OptGen

User Manual

VERSION 8.0

PSR

Table of Contents

1 Instalation and manipulation data notes 4

1.1 Installation....4

1.2 Required space for installation....4

2 First steps....5

2.1 Opening OptGen Graphical User Interface....5

2.2 Directory selection....5

2.3 Creating a new case....5

3 General overview....6

3.1 Interface organization....6

3.2 How to navigate....8

4 Input data....10

4.1 Payment schedules....10

4.2 Project data....10

4.3 User-defined expansion plan....21

4.4 Firm energy/capacity constraints....23

4.5 Minimum and maximum additional constraints....27

4.6 Hydro inflow scenarios....28

4.7 Typical day calculator....29

5 Model parameters....32

5.1 Study options....32

5.2 Selections....35

5.3 Execution options....35

6 The Graph Module....40

6.1 Introduction....40

6.2 General options....40

6.3 Stage selection....41

6.4 Load block selection....41

6.5 Series selection....41

6.6 Axis title (optional)....41

6.7 Variables, agents and macro agents selection....41

6.8 Filters 42

7 Model output files 43

7.1 Output files in worksheets 43

7.2 Additional output files 44

1 INSTALATION AND MANIPULATION DATA NOTES

1.1 Installation

The user can install the OptGen model by downloading it directly from our website www.psr-inc.com. At our webpage, in the menu located at the upper part, select "Software > OptGen". In the next page, the last available version will be on the right menu. Press it and step through the installation setup. The user can also save the setup file in the computer for a later installation.

Please observe that the program must be installed using Administrator rights in order to correctly install all the required files.

At the moment of installation, a password is required. This password is sent by email to the licensed users when a new version is released.

The new features and corrections of the model are described in the Changelog file. It can be accessed from OptGen's graphical interface in the main menu option "Help > Changelog". Please, read it carefully before using each new version of the model. OptGen user and methodology manuals can also be found in the "Help" option.

To run the model, a hard lock key inserted at one of the USB ports is required. This key is specifically programmed for each user and sent at the moment of the license acquisition.

1.2 Required space for installation

OptGen requires 500 MB of free disk space to install the system. Observe that the outputs generated by the model might fill a lot of disk space, depending on the study case dimensions.

2 FIRST STEPS

2.1 Opening OptGen Graphical User Interface

The model is initialized by opening the OptGen's graphical interface. Using Windows platform, the OptGen model can be executed from the desktop, by selecting the OptGen icon, or from the menu "Start > Programs > PSR > OptGen".

2.2 Directory selection

Once the interface is opened, the first step is to choose the directory where the input data are located. Click on Browse to search the chosen directory. Analogously to the SDDP model, OptGen also allows the user to keep, in the same directory, data for different load blocks configuration. For this reason, in this screen, the user must define the number of load blocks and the stage type (weekly or monthly) to be considered.

2.3 Creating a new case

If there is no OptGen data at the selected directory, the interface automatically creates new data considering standard values for the execution parameters.

3 GENERAL OVERVIEW

3.1 Interface organization

The OptGen model interface is divided in two main sections: a toolbar of the main menu and the main screen.

3.1.1 Main menu

At the top of the screen, the user can find the main menu (toolbar) that contains the buttons to access data editing, model execution and output visualization screens. Each of the options presents a series of secondary options which are presented below (those that are not described here have a section dedicated to its explanation in this document):

a) *File*
   - *Save*: saves changes made in the main screen options
   - *Directory*: selects a new data directory
   - *Compact case data*: generates a zip file containing all OptGen-SDDP input data files
   - *Exit*: exits the model

b) *Edit*
   - Launch SDDP: given an OptGen-SDDP database, all operating data is managed by the SDDP model, this option enables the user to directly access the SDDP interface and edit any operating data
   - *Payment schedules*
   - *Projects*
   - *User-defined expansion plans*
   - *Firm energy constraint*
   - *Firm capacity constraint*
   - *Minimum and maximum additional constraints*
   - *Hydro Inflow scenarios*
   - *Typical day calculator*

c) *Options*
   - *Set directories*: enables the user to set the installation directories for the SDDP model and the MPI application

d) *Run*
   - *Optimization*: executes expansion planning optimization
   - *Graph*: enables the user to access the *graph module* for output reports visualization

e) *Reports*
   - *Execution report*
   - *Optimal expansion plan*
   - *Detailed expansion plan*
   - *Convergence report*
   - *Optimal expansion CAPEX value*
   - *Optimal fixed expansion O&M value*
   - *Long run average cost*
   - *Long run marginal cost*

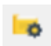
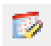
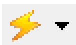
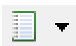
f) *Tools*

- *Activate dashboard:* enables the dashboard to be opened automatically after every execution

g) *Language*: allows the user to select the language of the graphical interface and output reports
- *English*
- *Spanish*
- *Portuguese*

h) *Help*: provides access to the following documents:
- *Detailed changelog*: file that contains a brief explanation of the latest modifications and improvements made in the model usually related to minor releases
- *Update license*: if the user gets the "Wrong Hard Lock – Error code 0003" error message, he should first use this option to update the licensing file and try to run the model again. If this error message still appears, the user should contact PSR's OptGen Support Service through e-mail: optgen@psr-inc.com
- *Methodology manual*: option to access OptGen's methodology manual
- *User's Manual:* option to access OptGen's user manual

In the second line of the menu are located the buttons with the most common options, according to the following table:

Button	Option
	Open
	Save
	Launch SDDP
	Payment schedules
	Project data
	User-defined expansion plans
	Firm energy constraint
	Firm capacity constraint
	Minimum and maximum additional constraints
	Hydro inflow
	Typical day calculator
	Optimization
	Clean case folder
	Check data
	Graph
	Open Dashboard
	Reports

	Exit
	Help

3.1.2 Main screen

The main screen is divided into three sections:

a) Study options

Constitute the general execution options of an expansion study, associated with planning criteria, study horizon, economical parameters, etc.

b) Selections

Projects

Presents all candidate projects that exist in the OptGen-SDDP database. In this screen, the user is able to (i) visualize a summary of the project characteristics at the bottom of the screen by clicking over the project and (ii) select (or unselect) each project to be considered (or not) in the current OptGen execution.

Constraints

Presents all constraints defined in the "Minimum and maximum additional constraints" screen and the user is able to select which ones will be contemplated (or not) in the execution.

Inflow scenarios

Contains the selection of deterministic or multi-deterministic Hydro inflow scenarios that will be considered in the study and their associated probabilities. It's worth noting that these scenarios will only be used if the "Operation model" option, in the "Expansion planning" or "Expansion plan simulation" frames in the "Study Option" tab, is set to be "Scenarios".

Critical scenarios

Contains the selection of the groups of sensitivities that have been created to emulate the severe conditions that will be considered in the resilience step during the expansion planning phase. These scenarios will only be used if the "Resilience (Critical scenarios)" option is checked in the "Expansion planning" frame in the "Study Option" tab.

c) Execution options

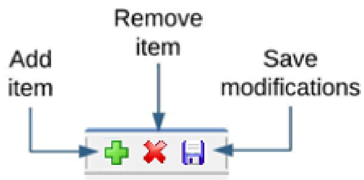
Contains the specification of execution and convergence parameters, and also the selection of heuristic solution procedures.

3.2 How to navigate

3.2.1 Opening, editing and saving data

The interface toolbar (second line of the main menu) allows the user to open the screens associated to each data type. By clicking on one of the buttons, the visualization and editing screen associated to the correspondent data opens immediately. A list displays items in the order they were added, and the first item is automatically selected.

At the upper part of the data screen, there is a toolbar that contains the options to add and remove items, as shown below, and other specific options for each data type.



By selecting an item from the list, all fields on the screen are associated with the information of this item. All enabled fields can be edited. If any data change occurs, a screen will appear asking for confirmation to save these modifications. The user can choose to either save or ignore the modifications. This message allows the user to discard undesired modifications.

An information button is available in some features to clarify the usability. Pause the mouse over it and an informative message will appear.

3.2.2 Data handling

OptGen incorporates a series of Microsoft Excel controls that can be utilized on all screens that have Excel-like cells, such as hydro inflow scenarios, firm capacity / energy constraints and other screens. Thereby, OptGen is provided with a powerful data editing and analysis tool, which includes: (i) compatibility with all MS Excel spreadsheets, i.e., the user can manage the data using an Excel spreadsheet and afterwards load it into OptGen, using Windows copy and paste functions; and (ii) buttons to cut, copy and paste directly in the interface.

Next chapter will describe all screens and input data of OptGen following the order the options are available in the interface.

4 INPUT DATA

In order to create an expansion planning study case, the user must inform the investment and operating data for all components of an electrical energy system. All the operating input data are handled by SDDP model and the detailed description is available in SDDP's User Manual.

In this chapter, the investment input data, which are handled by OptGen, will be described in detail. The data description will respect the order of the buttons in OptGen's main menu from left to right.

4.1 Payment schedules

Different payment schedules may be created to fulfill the characteristics of different types of projects. The configuration options are:

a) *Code*

b) *Number of disbursements*

Represents the number of annual disbursements (usually performed during the project's construction) to pay a project's investment cost, and it's used by the model in order to calculate the final capital expenditure (CAPEX) of the project.

c) *Year of entrance into operation*

Represents the relative year in which the project's starts operating since its construction decision. This value should be equal to the number of years for construction time plus one.

d) *Disbursements (%)*

Represents the percentage of the investment cost paid in each annual disbursement. The sum of all disbursements must be equal to 100%.

For more information on OptGen disbursements and how the payment schedules are used inside the model, please refer to the "Investment cost treatment and evaluation" session.

4.2 Project data

First of all, OptGen is very flexible and many different candidate projects may be contemplated in the study, such as: (i) energy production components: hydro, thermal and renewable plants; (ii) interconnection links and transmission circuits (lines, transformers, DC links, etc.); (iii) gas pipelines, production nodes, regasification stations. It is important to explain what a candidate project is and how to create one. For the sake of explanation, let's imagine that we are dealing only with energy production components and let's divide the plants into three different types:

- Type A: existing plants;
- Type B: future plants which have a date of entrance in operation already defined (committed plants that are usually part of the short-term expansion plan and may also already be under construction);
- Type C: future plants whose entrance in operation decision, whether it should be built and when, needs to be optimized (not yet committed plants that are part of a portfolio of candidate projects for long-term expansion).

Since all the operating data are defined in the SDDP model, then all the future plants of an SDDP database are eligible to be considered as projects by OptGen, i.e., the plants of Types B and C. This concept is extended to all other aforementioned agents that can be considered as candidate projects.

Based on that and assuming that all operating data are already defined in the SDDP model, then in OptGen's "Project Data" screen, there are two ways of creating new projects: (i) one by one addition by clicking on the button; (ii) an automated importation procedure by clicking on the button, which imports all future plants (those of Types B and C) presented in the SDDP database.

As a common practice, the importation procedure is only applied in the creation of the OptGen-SDDP expansion planning case. Afterwards, since only incremental project additions would be made (besides investment data updates), users usually perform one by one extra additions. It's worth noting that if the user defines some project data and then apply the importation procedure, all previous project data would be replaced.

4.2.1 One by one project addition and removal

The one by one addition procedure is straightforward. By clicking on the button, all future agents defined in the SDDP database will appear. Then, the user is able to filter by agent type and/or per system. After that, the user should click on the agent in the selection screen and click on the "Ok" button.

After creating the projects, the user is also able to remove any project by clicking over the project and then on the "Remove" button which stays immediately to the right of the "New" button. It's worth noting that the removal of a project from OptGen has no effect on the SDDP operating database.

4.2.2 Importation procedure

This feature allows the user to automatically create project data for OptGen's investment module by importing all the future agents from a SDDP database.

It is also possible to create typical values for project groups to be used by the importer, in the same importation screen. This option may be accessed by clicking on the "Show options >>" button. For each project group, it is possible to define a different investment cost, financial lifetime and O&M cost. The user can create project groups by selecting capacity intervals within each project type. For thermal projects, however, groups are created according to thermal plants' fuel.

Important note: the importation process overwrites all projects and payment schedules information. All previously created data will be erased from OptGen's current data directory.

It's also worth noting that while applying this importation procedure, all future plants of Types B and C will be brought as projects for OptGen. Further details on that will be provided in the next session.

4.2.3 Understanding how elements (whether being projects or not) are handled and the automatic integration between OptGen and SDDP

First, it is important to clarify that there is a clear separation of the plants defined in a SDDP database: (i) plants that only exist in SDDP model and (ii) plants that the user selected as projects for the OptGen model.

For elements belonging to group (i), the ones that only exist in SDDP, i.e. the existing and the future elements that are not selected as projects, all the modifications defined in the SDDP model will always be contemplated and will never be changed or deleted by the OptGen model.

For elements belonging to group (ii), the future elements selected as projects, the OptGen model itself controls all its modifications automatically. Therefore, all modifications previously defined in SDDP for plants selected as projects in OptGen will be automatically disregarded, since OptGen will decide if the element will be built and when.

Just to exemplify, if the user executes OptGen and it decides to build a plant X in 2025, a modification in this stage will be automatically printed in the corresponding SDDP modification file. If the user accesses the modification screen in SDDP interface, this information will be there. However, if the user makes a change in the case and runs the model again, then OptGen will automatically erase the entry of the plant X in 2025 and do all the optimization again. If, in this second execution, OptGen decides that plant X enters in operation in 2022, the modification of this plant will be printed for 2022.

Now back to the definition of Types A, B and C, all the plants of Type A belong to group (i) and all the plants of Type C belong to group (ii). With respect to the committed plants, the ones of Type B, they can be (or not) considered as projects for OptGen, depending on the user's choice. It's worth to remember that if the importation procedure is applied, they will be automatically imported also as projects. If the user wants, he can remove all of them of the project data. In this case, the elements of Type B will belong to group (i). On the other hand, if these plants remain as projects for OptGen, they will belong to group (ii).

Usually, the users that maintain them as being projects, do it in order to easily perform sensitivity analysis by changing their date of entrance into operation to see the impacts in the final expansion plan. As will be further explained in this document, the user can define an user-defined expansion plan and make the OptGen model read it through the "Read an expansion plan" option. So, since OptGen controls all modification data related to the projects, if the user just changes the date of entrance into operation of the project in the user-defined expansion plan, this will be automatically contemplated and handled by the OptGen model.

In summary, all modifications related to elements that are not defined as projects for OptGen, will never be changed by the OptGen model, only the user can manually change them. On the other hand, all the modifications referring to the projects are automatically controlled by OptGen.

4.2.4 Project decision and variable types

The project decision and variable types are located immediately below the project selection screen and are described in this section. In the following sections, the "Financial data", "Entrance schedule" and "Chronological costs" screens will be explained detail.

a) *Decision type*

Allows the user to choose whether a project's investment decision is optional or obligatory. For optional projects, OPTGEN decides when and whether it should be built or not. For obligatory projects, the decision to build the project is already taken beforehand and as consequence the model only decides when it should be built respecting the project's minimum and maximum dates of entrance into operation.

b) *Variable type*

Allows the user to choose whether a project's decision is represented in the optimization problem by a continuous, binary or integer variable.

In the case of continuous variable, OptGen can decide to build any percentage (between 0% and 100%) of the project's capacity. This option is usually applied to: (i) new hotspots of intermittent renewable projects, from which the user sets the maximum potential that is accepted in the hotspot and runs OptGen to determine the optimal amount for the system; (ii) in some specific studies when the complete detailing of thermal plants is not necessary and the user seeks to optimize the generation technology mix in a given year (usually the horizon year of the study horizon); (iii) generic projects for sizing new requirements on batteries, interconnections and DC links.

For binary variables, the model can only decide whether to build the entire project's capacity or not (0% or 100%). This option is usually used for (i) hydro projects; (ii) thermal projects, when all project details are available and (iii) transmission projects.

As the time required by the model to optimize the expansion problem is substantially affected by the number of binary or integer variables, the user can also define projects which are represented by binary variables during the first stages and continuous for the remaining planning period. The "Continuous after" option represents the stage in which a binary decision variable will be replaced by a continuous variable.

For integer variables, OptGen considers the project as being binary modules that can be added as many times as it's economical efficient during the optimization process. An upper bound on the total number of twin modules that can be added is informed in the "Maximum number of projects" field.

4.2.5 Financial data

a) *Investment cost (M$ or $/kW or M$/year)*
As presented above, there are three types of units in which the user can define the investment cost for each project. It's worth noting that inside the model, independently of the chosen unit, the investment cash flow will always be calculated as explained in the "Investment cost treatment and evaluation" session.

b) *O&M cost ($/kW year)*

Represents the fixed annual operation and maintenance cost of the project.

c) *Electric integration cost ($/kW)*

Represents the cost for connecting the project to the power network. Usually reflects the costs of the exclusive use transmission line and substation that are necessary to connect the plant to the grid.

d) *Project's annual discount rate (%)*

Represents the interest rate used to calculate the annualized investment cost of the project in case it's defined in M$ or $/kW. However, in order to calculate the Net Present Value (NPV) of the disbursements, OptGen will always use the systemic discount rate defined in the “Study options > General parameters” screen.

To calculate the annualized cost, if the checkbox is activated, OptGen will use the project’s discount rate defined by the user in this field. Otherwise, the model will use the systemic discount rate defined in the “Study options > General parameters” screen.

e) *Payment schedule*

Identifies the payment schedule used by the project and defined at the “Payment schedule” data screen.

f) *Financial lifetime (years)*

Represents the amortization time of the project’s total investment cost.

g) *Substitutes an agent*

Identifies an agent (plant, interconnection, transmission circuit, etc.) which will be replaced if the project enters in operation. This option is usually applied to evaluate the project’s repotentiation, refurbishment and retirement options.

h) *Mean capacity factor, warranted capacity factor and utilization factor (%)*

For each project, OptGen calculates a reference marginal cost ($/MWh) and print it in the execution report. The reference marginal cost is calculated as follows:

Hydro plants:

$$\frac{ca \cdot 10^6}{\omega \cdot MF \cdot 8760h}$$

Thermal plants:

$$\frac{ca \cdot 10^6 + co \cdot \omega \cdot MF \cdot 8760h}{\omega \cdot WF \cdot 8760h}$$

Renewable plants:

$$\frac{ca \cdot 10^6}{\omega \cdot MF \cdot 8760h}$$

Interconnections, DC links and circuits:

$$\frac{ca \cdot 10^6}{\omega \cdot UF \cdot 8760h}$$

where:

ca	Annual investment cost	M$
co	Unitary operative cost	$/MWh
ω	Installed capacity	MW
MF	mean capacity factor	p.u.
WF	warranty capacity factor	p.u.
UF	utilization factor	p.u.

The user defines MF, WF, and UF, depending on the project's technology. Based on that, OptGen computes the reference marginal cost of each project and print it in the execution report (optgen.out file). The reference marginal cost is also known as the Levelized Cost of Energy (LCOE) in the literature, which is a metric to compare different technologies directly in $/MWh. As can be seen, since the aforementioned calculation is based on user-defined parameters before OptGen's execution, the reference marginal costs are for information purposes only and don't affect the optimization results. Furthermore, it's very important to emphasize that the final LCOE of each project is a result of the optimization process, since the dispatch factor of all plants will depend on the system operation among the study horizon contemplating the optimal expansion plan. As a consequence, the reference marginal costs must be seen as a pre-processing information to provide feelings of each technology competitiveness in comparison to the others.

4.2.6 Entrance schedule

a) Minimum / Maximum dates

Represent the project's earliest and latest dates for entrance into operation.

b) Operative lifetime

Represents the number of years that the project remains in operation. In practical terms, after this period, the project will have its capacity set to zero and will no longer pay for the O&M costs.

c) Unit entrance schedule

While constructing a generation project, it is possible that the plant may not be fully powered all at once, given the plant's commissioning process and motorization. This schedule represents the units' entrance chronogram of a power plant project. The user can specify up to ten stages for powering the plant. To do so, one can complete a chronological data table with the number of generating units and the correspondent relative entering stage. The main application of this option is for big hydro power plant projects, on the other hand, it may also be applied to thermal and renewable projects, if needed.

In order to exemplify, let's imagine a power plant that has four generating units. The first two units come into operation in the project's date of entrance into operation and the other two enter six months after. So, in the first column, the user should define: row "Month" = 1; row "Units" = 2. In the second column, the user should define: row "Month" = 6; row "Units" = 2.

4.2.7 Chronological costs

4.2.7.1 Investment and O&M costs

In this screen, the user is able to define the project's investment cost changing in time. In the first column, the user sets the year, in the second the investment cost (respecting the same unit chosen for the given project) and in the third the fixed O&M cost. These costs are associated to the project's decision year, with the fixed O&M cost being applied during the project's operative lifetime. This means that if OptGen decides to build the project in year X, the investment and fixed O&M costs over the entire lifetime of the project will be the ones defined for this year X. If OptGen decides to build the project in year Y, these costs over the lifetime of the project will be those defined for year Y and so on.

For example, let's suppose a 3-year horizon planning study (2020-2022) and a project with the following chronological O&M cost definition:

Year	O&M ($/kW year)
2020	10
2021	20
2022	30

If the project is selected to enter in operation in 2020, it will pay 10 $/kW in 2020, 2021 and 2022. If it's selected to enter in 2021, it will pay 20 $/kW in 2021 and 2022; and if it's selected to enter in 2022, then it will pay 30 $/kW in 2022. In summary, as mentioned before, these costs are associated with the project's decision year.

This option is particularly useful to incorporate CAPEX reduction curves usually related to non-conventional renewables (such as solar and onshore/offshore wind) and batteries, since the price of these technologies are worldwide falling due to technology maturity and economic scale gains.

4.2.7.2 Variable O&M costs

In this tab, the user can inform different O&M costs to be considered at each year of the project's operative lifetime. Then, if the user activates the "Consider variable O&M costs" option, the (fixed) O&M costs that should be defined on this screen change over time after the in-service date, i.e., the value defined for year 1 will be used for the first year of operation; the value defined for year 2 will be used for the second year of operation, and so on, and so forth. When selected to be considered, this data overwrites every other value informed for the project's O&M cost.

For example, let's suppose a 3-year horizon planning study (2020-2022) and a project with the following chronological O&M cost definition:

Year	O&M ($/kW year)
1	10
2	20
3	30

If the project is selected to enter in operation in 2020, it will pay 10 $/kW in 2020, 20 $/kW in 2021 and 30 $/kW in 2022. If it's selected to enter in 2021, it will pay 10 $/kW in 2021 and 20 $/kW in 2022; and if it's selected to enter in 2022, then it will pay 10 $/kW in 2022.

4.2.8 Investment cost treatment and evaluation

In order to evaluate the investment cost associated to the construction of each project for each possible stage of the study horizon, the following input data (already taking a numerical case example into account to become more intuitive) is considered by the model:

Payment schedule:

N	number of disbursements	2	
n^0	year for entrance in operation	2	
p_n	disbursements	[60% ; 40%]	%

Project data:

c^{inv}	investment cost	99	M$
c^{ele}	electric integration cost	10	$/kW
$c^{o\&m}$	fixed operation & maintenance cost	10	$/kW-year
ω	installed capacity	100	MW
L	financial lifetime	10	years
tx^{prj}	project's discount factor	10%	%

For the sake of this exercise, let' imagine the study horizon T is 2030-2039 and the project enters in operation in 2031 (second year of the study horizon). In this case, the following annual disbursements are needed to pay the project's investment cost in this case example:

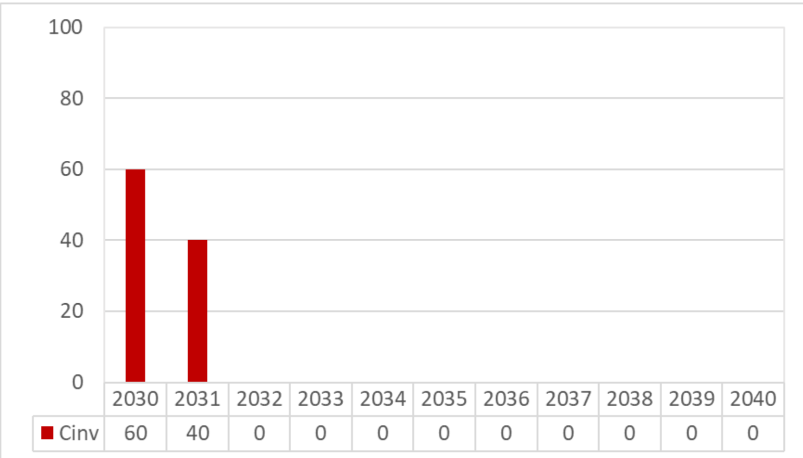


Figure 4.1 – Annual disbursements to pay a project's investment cost

Then, the following steps are automatically performed by the OptGen model:

Step 1: the sum of investment cost and electric integration cost is referred to the year of entrance into operation considering the payment schedule, as follows:

$$c0 = \left(c^{inv} + \frac{c^{ele} \cdot \omega}{1000}\right) \cdot \sum_{n=1}^{N} \frac{p_n}{100} \cdot (1 + tx)^{(n^0 - n)}$$

$$c0 = 100 \times (0.6 \times 1.1 + 0.4) = 106 \text{ M\$}$$

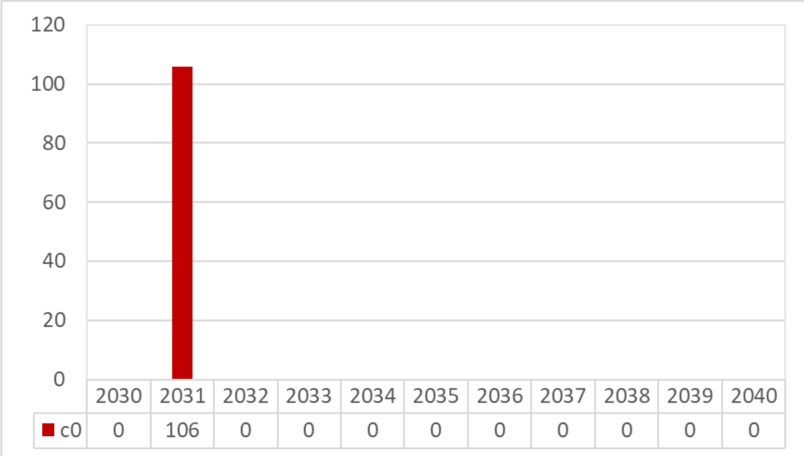


Figure 4.2 – Project's final CAPEX

Step 2: the annual investment cost (also called annualized cost) is calculated and contemplated as a periodic payment flow during the project's financial lifetime, which in turn will correspond to the total investment cost. Then, the fixed operation & maintenance cost is aggregated to this value:

$$ca = c0 \cdot \frac{tx \cdot (1+tx)^{(L-1)}}{(1+tx)^{L} - 1} + \frac{c^{o\&m} \cdot \omega}{1000}$$

$$ca = 106 \cdot \frac{0.1 \cdot (1.1)^{9}}{(1.1)^{10} - 1} + 1$$

$$ca = 16.68\ M\$/year$$

As a consequence, the figure below presents the investment cash flow of the project within the study horizon:

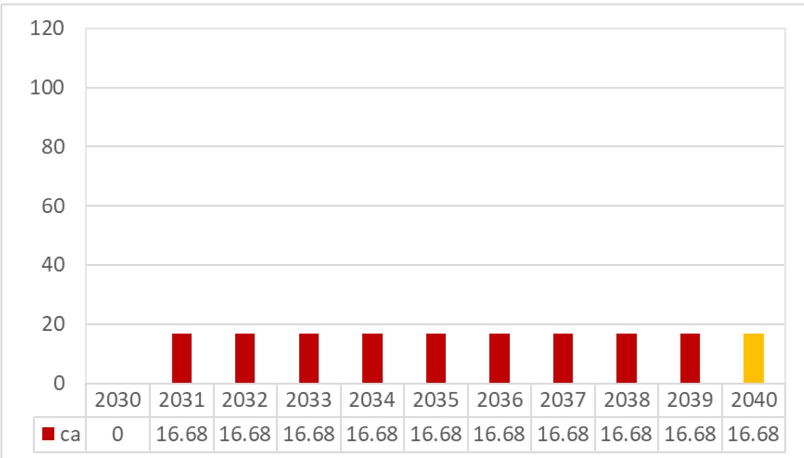


Figure 4.3 – Project's cash flow inside the study horizon 2030-2039

Although this cash flow can start before the project entrance date (during the construction period) and end many years after the end of the study horizon, the annuities considered by the model are associated to the period within the study horizon in which the project operates. As can be seen in the example, there are only 9 annualized costs within the study horizon and the project's financial lifetime is 10 years. In this case, the model automatically transforms the annual costs that go beyond the study horizon into an end-of-period residual value. This will be better detailed in the remaining of this session.

Step 3: the Net Present Value (NPV) of this cash flow is calculated and referred to the year of entrance into operation.

$$ce = ca \cdot \frac{(1+tx)^{L'} - 1}{tx \cdot (1+tx)^{(L'-1)}}$$

where L' is the number of years within the study horizon in which the project operates:

$$L' = min\{T - t^0 + 1, L\}$$

Therefore, the value of ce in this example will be:

$$ce = 16.68 \cdot \frac{(1.1)^9 - 1}{0.1 \cdot (1.1)^8}$$

$$ce = 105.68\ M\$$$

Step 4: this cost is now referred to the initial year of the study.

$$ct = ce \cdot \frac{1}{(1+tx)^{(t^0-1)}}$$

where t^0 is the stage of entrance into operation:

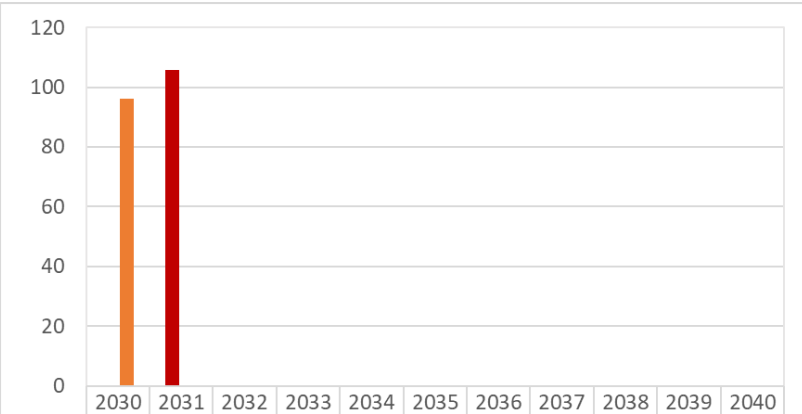
$$t^0 = t + (n^0 - 1)$$

Consequently, in this example case ct will be:

$$ct = 105.68 \cdot \frac{1}{(1.1)^1}$$

$$ct = 96.08\ M\$$$

The following figure presents the NPV of the project's investment cost:



	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
co	0	105.7	0	0	0	0	0	0	0	0	0
ct	96	0	0	0	0	0	0	0	0	0	0

Figure 4.4 – NPV of the project's investment cost

The table presented below summarizes the NPV of the investment cash flow based on the project's date of entrance into operation t^0:

t	t^0	L'	ct
1	2	9	96
2	3	8	81
3	4	7	67
4	5	6	55
5	6	5	43
6	7	4	33
7	8	3	23
8	9	2	15
9	10	1	7

For the evaluation of the terminal value cr, we define L^r as the remaining years of the project's financial lifetime after end of the study horizon:

$$L^r = L - L'$$

If $L' = L$, then $L^r = 0$ and, therefore:

$$cr = 0$$

Otherwise, the terminal value is calculated as the net present value of the annual disbursements associated to years after the end of the study horizon:

$$cr = ca \cdot \frac{(1 + tx)^{L^r} - 1}{tx \cdot (1 + tx)^{(T + L^r - 1)}}$$

In summary, for the sake of the investment cost evaluation, we assume that the annual disbursements:

- begin at the same year of the entrance in operation
- end at the final year of the study or at the end of the project's financial lifetime
- are paid at the beginning of each year

Based on that, the cost associated to the construction decision of each project in each investment stage is evaluated for the period in which the project is available for operation. Consequently, in the optimization process, both investment and operation costs are accounted for the same period within the study horizon.

In the next sections, relational constraints between projects are described. These constraints can be defined immediately after the project's creation/importation procedure.

4.2.9 Exclusive projects

The "exclusive projects" constraints may be defined by clicking on the button. This option allows the user to inform a set of mutually exclusive projects. The model creates an exclusivity constraint so that either one or none of the projects of the list can be decided for investment. One application of this feature, for example, is the optimal selection of a power plant from a set of projects with different technologies.

Procedure:

1. Press the “New” button. Inform the name of the constraint and press “Ok”.
2. Move projects that will be included in this constraint to the “Selected” list. Use the filters to help finding projects of a specific type and system.
3. Save changes and exit the screen.

4.2.10 Associated projects

The “associated projects” constraints may be defined by clicking on the button. This option allows the user to inform a set of associated projects. The model creates an association constraint so that either all or none of the projects of the list can be decided for investment. Since the associated projects can be constructed in different stages along the planning horizon, the user is also able to set a maximum delay (years) between the projects entrance in operation.

Procedure:

1. Press the “New” button. Inform the name of the constraint and press “Ok”.
2. Move projects that will be included in this constraint to the “Selected” list. Use the filters to help finding projects of a specific type and system.
3. Specify the maximum delay between the projects entrance in operation.
4. Save changes and exit the screen.

4.2.11 Precedence constraints

The “precedence” constraints may be defined by clicking on the button. This option allows the user to specify the projects entrance order with a minimum time delay.

Procedure:

1. Press the “New” button. Inform the name of the constraint and press “Ok”.
2. Move projects that will be included in this constraint to the “Selected” list. Use the filters to help finding projects of a specific type and system.
3. Use the up and down arrows located on the right part of the screen to switch projects’ precedence order.
4. Specify the minimum delay time between projects entrance date.
5. Save changes and exit the screen.

4.3 User-defined expansion plan

Allows the user to create a new expansion plan to be considered by the model. This feature can be used either (i) for the evaluation of a fixed plan or (ii) for contemplating a partial plan during the optimization process that should be complemented with additional projects if necessary. To create a new user-defined expansion plan, the user should click on the “New plan” button.

Procedure:

1. Set the type of the plan:
    a. *Fixed*
    The OptGen model will read the expansion plan and consider all decisions as fixed, i.e., there is no margin for expansion optimization. In practical terms, this is just a purely dispatch optimization (can be interpreted as a SDDP execution) with the advantage of presenting additionally all investment outputs produced by OptGen.
    b. *Complement with other projects if necessary*
    The model will consider as fixed the decisions that take part of the partial plan defined by the user and will evaluate if it is worth or not to build any other project presented in the project data and selected for the current execution.
2. Use the “Add project” button ( ) to incorporate a new expansion decision into the plan.
    a. Select a project from the list. Use the filters to help finding projects of a specific type and system.
    b. For a fixed plan, only the “Decision date > Fixed” option will be available. In this case, set the decision date and the added capacity (MW).
        i. Activate or not the “Planned decision” option:
            - In this case, for all projects, this option is merely illustrative for report purposes. The main idea behind this option is to differentiate projects between themselves, i.e., this option is used to separate projects which in practice are already under construction (planned decisions) from the projects the user is fixing based on his own assumptions (not officially planned decisions). This information will be written in the 10th field of the optimal expansion plan file.
    c. For a complementary plan, the user must:
        i. Set a “Fixed” or “Variable” decision date. In the case of being “Variable”, the user specifies initial and final dates, and the model optimizes the decision within this date range.
        ii. Set the decision type to be “Exactly”, “At least” or “At most” the specified value for added capacity (MW). Choosing the “Exactly” decision option means that OptGen will invest exactly the specified capacity value; “At least” decision means OptGen will invest more or equal the specified capacity value; lastly, “At most” decision means OptGen will invest less or equal the specified capacity value. Based on that:
            - For binary decision variables: it’s intuitive to see that only the “Exactly” option should be selected (if any other option is selected, an error message will appear while running the model). In this case, the project will be built in the fixed date or within the date range depending on the “Decision date” option;
            - For continuous or integer decision variables: if the user selects the “Exactly” option, the exact capacity value defined by the user will be built in the fixed date or within the date range depending on the “Decision date” option. By selecting the “At least” or “At most” options, this will be respectively considered as investment lower bound and upper bound in the fixed date or within the defined date range.
        iii. Activate or not the “Planned decision” option:

- In the case of binary decision variables: this option is merely illustrative for report purposes. This information will be written in the 10th field of the optimal expansion plan file.
- In the case of continuous or integer decision variables: this option affects the optimization process. If activated, the user does not allow the model to add more capacity of these projects out of the fixed date or outside the specified date range, since these projects are already under construction with the exact capacity defined by the user. If deactivated, then the model is free to add more capacity of the project in any other date which is different from the fixed one, or outside the specified date range.

3. Use the “Remove” button ( ) to eliminate an expansion decision selected from the plan.
4. Use the “Edit” button ( ) to modify decision dates and values of an expansion decision selected from the plan. For further details, see step 2.
5. Use the “Save” button ( ) to set the name of the expansion plan file.

It is also possible to open and edit previously defined expansion plans. The screen shows one plan at a time. To select another plan, use the “Open” button ( ).

After creating an expansion plan, the field “Read an expansion plan” will automatically appear as selected in OptGen’s main screen.

4.4 Firm energy/capacity constraints

Allows the user to specify firm energy or firm capacity constraints for each or all systems. By clicking on the button, the “Firm energy constraint” screen will be shown. If the user clicks on the arrow placed next to this button, the user will be able to select if he wants to access the “Firm energy constraint” or the “Firm capacity constraint” screen.

4.4.1 Firm energy constraint definition

Before explaining how to define the input data, it’s worth to provide a general overview of these constraints. The concept of firm supply arose at the end of the 19th century, when the sizing of reservoirs for water supply to the population was studied. The objective was to determine the storage capacity that would ensure a certain "firm" flow rate itself in the occurrence of the driest historical sequence.

The concept of firm supply was transferred to the electricity sector and applied to the economic sizing of hydroelectric projects. Essentially, for each capacity alternative of the reservoir and installation of machines, the resulting firm energy (sustainable energy production capacity) was calculated. The relationship between the construction cost of each alternative and its respective firm energy was used as a cost / benefit index that allowed comparing different project alternatives.

The concept of firm energy was then extended to a set of plants, with the aim of guaranteeing a certain amount of energy production, allowing oscillations of each plant’s production. This concept was widely used in inventory studies, which served to define the "fall division" of each river.

Subsequently, a probabilistic criterion has been proposed. Instead of guaranteeing a firm supply of water (or energy) considering the historical inflows (in particular, the “firm offer” is superiorly limited due to the worst historical drought), the “assured energy” was calculated, defined as the maximum production that can be maintained at a certain percentage - for example, 95% - of the simulated hydrological years. This probabilistic criterion, together with the consideration of the economic impact of the supply failures, began to allow a more detailed analysis of the cost / benefit ratio of investments.

In summary, countries dominated by hydroelectric power (*energy-constrain*ed systems), as in the case of Brazil, firm energy criteria are related to security of supply and are usually defined in order to minimize the risk of rationing, protecting the system from extreme situations. As stated above, there are different methodologies that can be applied in order to calculate the firm energy "certificate" of each plant, which could be based on (i) a probabilistic criterion or (ii) determinative criterion, for example, by seeing the maximum energy that each plant can produce with the worst historical inflow record (also known as the critical period).

At the end of the day, while expanding the system, the user is able to assign firm energy certificates to the plants (existing and future) and a systemic requirement to be met in each year (or in each investment stage, if desired). This is interesting because these constraints enter as "hard" planning criteria inside the investment module, that is, the OptGen model has to comply with it, otherwise the optimization problem is infeasible.

4.4.2 Firm capacity constraint definition

In *peak-constrain*ed systems, the major concern in the expansion planning task is to ensure that the system will be able to meet the peak demand in the long-term. Therefore, in order to protect the system against (unexpected) forced outages and lack of generators available in the system under "stress" situations, which usually happen at peak load moments, the user should incorporate a planning criterium in order to guarantee a certain (minimum) over-supply amount. This over-supply amount is defined as reserve margin. The reserve margin is the difference between the system available capacity and the demand, and as consequence, should incorporate warm and cold reserve requirements.

Based on that, the user may assign a firm capacity "certificate" of each plant (also known as capacity credit) and a systemic requirement to be met in each year (or in each investment stage, if desired). This is interesting because these constraints enter as "hard" planning criteria inside the investment module, that is, the OptGen model has to comply with it, otherwise the optimization problem is infeasible.

As stated above, this issue was an important concern only for *peak-constrain*ed systems. On the other hand, with the fast penetration of Variable Renewable Energy (VRE) in the systems, this scenario has changed.

The penetration of these new sources has also raised some concerns for both planners and operators for two main reasons: (i) most of these sources are non-dispatchable, i.e., its generation cannot be controlled by the system operator; and (ii) its energy production presents strong volatility, i.e., the production can change significantly from one hour to the next (due to its fluctuating nature). As a consequence, all systems with a massive penetration of VRE, which in the past could be classified as *energy-constrained* or *peak-constrained*, need to prepare themselves in order to have enough dispatchable generation in all moments, since we cannot guarantee that the wind will blow and there will be no cloud in the sky. Therefore, the firm capacity concern doesn't exist only in the peak load moments anymore.

In summary, the systemic requirement and capacity credit assignment must be carefully defined, especially for intermittent renewables.

4.4.3 Firm energy/capacity requirement definition

First of all, it's important to remind that the user is able to add firm energy and/or firm capacity constraints, as desired. Moreover, there are two different ways of defining the firm energy/capacity requirement. The first one is a simplified way through which the user specifies a firm energy/capacity factor per year.

As explained in the beginning of this session, if the user clicks on the arrow placed immediately after the  button, the user will be able to select if he wants to access the "Firm energy constraint" or the "Firm capacity constraint" definition screen. It's worth to emphasize that operationally speaking, the data definition in both screens are equal (and of course inside the model both are differently treated).

In the "Firm energy" or in the "Firm capacity" screen, the user should select first if he wants to incorporate a firm energy/capacity requirement for "<All systems>" and/or for each system (that means that the user can set one for "<All systems>" and also one for each system; or only for "<All systems>"; or only for a subset of the defined systems). All the systems that exist in the SDDP database will appear in this selection screen.

In order to better explain why the aforementioned options are available, we can use some examples. The Brazilian system is divided in many systems and the firm energy requirement is defined for the entire country. In this case, only one requirement for "<All systems>" is enough. Now, imagine another example in which the user doesn't want to rely on interconnections between system to supply the load. Then, he could also incorporate a firm energy/capacity constraint in each system. On the other hand, imagine we want to perform a study with the Central American database contemplating six countries. In this case, we could define firm energy/capacity constraints for each system, but there is no need to define for "<All systems>", since the countries import/export are based on opportunities.

Based on that, let's move on to the Firm Energy/Capacity Factor definition:

a) *Firm Energy Factor*

The user defines a factor per year. For each year, OptGen sums the demand in GWh defined in all blocks from all stages and divides by 8760 hours and will have the demand in GWaverage (GWavg) for each year. Then, the model multiplies this value by the Firm Energy Factor defined by the user in p.u. As expected, this value should always be greater than 1 p.u.

b) *Firm Capacity Factor*

The user defines a factor per year. For each year, OptGen picks the demand in GWh defined in all blocks from all stages and divides by the duration of the block and will have the demand in GW for all blocks in all stages for each year. Then the model picks the maximum value observed in the year and multiplies by the Firm Capacity Factor defined by the user in p.u. As expected, this value should always be greater than 1 p.u.

As can be seen, the approach to model firm energy/capacity constraints through yearly factors is a straightforward but fixed option, i.e., these factors are treated inside the model and the user has no flexibility to define any different constraint. The second way to define firm energy/capacity constraints is through minimum and maximum additional constraints, which will be detailed later in this document. This option is very flexible, allowing the representation of any user-defined firm energy/capacity constraint. In this case, the user includes as many plants as desired, introduces the requirement and also sets the dates of the constraints (incorporating therefore as many investment stages as wanted).

4.4.4 Firm energy/capacity certificate definition

There are two ways of defining the firm energy/capacity certificate of each plant: (i) by a systemic factor per technology or (ii) by each plant individually. Let's start with procedure (i). Since the certificate assignment methodology can change from system to system, first of all the user needs to select the systems he wants to define the factors.

Procedure:

1. From the list on the top of the screen, select the system for which the factor will be applied.
2. After selecting the system, the "Default value of firm energy/capacity (p.u.)" frame will be unlocked in the top right corner of the screen. Set the default firm energy/capacity value (p.u.) for the different types of plants (hydro, thermal and renewable) of the given system.

The default values (before user's edition) are:

	Firm Energy (p.u.)	Firm Capacity (p.u.)
Hydro plant	0.6	1
Thermal plant	1	1
Renewable source	0	0

The second way of defining the firm energy/capacity certificate of each plant is: (ii) by each plant individually. This can be done in the "Hydro plant data" / "Thermal plant data" / "Renewable source data" screens.

4.4.4.1 Hydro plant data / thermal plant / Renewable source data

These screens allow the user to set the firm energy (MWavg)/capacity (MW) certificates for each hydro / thermal / renewable plant presented in all systems. The values that automatically appear are the default values for each plant, i.e., the nominal capacity multiplied by the default firm energy/capacity value per technology (in p.u.). It's also worth mentioning that for the hydro plants, the "Capacity (MW)" shown is the minimum between the installed capacity and the product of the maximum turbining outflow and the mean production coefficient.

It's intuitive to see that if the user sets a specific value for a given plant, this value will overrule the default one and if no specific value is set for another plant, then the default value will be the applied one.

4.4.4.2 Hydro plant data / thermal / renewable source data modification

The modification screens allow the user to change the firm energy (MWavg)/capacity (MW) configuration data of hydro / thermal / renewable plants in time. Modifications can be included per plant in the "By plant" screen or per date in the "By date" screen (the latter respects the plant selected in the "By plant" screen). Modifications will overrule the information set in "Hydro plant data" / "Thermal plant data" / "Renewable source data".

4.4.4.3 Firm energy/capacity certificates during plant's commissioning process

As explained in the entrance schedule section, while constructing a generation project, it is possible that the plant may not be fully powered all at once and as consequence it presents a unit entrance schedule. In this case, during the motorization, the certificates will be calculated as follows:

- For thermal and renewables: both firm energy and firm capacity certificates follow the same logic and will be multiplied by an availability factor, which in turn is calculated as number of units in operation in the current investment stage divided by the total number of generating units. It can be interpreted as a linear ramp-up proportional to the number of units in operation.
- For hydro plants: the firm energy certificate will be the minimum between the firm energy certificate and the product of the maximum turbining outflow, the mean production coefficient and the availability factor. This means that up to the firm energy certificate of the entire plant, there is enough water for the units that are in operation and therefore the firm energy in the given time stage should be equal to the current installed capacity of the plant. Then, when the firm energy certificate of the entire plant is reached, it remains constant. On the other hand, the firm capacity certificate will be just multiplied by the availability factor (same logic as applied for thermal and renewables).

4.5 Minimum and maximum additional constraints

The expansion planning task must meet operational, economic and environmental criteria, within the framework of national policies on energy. Consequently, additional constraints can be defined in this screen in order to enforce OptGen to meet user-defined criteria so that the aforementioned expansion assumptions are attended.

This screen was designed to be very flexible in order to englobe a wide range of additional constraints the users can define, such as, specific reserve margin constraints, governmental policies regarding the insertion of a given technology, renewable penetration target, budgetary constraints, etc.

It allows the user to inform minimum and/or maximum installed capacity, or firm energy or firm capacity constraints for a set of existing and future elements.

Procedure:

1. Press the "New" button. Inform the name of the constraint and press "Ok".
2. Set the constraint type: "Installed capacity (MW)", "Firm energy (MWavg)" or "Firm capacity (MW)".
3. Set if the constraint will be "Incremental" or "Total":
    a. "Incremental": in this case, the user must set both initial and final dates in step 7.
    b. "Total": in this case, the user must set just the final date in step 7.

4. Set the constraint limit type: "Minimum (>=)" or "Maximum (<=)".
5. Set if the Right Hand Side (RHS) of the constraint will be an "Absolute value" or a percentage related to a single system or all systems. It's worth noting that the percentage options are only available in the case of "Total" constraints.
6. Inform the constraint RHS value:
   a. If the constraint is "Incremental", the defined value corresponds to the minimum/maximum that can be added in the specified time interval in step 7.
   b. If the constraint is "Total", the value corresponds to the total until the specified final date in step 7.
7. Set the initial (only for "Incremental" constraints) and final dates.
8. Select elements that will be included in the Left Hand Side (LHS) of the constraint. Use the filters to help finding elements of a specific type and/or system. It's very important to emphasize that not only projects are available in this selection screen, but all elements being existing or future (belonging to Types A, B and C) may be selected:
   a. In the case of a "Incremental" constraint, since the lower or upper limit value corresponds to the incremental amount that can be added in the chosen time interval, usually only future plants (belonging to Types B and C) are in the LHS of the constraint.
   b. In the case of a "Total" constraint, since the initial date is not specified, then the limit value corresponds to the total minimum/maximum amount that should be in the system by the final informed date. In this case, depending on the constraint application, it may (or not) incorporate existing and committed plants. As an example, if the user sets a total constraint to enforce a maximum penetration of carbon thermal plants in the system, since it should englobe all thermal plants that burn carbon, not only projects, then also existing and committed plants (belonging to Types A, B and C) should be in the LHS of the constraint.

4.6 Hydro inflow scenarios

Hydrological uncertainty is considered in the optimization of the expansion planning problem and its representation depends on the operative model (SDDP or Scenarios) selected by the user in the "Study options" tab of OptGen's main screen.

4.6.1 SDDP

The historical hydrological data of each plant, as well as the parameters of the stochastic model considered in the system operation are defined in SDDP interface. For further details, see the SDDP's User Manual.

4.6.2 Scenarios

The hydro inflow scenarios are defined in OptGen interface in the "Hydro inflow scenario" screen, where the values are informed in m^3/s for all hydro plants in each stage. To create a new scenario the user must press the "New" button and select how the scenario will be generated: manually or by extracting from SDDP / TSL scenario file or SDDP historical file.

When "Manual" option is selected, the user will add only one scenario at a time:

1. Inform the name of the scenario and press "Ok" button.

2. Select each hydro plant from the list on the right part of the screen.
3. Inform the water inflow values for each hydro plant in each stage. This data is handled by a chronological data table.

When “Extract from SDDP / TSL scenario file” option is selected, a set of scenarios will be imported from SDDP or TSL (Time Series Lab) forw.dat file. For further information about how this file is generated by SDDP or TSL models, please refer to the User Manual of the corresponding model.

1. Select the forw.dat file using the browsing tool.
2. Press “Ok” button.
3. All scenarios are automatically imported from the forw.dat file with identical occurrence probabilities by default.
4. Select each scenario from the list on the left and each hydro plant from the list on the right part of the screen to visualize and edit the inflow values.

When “Extract from SDDP historical file” option is selected, the user will import a set of scenarios from SDDP hinflw.dat file.

1. Select the hinflw.dat file using the browsing tool.
2. Inform the number of scenarios to be extracted and number of years that each scenario will have.
3. Inform if scenario MLT (mean long term) should be included. In this case, one of the scenarios will consist of a static scenario containing the monthly average inflow data.
4. Inform the year of the historical file associated to the initial year of each scenario.
5. Inform the occurrence probability of each scenario in p.u. The user can choose to inform these values manually or by pressing the button “Automatically generate probability”. In this case, all scenarios will have the same probability. Note that the sum of probabilities of all scenarios must always be equal to 1.
6. Inform if negative inflows should be turned into null values.
7. Inform if scenarios should be static. In this case, the inflows of the specified initial year will be repeated for all the years of each scenario.
8. Press “Ok” button.
9. Select each scenario from the list on the left and each hydro plant from the list on the right part of the screen to visualize and edit the inflow values.

After creating all the inflow scenarios, scenario selection and probability editing can be managed in the “Scenario selection” tab in the main screen.

4.7 Typical day calculator

First of all, it is important to point out that the “Typical day calculator” option is only useful for the solution strategy “OptGen 2” (this option has no effect on the solution strategy “OptGen 1”). Next a brief review on some important concepts about “OptGen 2” is presented below:

- The model considers annual investment stages, that is, a problem of co-optimization of the investment and operation is solved for each year forward in time in a rolling horizon scheme;
- Each year is divided into T seasons (for example, months or quarters). Seasons are a broader group of SDDP’s stages. While SDDP supports only weekly and monthly stages, seasons can last from a week up to one entire year. Seasons reduce computational execution times by

aggregating similar stages in the same operative decision. Seasons should follow each electric system seasonality and must be chronological.

- In turn, each season is composed of D 24-hour load profiles (for example, working days and holidays/weekends), also called typical days. The typical days are days within a season that are considered representative of the input data. Thus, instead of representing all days of a season, the user should select a certain number of typical days to represent different load profiles of each season. In this case, each typical day represents a group of "real" days (of course with similar load profiles). For instance, it is common to differentiate weekday from the weekend. A third group could also be created representing only Sundays and holidays;
- There may be S scenarios of renewable production and inflows for each season;
- System operation is carried out on an hourly basis, with unit commitment, generation reserve (including batteries and other storage devices) and regional interconnections (a full transmission network model is also available).
- Since "OptGen 2" performs the operation of the system using chronological hourly time steps with unit commitment, even applying the aforementioned assumptions and heuristics, for some large scale real systems the computational effort might be very high. In this case, another type of heuristic is available, which is called commitment blocks per day. The commitment blocks are used only to tie thermal commitment decisions. In other words, the model will decide the operative state of the thermal plants representing unit commitment at the beginning of each block and will maintain the same status until de end of the block.

For further methodological details, please refer to the OptGen Methodology Manual.

Based on the aforementioned review, the "Typical day calculator" option creates automatically the seasons, the typical days and the commitment blocks per day. So, after clicking on the  button, there are two parameters that can be chosen:

d) Number of seasons per year

The user must inform the desired number of seasons in the year. For monthly cases, the default value is 12 meaning that each month will be one season. For weekly cases, the default value is 52 meaning that each week will be one season.

e) Number of commitment blocks per day

The user must inform the desired number of hours in each commitment block per day. The default value is 24 meaning that the unit commitment decision will be performed in each hour from each typical day inside each season.

It's worth to emphasize that this execution requires hour-block mapping data already defined in the SDDP database. For further information on that, please refer to the SDDP User Manual.

After setting these parameters, the user may press the "Run" button. This calculator will perform the following actions:

- Mapping of months/weeks to seasons;
- Mapping real days to typical days. The calculator will create two typical days in each season (weekdays and weekends). The first typical day of each season will be calculated based on every weekday, i.e., using the hourly demand of the five days with the greatest load values in

each week. The second will represent the weekends (based on the two days with the lowest load values in each week;

- Mapping hours of the day into the commitment blocks.

The calculator will create OptGen input data files containing this information, which is mandatory to run the solution strategy “OptGen 2” with an hourly resolution.

5 MODEL PARAMETERS

The data described in the following sections are associated to the selection and specification of general parameters of the model in order to perform an expansion planning study.

5.1 Study options

First of all, it's very important to point out that while running OptGen, no matter which solution strategy is being applied, two tasks will be automatically performed by the model:

- Task 1 – the expansion planning task: in which the model will evaluate the expansion alternatives and find the optimal expansion plan based on the minimization of investment plus expected value of operating costs;
- Task 2 – the expansion plan simulation: after finding the optimal expansion plan in Task 1, OptGen will automatically run the SDDP model to perform the final dispatch optimization and print all results in the output files.

The aforementioned tasks correspond to separated procedures which can be performed with different assumptions and criteria, according to the selected options for operation and reliability models.

5.1.1 Expansion Planning

a) Solution Strategy

The user should select which expansion approach will be applied to find the optimal expansion plan:

- "OptGen 1": uses the decomposition techniques allowing the use of the SDDP model to incorporate a multistage trade-off evaluation considering stochastic hydrothermal operation;
- "OptGen 2": uses hourly operation model and inflow/renewable scenarios to incorporate unit commitment, ramping constraints and probabilistic generation reserves.

For further details about "OptGen 1" and "OptGen2" approaches, see the Methodology Manual

b) Operation Model

The selection of the operation model is related to the type of uncertainty representation:

- "SDDP": SDDP model uses the specified stochastic parameters to calculate an operative policy which is then simulated for a set of scenarios. For further details about SDDP algorithm and parameters, see SDDP's Methodology and User Manuals.
- "Scenarios": the operation model uses multi-deterministic scenarios for hydro inflow, renewable generation and other sources of uncertainties. For the hydro inflows, specifically, the user is able to define the set of scenarios and their occurrence probabilities in OptGen's "Hydro Inflow Scenarios" screen. In this case, no operative policy is calculated by the SDDP algorithm

When the solution strategy selected by the user is the "OptGen 1", the decomposition procedure separates the investment and operation decisions, allowing the user to select the operative model as multi-deterministic (through the scenarios and probabilities representation) or stochastic (full SDDP run).

When the solution strategy is the "OptGen 2", the "Scenarios" option is the only one available since the approach considers a built-in multi-deterministic operation model, where investment and operation are co-optimized within the same optimization problem.

c) *Reliability Model*

- "Coral": This option enables the consideration of security constraints in the planning task using Coral model to evaluate the system reliability during OptGen's decomposition procedure. For this reason, this option is only available when the selected solution strategy is the "OptGen 1". For further details about algorithm and parameters, see Coral's Methodology and User Manuals.

Besides all input data required to run Coral, when the reliability model is selected, a security criterium in terms of a maximum accepted Expected Power Not Supplied (EPNS) should be defined by the user. For more information, please see the "Reliability Parameters" section.

d) *Resilience (Critical scenarios)*

- This option enables the consideration of high-impact low probability events during the expansion planning task. This is done through the decomposition procedure adopted by OptGen where feasibility cuts for the optimal expansion plan are obtained by solving dispatch problems that minimize the energy deficit for sub-horizons under pre-defined extreme conditions. This option is only available when the selected solution strategy is the "OptGen 1".

5.1.2 Expansion plan simulation

As explained in the beginning of this chapter, after finding the optimal expansion plan in Task 1, OptGen will automatically run the SDDP model to perform the final dispatch optimization and print all investment and operative results in the output files, independently of the solution strategy and other expansion planning options the user has selected.

a) *Operation Model*

The selection of the operative model in order to evaluate the operative results taking the optimal expansion plan into account: "Scenarios" or "SDDP" (both approaches were explained in the "Expansion Planning" section).

b) *Reliability Model*

By activating this option, a reliability analysis will be performed in order to compute the reliability indexes of the system taking the optimal expansion plan into account, in other words, this is just a post processing that does not affect the project's investment decision-making process (as happens when the user contemplates reliability criterium in the expansion planning task).

5.1.3 General parameters

a) *Initial year, final year and number of years*

These three fields should be used to set the study horizon. The user must always set the "Initial year". After that, he can either set the "Final year" or the "Number of years" (as one of the fields is informed, the other one is automatically updated).

b) *Investment stage*

The selection of the time step for investment decisions that can be annual, semiannual, quarterly or monthly. For the great majority of long-term expansion studies, annual investment step is usually enough. The need to increase the granularity of the investment stages should be evaluated in detail by the user.

c) Operation stage

This field shows the time step for operative decisions that can be monthly or weekly, and this information comes from the SDDP data. In the SDDP's "Study Options" screen, the user is also able to select "Hourly representation" of the operative simulation results.

d) Load blocks

This field shows the number of load blocks defined in the SDDP database.

e) Discount rate (%)

This field sets the annual interest rate used to evaluate the present value of future cash flows. To calculate the annualized investment cost the user can choose to specify individual discount rates for each project in the "Project's Data" screen, otherwise the model will consider the value informed in this field.

5.1.4 Read an expansion plan

This feature allows the user to drive different types of planning studies depending on the flexibility level given to the optimization model in terms of expansion decisions informed by an User-defined expansion plan:

- Manual: the user defines a fixed expansion plan containing all the projects that will be built and their associated decision dates and values. This option is used for simulating investment and minimum operation costs for trial expansion plans.
- Semi-automatic: the user defines a partial expansion plan containing fixed and/or flexible projects that should be built and let the optimization model complement the expansion plan with additional projects if necessary.
- Automatic: no previously defined expansion plan is considered, and the model optimizes all expansion decisions.

Thus, the user can choose an expansion plan file from the data directory (Manual or Semi-automatic modes) or don't choose any plan and let the model work in the Automatic mode.

5.1.5 Reliability parameters

a) Maximum EPNS

Represents the maximum expected power not supplied in terms of p.u. of load in the security constraint. This information is used when reliability planning criteria is selected. For more information on EPNS, please refer to Coral's methodology manual.

5.2 Selections

5.2.1 Projects

This screen allows the user to select which projects should be considered by the model as candidate options to the expansion plan.

5.2.2 Constraints

This screen allows the user to select which minimum and maximum additional constraints should be considered by the model during the expansion planning optimization.

5.2.3 Inflow scenarios

When the user selects "Scenarios" as the operation model for either the expansion planning or the expansion simulation tasks, this screen allows the user to select which hydrology scenarios should be considered and their associated occurrence probability. The model will solve multi-deterministic operative problems for all scenario and calculate the average solution weighted by its probabilities. Refer to Hydro Inflow Scenarios section for further details about how to create those scenarios.

5.2.4 Critical scenarios

When the user checks "*Resilience (Critical scenarios)*" in the expansion planning options, this screen allows selecting which sensitivity groups, defined in SDDP, should be considered as critical scenarios in the feasibility problems solved by the resilience module. Additionally, the initial year, the number of years and SDDP's forward series number are informed for each scenario. The model will solve multi-deterministic operative problems that minimize deficit for each scenario. If the deficit is greater than zero, the problem solution is used to construct a new feasibility cut for the expansion problem, resulting in the elimination of the corresponding expansion plan, and thus incorporating the resilience criterion in the search for the best expansion plan for the system.

5.3 Execution options

Traditionally, OptGen model solves a problem for obtaining the "timing" of the expansion, or the project's decision dates for entrance in operation along the study horizon. Depending on the number of projects considered and the size of the study horizon, the problem of finding the optimal expansion plan can be very complex because of the combinatorial nature of the feasible solution set.

For example, considering a study horizon of only 1 year and a set of 3 candidate projects with binary decision variable, then the number of possible expansion plans are $2^3 = 8$, as follows:

Expansion Plans	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6	Plan 7	Plan 8
P1		x		x		x		x
P2			x	x			x	x
P3					x	x	x	x

In general terms, the number of possible expansion plans grows exponentially with the number of years and binary projects. For a study case with X years and Y projects, this number is 2^{X*Y}.

The definition of the study horizon is an important task as the expansion planning may be ineffective with too small horizon due to the effect of projects construction time and economies of scale, for example. On the other hand, the longer the horizons, the smaller the effects of the decisions taken in the last years of the study, because of the discount rate. This is known as the end-of-horizon effect and may lead to a poor planning strategy in the final years.

The solution strategies of Horizon Year and Rolling Horizon can be applied to the planning problem in order to reduce the computational time spent to achieve a least-cost expansion plan and to minimize the end-of-horizon effects for a long-term planning horizon.

The Horizon Year strategy is based on a two-stage procedure. In the first stage the model solves a sizing problem in order to find the projects that should belong to the system in the horizon year. Using the solution of this problem, the model solves the timing problem, by automatically selecting this restricted project list to be considered as expansion options. In other words, the sizing problem decides which projects should be constructed, and the timing problem decides when they should be constructed.

The Rolling Horizon strategy is used to solve the timing problem and consists of chained solution of expansion problems obtained by splitting the study horizon into smaller sub-horizons. It is important to notice that the solution strategy “OptGen 2” always use the Rolling Horizon heuristics, automatically splitting the horizon into sub-horizons of 1 year. For further details of “OptGen 2” methodology, see the Methodology Manual.

5.3.1 Use horizon year

By selecting this option, the model performs the solution of the sizing problem considering the horizon year static configuration, which is fixed for the number of years specified by the user. This procedure can even be done incrementally, by defining intermediate horizon years and their respective fixed number of years. The solution of these sizing problems is used to reduce the candidate projects list that will be considered in the timing decision problem.

For example, let’s suppose a study horizon of 2021-2040, a set of 100 candidate projects and the selection of the option “Use horizon year” for 2 sizing problems as follows:

- Horizon year 2030, 5 years
- Horizon year 2040, 5 years

In this case, the model will automatically perform the expansion planning task in 3 steps:

1. Solves a 5-year expansion problem with static configuration of year 2030, considering the original candidate project list.
2. Solves a 5-year expansion problem with static configuration of year 2040, considering the expansion plan obtained from step 1 as a complementary plan, where the model will include, if necessary, new expansion decisions of projects from the original candidate list.
3. Let’s suppose that the resulting expansion plan obtained after steps 1 and 2 contains 20 projects from the original 100 candidate list, then the model solves the original 2021-2040 case considering only those 20 projects as candidates for the timing decisions.

5.3.2 Use rolling horizon

By default, the timing problem is solved for the whole study horizon. By selecting this option, the user can inform the study partitioning which allows the model to chain the expansion solutions of smaller sub-horizon problems. By setting the initial year and the number of years of each sub-horizon, the model automatically keeps the decisions taken for the years prior to the initial year of each new horizon. At the end, the model simulates the expansion plan to generate results for the whole study horizon.

For example, let's suppose a study horizon of 2021-2040 and the selection of the option "Use rolling horizon" for 3 timing problems as follows:

- Initial year 2021, 10 years
- Initial year 2026, 10 years
- Initial year 2031, 10 years

In this case, the model will automatically perform the expansion planning task in 4 steps:

1. Solves the 2021-2030 expansion problem.
2. Solves the 2026-2035 expansion problem, considering the expansion decisions obtained in step 1 for the years 2021-2025 as a complementary plan.
3. Solves the 2031-2040 expansion problem, considering the expansion decisions obtained in steps 1 for the years 2021-2025 and in step 2 for the years 2026-2030 as a complementary plan.
4. Solves an expansion plan simulation, considering the decisions obtained in the previous steps for the whole study horizon as a fixed plan.

5.3.3 Model parameters

Model parameters are set independently for the sizing and timing problems and are different for OptGen 1 and OptGen 2 strategies.

5.3.3.1 OptGen 1 parameters

a) Restart

When selecting "Yes", this option allows the user to restart the optimization model considering the best solution found in a previous run. In this case, OptGen solves the investment problem for the best plan of the original execution to check feasibility. If this plan is feasible for the restarted run (this new one after the restart), OptGen executes the operative model for the best solution from the previous run and recalculates/updates the upper bound before executing the new iterations of the investment model. In case the best plan from the previous run is not feasible, OptGen just takes advantage of the previous cuts and looks for a new solution.

Note that the most common application for this restart option is to find a lower cost expansion solution with a narrower convergence gap, even without any change to the case input data.

Now, if, before restarting the case, the user decides to change some data of the investment problem, such as, for example, to include security constraints in the planning procedure, or to increase the investment cost of some project, it may be case that these changes cause that the optimal expansion plan of the new run is more expensive than the best plan obtained in the original execution, however, in any case, when using this restart option, the cuts were taken advantage of and this can accelerate the convergence process of this case, saving processing time until the optimal solution is obtained.

b) Minimum number of iterations

Represents the minimum number of Benders decomposition iterations that will be performed by the model before applying any stopping criteria.

c) Maximum number of iterations

Stopping criteria for decomposition strategy, it represents the maximum number of Benders decomposition iterations.

d) Convergence tolerance (%)

Stopping criteria for decomposition strategy, it represents the minimum tolerance for the relative gap calculated from upper and lower bounds at each Benders decomposition iteration. It is related to the integration between operation and investment modules.

e) MIP convergence tolerance (%)

Stopping criteria for MIP (mixed integer problems), it represents branch-and-bound's convergence tolerance that will be considered while solving each investment problem.

f) MIP limit time (s)

Stopping criteria for MIP problems, it represents branch-and-bound's maximum CPU time.

g) Use consecutive iterations

This option is a convergence strategy that fixes investment decisions of projects that have their solution repeated for the number of consecutive iterations selected by the user (N). That is, if the model chooses not to invest in a certain project for at least N iterations in a row, then the decision of not investing in this project will become fixed. The same happens with projects that have the same investment decision for this number of consecutive iterations. When the OR logic is used (which refers to leaving the  option active), repetitions are counted when at least one of the following criteria is met:

- the total number of iterations is greater or equal to a specific value; or
- the convergence gap is lower or equal to a specific value.

For example, let us consider the following parameters:

a) Number of repetitions (consecutive iterations): 2
b) Iteration number ≥ 3
c) Convergence gap ≤ 15%
d) 3 projects with binary decisions
e) The following convergence gap / investment decision for the first 5 iterations:

Iteration	gap (%)	Project 1 (%)	Project 2 (%)	Project 3 (%)
1	100	0	0	0

2	90	0	100	100
3	70	0	100	0
4	40	100	100	0
5	15	0	100 (Fixed)	0 (Fixed)

Since the gap required for fixing decisions is only achieved in iteration 5, the criteria that activates this strategy is the minimum number of iterations (3). From iteration 3 the model starts computing the investment decisions and repetitions are restarted to 1 when the investment decision changes from one iteration to the other. We can see that, in iteration 5, Project 1 is not fixed because OptGen changed its investment decision from iteration 3 to 4. Project 2 and 3 decisions are fixed because their investment decisions are repeated in iterations 3 and 4.

When the AND logic is used (which refers to leaving the  option active), repetitions are counted when both criteria are met.

This strategy is meant to help convergence usually when the gap is close to the tolerance. If this option is misused, for example, by setting a small number of consecutive iterations to fix solutions, especially when the convergence gap is still very large, then the model may take decisions to fix projects that would probably not be part of the optimal solution. In terms of the model's convergence, a negative gap can sometimes be observed in these cases.

5.3.3.2 OptGen 2 parameters

a) Convergence tolerance (%)

Since OptGen 2 co-optimize investment and operation problems in the same optimization model, the convergence tolerance is the MIP tolerance of this solving process. This tolerance is the difference between the best binary feasible solution and the optimal linear solution (which is infeasible since the variables are binary and not linear). So, for example, if the user is executing a case without any binary variables (commitment, binary or integer investment variable), then the convergence tolerance will not be used, since the optimal linear solution is also a feasible solution.

b) Limit time (s)

This parameter limits the total time execution for OptGen 2. For example, if a case has 5 year and the limit time is 300 s, then OptGen 2 will have 300 s to solve all the 5 years. If the limit time is reached, a partial solution will be available.

6 THE GRAPH MODULE

6.1 Introduction

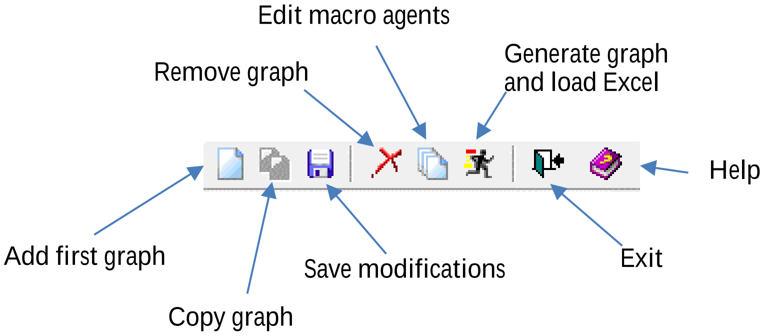
The Graph module allows the user to graphically visualize most of the output results generated by OptGen and SDDP models. To access this module, click on the correspondent button on OptGen's menu bar:

The Graph module screen is divided as follows:

- General options
- Stage selection
- Block selection
- Series selection
- Axis title
- Variables, agents and macro agents selection

After setting up all the parameters, the "Execute" button generates Excel formatted graphs.

6.2 General options



a) Creating the first graph

If no graphs have been defined so far, use the "Add" button to create a new graph. Enter the graph name and press "Ok".

b) Selecting a graph

Use the combo box located on the upper part of the screen to select a graph for visualization and editing.

c) Copying graphs

Use the "Copy" button to generate a new graph from a previously defined one. Enter the new graph's name and press "Ok".

d) Eliminating graphs

Use the "Delete" button to select the graphs that will be removed from database.

e) Handling macro agents

Use “Macro Agents Editor” button to manage macro agents, which are defined as weighted sum of a set of agents. Use the “Delete” or “Edit” buttons to remove or modify a selected macro agent. Use “Add” button to create a new macro agent: inform the macro agent’s name, the associated variable and select the agents that will be summed with their specified coefficients (weights).

For example, one can define a macro agent called HydroX which contains the sum of the generations of all hydro plants of company X. Standard macro agents are also available, such as: TotalHydro (all hydro plants), Exist.Hydro (all existing hydro plants), etc.

6.3 Stage selection

Allows the user to specify the date range of interest, within the study horizon, for generating the graph.

6.4 Load block selection

Allows the user to select the load blocks of interest, by pressing over each block’s number.

Additionally, the user can aggregate values of a graph by setting the options to sum values by block and sum values by year.

6.5 Series selection

Allows the user to either select all or individually select the inflow series of interest.

Additionally, the user can plot different types of quantities for these series:

- Graph series: plots the individual value for each selected series.
- Graph mean: plots the average value of selected series.
- Graph standard dev.: plots the standard deviation of the selected series.
- Graph upper percentile: plots the upper quantile of x%, that is, the Qx value such that P(Q<Qx) = x/100, where Q is the selected variable.
- Graph lower percentile: plots the lower quantile of x%, that is, the Qx value such that P(Q>Qx) = x/100, where Q is the selected variable.

6.6 Axis title (optional)

Represents the labels for the X axis, Y axis, and secondary axis.

6.7 Variables, agents and macro agents selection

Variables are results obtained from the model execution and are associated to the worksheet files. Agents are the entities associated with the output results. For example, *Hydro Installed Capacity* is a variable that applies to hydro plants, which are agents.

By pressing the “Variables” button, in the main screen, a new window shows up. Select and discard variables from the “Selected Variables” list using buttons (<<) and (>>). The same procedure applies to agents and macro agents selection. To select all the variables in the list, one can select the first variable, press “Shift” and ↓ on the keyboard.

6.8 Filters

The filter tool is located in the Agents selection window and it allows the user to specify logical expressions over agents attributes in order to help selecting a subset of interest.

By pressing the “Filters” button, a new window shows up where operators and attributes can be combined as sophisticated logical expressions in order to build a desired filter.

1. Select an attribute.
2. Select the type of constraint (between, equal to, etc..)
3. Set the constraint value
4. Press the “Add” button
5. Use parenthesis and logical operators to combine constraints.
6. Use the “Clear” button to eliminate the whole expression

7 MODEL OUTPUT FILES

7.1 Output files in worksheets

These are the output files that can be handled by the Graph Module.

Keys to Worksheet description tables

Type	Description
DE	Input data
DI	Investment decisions

Agent	Description
H	Hydro plants
T	Thermal plants
R	Renewable plants
S	System
I	Interconnections
F	Fuels
P	Project

To generate the desired graph, the user should select in the Graph Module the correspondent variable.

In addition to all the operative outputs generated by the SDDP model, those are the output files generated by the OptGen model:

Graph	CSV File Name	Agent	Unit	Type
Invested capacity	outidec.csv	P	MW	DI
Investment cost (CAPEX)	outdcinv.csv	P	k$	DI
Fixed O&M cost	outdcoem.csv	P	k$	DI
Investment cost + fixed O&M cost	outdisbu.csv	P	k$	DI
Total investment cost	outdbtot.csv	P	k$	DI
Hydro firm energy	outhea.csv	H	MWavg	DE
Hydro firm capacity	outhpa.csv	H	MW	DE
Thermal firm energy	outtea.csv	T	MWavg	DE
Thermal firm capacity	outtpa.csv	T	MW	DE
Renewable firm energy	outrea.csv	R	MWavg	DE
Renewable firm capacity	outrpa.csv	R	MW	DE

7.2 Additional output files

All files presented in this section can be accessed by the interface, in “Reports” button, at the upper level of the main screen.

7.2.1 Execution report

OptGen execution report file (optgen.out) has the following sets of output data:

- Summarized input data
- Annualized investment costs
- Generation and transmission reports
- Convergence report
- Optimal expansion plan
- Total costs
- CPU time required for the optimization

7.2.2 Optimal expansion plan

The outpdec.csv file represents the optimal expansion plan for the current study case. This file has the exact form of an user-defined expansion plan and can be used as an input data. The first line contains the file version, the second line is a header and the third line contains the type of the plan. In this file, the type of the plan is always exactly – see “User-defined expansion plan” for details on types of plan.

The fourth line is also a header and the following lines contain the records described below:

Field	Description
1	Entrance in operation date (month)
2	Entrance in operation date (year)
3	Investment decision date (month)
4	Investment decision date (year)
5	Project code
6	Project name
7	Project type: 0 = thermal plant 1 = hydro plant 2 = interconnection 3 = gas field 4 = gas line 5 = circuit 6 = renewable generator 7 = DC link 8 = battery 9 = AC bus 10 = AC transmission line 11 = transformer 12 = three-winding transformer 13 = switchable series capacitor 14 = DC bus 15 = DC transmission line 16 = LCC converter 17= P2P converter

	18 = VSC converter 19 = shunt equipment 22 = CSP 23 = Producer (Electrification/Hydrogen) 24 = Transport (Electrification/Hydrogen) 25 = Storage (Electrification/Hydrogen) 999 = N/I
8	Added capacity (MW)
9	Key: exactly = exact decision value;
10	Decision type: -1 = fixed planned decision -2 = optimized decision -3 = flexible planned decision
11	Project's decision in p.u of the installed capacity (accumulated in case of continuous or integer variables)

Additionally to the optimal expansion plan, OptGen model also generates a file for the expansion plan of each iteration. These files are not accessed by the model's interface, but they can be found in the study case data directory and they are identified as outpdec_XXXXYYY.csv, where XXXX is the number of the iteration and YYY is the identification of the sizing or timing problem.

7.2.3 Detailed expansion plan

The detailed expansion plan can be found in the optsol01.csv file. Its records are presented in the following format:

Field	Description
1	Date of entrance into operation
2	F = if operation date is fixed R = if existing unit is replaced
3	> = if operation date is the maximum date < = if operation date is the minimum date * = if operation date is unique
4	Project type: TPP = thermal plant HPP = hydro plant INT = interconnection GAS = gas field GPL = gas line CIR = circuit RNW = renewable generator DCL = DC link BAT = battery BUS = AC bus LIN = AC transmission line TRF = transformer TR3 = three-winding transformer SSC = switchable series capacitor DCB = DC bus DCL = DC transmission line CNV = LCC converter P2P== P2P converter VSC = VSC converter SHT = shunt equipment

	CSP = CSP EPD = Producer (Electrification/Hydrogen) ETR = Transport (Electrification/Hydrogen) EST = Storage (Electrification/Hydrogen) N/I = N/I
5	System
6	Project name
7	Investment decision (%)
8	Added capacity (MW)

7.2.4 Convergence report

The optgconv.csv file contains the convergence report of OptGen. It consists of the following columns:

- Character "*" identifies that a better solution was found and upper bound is updated
- Character "B" identifies that the MIP solution was interrupted by CPU time limit
- Investment cost (M$)
- Approximated operation cost (M$)
- Expected operation cost (M$)
- Total cost (M$)
- Lower bound (Investment cost + Approximated operation cost) (M$)
- Upper bound (Investment cost + Expected operation cost) (M$)
- Convergence gap (Percentage difference between upper and lower bounds) (%)
- Convergence tolerance (%)
- CPU time of the investment problem (min)
- CPU time of the operation problem (min)
- Security constraint infeasibility (GWh)
- Reliability criteria (Maximum EPNS) (%)
- EPNS of the best solution (%)
- CPU time of the reliability problem (min)
- Number of SDDP iterations
- SDDP upper bound (M$)
- SDDP lower bound (M$)
- SDDP convergence gap(M$)
- SDDP convergence tolerance (M$ or %)

If year horizon or rolling horizon strategies (see "Execution options") are selected, this report will contain the convergence of every sub problem execution.

7.2.5 Optimal expansion CAPEX value

The outcapex.csv file contains the non-discounted CAPEX value (in k$) of each project at the end of each year, when it actually incurs. The first line contains the file header, with the columns names. From the second line and on, the data is written in the following format: the first column contains a year of the study and the others contain the CAPEX values for each project for that specific year.

7.2.6 Optimal expansion fixed O&M value

The outcoem.csv file contains the non-discounted O&M value (in k$) of each project at the end of each year, when it actually incurs. The O&M is fixed, that is, depending only on the amount of capacity invested in the project. The first line contains the file header, with the columns names. From the second line and on, the data is written in the following format: the first column contains a year of the study and the others contain the O&M values for each project for that specific year.

7.2.7 Long-run average cost (LRAC)

The outlrac.csv file contains the values related to the Long-run Average Cost (LRAC) of the system (in $/MWh). For each year, OptGen calculates the LRAC ($/MWh) as follows.

$$LRAC_t = \frac{\sum_{i=1}^{\min(\tau,\mathrm{T-t})} TC_{t+i-1}/{tx_a}^{i-1}}{\sum_{i=1}^{(\tau,\mathrm{T-t})} TD_{t+i-1}/{tx_a}^{i-1}}, \qquad t = 1, \ldots, T$$

where:

TC_t	Annual total cost (investment + operation)	$
TD_t	Total annual demand	MWh
τ	Amortization period[1]	Years
T	Study horizon	Years
tx_a	Annual discount rate	p.u.

As an example, please take the following data into account:

- Study horizon (T): 10 years
- Amortization period (τ): 2 years.

Now, let's apply the following procedure:

1. Take the investment + operating costs of each month of the 1st year and bring them to January of Year 1. Let's call the sum of these values TC1;
2. Take the investment + operating costs of each month of the 2nd year and bring them to January of Year 2. Let's call the sum of these values TC2;

In this case example, the first LRAC(1), related to the first year, will be calculated as follows:

$$LRAC_{(1)} = \frac{\frac{(TC1)}{({tx_a}^0)} + \frac{(TC2)}{({tx_a}^1)}}{\frac{(TD1)}{({tx_a}^0)} + \frac{(TD2)}{({tx_a}^1)}}$$

In summary, the LRAC is basically calculated as the following ratio: net present value of the (investment + operating costs) / (demand) over the amortization period. The annual discount rates are being applied to bring the future values to January of Year 1.

[1] The default value for the amortization period is 5 years. Despite not being in the OptGen GUI, this value can be changed and if the user is interested, please contact us: optgen@psr-inc.com.

7.2.8 Long-run marginal cost (LRMC)

The outlrmc.csv file contains the values related to the Long-run Marginal Cost (LRMC) of the system (in \$/MWh). For each year, OptGen calculates the LRMC (\$/MWh) as follows.

$$LRMC_t = \frac{\sum_{i=1}^{\min(\tau, T-t)} (TC_{t+i} - TC_{t+i-1}) / \left(tx_a{}^i\right)}{\sum_{i=1}^{\min(\tau, T-t)} (TD_{t+i} - TD_{t+i-1}) / \left(tx_a{}^i\right)}, \qquad t = 1, \dots, T-1$$

where:

TC_t	Annual total cost (investment + operation)	\$
TD_t	Total annual demand	MWh
τ	Amortization period[1]	Years
T	Study horizon	Years
tx_a	Annual discount rate	p.u.

As an example, please take the following data into account:

- Study horizon (T): 10 years
- Amortization period (τ): 2 years.

Now, let's apply the following procedure:

1. Take the investment + operating costs of each month of the 1st year and bring them to January of Year 1. Let's call the sum of these values TC1;
2. Take the investment + operating costs of each month of the 2nd year and bring them to January of Year 2. Let's call the sum of these values TC2;
3. Take the investment + operating costs of each month of the 3rd year and bring them to January of Year 3. Let's call the sum of these values TC3;

In this case example, the first LRMC(1), related to the first year, will be calculated as follows:

$$LRMC_{(1)} = \frac{\frac{(TC2 - TC1)}{(tx_a{}^1)} + \frac{(TC3 - TC2)}{(tx_a{}^2)}}{\frac{TD2 - TD1}{(tx_a{}^1)} + \frac{TD3 - TD2}{(tx_a{}^2)}}$$

In summary, the LRMC is basically calculated as the following ratio: net present value of the (delta [investment + operating costs]) / delta [demand] of the years that are part of the amortization period. The annual discount rates are being applied to bring the future values to January of Year 1.

[1] The default value for the amortization period is 5 years. Despite not being in the OptGen GUI, this value can be changed and if the user is interested, please contact us: optgen@psr-inc.com.