and a shape for EV owners that cannot charge at work. The weighing of each shape depends on the workplace charger availability dropdown.
	Mid	
	High	
EV Charging Flexibility	Low	This dropdown varies the fraction of EV demand that is fully flexible. EV demand that is fully flexible will be optimized endogenously by the RESOLVE model, subject to constraints on charging limits and fraction of plugged in vehicles for a given hour.
	Mid	
	High	
Allow Shift DR?	0	This dropdown controls whether shift DR is available or not.
	1	
Renewables Assumptions		
RPS Target	None	This dropdown varies the 2030 RPS target and the corresponding trajectory.
	50% RPS by 2030	

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	55% RPS by 2030	
	60% RPS by 2030	
GHG Target	None	This dropdown varies the CAISO greenhouse gas emission target. The dropdown designates how big the share is that the electricity sector takes on it the economy wide decarbonization. E.g. "Large" means that the electricity sector takes on a large part of the decarbonization effort and thus reflects a relatively strict carbon target.
	Default	
	Medium	
	Large	
	Very Large	
Environmental Screen for Renewables	Base	This dropdown varies the resource screen that is used in the RPS supply curve when determining the resource potential. Depending on the screen, certain projects in the Supply Curve are de-rated or fully eliminated to reflect environmental and other constraints for development. A stricter environmental screen will decrease the resource potentials used in the model.
	Env Baseline	
	NGO1	
	NGO1&2	
	DRECP/SJV	
	Conservative	
Banking	Optimize Banking	This dropdown varies the REC banking logic used in the model. In the case of "Optimize banking", the RESOLVE model will endogenously decide when to use banked RECs (and create more if appropriate) and the user only needs to input the starting amount of banked RECs. When "Specified Bank Redemption" is selected, the model will use a predefined bank redemption trajectory defined in the SYS_RPS_GHG_TARGET tab. "No banking" does not allow banking of RECs.
	Specified Bank Redemption	
	No Banking	
Allow Curtailment	0	This dropdown controls whether curtailment is allowed or not.
	1	
Out-of-State Resource Screen	None	This dropdown varies the out-of-state (OOS) resource screen being used. "None" will disallow any renewables that are physically OOS. "Existing Tx Only" only allows RESOLVE resources that can be brought in through existing transmission (a limited amount of Northwest and Southwest). "Existing & New Tx" allows the former plus OOS resources that require new transmission, such as Wyoming wind. Note that under the default assumptions, some resources have been made unavailable in all resource screens.
	Existing Tx Only	
	Existing & New Tx	
Costs		
Fuel Prices	Low	This dropdown varies the natural gas price trajectory.
	Mid	
	High	
Carbon Price	Low	This dropdown varies the carbon price trajectory.
	Mid	
	High	
	None	
Solar PV Costs	Low	This dropdown varies the solar PV cost trajectory.
	Mid	
	High	
Li-Ion Battery Costs	Low	This dropdown varies the Li-ion battery cost trajectory.
	Mid	
	High	
Flow Battery Costs	Low	This dropdown varies the flow battery cost trajectory.
	Mid	
	High	
Enable ITC/PTC	0	This dropdown controls whether the ITC/PTC is enabled (1) or not (0). If disabled, the ITC and PTC will expire early (solar ITC will remain at 10%).
	1	

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Discount Rate	(percentage)	This input sets the discount rate used to weigh each of the model period's costs in the RESOLVE objective function.
Final Year Weight	(integer)	This input sets the amount of years that the final model year represents. E.g. if it is 20 and the final period is 2030, the model will assume that the last model period represents 20 years of costs and operations when determining that period's weight in the objective function.
Operations		
CAISO Export Limit	Low	This dropdown varies the simultaneous export limit for the CAISO system.
	Mid	
	High	
Load Following Reserves	33%	This dropdown varies the hourly load following requirements based on subhourly analysis that was done on 33% RPS and two different 50% RPS portfolios. 50% high Solar (the default) represents a solar heavy portfolio that will have the highest load following requirements during the morning and evening when solar productions rise and falls.
	50% High Solar	
	50% Diverse	
Max Fraction of Load Following Down Met by Renewables	(percentage)	This input sets what maximum fraction of the load following down requirement can be met by renewables. Renewables can theoretically provide load following down very cheaply by being curtailed on the subhourly level.
Min Gen Commitment (MW)	(integer)	This input sets the minimum amount of eligible thermal generation (MW) that must be online at all times to maintain system stability.
Other Inputs		
Local Capacity Needs	Low	This dropdown varies the local capacity needs. Local capacity represents capacity requirements that are not captured by the system-wide PRM target due to local constraints, e.g. the L.A. basin.
	Mid	
	High	
Coal Flexibility	Dispatchable	This dropdown varies whether coal is a dispatchable resource that can be turned off, or a must-run resource.
	Must-Run	
Storage Mandate	None	This dropdown varies the amount of batteries present in the baseline due to the storage mandate from zero ("None") to 1,825 MW by 2020.
	1,325 MW by 2020	
	1,825 MW by 2020	
Allow Pumped Storage	0	This dropdown controls whether new pumped storage build is allowed (1) or not (0).
	1	
Allow Battery Storage	0	This dropdown controls whether new battery storage build is allowed (1) or not (0).
	1	
Allow Gas Build	0	This dropdown controls whether new gas capacity build is allowed (1) or not (01).
	1	
Diablo 1 Retirement	(date)	This input allows the user to set the retirement date for Diablo Unit 1.
Diablo 2 Retirement	(date)	This input allows the user to set the retirement date for Diablo Unit 2.
Gas Retirement (excl. CHP)	No early retirement	This dropdown allows the user to set an early retirement date for all gas plants except for the CHP units. "Retirement after xx years" will retire all gas units xx years after their COD date reported in the CAISO generator list.
	Retirement after 20 years	
	Retirement after 25 years	
	Retirement after 30 years	
CHP Retirement	No early retirement	This dropdown allows the user to set an early retirement date all CHP units. "Retirement after xx years" will retire all CHP units xx years after their COD date reported in the CAISO generator list.
	Retirement after 20 years	
	Retirement after 25 years	
	Retirement after 30 years	
Specified Resources		

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Resource ID		With this input the user can force in a specific RESOLVE resource from the drop down menu. This resource will be built regardless of whether it is optimal.
Quantity (MW)	(integer)	This input sets the quantity (MW) that of the selected resource that the user wants to force.
Year	(year)	This input designates in which year the forced in resource should be built.
Simulation Years		
2015-2050	0	This input allows the user to change the periods that are modeled. The default is 2018, 2022, 2026, and 2030.
	1	

Note: further background information on each toggle can be found in the "RESOLVE Model Documentation: Inputs & Assumptions."

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3.1.3 RUNNING A BATCH OF SCENARIOS

The Batch Run module on the Dashboard allows users to run a batch of many scenarios at once. This can be useful if a user wants to run many scenarios and does not want to wait for a scenario to finish before running another scenario.

To run a batch of cases, follow the steps below:

1. [*Optional*] Create and save custom scenarios. See section 3.1.1 for instructions.

2. Refresh the list of saved scenarios by pressing **"Refresh Saved Scenarios List"**. This macro lists all scenarios, both pre-defined and custom, that are present in the "Scenario Settings" worksheet. Note that the user first needs to save a custom scenario (see Section 3.1.2) for it to show up here.

3. [*Optional*] If necessary, remove any scenarios you don't want to run from the "Scenarios to Be Run" list by using the **"Remove Selected Scenario(s)"** or **"Remove All"** Button.

    a. The **"Remove Selected Scenario(s)"** macro will remove the selected scenario from the list of scenarios listed under "Scenarios to be Run". Note that in this context, selected scenario means the cell that is selected within the "Saved Scenarios Menu" box (not the value in cell D6). If a cell outside of this box is selected, a warning will pop up and the macro will stop.

    b. The "**Remove All"** macro will remove all scenarios listed under "Scenarios to Be Run".

4. Add scenarios of interest to the "Scenarios to Be Run" list using the **"Add Selected Scenario(s)"** or **"Add All"** buttons.

    a. The **"Add Selected Scenario(s)"** macro will add the selected scenario to the list of scenarios listed under "Scenarios to be Run". Note that in this context, selected scenario means the cell that is selected within the "Saved Scenarios Menu" box (not the value in

cell D6). If a cell outside of this box is selected, a warning will pop up and the macro will stop.

b. The **"Add All"** macro will add all scenarios listed under "Saved Scenarios" to the list of scenarios listed under "Scenarios to Be Run".

5. Run RESOLVE for all selected scenarios by pressing **"Run Scenario Batch"**. This macro will run the RESOLVE model for each of the scenarios listed under "Scenarios to Be Run". The macro will first loop through each of the scenarios and create the RESOLVE input files (.tab). As discussed earlier, this step could take a long time and slow down the user's computer significantly. Once all RESOLVE inputs are created, the model will run the cases in series through a command prompt window.

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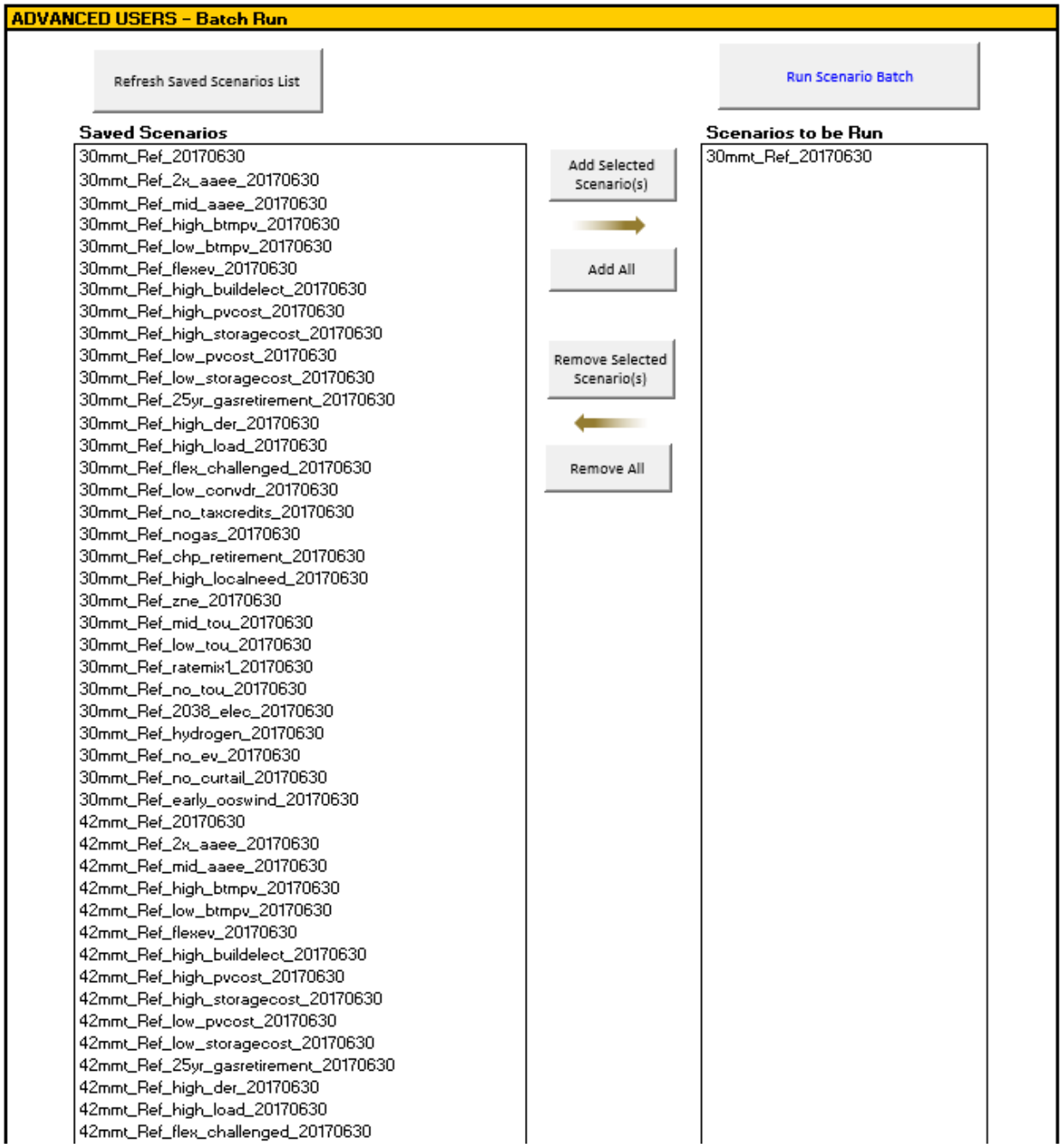

Figure 5. Dashboard options for running a batch of scenarios.

3.1.4 DATA WORKSHEETS

The data worksheets show the underlying input data for each of the input toggles. The data input worksheets are grouped by their respective overarching theme (SYS = System, Loads, REN = Renewables, CONV = Conventional Generation, HYD = Hydro, STOR = Storage, DR = Demand Response, and Costs).

In these worksheets the following color-coding is used:

- Yellow-shaded cells are raw inputs. These can be changed by the user, although it is advised to keep the default inputs, and choose from any of the existing options through the scenario toggles in the Controls tab.
- Grey-shaded cells are intermediate calculations and should not be changed by the users.
- Light-blue shaded cells show the data that is currently active, depending on the settings in the Controls worksheet. E.g. if there is a "Mid", "Low", and "High" fuel cost trajectory (yellow-shaded cells), and the user has selected the "Low" option for fuel costs in the Dashboard, the light-blue-shaded cells will show the "Low" fuel costs (note that the user might have to recalculate the worksheet).
- Light-green shaded cells are typically the derived, final inputs that will go into RESOLVE.

Additional documentation of the contents of the data worksheets in the User Interface can be found in the "RESOLVE Model Documentation: Inputs & Assumptions."

3.2 Results Viewer

The Results Viewer allows the user to look at the summary results of a scenario of interest. It contains five (groups of) worksheets: Dashboard, Portfolio Analytics, Scenario Comparison, Raw Summary Results, and Lists.

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3.2.1 DASHBOARD

The Dashboard worksheet is the main worksheet the user will interact with to look at the results of a single scenario.

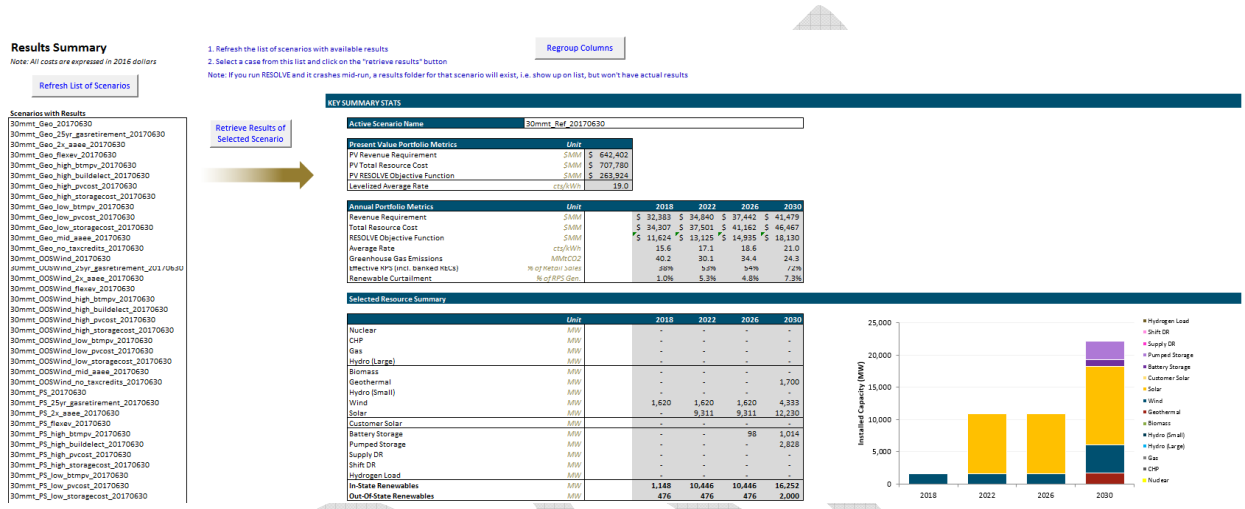

Figure 6. Results Viewer Dashboard

The Dashboard contains the following macro buttons:

- The **"Refresh List of Scenarios"** macro lists all subdirectories that exist in the results directory. Note that the existence of a scenario subdirectory typically means that there are results available, but there are cases when there's not, such as when a RESOLVE run is interrupted mid-run. In that case, a results folder will be created for that run, but no results will be available yet.
- After selecting one of the scenarios from the list under "Scenarios with Results", the **"Retrieve Results of Selected Scenario"** macro will load all summary results files into the appropriate worksheets (named raw_ + file name) for the selected scenario.

Note that a common cause of errors is the fso.GetFolder() function in the VBA macro. If this function raises an error, go to Tools > References > find and tick 'Microsoft Scripting Runtime'.

The Dashboard worksheet also contains key summary results for the CAISO zone, such as the total selected (i.e. chosen by RESOLVE) solar buildout, storage buildout etc. The worksheet also includes graphs on the right side of some of the tables.

The year columns are grouped using Excel's grouping functionality (see Data > Outline > Group), and can be expanded and minimized by clicking on the "+" or "-" signs in the columns sidebar, or by clicking on the numbers (1,2) on the top left of the spreadsheet. Please note that expanding the grouped columns will interfere with the formatting of these charts. If the user has created a RESOLVE scenario that looks at a different set of years than the default case (2018, 2022, 2026, 2030), the **"Regroup Columns"** macro will regroup the columns to show the representative set of years.

3.2.2 PORTFOLIO ANALYTICS

This worksheet contains more detailed summary tables that are pulled from the raw summary results worksheets, and processed where necessary.

The results are grouped using Excel's grouping functionality (see Data > Outline > Group), and can be expanded and minimized by clicking on the "+" or "-" signs in the rows/columns sidebar, or by clicking on the numbers (1,2) on the top left of the spreadsheet. If the user has created a RESOLVE scenario that looks at a different set of years than the default case (2018,2022,2026,2030), the **"Regroup Columns"** macro will regroup the columns to show the representative set of years.

The cells in this worksheet are color-coded as follows:

- Light-grey shaded cells contain data that is pulled from the raw results worksheets
- Dark-grey shaded cells contain data that is linked to other data in the Portfolio Analytics spreadsheet.

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3.2.3 SCENARIO COMPARISON

This worksheet is set up so the user can easily compare summary results of multiple scenarios. It allows the user to select scenarios of interest and to compare the summary results of these scenarios for a year of interest. The summary results are the same as those shown on the Dashboard for an individual scenario.

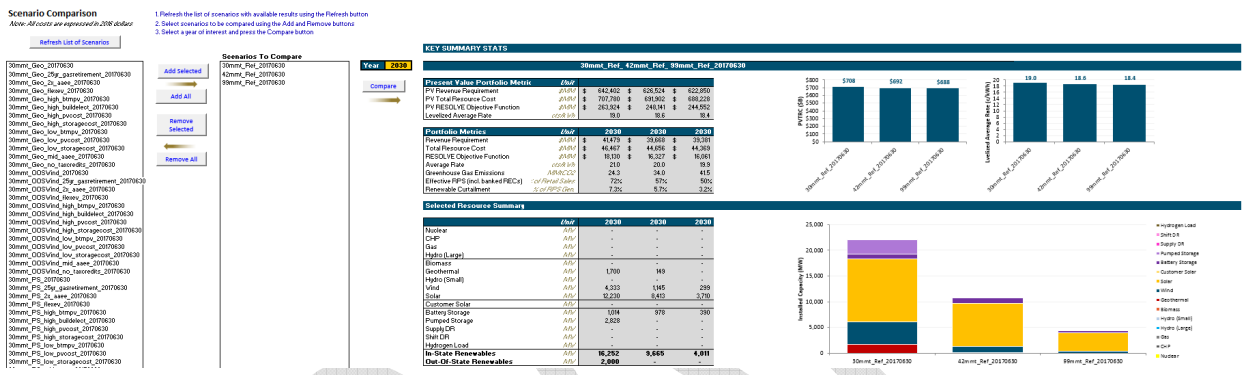

Figure 7. Results Viewer - Scenario Comparison Worksheet

To compare a set of scenarios, follow the steps below:

1. Refresh the list of available scenarios by pressing **"Refresh List of Scenarios"**. This macro lists all subdirectories that exist in the results directory. Note that the existence of a scenario subdirectory typically means that there are results available, but there are cases when there's not, such as when a RESOLVE run is interrupted mid-run. In that case, a results folder will be created for that run, but no results will be available yet.

2. [*Optional*] If necessary, remove any scenarios you don't want to compare from the "Scenarios to Compare" list by using the **"Remove Selected"** or **"Remove All"** Button.

a. The **"Remove Selected"** macro will remove the selected scenario from the list of scenarios listed under "Scenarios to Compare". Note that in this context, selected scenario means the cell that is selected within the "Scenarios to Compare". If a cell outside of this box is selected, a warning will pop up and the macro will stop.

b. The "**Remove All"** macro will remove all scenarios listed under "Scenarios to Compare".

3. Add scenarios of interest to the "Scenarios to Compare" list using the **"Add Selected"** or **"Add All"** buttons.

   a. The **"Add Selected"** macro will add the selected scenario to the list of scenarios listed under "Scenarios to Compare". Note that in this context, selected scenario means the cell that is selected within the "Saved Scenarios Menu" box (not the value in cell D8). If a cell outside of this box is selected, a warning will pop up and the macro will stop.

   b. The **"Add All"** macro will add all scenarios listed under "Saved Scenarios" to the list of scenarios listed under "Scenarios to Compare".

4. Select a year of interest in cell I8 (shaded yellow). Please ensure that this is a year for which there are RESOLVE results.

5. Compare all selected scenarios by pressing the **"Compare"** macro button. This macro will load the summary results for each of the scenarios listed under "Scenarios to Compare" to the Dashboard, and then copy the results for the year of interest to the Scenario Comparison table. If you are comparing a lot of results, this might take a few minutes, as the **"Retrieve Results of Selected Scenario"** macro on the Dashboard will be called upon many times in a row.

3.2.4 RAW SUMMARY RESULTS

The set of worksheets that start with "raw_" contain a copy of the raw summary results files for the scenario of interest. Whenever the macro "Retrieve Results for Selected Scenario" is run, these worksheets are updated.

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3.2.5 LISTS

This worksheet contains a set of lists to support the functions in this workbook. The user should not change anything in this worksheet.

3.3 Dispatch Viewer

The Dispatch Viewer is a tool to easily look at the dispatch results of a scenario of interest. It contains 4 (groups of) worksheets: Dashboard, Curtailment, Transmission, Raw Dispatch Results, and Lists.

3.3.1 DASHBOARD

The Dashboard is the main worksheet the user will interact with. It contains the following macro buttons:

- The **"Refresh List of Scenarios"** button lists all subdirectories that exist in the results directory. Note that the existence of a scenario subdirectory typically means that there are results available, but there are cases when this is not the case, such as when a RESOLVE run is interrupted mid-run. In that case, a results folder will be created for that run, but no results will be available yet.
- After selecting one of the scenarios from the list under "Scenarios with Results", the **"Retrieve Results of Selected Scenario"** button will load all dispatch results files (which are found in the dispatch subdirectory of the summary directory) into the appropriate worksheets (named raw_ + file name) for the selected scenario.

Note that a common cause of errors is the fso.GetFolder() function in the VBA macro. If this function throws an error, open the VBA editor, go to Tools > References, and find and tick 'Microsoft Scripting Runtime'.

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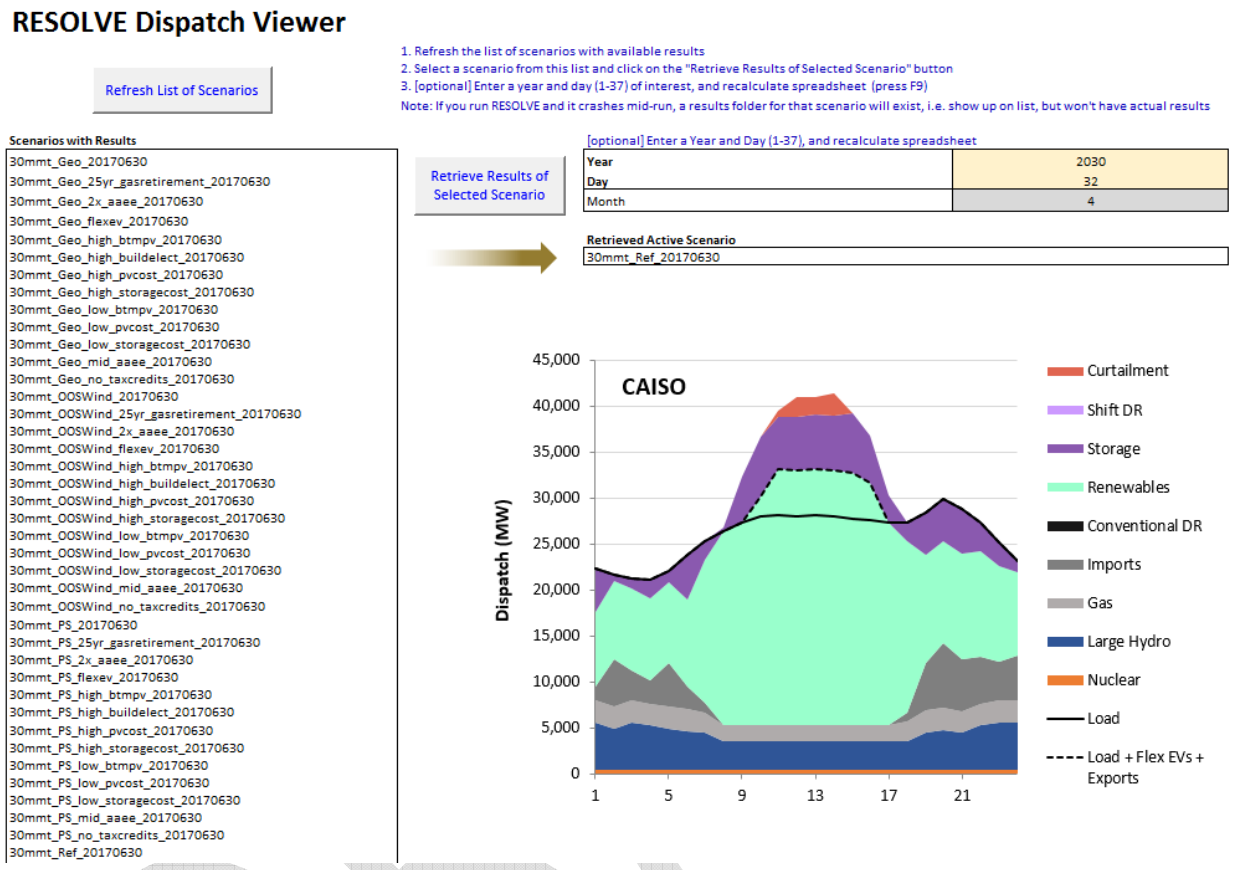

Figure 8. Dispatch Viewer Dashboard

After loading a scenario, the user can pick any year or day (between 1-37) of interest and view the dispatch of each of the zones by pressing F9 (this will recalculate the worksheet). The battery dispatch in CAISO is also shown at the bottom of the worksheet. The grey areas above and below the net dispatch represent the upward and downward reserves that are offered. Please note that updating the calculations can take up to a minute, as the raw_operations_by_zone_tech_tmp worksheet is very large.

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Exports and/or flexible EV charging are shown by plotting both the load, and load + flex EVs + exports as two lines. Anything between the load line and the load + flex EVs + exports line are exports and/or flexible EV charging.

3.3.2 RAW DISPATCH RESULTS

The set of worksheets that start with "raw_" contain a copy of the raw dispatch results files for the scenario of interest. Whenever the macro "Retrieve Results for Selected Scenario" is run, these worksheets are updated.

3.3.3 LISTS

This lists worksheet contains a set of lists to support the functions in this workbook. The user should not change anything in this worksheet.

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4 RESOLVE Model Detail

After RESOLVE has been run, a set of raw output files will be created in the appropriate subdirectory (named after the scenario name) of the results directory. E3 has created a results viewer as well as a dispatch viewer to support analysis of the model results. Advanced users may also review results provided in the raw output files directly and do their own analysis.

4.1 Raw Input Files

When the user selects and runs a scenario from the User Interface, RESOLVE will generate a series of text-based input files for the linear program. While running RESOLVE does not require users to manipulate these files directly, users may wish to review their contents and structure. Each of the input files to RESOLVE is described in Table 2.

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Table 2. RESOLVE raw input files

Input File	Description
capacity_limits.tab	The maximum capacity of each resource that can be built in each period. Resources that do not have capacity limits enforced are not included.
capacity_limits_local.tab	The maximum capacity of each resource that can be built in each period, specifically in local capacity areas.
conventional_dr_period_limits.tab	The maximum amount of energy that can be dispatched (shed) annually from conventional demand response resources in the main zone.
curtailment_in_other_zones.tab	The maximum curtailment allowed in each zone other than the main zone by timepoint.
day_weights.tab	The weight associated with each day in RESOLVE; should sum up to 365.
elcc_surface.tab	Effective load carrying capability (ELCC) surface facet coefficients for wind and solar power.
ev_params.tab	The charging efficiency of each EV fleet.
ev_period_params.tab	The total battery capacity of each EV fleet in each period, and the minimum energy that must always be available in each fleet's battery.
ev_timepoint_params.tab	The amount of demand from each EV fleet in each timepoint.
flexible_load_capacity_period_params.tab	Flexible load (shift) minimum and maximum resource potential limits for each period.
flexible_load_cost_curve.tab	Flexible load (shift) supply curve for each period.
flexible_load_cost_curve_index.tab	Indices that define each breakpoint in the flexible load (shift) supply curve.
flexible_load_timepoint_params.tab	The amount of load that can be shifted up or down in each timepoint as a fraction of the total daily flexible load potential.
fuel_prices.tab	The price of each fuel by period and month.
fuels.tab	Defines the set of fuels and the carbon content of each fuel.

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Input File	Description
ghg_import_rates.tab	The assumed greenhouse gas (GHG) emissions intensity resulting from imports into the main zone in each period for each transmission line.
ghg_targets.tab	GHG targets for the main zone in each period.
hurdle_rates.tab	Hurdle rates (cost per MW of energy flow) on each transmission line by period for both flow directions.
hydro_daily_params.tab	The daily energy budget, minimum generation level, and maximum generation level for each hydro resource and each day.
hydro_ramps.tab	The limits on hydro ramps for each ramp duration for the main zone hydro resource.
hydrogen_electrolysis_daily_params	The minimum hourly hydrogen load and daily average hydrogen load for the main zone for each day.
Hydrogen_electrolysis_period_params	The hydrogen electrolysis installed capacity for each period.
maintenance_schedules.tab	The maintenance derate fraction (1 is fully available, 0 is completely unavailable) for each day for each resource that has a specified maintenance schedule.
min_cumulative_new_build.tab	The minimum amount of new capacity of each resource that must be built through each period. The cost of building these resources is *not* assumed to be sunk (in contrast to planned_installed_capacities.tab)
period_discount_factors.tab	The weight/discount factor applied to costs occurring in each period, and the number of years represented by each period.
planned_installed_capacities.tab	The planned installed capacity of each resource in each period. The cost of capacity included here is assumed to be sunk and consequently is not included in the optimization.
planned_storage_energy_capacity.tab	The planned installed energy capacity of each storage resource in each period.
planning_reserve_margin.tab	The planning reserve margin target for the main zone in each period, and other quantities related to the planning reserve margin. Also included is the amount of capacity needed in local areas within the main zone in each period.
reflex_constraints.tab	The slope and intercept of each facet of the surface by period for the main zone.
reflex_facets.tab	Indices for each of the REFLEX facets.
renewable_targets.tab	The RPS target in the main zone by period (in MWh).
resource_firm_capacity_prm.tab	The net qualifying capacity (NQC) fraction for firm capacity resources.

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Input File	Description
resource_tx_zones.tab	The transmission zone for newly buildable renewable resources. Also specifies whether the resource is located inside or outside of the main zone.
resource_variable_renewable	Flags indicating which variable renewable resources are curtailable.
resource_variable_renewable_prm.tab	Parameters related to variable renewable resource participation in the planning reserve margin and local capacity constraints.
resource_vintage_params.tab	The annual fixed cost per unit of capacity ($/kW-yr) by resource (new build resources only) and vintage.
resource_vintage_storage_params.tab	The annual fixed cost of per unit of energy capacity ($/kWh-yr) for storage resources by vintage.
resources.tab	All resources with their technology, zone, and contract as well as flags for whether new capacity can be built at the resource, whether the resource can be retrofitted or represents a retrofitted resource, whether there is a limit on the total capacity that can be built for the resource, whether the resource can satisfy local capacity needs, and whether the resource has local capacity limits.
retrofits.tab	The retrofitted resource name corresponding to each resource that can be retrofitted.
retrofits_allowed.txt	Boolean for enabling the retrofit functionality of RESOLVE
shapes.tab	The normalized profiles for each variable resource for each day and hour.
simultaneous_flow_group_lines.tab	The line-directions included in each simultaneous flow group.
simultaneous_flow_groups.tab	The names of the groups of lines over which simultaneous flow constraints are enforced.
simultaneous_flow_limits.tab	The limits on flow over each simultaneous flow group by period.
subhourly_curtailment_limits.tab	Limits on sub-hourly curtailment imposed in the main zone by timepoint.
system_params.tab	A range of single-value parameters including penalties for unserved energy, overgeneration, and reserve violations; the durations of hydro and intertie ramps to constrain; parameterizations of the sub-hourly behavior when providing regulation and load-following reserves; parameterizations of the ability of variable generation to provide reserves; whether to require renewable overbuild when satisfying RPS constraints; whether to allow RPS banking; whether to enforce GHG targets; the number of hours of duration that receives full ELCC credit; and the assumed timeframe for operational reserves.
tech_dispatchable_params.tab	Parameters associated with each dispatchable thermal technology: minimum stable level as fraction of capacity,

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Input File	Description
	ramp rate as fraction of capacity, startup and shutdown time (integer hours), unit size, and startup and shutdown costs.
tech_storage_params.tab	Parameters associated with each storage technology: charging and discharging efficiencies, and minimum storage duration.
tech_thermal_params.tab	Parameters associated with each thermal technology: the fuel used, and the fuel burn slope and intercept.
technologies.tab	All technologies modeled, with flags for various operational characteristics.
timepoints.tab	All timepoints modeled with their associated metadata: which period, month, and day the timepoint is in, and which hour of the day it represents.
transmission_lines.tab	All transmission lines with their origin (from) and destination (to) for the positive flow direction, the minimum and maximum flow on the line, a flag for whether the line is ramp-constrained, and a flag for whether a hurdle rate is applied on the line.
transmission_ramps.tab	The up and down ramp limits for each ramp-constrained line for each ramp duration.
tx_zones.tab	The transmission zone aggregations for which energy only or fully deliverable transmission capacity will be built for new renewable resources. Capacity limits for energy only and zero-cost fully deliverable capacity are included, along with the cost to build new fully deliverable capacity.
zone_curtailment_costs	The cost of curtailment in each zone in each period
zone_main_timepoint_params.tab	The regulation and load-following reserve requirements in each timepoint in the main zone.
zone_timepoint_load.tab	The input load in each zone in each timepoint.
zones.tab	The zones modeled; the main zone is flagged here; this file also includes the minimum generation, frequency response, and spinning reserve requirements for the main zone.

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4.2 Python Scripts

The input files described in Section 3.2 are read into a linear program formulated in Python to solve for the optimal system capacity expansion. Users are not required to interact with Python directly to run RESOLVE; however, users are welcome to review the structure and logic of RESOLVE's formulation. The Python scripts that make up the RESOLVE model are summarized in Table 3.

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Table 3. RESOLVE Python scripts

Python Script	Description
run_opt.py	This is the 'main' script of the RESOLVE model. It takes one required argument: the name of the scenario to run. For example, to run a scenario named '`full_run`,' we need to run the `run_opt.py` script and give it the argument `full_run`. The scenario name must be the same as the name of a subdirectory in the `inputs` directory.
model_formulation.py	This script contains the RESOLVE problem formulation. RESOLVE is written in **Pyomo**, a Python-based optimization modeling language. The model object is defined in `model_formulation.py` and is called `resolve_model`. It is a Pyomo `AbstractModel` class, which is then assigned various attributes—parameters, sets, variables, and constraints—that describe the RESOLVE linear problem.
load_inputs.py	This script contains the `scenario_data` function that returns a `DataPortal` Pyomo object. The `DataPortal` is a way to load data into a Pyomo `AbstractModel` class. The `scenario_data` function takes the scenario inputs directory as argument, finds the TAB files containing the scenario data, and initializes the `resolve_model` class with these data (see the `create_problem_instance` function in `run_opt.py`).
export_results.py	This script contains the `export_results` function, which is called by `run_opt.py` when the problem is solved. This function takes the model instance, results, and scenario results directory as arguments. A final argument, `debug_mode`, tells the function how to handle errors that may arise: exit if `debug_mode` is set to 0, launch the Python debugger if `debug_mode` is set to 1. The `export_results` function calls other functions that export various optimization results, e.g. the build variables, the operations variables, the transmission flows, etc.
create_summaries.py	Once results are exported, `run_opt.py` calls the `create_summaries` function from `create_results_summaries.py` file. This function calls various other functions, also in the `create_results_summaries.py`, that perform various aggregations of the results and write them to the `summary` subdirectory in each scenario's results directory.
runbatch_py	This script simply runs the run_opt.py file in series for each of the scenarios listed in 'cases_to_run.csv'. It allows users to run a batch of scenarios simply, rather than waiting for each scenario to finish before running the next one. Note: advanced users may wish to run many scenarios in parallel by opening multiple command prompt windows. Runbatch.py runs each scenario in series, not in parallel.

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Assuming we are starting in `yourdirectory`, we can do this as follows on the command line (cmd.exe in Windows):

```
>> cd resolve_code
>> python run_opt.py full_run
```

The first line changes directory to `resolve_code`. The second line runs the `run_opt.py` script with `test_scenario` as the script argument. The script will then create the `full_run` results subdirectory, get the model formulation, load data into the model to create a problem instance, call the solver, solve the problem, and write results to the `full_run` results subdirectory.

RESOLVE will use the CBC solver by default unless ana second optional second command line argument – the name of the desired solver - is included. For example, to run the scenario `full_run` with the solver Gurobi, use this on the command line:

```
>> python run_opt.py full_run gurobi
```

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4.3 Raw Output Files

Output files in the root results directory are created by *export_results.py.* Output files in the summary directory are created by *create_results_summary.py.*

Note that the term 'dual' is used frequently to refer to the shadow price of a constraint. Technical note on dual values: the reported values reflect real dollars in either hourly or annual quantities.

summary directory

The summary directory contains various aggregations and combinations of the data in the results files described below. Only data in the summary directory is imported into the results viewer. Files in the root results *directory* are *not* directly used in the results viewer, but are available when more detailed analysis of results is required.

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Table 4. RESOLVE raw output files

Output File	Description
curtailment.csv	This file contains hourly and sub-hourly variable renewable curtailment decisions for each zone in RESOLVE. Blanks cells indicate that RESOLVE does not make this decision.
elcc_surface_facets.csv	This file contains results for each facet of the effective load carrying capability (ELCC) surface in each period. These results can show which (if any) of the ELCC facets is active in each period.
fuel_burn_by_resource.csv	This file contains the hourly fuel burn and greenhouse gas (GHG) emissions by resource.
ghg.csv	This file contains the input GHG emissions target in each period, and the shadow price of meeting that target. Blanks cells indicate that a GHG emissions target was not modeled.
ghg_imports.csv	This file contains the hourly GHG emissions imported into the main zone along transmission lines.
hurdle_rate_costs.csv	This file contains the hourly hurdle rate costs incurred by sending power along transmission lines that have a non-zero hurdle rate.
incremental_fixed_costs.csv	This file contains the annualized cost of investment decisions made by RESOLVE for each resource in each period.
loads_and_power_balance.csv	This file contains hourly loads for each zone and timepoint that were input into the RESOLVE optimization, as well as the amount of overgeneration and unserved energy for each zone and timepoint. It also contains the shadow price of the zonal power balance constraint for each timepoint, which is analogous to the hourly energy price. Care should be taken interpreting this energy price as the RESOLVE investment framework differs in several fundamental ways from a conventional production simulation.
local_capacity_resources.csv	This file contains the local capacity investment decisions made by RESOLVE for each local capacity resource in each period.
main_zone_timepoint_duals.csv	This file contains the hourly shadow prices of meeting various reliability and reserve constraints in the main zone.
objective_function_value.txt	The final value of the objective function for each RESOLVE run.
operational_costs.csv	This file contains the hourly operational cost of the decisions made by RESOLVE for each resource, including variable costs, fuel costs, start-up costs, and shut-down costs.

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Output File	Description
operations.csv	This file contains the hourly operational decisions made by RESOLVE for each resource on all days modeled in RESOLVE (currently 37 days per year). Types of operational decisions included in this file are: unit commitment, power production, reserve commitment, and flexible load dispatch. Blanks cells indicate that RESOLVE does not make this decision.
planning_reserve_margin.csv	This file contains the input planning reserve margin (PRM) and local capacity targets in each period, as well as the shadow price of meeting those targets. A summary of PRM contributions by resource type is also included.
ramping_duals.csv	This file contains the hourly values relating to ramp constrains of dispatchable thermal generation.
reflex_res_provision.csv	This file contains the hourly values relating to variable renewables providing downward load following reserves via REFLEX surfaces.
reserve_violations.csv	This file contains the hourly reserve commitment shortfalls (or violations) for each reserve product. This file is used primarily for diagnostic purposes as reserve shortfalls are uncommon.
resource_build.csv	This file contains the investment decisions made by RESOLVE for each candidate resource in each period as well as the capacities of resources for which no investment decisions were made (e.g. existing resources and contracted resources that come online at some point in the future). The fully deliverable/energy only status of new renewable resources is included. Blanks cells indicate that RESOLVE does not make this decision.
rps.csv	This file contains the input RPS target level in each period, as well as the shadow price of the RPS constraint, the RPS credits banked, and a high-level summary of the components of the RPS constraint.
sim_flow_group_duals.csv	This file contains the hourly shadow prices of constraints that limit the sum of flows on groups of transmission lines.
storage_build.csv	This file contains investment decisions made by RESOLVE in every period for the energy capacity of each storage resource. Blanks cells indicate that RESOLVE does not make a decision.
transmission_costs.csv	This file contains the cost of building new transmission in each period triggered by new renewable resource investment decisions made by RESOLVE. Also included is the breakdown of fully deliverable/energy only capacity in each transmission zone in each period.
transmit_power.csv	This file contains the hourly transmission dispatch decisions made by RESOLVE for each transmission line, as well as the shadow price of flow limits on each line.

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5 Using RESOLVE Outputs in Other Models

To facilitate the adaptation of RESOLVE cases for use in other modeling platforms, RESOLVE produces a series of .csv files summarizing key inputs and outputs in a format designed to allow benchmarking against and input into other production simulation models. For each case run in RESOLVE, these files provide detail on the assumed infrastructure buildout within CAISO over the time frame of the analysis as well as supplemental data needed to represent those resources in production simulation modeling. The contents of the PCM Input Files package are summarized in Table 5.

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Table 5. Summary of PCM Input Files package produced by RESOLVE

PCM Input File	Description
conventional_generators_baseline.csv	This file provides assumptions on the committed fleet of conventional generators. It provides plant-specific assumptions (e.g., size, operating assumptions, online & retirement dates) for all conventional thermal and hydro generators in CAISO. The types of generators included in this file include
renewable_generators_baseline.csv	This file summarizes the committed buildout of renewable resources. This fiyle includes a summary, by installation vintage and technology, of all renewable resources physically located in the CAISO footprint, as well as summaries of renewable resources physically located in external regions but contracted to CAISO utilities.
gen_optimized.csv	This file provides a summary of all resources selected by RESOLVE for inclusion in the portfolio in its optimization. It shows all types of new resources, including conventional, renewable, and storage.
annual_loads.csv	This file summarizes the annual load forecast inputs to RESOLVE, including both the baseline consumption, all assumed load modifiers, and assumed transmission & distribution losses.
dr_baseline.csv	This file summarizes the assumed trajectory of IOU demand response programs through the analysis.
storage_baseline.csv	This file summarizes the committed buildout of energy storage resources. This file includes a summary, by installation vintage and technology, of all storage resources physically located in the CAISO footprint.

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