RESOLVE
Capacity Expansion Model

User Manual

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Energy+Environmental Economics

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1 Introduction

1.1 Overview

The purpose of this document is to provide users with the guidance needed to set up and run the RESOLVE model 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.

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 that 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 incorporates a representation of neighboring regions in order to characterize transmission flows into and out of a main zone of interest endogenously. As shown in **Figure 1.1**, RESOLVE can solve for the optimal investments in renewable resources, energy storage technologies, demand response, new gas plants, and retention of existing thermal plants. These least-cost decisions are subject to annual constraints on delivered renewable energy that reflects the RPS policy, annual constraints on greenhouse gas emissions, capacity adequacy constraints to maintain reliability, and constraints on the ability to develop specific renewable resources. RESOLVE simulates operations on sampled days and includes a linearized version of the unit commitment problem. An overview of constraint groups is shown in **Table 1.1**.

Figure 1.1. RESOLVE Least-Cost Capacity Expansion Model

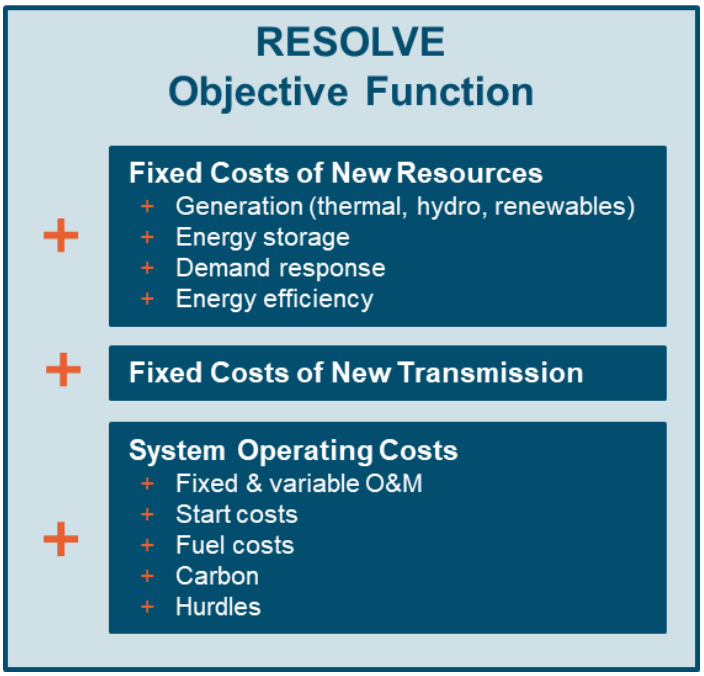


Table 1.1. Overview of Key Constraint Groups in RESOLVE

Category	Constraint Group	Description
Capacity	Capacity Expansion	Tracks annual resource capacity, including economic resource buildout. Interacts with resource dispatch and reliability constraints.
	Economic Retention	Thermal resources are retained if ongoing fixed costs are lower than value of services provided to the system. A minimum amount of retention can be enforced.
	Transmission Deliverability	Categorize renewable build into "Fully Deliverable" and "Energy Only." Build new transmission within CAISO.
Power Balance	Zonal Power Balance	Ensure that generation and imports match loads in each modeled zone and in hour. Sets the hourly zonal marginal energy price.
Loads	Economic EE Investment	Economically select energy efficiency (EE) measures or bundles.
	EV Smart Charging	Optimally charge EVs subject to driving pattern limitations.
	Hydrogen Electrolysis	Produce hydrogen for non-electricity uses.
	Shed DR	Constrain shed DR programs to limited amount of dispatch per year.
	Shift DR	Constrain shift DR programs to maintain energy neutrality and underlying availability shape.
Operating Reserves	Reserve Requirements	Maintain sufficient frequency response, regulation up/down, load following up/down, and spinning reserves. Sets the hourly operational reserve price for each reserve type.
Policy Targets	GHG Target	Meet an annual GHG target, including GHG emissions from unspecified imports into the GHG target zone.
	RPS/CES Target	Meet an annual RPS or CES target, including unbundled Renewable Energy Certificate (REC) accounting.

Reliability	Planning Reserve Margin	Meet a Planning Reserve Margin (PRM) requirement in each year. Sets the annual capacity price.
	Local Capacity Area	Build a certain qualifying capacity of resources "locally" – within sub-zones of the primary zone.
	Energy Sufficiency	Analogous to the single-hour PRM but evaluates if there is sufficient available energy across the year on a variable timescale.
	Variable Renewable ELCC	Quantifies the cumulative capacity contribution (the PRM contribution) of wind and solar using an ELCC surface.
Resource Dispatch	Operating Limits	Constrain output to operating limits (including hourly ramping) or expected output.
	Storage Energy Tracking	Track state of charge of storage resources to optimally dispatch for energy and reserves.
	Unit Commitment	Constrain energy and reserve dispatch of thermal resources using linearized unit commitment constraints.
	Hourly Profiles	Constrain variable resources to fixed production profiles, which can be optimally curtailed for hourly energy dispatch or to provide operating reserves.
Transmission	Transmission Flows	Limit energy flows between zones (including optional hourly ramps). RESOLVE is a zonal model. Sets hourly congestion price for energy.
	Transmission Expansion	Economically build transmission (increase path ratings) between balancing areas. Interacts with resource dispatch and reliability constraints. RESOLVE's transmission expansion feature is not used for 2019 IRP modeling.

1.2 Structure of This Document

The remainder of this document is organized as follows:

- **Section 2. Setting Up RESOLVE**
  Describes system requirements for running RESOLVE and recommended installation instructions.
- **Section 3. Interacting with RESOLVE Interfaces**
  Overview of how to use the Excel-based user interfaces (Scenario Tool and Results Viewer). For users seeking only to run RESOLVE cases and view model outputs, this section provides the necessary background to do so.
- **Section 4. RESOLVE Model Details**
  More in-depth discussion on core RESOLVE implementation (input/output text files and Python scripts).

2 Setting Up RESOLVE

2.1 System Requirements

2.1.1 OPERATING SYSTEM

The underlying Python code powering RESOLVE has been tested on Windows, macOS, and Ubuntu. Other Linux distributions will likely also be able to run the model.

The Excel interfaces used to interact with RESOLVE require access to Microsoft Excel. The RESOLVE user interface has been tested extensively on Windows.

2.1.2 PYTHON

RESOLVE is compatible with the latest **Python 3**, while also being backward compatible with Python 2. E3 currently uses Python 3.7.3 (64-bit). E3 recommends installing **Anaconda** to obtain Python, which also includes some of the mathematical packages needed to run RESOLVE.

RESOLVE relies on the open-source Python packages **numpy**, **pandas**, and **pyomo** to formulate the optimization model and process inputs/outputs. Both **numpy** and **pandas** are included when installing Anaconda. E3 currently uses **pyomo** version 5.6.6.

2.1.3 SOLVERS

The default, open-source solver to use with RESOLVE is called **cbc**.[1] Download **cbc-win64.zip**, unzip, and move the executable (**cbc.exe**) to a folder of your choosing. 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 2.9.9 (64-bit) on Windows 10. Executables for macOS, and Linux can also be obtained from the link in the footnote and added to the system **PATH** following the appropriate instructions for each operating system or by using the **COIN-OR Optimization Suite** installer.

If users have licenses for other, commercially available solvers (such as **CPLEX** and **Gurobi**[2]), these can be used with RESOLVE and may provide significantly faster solution times than **cbc**. RESOLVE model cases created for the 2019 CPUC IRP experience very long runtimes and E3 and recommends using a commercial solver if the user plans to run more than a handful of cases. Both CPLEX and Gurobi provide onsite and cloud licensing options and other commercial solver vendors may have similar options. As with CBC, to utilize a commercial solver, you will need to make sure the executable for the solver is added to your system **PATH**.

2.2 Installing Python and RESOLVE

In this user guide, we offer two installation instructions:

+ **Basic Installation**

  Users may want to consider this option if they:

[1] A 64-bit compatible cbc executable compiled by AMPL Optimization, Inc. can be downloaded at the following link: https://ampl.com/products/solvers/open-source/

[2] E3 has tested Gurobi extensively and has observed that in specific instances Gurobi can have numerical issues when solving RESOLVE cases, resulting in longer runtimes than expected. Solver settings for Gurobi in **run_opt.py** address most of the numerical issues, but in certain circumstances the user may need to change solver settings to allow a case to solve with an acceptable runtime. If the user is experiencing numerical issues with Gurobi on a specific model run, removing some of the Gurobi solver settings in **run_opt.py** frequently results in improved performance.

1. Do not use any other Python-based applications on their computer
2. Are not concerned about the specific version of certain Python packages interacting with other applications on their system

+ **Advanced Installation**

  Users may want to consider this option if they:

  1. Have previously installed a specific version of Python on their system
  2. Have applications or scripts on their computer that require a specific version of Python or Python packages that are incompatible with RESOLVE

2.2.1 BASIC INSTALLATION & UPDATING PACKAGES

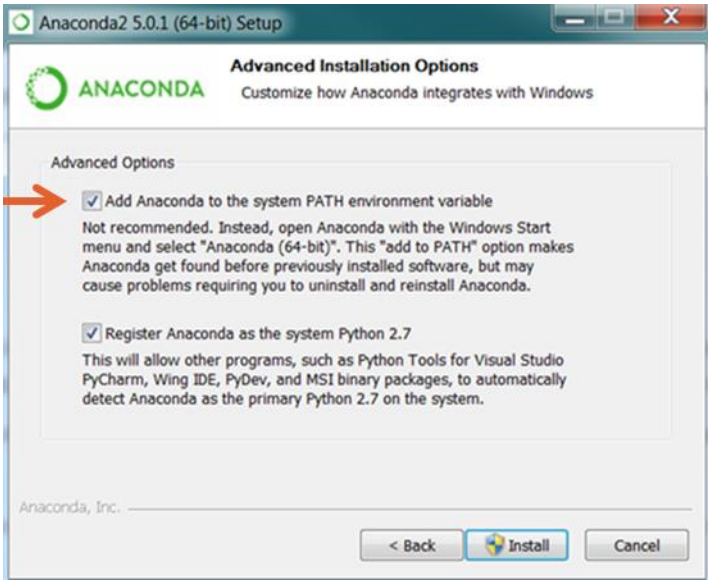
As previously discussed in **Section 2.1.2**, E3 recommends installing the Anaconda distribution of Python. This installation method will install or update the packages RESOLVE depends on directly to your "base" Python location using Python's standard **`pip`**[3] installer.

1. **Install the Anaconda distribution of Python.**
   (Skip this step if you would like to use an existing installation of Python).

   During the installation process, you should see "Add Anaconda to the system PATH environment variable" in the Advanced Installation Options (as shown in the screenshot below). This will allow us to find the installed Python easily when running RESOLVE.[4]

[3] Read more about pip **here**

[4] If you are not sure if it is in your PATH environment variable, open a Command Prompt window and type the command "**`python`**" and press Enter. If you see a message to the effect of, **`'python' is not recognized as an internal or external command`**, you will need to follow the **instructions** to add python to your PATH environment variable.



Note: Users with prior installations of Python should be careful of the implications of installing another version of Python on their system if they have other Python scripts and dependencies.

2. (Optional) If you have a pre-existing installation of Python, you may want to use the following commands to update **numpy** and **pandas** to the specific versions that have been tested by E3:

```
pip install numpy>=1.13.3
pip install pandas>=0.24.0
```

3. Install the specific version of **pyomo** for RESOLVE using the following commands:

```
pip install pyomo==5.6.6
```

2.2.2 ADVANCED INSTALLATION (CONDA VIRTUAL ENVIRONMENT)

This installation method uses **conda**'s environment[5] functionality to create a virtual environment to install a separate version of Python and dependencies specifically for RESOLVE.

[5] Read more about **conda** environments here

1. If you have not yet installed Anaconda, follow the first step in the Basic Installation instructions.**RESOLVE Scenario Tool**, users will find two options for controlling how the VBA buttons call RESOLVE from the Scenario Tool:

    a. **Python Path:**
    Copy the path you found in step (2) into the yellow input cell. By default, the cell is blank, and RESOLVE will use the default Python installed on your computer. By inputting a path here, you are telling RESOLVE to use this specific version of Python.

    b. **Solver:**
    By default, this is set to **`cbc`** (which is a free open-source solver that can be used with RESOLVE, see **Section 2.1.3**). Other options (if the user has correctly installed them) are **`cplex`** and **`gurobi`**, and advanced users could modify the Scenario Tool to use additional solvers if desired.

2.3 RESOLVE Package Organization

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. A schematic of the RESOLVE environment is shown in **Figure 2.1**.

Figure 2.1. Schematic of RESOLVE Modeling Components

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

1. **RESOLVE Resource Costs and Build Workbook**

   Excel workbook containing upstream information on baseline resources, candidate resource cost and potential, and the Pro Forma financial model. Data updates can be implemented in this workbook and manually copied over to corresponding sheets in the Scenario Tool.

2. **RESOLVE Scenario Tool**

   Excel workbook that includes a scenario management dashboard and input data worksheets. The Scenario Tool provides a simple interface to develop and run RESOLVE scenarios after setting up data inputs to the model.

3. **Input Files: `inputs/`**

   RESOLVE accepts scenario inputs as tab-delimited (.tab) text files. These are created by the Scenario Tool and contain the minimal set of data needed to define scenario assumptions. The **`inputs`** directory contains scenario subdirectories with input files for each scenario.

4. **RESOLVE Python Scripts: `resolve_code/`**

   RESOLVE is written in Python and consists of multiple scripts that (1) read the raw input files, (2) formulates a linear programming optimization model to minimize total incremental system

costs, and (3) exports the resulting optimal portfolio of investments and operations across the analysis time horizon. The **`resolve_code`** directory contains the RESOLVE Python scripts.

5. **Output Files: `results/`**
   RESOLVE prints out results in CSV files. These results files contain all results read by the Results Viewer, as well as other files that report detailed information. The **`results`** directory and scenario-specific subdirectories are created automatically upon running the RESOLVE code.
6. **Results Viewer**
   Excel workbook that is the interface through which users may review results of a completed RESOLVE run and compare results across runs. 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. Scenario-specific subdirectories in the **`results_summaries/`** directory containing result summaries for each scenario are created automatically when results are loaded into the Results Viewer.
7. **`setup.py`**
   Setup script that installs relevant dependencies to configure RESOLVE.
8. **`environment.yml`**
   Optional file used by **`conda`** to define a new virtual environment.

If the user is interested in reviewing inputs and outputs to the pre-built RESOLVE scenarios, the **Resource Cost and Build Workbook**, **Scenario Tool**, and **Results Viewer** provide can be used directly in Excel without installing Python or setting up RESOLVE.

2.3.1 RESOLVE PACKAGE FILE HASHES

File hashes for the current public release of RESOLVE are listed in **Table 2.1**.

Table 2.1. RESOLVE File Hashes

RESOLVE File	SHA-256 Hash
setup.py	771da4bba9eeaeba06f05ebaa92bd970c3250477dac9d21265c7b0a280ccc0b6
environment.yml	8614b3e68e5fbe57ffee555b3d75bd3e422af89f4884f3092e6bae35907da733
resolve_code/create_results_summary.py	bf678e70dc7a638a7faea2f279010a6f55750e53167b3412e283779ab1874920
resolve_code/export_results.py	32e2adda33cd56c0c552f4a9d841de1e4593fc3190fcfacf851493921886aae3
resolve_code/fileio.py	6b9ffba288f440a5670bd0376b0c5635fc44efaef2e62da135e23b3e938653b5
resolve_code/load_data.py	83bea04d476e43140a9461b7312c4a28874438bfdc56191d88fd90a99b117c68
resolve_code/model_formulation.py	0777225ef7f91fb1150bc8ac53d53a978e7ca3b2f8aa3df887ca52f9a42c4be9
resolve_code/run_opt.py	698871f7e374f1353f2e0c5b30c8786137c853421d0b4e8dce4c90ce533398c2
resolve_code/runbatch.py	4c9a34b949b424e5baa545bfef87154d08aa55c8e71a5ab504b1669d2ff55d61

3 Interacting with RESOLVE

3.1 RESOLVE Scenario Tool

Cells throughout the Scenario Tool are color-coded to indicate how users should interact with them.

Figure 3.1. RESOLVE Scenario Tool Dashboard

Cell Type	Notes
Inputs	Yellow cells indicate user-defined inputs. These can be changed by the user, although it is advised to choose from any of the existing options through the scenario toggles in the Dashboard tab.
Dropdown	Orange cells indicate values. These can be changed by the user but must adhere to a set of pre-defined options listed in the dropdown list. For example, True/False toggles or the names of available zones in the pre-defined cases. (Note: True/False toggles will change color from green to red to help indicate the toggle setting)
Results	Green cells indicate cells linked to other inputs via formulas. These should automatically update, and it is advised not to change the formulas to ensure links stay intact.
Fixed or Inactive	Grey cells indicate calculations that should not be changed or values that are inactive.
Labels	These are hard-coded labels indicating what the cell(s) adjacent to it should be used for.

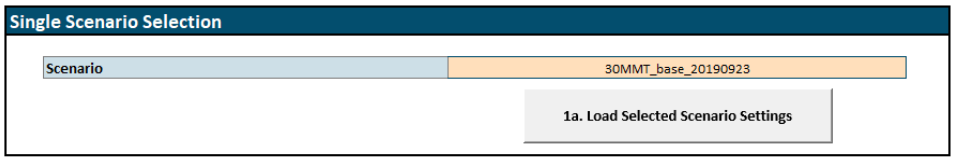
3.1.1 RUNNING PRE-DEFINED SCENARIOS

The RESOLVE Scenario Tool comes with a set of predefined scenarios. Users can load and run a predefined scenario as follows:

1. The dropdown menu in cell **D6** of the Dashboard lists all predefined scenarios (stored on the Scenario Settings tab). You can use the **Single Scenario Selection** dropdown and **1a. Load**

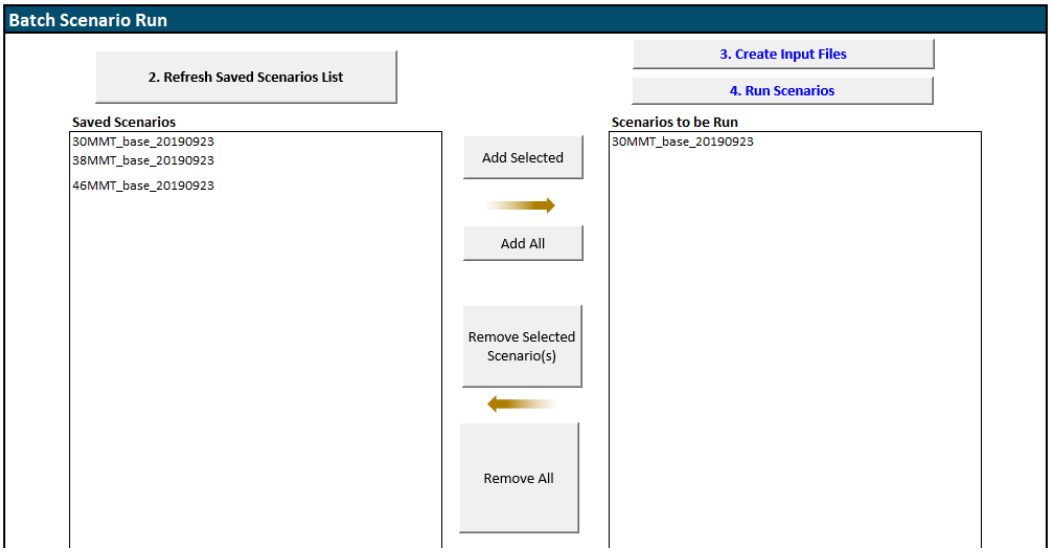
Selected Scenario Settings button (shown in **Figure 3.2**) to load a scenario's settings into the Dashboard for viewing.

Figure 3.2. RESOLVE Single Scenario Selection Interface



2. To run scenarios, use the **Batch Scenario Run** section of the Dashboard to add/remove named scenarios (listed in the **Saved Scenarios** list). You may need to press the **2. Refresh Saved Scenarios List** button to update the list. To add selected scenarios, select the cells with the scenario names you are interested in running, then press the **Add Selected** button. The selected scenarios should appear in the **Scenarios to be Run** list to the right. The **Add All** button will add all scenarios in the **Saved Scenarios** list to the right side. The **Remove Selected/All** buttons works similarly.
3. Press the **3. Create Input Files** button, which will invoke VBA code that prints out the input data into the appropriate scenario-specific input files in an input subdirectory with the scenario's name.

Figure 3.3. RESOLVE Scenario Run Interface



4. Press the **4. Run Scenarios** button to run RESOLVE. This will open a command prompt window and show text output as RESOLVE runs. RESOLVE runs can take anywhere between 10 minutes to many hours depending on specific scenario settings and which solver is being used. Note that the command prompt window will stay open even after RESOLVE has completed running.

3.1.1.1 Running RESOLVE via Command Line

There are a few reasons you may choose to run RESOLVE via the command line. For example, if you are running on a Linux or macOS machine, a machine without Excel installed, or a machine where you cannot use VBA macros, you will not be able to use the Scenario Tool to run RESOLVE. Additionally, if you want to use a non-default solver (as described in Section 2.1.3), the easiest way to specify the name of the solver is as a command line argument.

To run RESOLVE via the command line, navigate in your selected command line terminal (e.g., Command Prompt, PowerShell, bash, etc.) to the **`resolve_code`** directory. This is generally done using the **`cd`**

command (for change directory). For example, to switch to the directory where you have stored your **resolve_code** folder, you would use the command once, as shown below:

```
>> cd resolve_code
```

From within the **resolve_code** directory, you have two options for running RESOLVE cases.

1. The first is to run a single case using the **run_opt.py** script. There are two command line arguments that follow. The first argument is required, **[scenario name]**, and is the name of the single scenario you plan to run. This must correspond to the name of a directory in the inputs folder. The second argument is optional, **[optional: solver name]**, and is used to specify a different solver than the default CBC solver:

   ```
   >> python run_opt.py [scenario name] [optional: solver name]
   ```

   For example, to run the scenario **full_run** with and without the solver Gurobi, use the commands:

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

2. The second option is to run a batch of scenarios using the **runbatch.py** script by populating the CSV file called **cases_to_run.csv** with the list of scenarios you wish to run. **runbatch.py** runs all of the scenarios **cases_to_run.csv** in serial. The command line input is:

   ```
   >> python runbatch.py [optional: solver name]
   ```

   To run a batch of scenarios with and without the solver Gurobi, use the commands:

```
>> python runbatch.py gurobi
>> python runbatch.py
```

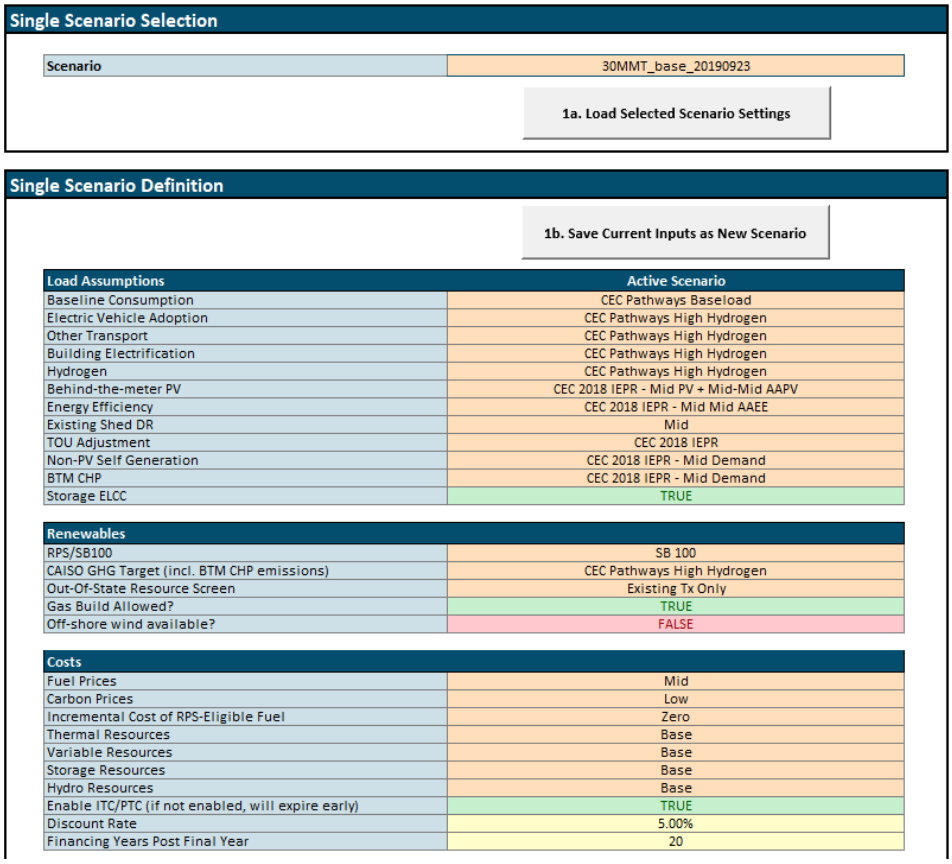
3.1.2 CREATING NEW SCENARIOS

Users may wish to create and run new scenarios based on existing input data, rather than the pre-defined scenarios. This can be done by adjusting the dropdowns in the Scenario Definition box on the RESOLVE Dashboard.

To create a new scenario:

0. (Optional) Select and load a scenario of interest in the **Single Scenario Selection** box
1. Customize the dropdown toggles in the **Single Scenario Definition** box (as shown in **Figure 3.4**). As indicated by the cell color, most of the inputs are dropdowns, but some (such as discount rate) are direct user inputs.

Figure 3.4. RESOLVE Dashboard Single Scenario Selection and Scenario Definition Interface



Single Scenario Selection

Scenario	30MMT_base_20190923

1a. Load Selected Scenario Settings

Single Scenario Definition

1b. Save Current Inputs as New Scenario

Load Assumptions	Active Scenario
Baseline Consumption	CEC Pathways Baseload
Electric Vehicle Adoption	CEC Pathways High Hydrogen
Other Transport	CEC Pathways High Hydrogen
Building Electrification	CEC Pathways High Hydrogen
Hydrogen	CEC Pathways High Hydrogen
Behind-the-meter PV	CEC 2018 IEPR - Mid PV + Mid-Mid AAPV
Energy Efficiency	CEC 2018 IEPR - Mid Mid AAEE
Existing Shed DR	Mid
TOU Adjustment	CEC 2018 IEPR
Non-PV Self Generation	CEC 2018 IEPR - Mid Demand
BTM CHP	CEC 2018 IEPR - Mid Demand
Storage ELCC	TRUE

Renewables	
RPS/SB100	SB 100
CAISO GHG Target (incl. BTM CHP emissions)	CEC Pathways High Hydrogen
Out-Of-State Resource Screen	Existing Tx Only
Gas Build Allowed?	TRUE
Off-shore wind available?	FALSE

Costs	
Fuel Prices	Mid
Carbon Prices	Low
Incremental Cost of RPS-Eligible Fuel	Zero
Thermal Resources	Base
Variable Resources	Base
Storage Resources	Base
Hydro Resources	Base
Enable ITC/PTC (if not enabled, will expire early)	TRUE
Discount Rate	5.00%
Financing Years Post Final Year	20

2. Save the new custom scenario by pressing the **1b. Save Current Inputs as New Scenario** button. A macro will prompt the user to enter a new scenario name and saves the scenario settings in the **Scenario Settings** tab. If a user would like to overwrite an existing scenario, they can do so by entering an existing scenario name in the dialog box. The macro will prompt you to confirm overwriting the scenario.

   Note that if a user changes any scenario toggles, they must be saved via the macro button for them to take effect in subsequent runs.

3. Press the **3. Create Input Files** button, which will invoke VBA code that prints out the input data into the appropriate scenario-specific input files in an input subdirectory with the scenario's name.

4. Press the **4. Run Scenarios** button to run RESOLVE. This will open a command prompt window and show text output as RESOLVE runs. RESOLVE runs can take anywhere between 10 minutes to many hours depending on specific scenario settings and which solver is being used. Note that the command prompt window will stay open even after RESOLVE has completed running.

3.1.3 INPUT DATA WORKSHEETS

The input data worksheets in the Scenario Tool are categorized into three high-level themes: system, loads, and resources. Brief summaries of each tab are included in **Table 3.1**. The cells in these data worksheets also adhere to the color-coding described at the start of **Section 3.1**.

Additional documentation of the contents of the data worksheets is provided in the Inputs & Assumptions documentation.

Table 3.1. Description of RESOLVE Scenario Tool Worksheets

Section	Tab	Description
DASHBOARD	Dashboard	*Contains a user interface to prepare and run scenarios. This is the main tab the user will interact with*
SCENARIOS	Scenario Settings	*Database with scenario settings that were saved through the user interface*
SYSTEM	Sys - Fuels	*Fuel cost assumptions and calculations*
	Sys - PRM	*Planning reserve margin assumptions and calculations*
	Sys - RPS GHG	*Renewable Portfolio Standard and greenhouse gas target assumptions*
	Sys - Reserves	*Operating reserves requirement assumptions*
	Sys - Tx	*Regional assumptions, such as transmission limits, hurdle rates, etc.*
	Sys - Inputs Passthrough	*Inputs to passthrough to the results (e.g., baseline costs)*
LOADS	Loads - Profiles	*Hourly load profiles by end-use*
	Loads - Forecasts	*Database of load forecasts*
	Loads - Hydrogen	*Inputs for hydrogen electrolysis feature*
	Loads - EE	*Inputs for EE investment feature*
	Loads - EV	*Electric vehicles assumptions and calculations*
	Loads - DR	*Assumptions for candidate demand response resources*
	Loads - Flexible	*Assumptions for flexible loads*
SUPPLY RESOURCES	Technologies	*Technology characteristics*
	Resources - All	*Resource inputs and mapping to technologies*
	Resources - Candidate	*Inputs for resources that can be expanded*
	Resources - Variable	*Shapes for variable resources*
	Resources - Hydro	*Energy budgets and constraints for hydro resources*
	Resources - Maintenance	*Maintenance/derate schedules (if not defined, resource will be rated at 100%)*
	Resources - Scenarios	*Scenario combinations of cost and planned installed capacities*
	Resources - Scenario Costs	*Database of resource all-in fixed investment costs for expansion*
	Resources - Scenario Build	*Database of resource planned installed capacities*
RAW INPUTS	Inputs2Write	*Calculation worksheet that converts inputs from all other tabs into model-ready input tables. Do not edit*
	Inputs2Write_Hourly	*Calculation worksheet that converts inputs from all other tabs into model-ready input tables. Do not edit*
LISTS	Lists	*Calculation worksheet with supporting lists and tables. Do not edit*

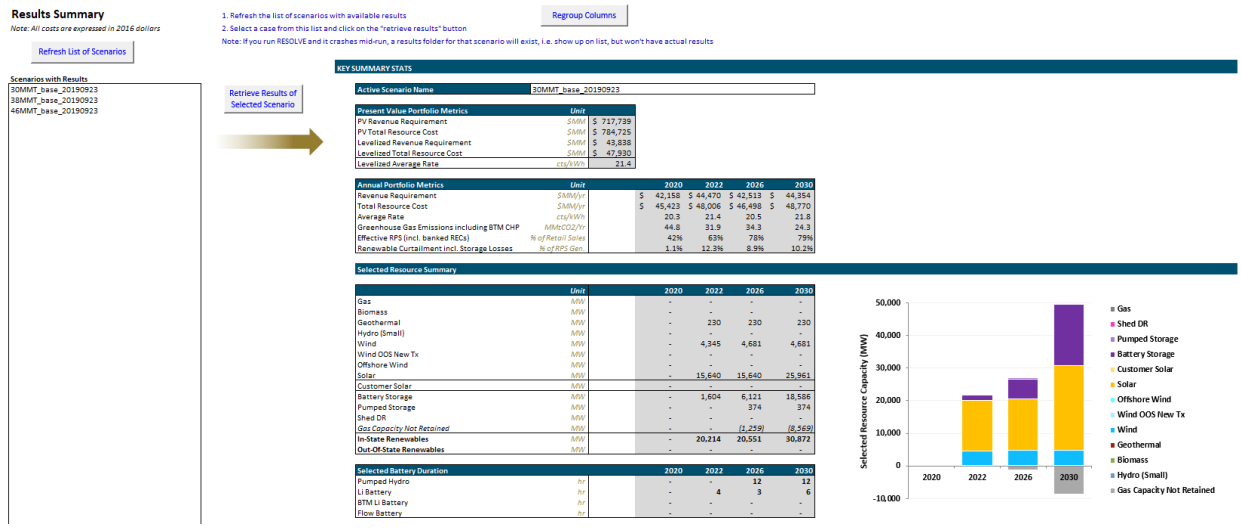
3.2 RESOLVE Results Viewer

The Results Viewer allows the user to look at the summary results of a scenario of interest. It contains four main worksheets: Dashboard, Portfolio Analytics, Scenario Comparison, and Lists. In addition, it contains a number of "raw" summary results files for the scenario of interest.

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 3.5. Results Viewer Dashboard



The Dashboard contains the following macro buttons:

4. The **"Refresh List of Scenarios"** macro lists all subdirectories that exist in the results directory. Note that if a RESOLVE run is interrupted mid-run, a results folder will be created but no results

will be available. Consequently, the user will not be able to load results for that scenario until the simulation has completed running.

5. 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.

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 contains key summary results for the CAISO zone, such as the resource buildout, portfolio costs, etc. The worksheet also includes graphs on the right side 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. Note that expanding the grouped columns will interfere with the formatting of the charts. If the user has created a RESOLVE scenario that looks at a different set of years than the default case (2020, 2021, 2022, 2023, 2024, 2026, 2030), the **"Regroup Columns"** macro will regroup the columns to show the representative set of years.

3.2.2 PORTFOLIO ANALYTICS

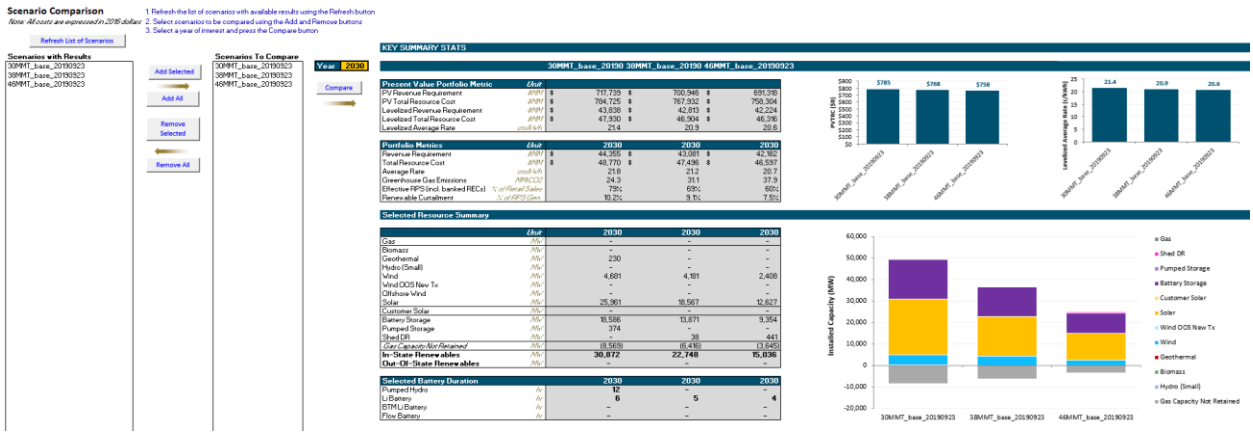
This worksheet contains more detailed summary tables that are pulled from the raw summary results worksheets and processed where necessary.

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, the **"Regroup Columns"** macro will regroup the columns to show the representative set of years.

3.2.3 SCENARIO COMPARISON

This worksheet is set up so the user can 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 3.6. 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. Results files must be present for all scenarios for the scenario comparison function to work.

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. It can take a few minutes to compare the results of many scenarios because the **"Retrieve Results of Selected Scenario"** macro on the Dashboard is 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 of Selected Scenario"** is run, these worksheets are updated. Note that while the user should be able to find all the information needed in the first three tabs, if there is interest in investigating the "raw_" tabs to filter or edit any specific data, rerunning the **"Retrieve Results of Selected Scenario"** macro will overwrite any changes that have made. In that case, make sure to press the **"Retrieve Results of Selected Scenario"** button twice to ensure all the "raw_" tabs are fully refreshed.

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.

4 RESOLVE Model Details

Advanced users may want to review the raw input and output files directly for their own analyses. This section provides a description of the raw files.

4.1 Raw Input Files

When the user selects and runs a scenario from the Scenario Tool, 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 4.1**. Some input files are only written when certain features are enabled.

Table 4.1. RESOLVE Raw Input Files

Input File	Description
capacity_groups.tab	Specifies which resources are in each annual capacity installation limit group.
capacity_limits.tab	The maximum capacity of each resource that can be built in each period. Resources that do not have capacity limits 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 and daily capacity factor limit (i.e., call hours/day) from conventional (Shed) demand response resources.
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.
feature_toggles.tab	Toggles to enable/disable optional features. Some optional features may not work without input data.
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.

Input File	Description
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.
flexible_params.csv	The maintenance derate fraction (1 is fully available, 0 is completely unavailable) for each resource that has a specified maintenance schedule. Other parameter values can also be set using this input file.
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.
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.
hydro_resources_ramp_limited.tab	Hydro resources that are subject to multi-hour ramping constraints.
hydrogen_electrolysis_daily_params.tab	The minimum hourly hydrogen load and daily average hydrogen load for each day.
hydrogen_electrolysis_period_params.tab	The hydrogen electrolysis installed capacity for each period.
inputs_passthrough.csv	Values to calculate total future revenue requirement and rate impacts of RESOLVE investment and operational decisions.
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).

Input File	Description
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, minimum operational capacity (lower bound on thermal retention), and fixed O&M cost of each resource in each period (as opposed to varying by vintage for new build resources). The capital 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 and fixed O&M cost of each storage resource in each period.
planning_reserve_margin.tab	The planning reserve margin target in each period, and other quantities related to the planning reserve margin. Also included is the amount of capacity needed in local areas in each period.
renewable_targets.tab	RPS target information by period.
reserve_resources.tab	Determines which resources can provide different reserve types.
reserve_timepoint_requirements.tab	The regulation and load-following reserve requirements in each timepoint.
resource_prm_nqc.tab	The net qualifying capacity (NQC) fraction for firm capacity and storage resources.
resource_tx_zone_map.tab	Specifies the relationship between resources and transmission deliverability zones.
resource_tx_zones.tab	Specifies whether the resource is located inside or outside of the planning reserve margin area (for resource adequacy accounting).
resource_use_tx_capacity.tab	Allocate dedicated firm transmission rights between zones to certain resources.
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.

Input File	Description
resource_vintage_params.tab	The annual capital cost per unit of capacity ($/kW-yr) and fixed O&M cost by resource (new build resources only) and vintage.
resource_vintage_storage_params.tab	The annual fixed cost of per unit of energy capacity ($/kWh-yr) and fixed O&M cost for storage resources by vintage.
resources.tab	Defines for each resource the associated technology, zone, RPS eligibility, and other characteristics.
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.
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, 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.

Input File	Description
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_timepoint_load.tab	The input load in each zone in each timepoint.
zones.tab	The zones modeled, as well as flags that determine if the zone is included or excluded from various constraints (RPS, GHG, Planning Reserve Margin, Load Following), and the zonal spinning reserve requirements.

4.2 Python Scripts

The input files described in Section 4.1 are formatted to be the minimal set of information needed to formulate the linear programming optimization model written in Python. Users are not expected to interact directly with the Python optimization model or its accompanying input/output scripts; however, users are welcome to review the structure and logic of RESOLVE's formulation.

The Python scripts that make up RESOLVE are summarized in Table 4.2

Table 4.2. RESOLVE Python Scripts

Python Script	Description
run_opt.py	This is the 'main' script of the RESOLVE model. As described in Section 3.1.1.1, it takes one required argument: the name of the scenario to run. For example, to run a scenario named '**full_run**,' the user would 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** object, 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

Python Script	Description
	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.
fileio.py	Stores functions related to file input and output.

4.3 Raw Output Files

Output files in the root scenario **results** directory (e.g., **results/full_run/**) are created by **export_results.py**. 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.

Output files in the **summary** subdirectory within each scenario results directory (e.g., **results/full_run/summary/**) are created by **create_results_summary.py**. 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.

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.

Table 4.3. 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. Blank 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.

Output File	Description
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. Blank cells indicate that a GHG emissions target was not modeled.
ghg_imports.csv	This file contains the hourly GHG emissions imported along transmission lines.
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.
objective_function_value.txt	The final value of the objective function for each RESOLVE run.
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 • flexible load dispatch • storage charging These operational decisions are also converted to operational costs, including variable O&M costs, fuel costs, startup/shutdown costs, and curtailment costs. Blank cells indicate that RESOLVE does not make this decision.

Output File	Description
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 constraints of dispatchable thermal generation.
reserve_timepoints.csv	This file contains the hourly reserve commitment shortfalls (or violations) and shadow prices for each reserve product.
resource_build.csv	This file contains the investment and economic thermal retention decisions made by RESOLVE for each candidate resource in each period. This file also contains 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. The associated capital and fixed O&M costs for these build and retirement decisions is also included. Blank 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. Blank 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.