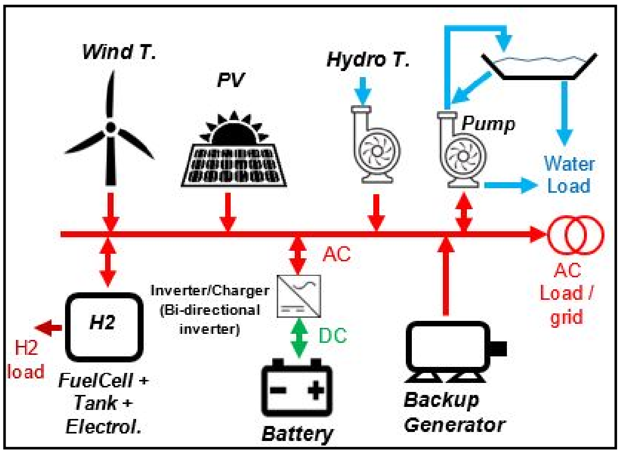
MHOGA

Version 3.4

User's manual

January 18th, 2024



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CONTENTS.

1. INTRODUCTION AND OVERVIEW

MHOGA (MegaWatt Hybrid Optimization by Genetic Algorithms) is a software developed in C++ for simulation and optimization of Hybrid Renewable Systems, including grid-connected generating systems with or without storage and with or without load consumption, and off-grid systems. Storage in batteries, pumped hydro storage (PHS) or hydrogen are allowed.

Two types of optimization can be performed: minimization of the net present cost (NPC) for cases with high load or off-grid or maximization of the net present value (NPV) for grid-connected generating systems.

Minimization of LCOE or LCOH and other optimizing options are also available.

Different cases of **Net Metering and Net Billing** can be defined.

The software includes **multiperiod simulation and optimization** (considering the increase in load and the decrease of electricity production from the renewable sources during the years of the system lifetime), multi-objective optimization, simulation in time steps from 1 minute to 1 hour, sensitivity analysis, probability analysis (Monte Carlo simulation), etc.

There is a "Getting started guide" with which to quickly learn the basic operation of the program.

Modifications in this version (3.4).

January 18th, 2024:

- Corrected bug in some cases in simulation of projects with water pump and batteries.
- Added constraint of maximum unmet load in NPV maximization projects.
- Added the possibility to consider the generation (transfer) charge for the energy injected to the grid (by default) or for the renewable energy generated.
- The generation (transfer) charge can be negative, that is, the system would receive money due to the renewable energy generated (in the case there is a state subsidy due to emissions reduction). This will be subtracted from the cost of purchasing electricity to the grid.

- Added the possibility to calculate LCOE in NPV maximizing projects considering the energy sold to the AC grid only (by default) or including the load energy consumed by the system.

- Improved estimation of computation time.

- In optimization of energy arbitrage (for batteries, PHS or hydrogen) with two variables, reduced computation time (lower price setpoint can't be higher than higher setpoint) by default.

- Fixed minor bugs.

December 26th, 2023:

- Added the selection of months for battery availability under arbitrage.
- Added the possibility to force to pump using AC grid or to use turbine to inject to AC grid regardless arbitrage, with same selection of hours and months as for batteries.
- Added in the report the number of starts of turbine, pump, fuel cell and electrolyzer.
- Added in the Excel of the simulation, for each time step and for the total monthly, the incomes of selling hydrogen.
- Corrected bug in IRR calculation in some cases when adding extra costs.
- Improved optimization speed in NPV minimization projects.
- Added in Extra costs the possibility to introduce a value with a fixed annual inflation.
- In MHOGA, added maximum land use constraint in minimization of NPC projects.
- Added the possibility to consider the cost of the CO2 emissions due to the energy purchased to the grid.
- Corrected display errors of some graphs in time steps of less than 1 h
- Fixed minor bugs.

November 14th, 2023:

- Fixed bugs of previous build when changing default currency.

November 8th, 2023:

- Fixed bugs.

November 2nd, 2023:

- In multi-period simulation, added the possibility to use different electricity sell (and buy) hourly prices for the different years (not just updating with inflation, but using different hourly files for the different years). Two options, import the different electricity hourly prices files for the different years, or generate them as shown in the paper: Optimisation of size and control strategy in utility-scale green hydrogen production systems. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.08.273.

- Added the possibility to optimize battery SOCmax (in Li-ion batteries).

- Corrected error in some stand-alone projects with diesel always on (creating the grid refference)

September 4th, 2023:

- Added option for LCOH minimization. Also maximization of capacity factor and minimization of LCOE, with weights. Also maximization of IRR.

- Added control strategy for grid-connected electrolyzer: run at full load, buying electricity to the grid if necessary; at high electricity price electrolyzer power can be supplied by the battery.

- Updated wind data downloading from Renewables Ninja.

- Fixed minor bugs.

June 27th, 2023:

- In the simulation of multi-period projects, now you can choose to see the electricity price of the year shown (by default now) or of the year 0 (as before).
- In the Excel of the simulation, added specific units for each column and fixed bugs.
- Added two more decimal places in the LCOE column of the results table in NPC minimization projects.
- Corrected bugs in the visualization of the simulation of multi-period projects.
- Corrected bug in the visualization of the value of Initial Investment in the report in NPC minimization projects.
- Fixed minor bugs.

June 20th, 2023:

- -Added the calculation of corporate taxes, considering EBIT, interest payment, linear depreciation and amortization.
- -Added the possibility to define the inverter-charger power depending on the battery duration wanted, considering only the first inverter-charger of the list.
- -In pumped-hydro-storage (PHS), added the possibility to define the water tank or reservoir capacity as the turbine maximum flow multiplied by the duration wanted.
- -Added the possibilty to consider the water flow defined in the hydro resource as water inlet in the water tank or reservoir.
- -Added more parameters for the electrolyzer electricity consumption and efficiency, with the possibility of obtaining efficiency curves more similar to the real ones.
- -Added electrolyzer unavailability in PV systems during night time and in wind systems if there are several consecutive hours with calm wind. After the stop, when the electrolyzer starts again, a cold-start time is considered, and also an extra ageing (in minutes) due to each cold-start.
- -Added the possibility to use a fixed value for the hydrogen tank capacity, which is the maximum (in systems where a hydrogen load must be met). In previous versions, the H2 tank capacity was determined at the end of the simulation of each combination, as the minimum necessary.
- -Added the possibility to account for the replacement costs of the PV inverter (its own inverter in AC coupled systems), the PV inverter replacement costs will be added to the O&M costs of the PV generator.
- -Added ratio rated apparent power / rated active power of the backup generator.
- -Added the possibility to update the results table to the present data (simulating again each combination of the results table) when saving the project.
- -Added zoom in the electricity price chart which is over the simulation chart (simulation screen)
- -Corrected bugs in multi-period optimization of the limitation of the AC power of the PV due to its own inverter.
- -Corrected bug when downloading hourly irradiation data from PVGIS, horzontal axis tracking.

- -Corrected errors when opening project with sensitivity analysis.
- -Corrected bugs with databases changing the currency.
- -Corrected bug in optimization of arbitrage with 3 variables (before, in optimization the price limits were < and > and in simulation <= and >=, now both the same, < and >).
- -Fixed minor bugs.

March 29th, 2023:

- - Added auxiliary load consumption for the batteries (cooling, heating, BMS..,) as a percentage of the maximum power (Pamx=Imax·Vnom) of the battery.
- - Added the possibility to set the maximum SOC for li-ion batteries.
- - Added water cost for the hydrogen generation (this cost will be increased during the years with general inflation).
- - Added value of purchase electricity price below which the storage/generator will have priority to supply the load (instead of the AC grid).

Previous modifications:

- - Added the possibility to inject power to the AC grid from the fossil fuel generator (AC generator) in NPV maximizing systems (in generating systems which sell electricity to the grid).
- - Added C-rate for grid-connected battery charge / discharge.
- - Added the possibility to consider wake effect in wind turbines.
- - Added the availability (hourly and monthly) for electrolyzer and for fuel cell.
- - Added variable efficiency for the water pump (for PHS and for water supply).
- - Choose power limit for priority to use surplus Energy in pump or in batteries.
- - In Excel file obtained in simulation, added column of efficiency of turbine, efficiency of pump and efficiency of electrolyzer (% of HHV).
- - Improved visual effects in graphs, adding checkbox for the different series.

- - In load window the graph includes the water load (in energy pumped) and shows the total average daily energy for each month.
- - In iHOGA high power projects and in MHOGA, added the possibility to connect PV generator and wind turbines to the DC bus.
- - Extended download irradiation/wind/temperature hourly data from PVGIS for all around the world.
- - Changed maximum current in li-ion batteries databases to C/2.
- - Corrected problem with full equivalent cycles model of li-ion batteries when including calendar ageing for cases of very low discharge current.
- - Corrected bugs in some cases with PHS storage.
- - Corrected bugs related to systems with hydrogen load consumption.
- - Corrected bugs when showing unmet load in multi-objective optimization.
- - Fixed minor bugs.

1.1 Conditions for using MHOGA.

You may not modify, reverse engineer, decompile, or disassemble the object code portions of this software. You may not sell, rent, lease, or otherwise charge for the distribution, installation, copying, or storage of the Software. This Software is owned by Rodolfo Dufo-López, and is protected by copyright law and international copyright treaty.

Conditions to use this software:

1. This software is provided 'as is' and without any warranties expressed or implied, including, but not limited to, implied warranties of fitness for a particular purpose, and non-infringement.

2. You expressly acknowledge and agree that use of the Software is at your sole risk.

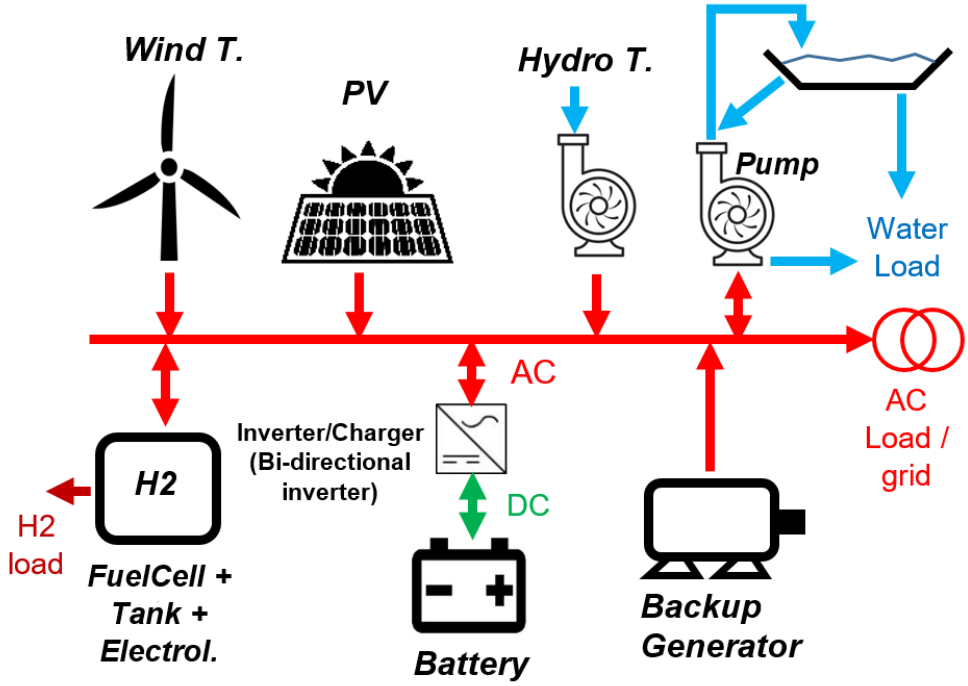
3. Calculations involving meteorological variables (irradiation, temperature, wind, etc.) and financial variables (interest rate, inflation rate, etc.) are estimates that may differ significantly from the actual values, the system models may differ significantly from actual performance and results of the simulations and optimizations could differ significantly from actual operation and actual costs of equipment and systems.

4. Data of components of the databases have been obtained on manufacturers websites and on different publications, and costs have been obtained from online shops or different publications at a certain date. Current costs and features can be different from costs shown on database. Some data have been estimated and may differ from actual data.

5. You give up the ability to require the author any responsibility for any defects, errors or omissions or malfunctions or data from the software or from the databases.

1.2 Software overview.

MHOGA is a simulation and optimization software of electric systems based on renewable energies, for grid-connected generating systems (which can include storage) or for off-grid systems.



The default values are for generating systems (without any load), where we want to maximize the benefits of selling electricity to the grid. Power is measured in MW, monthly or annual energy in GWh and costs in Mega monetary units (M€, M$ or any other).

1.2.1 Optimization.

In generating systems, where all or almost all the electricity is sold to the AC grid, optimization is achieved by maximizing the total incomes during the system lifetime (Net Present Value, NPV), this is the default optimization type.

In the systems where we want to cover a high load demand (off-grid or grid-connected systems), optimization is achieved by minimizing total system costs throughout the whole of the useful lifespan of the system, where those costs (and incomes) are referred to or updated for the initial investment (Net Present Cost, NPC).

Default optimization is therefore financial (mono-objective). However, the software allows for multi-objective optimization, where additional variables may also be minimized: equivalent CO_2 emissions or unmet load (energy not served), as selected by the user. Since all of these variables (cost, emissions, or unmet load) are mutually counterproductive in many cases, more than one solution is offered by the programme, when multi-objective optimization is performed (called "pareto front"). Some of these solutions show better performances when applied to emissions or unmet load, whereas other solutions are best suited for costs.

The program can **optimize the combination of elements and also the control stratetgy** (which determines when to charge or dischare grid-connected batteries, when to pump or turbine sotred water, when batteries or diesel genset must supply the load, to what level the batteries should be charged, ...).

1.2.2 Possible components of the system.

The hybrid system can include the following components:

- Photovoltaic generator (bifacial PV and concentrating PV, CPV, can be considered)
- Wind Turbines
- Hydro turbine (with or without Pumped Hydro Storage)
- Fuel cell
- H2 tank
- Electrolyzer
- Batteries (lead-acid or lithium-ion)

• Inverter (DC/AC converter) or bi-directional converter (inverter/charger)

• Fossil fuel or back-up generators (diesel, biomass, or any other type)

Although the combination of all of them is possible, in many cases it will be interesting that the hybrid system only includes some of them.

Different system loads are possible:

- Electric AC loads.
- Electric DC loads.
- Hydrogen loads (production of H_2 for external consumption, e.g., electricity-powered fuel-cell vehicles).
- Water pumping load.

1.2.3 Grid connection.

The software allows for **selling AC electric energy to the grid**, **purchasing AC electric energy to the grid** or **selling surplus hydrogen**, green hydrogen produced in the electrolyzer and stored in the tank. Time of use (TOU) or real-time tariffs can be defined for the energy sold to the AC grid and for the energy purchased. Also limits for the power injected to the AC grid and for the power purchased from the grid can also be defined (even in hourly periods, even they can be optimized).

It can also be considered the **case of systems with batteries connected to the AC grid**, optimizing the periods of charging (purchase of energy to the AC grid) and discharge (supply the consumption load by means of the battery and/or inject energy into the AC grid to sell it). The battery control strategy can be optimized. Also **Pumped Hydro Storage** (PHS) can be considered, with similar control strategies as the batteries control. **The generation of hydrogen** in the electrolyzer can also be optimized with similar strategies.

1.2.4 Energy storage.

Energy storage can be carried out using batteries (lead-acid or lithium-ion batteries), pumped hydro storage (PHS) or hydrogen.

1.2.5 Backup generator.

Often, in off-grids, to ensure the uninterrupted supply of energy to the loads of the system, the system include back-up AC generators (usually Diesel).

1.2.6 Hydrogen.

The storage of electrical energy in hydrogen by means of fuel cells combined with electrolyzers may, in the future, supplement or replace the storage in batteries. The electrolyzer generates H_2 with the surplus energy produced by renewable sources, which is stored in the H_2 tank. Subsequently, when the energy demand is higher than that produced by renewable sources, the fuel cell uses the stored H_2, which, combined with O_2 from the air, by reverse electrolysis produces electricity and water.

There is also the option that the fuel cell uses H_2 (not from the electrolyser), methane, etc., that has been purchased externally.

Also the generation of hydrogen in the electrolyzer for external use (to be sold) can be considered, without fuel cell.

1.2.7 MHOGA exclusive features.

Unlike other commercial hybrid optimization software, MHOGA uses advanced models in the simulations: variable inverter efficiency (dependant on the inverter output power), advanced battery lifetime models (lead-acid and Li-ion), advanced grid-connected storage control and advanced grid options (hourly electricity purchase price, hourly sell price, hourly periods and optimization for the contracted power, net metering and net billing and other features), electrolyzer and fuel cell variable consumption (depending on the output hydrogen mass flow or on the output power), electrolyzer stand-by power consumption, variable efficiency for water pump and for water turbine, wake effect for wind turbines, etc. In the economic calculations, MHOGA uses different annual inflation rates for different concepts (electricity purchased to the AC grid, electricity sold to the AC grid, hydrogen sold, fuel of the backup generator, etc.). The software can perform probabilistic analysis of the system. Also, optimization can be mono-objective (economical optimization, minimizing NPC or LCOE or LCOH or maximizing NPV) or multi-objective (economical optimization and also minimization of emissions and/or unmet load).

The optimization of a hybrid system is very complex, due to the variability of the availability of renewable resources (solar irradiation, wind, hydro resource), as well as energy load. In addition, some components of the system have non-linear characteristics, and the number of variables influencing the optimization is very high. The hybrid system to optimize has a large number of possible solutions (combinations of photovoltaic generator, wind turbines, hydraulic turbine, batteries, backup generator, fuel cell, electrolyser, inverter-charger or some of them, and also control strategy variables). All this makes optimization a complicated task with classical mathematical techniques (for example with mixed-integer programming).

There are different software of simulation and optimization of MW hybrid systems, but none uses advanced optimization algorithms except MHOGA. Other programs perform the optimization by testing all possible combinations. One problem with this methodology is that if the number of possible combinations is very high, the calculation time increases enormously and becomes inadmissible. MHOGA can use genetic algorithms (GA) reducing the optimization time to less than 0.1% of the computation time needed to evaluate all the combinations, with great probability of obtaining the optimal solution or a very close solution (Bernal-Agustín & Dufo-López, 2009a).

In addition, the control strategies used by other software tools are too simple, and no in-depth optimization is possible as in MHOGA. MHOGA can optimize the grid-connected batteries control, the pumped hydro storage and the hydrogen generation, as well as the off-grid systems control strategies.

Other advantages of MHOGA are in the models used, more precise than other software tools, in the components as well as in the economic calculations, besides functionalities like the pre-sizing, the optimization of the slope of the photovoltaic generator, the probability analysis, the advanced battery ageing models, multi-objective optimizations, etc.

1.3 System optimization.

In Annex 1 there is more info about the Genetic Algorithms used in the optimization.

MHOGA makes use of two genetic algorithms, the main algorithm and the secondary algorithm. The **main algorithm** provides an optimum configuration for the PV generator, the wind turbines, the hydraulic turbine, the batteries, the AC generator, the fuel cell, the electrolyzer, and /or the inverter-charger, in order to **minimize total system costs (NPC) in the cases where we want to supply a certain load or to maximize NPV in the cases of generators (or minimize LCOE or LCOH).**

Minimization of NPC:

When minimizing the NPC, it calculates the total cost during the system lifespan, calculating the cash flow for each year and updating it with respect to the initial time, i.e. it calculates the Net Present Cost (NPC) of the system, in mono-objective optimization. Costs are accounted as positive amounts of money while incomes (if any) are accounted as negative amounts of money.

For each possible solution obtained from both algorithms (combination of components and control strategy), the sum of the cash flow during the years transferred to the initial moment of the installation (NPC) is be calculated, which includes:

- The initial costs of the system (acquisition of the different components of the system).
- The fuel cost of the AC generator (diesel fuel usually)
- The fuel cost of the fuel cell in the event that it consumes external fuel, i.e. not generated by an electrolyzer.
- The costs of operation and maintenance of the different components.
- The costs of purchasing unmet load (electrical energy not served by the system) to the AC grid (if there is AC grid).
- The replacement costs of the elements whose lifespan is less than the study period (usually 25 or 30 years, and usually coincides with the duration of the photovoltaic modules).
- The incomes (which are subtracted from the costs) due to the sale of surplus electric power to the AC grid as well as the sale of surplus H_2 generated (if any).

- Revenues (which are subtracted from costs) by sale of the different components (if residual lifespan remains) at the end of the study period of the installation. The revenues from these sales are assumed proportional to the life left. There is the possibility of considering these incomes or not.

In stand-alone systems, *NPC* of each combination of components *i* and control strategy *k* ($NPC_{i,k}$) is computed considering the acquisition cost of all the components of the hybrid system and also the replacement of the components, the operation and maintenance (O&M) costs, the fuel costs, the electricity costs (purchased to the AC grid) and the incomes (of selling electricity and/or hydrogen) during the hybrid system lifetime $Life_{HS}$ (years). $Life_{HS}$ (years). Defining $Cost_j$ as the acquisition cost of component *j* (year 0), NPC_{rep_j} the sum of the replacement costs of component *j* during the system lifetime converted to the initial moment of the system (year 0), $Cost_{O\&M\_j}$ the annual O&M cost of component *j* in year 0, $Cost_{F\_y}$ is the cost of the fuel used by the fossil fuel generator (backup generator) during year *y*, $Cost_{purch\_E\_y}$ is the cost of the electricity purchased to the AC grid during year *y*, $Incomes_{sell\_E\_y}$ is the income due to the electricity sold to the AC grid during year *y*, $Incomes_{sell\_H2\_y}$ is the income due to the hydrogen sold for external use during year *y* and $Cost_{INST}$ is the installation cost (engineering, terrain, cabling…). *NPC* is calculated as follows:

$$NPC_{i,k} = \sum_j \left(Cost_j + NPC_{rep\_j} + \sum_{y=1}^{Life_{HS}} \left(Cost_{O\&M\_j} \frac{\left(1+Inf_{gen}\right)^y}{(1+I)^y} \right) \right) + \sum_{y=1}^{Life_{HS}} \left(\frac{Cost_{F\_y}}{(1+I)^y} \right) + \sum_{y=1}^{Life_{HS}} \left(\frac{Cost_{purch\_E\_y}}{(1+I)^y} \right) - \sum_{y=1}^{Life_{HS}} \left(\frac{Incomes_{sell\_E\_y}}{(1+I)^y} \right) - \sum_{y=1}^{Life_{HS}} \left(\frac{Incomes_{sell\_H2\_y}}{(1+I)^y} \right) + Cost_{INST}$$

where Inf_{gen} is the general annual expected inflation and *I* the annual interest rate (nominal discount rate).

$$Cost_{F\_y} = Fuel_y \cdot PrFuel_0 \cdot (1 + Inf_F)^y$$

where $Fuel_y$ is the fossil fuel generator (backup generator) consumption of year *y*, $PrFuel_0$ the fuel cost of the year 0 (monetary unit / fuel unit) and Inf_F the annual expected fuel inflation.

The sum of replacement costs during the system lifetime is the total replacement cost of component *j*:

$$NPC_{rep\_j} = \sum_{m=1}^{N_{rep\_j}} \left(Cost_j \frac{\left(1 + Inf_j\right)^{m \cdot Life_j}}{(1+I)^{m \cdot Life_j}} \right) - Cost_j \frac{\left(Life_j - \left(Life_{HS} - N_{rep\_j} Life_j\right)\right)}{Life_j} \frac{\left(1 + Inf_j\right)^{Life_{HS}}}{(1+I)^{Life_{HS}}}$$

where $Life_j$ (years), Inf_j and N_{rep_j} are, respectively, the lifespan of component *j*, the annual expected inflation of its acquisition cost and N_{rep_j} the number of times it is replaced during the system lifetime ($Life_{HS}$):

$$N_{rep\_j} = \text{Integer}\left(Life_{HS}/Life_j\right)$$

The levelized cost of energy (LCOE) of the energy supplied by the system of components *i* and control strategy *k* during system lifetime, that is, the levelised cost of energy (LCE) (€/kWh) is calculated as follows:

$$LCOE_{i,k} = \frac{NPC_{i,k}}{\sum_{y=1}^{Life_{HS}} \left[\sum_{t=0}^{8760h} E_{load\_y}(t) \cdot \left(1 + Inf_{gen}\right)^y / (1+I)^y \right]}$$

where E_{load_y} (t) is the consumption load during each time step of year *y* supplied by the off-grid system plus the load supplied by the AC grid. The term $\left(1 + Inf_{gen}\right)^y / (1+I)^y$ can be considered as in shown in the previous equation (as usually LCOE is defined) or replaced by 1, it is decided by the user.

In the case of grid-connected systems, there can be a cost of purchasing electricity to the AC grid, which is affected by its own inflation, and there can be incomes due to selling electricity to the AC grid (and/or selling hydrogen for external use), these incomes will be counted as negative values in the NPC calculation, and they are affected by their own inflation.

The levelized cost of hydrogen (LCOH) of the hydrogen supplied to the load (hydrogen load) by the system of components *i* and control strategy *k* during system lifetime (€/kg) is calculated as follows:

$$LCOH_{i,k} = \frac{NPC_{i,k}}{\sum_{y=1}^{Life_{HS}} \left[\sum_{t=0}^{8760h} H2_{load\_y}(t) \cdot \left(1 + Inf_{gen}\right)^y / (1+I)^y \right]}$$

where $H2_{load\_y}$ (t) is the hydrogen consumption load (kg) during each time step of year *y* supplied by the system.

Maximization of NPV:

If the optimization is the maximization of NPV (gird-connected generating systems with no load or very low load), in its calculation incomes are positive (selling electicity to the AC grid and/or selling hydrogen for external use) and costs are negative. It is calculated as follows:

$$NPV_{i,k} = \sum_{y=1}^{Life_{HS}} \left(\frac{Incomes_{sell\_E\_y}}{(1+I)^y}\right) + \sum_{y=1}^{Life_{HS}} \left(\frac{Incomes_{sell\_H2\_y}}{(1+I)^y}\right) - \sum_{y=1}^{Life_{HS}} \left(\frac{Cost_{purch\_E\_y}}{(1+I)^y}\right) - \sum_{j}\left(Cost_j + NPC_{rep\_j} + \sum_{y=1}^{Life_{HS}}\left(Cost_{O\&M\_j}\frac{(1+Inf_{gen})^y}{(1+I)^y}\right)\right) - \sum_{y=1}^{Life_{HS}}\left(\frac{Cost_{F\_y}}{(1+I)^y}\right) - Cost_{INST}$$

The electrical energy incomes and costs during year *y* are calculated as follows:

$$Incomes_{sell\_E\_y} = \sum_{t=0}^{8760h} \left(Esell_y(t) \cdot PrEsell_0(t)\right) \cdot \left(1 + Inf_{sell\_E}\right)^y$$

$$Cost_{purch\_E\_y} = \sum_{t=0}^{8760h} \left(Epurch_y(t) \cdot PrEpurch_0(t)\right) \cdot \left(1 + Inf_{purch\_E}\right)^y$$

where $Esell_y$(t) and $Epurch_y$(t) are, respectively, the electrical energy sold to the AC grid and the electrical energy purchased from the AC grid during each time step of year *y*; $PrEsell_0$(t) and $PrEpurch_0$(t) are the prices of electrical energy sold to the AC grid and of the electrical energy purchased from the AC grid during each time step of year 0*;* Inf_{sell_E} and Inf_{purch_E} are their respective price annual inflations.

The incomes due to hydrogen sold during year *y* are calculated as:

$$Incomes_{sell\_H2\_y} = \left(H2sell_y \cdot PrH2sell_0\right) \cdot \left(1 + Inf_{sell\_E}\right)^y$$

where $H2sell_y$(t) is the amount of hydrogen sold during year *y*; $PrH2sell_0$ is price of selling hydrogen at year 0 and Inf_{purch_H2} is the price annual inflation.

In this kind of grid-connected systems, where there is no load or load is very low, the LCOE of the energy injected in the AC grid by the system of components *i* and control strategy *k* during system lifetime, is calculated as follows *(the user can select to use the electricity sell price inflation instead of the general inflation in the equation)*:

$$LCOE_{i,k} = \\ = \frac{Total\_Present\_Cost}{\sum_{y=1}^{Life_{HS}}\left[\left(\sum_{t=0}^{8760h} Esell_y(t) + H2_{sold_y} \cdot 39.4\right) \cdot \left(1 + Inf_{gen}\right)^y / (1+I)^y\right]}$$

Where *Total_present_cost* is the sum of the total present costs of the system during its lifetime (NPV minus incomes), $\sum_{t=0}^{8760h} Esell_y(t)$ is the energy injected in the AC grid during year *y*, $H2_{sold\_y}$ is the amount of hydrogen sold for external use during year *y* and 39.4 kWh/kg is the conversion factor from hydrogen to energy (higher heating value).

$$Total\_Present\_Cost = \\ = \sum_{y=1}^{Life_{HS}}\left(\frac{Cost_{purch\_E\_y}}{(1+I)^y}\right) \\ + \sum_j\left(Cost_j + NPC_{rep\_j} + \sum_{y=1}^{Life_{HS}}\left(Cost_{O\&M\_j}\frac{\left(1+Inf_{gen}\right)^y}{(1+I)^y}\right)\right) \\ + \sum_{y=1}^{Life_{HS}}\left(\frac{Cost_{F\_y}}{(1+I)^y}\right) + Cost_{INST}$$

The LCOH (€/kg) of the hydrogen sold, produced by the system of components *i* and control strategy *k* during system lifetime, is calculated as follows (R Dufo-López, Lujano-Rojas, & Bernal-Agustín, 2023) *(the user can select to use the electricity sell price inflation instead of the general inflation in the equation)*:

$$LCOH_{i,k} = \frac{Total\_Present\_Cost\_H2}{\sum_{y=1}^{Life_{HS}}\left[\left(\sum_{t=0}^{8760h} H2_{sold_y}\right) \cdot \left(1 + Inf_{gen}\right)^y / (1+I)^y\right]}$$

Where *Total_present_cost_H2* is the sum of the total present costs of the system during its lifetime (NPV minus incomes due to selling hydrogen).

$$Total\_Present\_Cost\_H2 =$$

$$= \sum_{y=1}^{Life_{HS}} \left(\frac{Cost_{purch_{E_y}}}{(1+I)^y}\right) - \sum_{y=1}^{Life_{HS}} \left(\frac{Incomes_{sell\_E\_y}}{(1+I)^y}\right)$$

$$+ \sum_j \left(Cost_j + NPC_{rep\_j} + \sum_{y=1}^{Life_{HS}} \left(Cost_{O\&M\_j} \frac{\left(1+Inf_{gen}\right)^y}{(1+I)^y}\right)\right)$$

$$+ \sum_{y=1}^{Life_{HS}} \left(\frac{Cost_{F\_y}}{(1+I)^y}\right) + Cost_{INST}$$

Multi-objective optimization:

For multi-objective optimization (Bernal-Agustín, Dufo-López, & Rivas-Ascaso, 2012)(Rodolfo Dufo-López & Bernal-Agustín, 2008)(Bernal-Agustín & Dufo-López, 2009b)(Rodolfo Dufo-López et al., 2011) (Rodolfo Dufo-López, Cristóbal-Monreal, & Yusta, 2016a)(Coello, Veldhuizen, & Lamont, 2002)(Zitzler & Thiele, 1999), MHOGA looks for solutions with low NPC and low CO_2 and/or low unmet load by the stand-alone system.

MHOGA also obtains, for each combination of components provided by the main algorithm, the control strategy (combination of control variables, see Annex 2 for more information on control strategies) more suitable to minimize NPC (through the secondary algorithm) or maximize NPV, depending on the type of project.

Total CO_2 cycle life emissions are also obtained, including those generated by the AC generator fuel (usually diesel), as well as those generated in the manufacture, transportation and recycling of the components of the system, and those generated in the electricity purchased from the grid, if applicable (Rodolfo Dufo-López et al., 2011). The result is obtained in kton of CO_2 per year (total emissions during the study period from fuel and from manufacturing, transportation and recycling of components are divided by the number of years of system life).

Probabilistic optimization:

You can also perform probabilistic optimization (using Monte Carlo Simulation) (Rodolfo Dufo-López, Pérez-Cebollada, Bernal-Agustín, & Martínez-Ruiz, 2016)(Rodolfo Dufo-López, Cristóbal-Monreal, & Yusta, 2016b), where meteorological data and load demand follow certain functions of probability, obtaining results that are also probability distributions.

Optimization of the grid-connected battery management (see section 3.1.3.2): and/or the pumped hydro storage:

It is also possible to optimize the management of batteries in systems connected to the AC grid, to charge when the electricity price of the AC grid is low and to discharge when the price is high (Rodolfo Dufo-López, 2015).

The management of the pumped hydro storage or the hydrogen generation can also be optimized.

1.4 System performance simulation.

For each combination of components and control variables, the system is simulated for a full year or for the whole system lifetime (multiperiod optimization), in time steps which can be defined from 1 minute to 1 hour.

1.4.1 Simulation during 1 year.

If the simulation during just 1 year is selected, it is assumed that all years of the system's lifetime will be the same (except in the case where the advanced lead-acid batteries life model proposed by Schiffer et al., 2007 (Schiffer et al., 2007) is selected, where the simulation of the system must be carried out until the end of the battery lifetime).

That is, in general (except "Schiffer" battery model) the results obtained in the simulation for one year are assumed to be the same for the rest of the life of the system. During that year, at intervals of between 1 minute and 1 hour (depending on the designer's choice), all variables are obtained to define the behavior of the system, considering the characteristics of the elements that compose the system, the control variables, energy demand data and meteorological data. We consider the semi-stationary system, so that in each interval (between 1 minute and 1 hour) the different variables of the system remain constant.

If the battery model is that of Schiffer et al., 2007 (Schiffer et al., 2007), which takes into account the aging of the batteries (due to degradation and corrosion), not every year are the same, but the simulation is done continuously until the batteries end their lifespan (when the remaining capacity drops to 80% of nominal or to the value selected by the user). From that moment, the cycle is repeated.

1.4.2 Multiperiod simulation.

If the multiperiod simulation is selected, the simulation during the whole lifetime of the system is performed (usually 25 years). It takes much more computation time than the simulation of just 1 year, but the results are much more accurate. It considers the increase in load during the years (a percentage of increase in load of each year compared to the previous year) and it also considers the decrease in the PV generation (a reduction in % for each year) and for the other generation technologies. Also different irradiation and wind speed can be considered for each year. Even different operation and maintenance costs for the PV generator or for the wind turbines can be considered for each year.

1.4.3 Variables considered in the simulations.

In the most complex case, with all the components of the system included, during each time interval of the year or of the system lifetime, MHOGA must estimate the following variables: the power generated by the renewable sources, which depends on solar irradiation, wind and hydraulic flow in that interval; the electrical energy consumed by the loads (AC usually) and the amount of external H_2 consumption, which depends on the loads expected for that interval, the State of Charge (SOC) of the batteries, as well as the amount of H_2 available in the hydrogen tank and the amount of water available in the water tank (in its case).

In the case of not having measured values for the solar irradiation, or downloaded from PVGIS, Renewable Ninja or NASA, solar hourly irradiation over the tilt surface of the PV generator can be calculated from the monthly data using the model of Graham (1990) (Graham & Hollands, 1990), which entails statistical variability, or using the models of Liu and Jordan, 1960 (Liu & Jordan, 1960), Hay and Davis, 1978 (Hay & Davies, 1978) and Rietveld (Rietveld, 1978), by using different correlations: Liu and Jordan (1960) (Liu & Jordan, 1960), Collares-Pereira (1979) (Collares Pereira & Rabl, 1979) and Erbs et al (1982) (Erbs, Klein, & Duffie, 1982). We can calculate the irradiation over the back surface of the PV modules (for bifacial PV), using the methodology shown in (Durusoy, Ozden, & Akinoglu, 2020), expanded to any azimuth and tracking method. Also direct irradiation over the tilt surface (for CPV) is obtained.

From the above data, the irradiation in steps of 1 minute is obtained following a first-order autoregressive function model based in the one used by Meteonorm software (*Meteonorm. Global meteorological database. Handbook part II: Theory. Version 7.1,* 2015).

Regarding the wind speed, if no measured values are available, MHOGA calculates it from the monthly data using the Dufo-Lopez and Bernal-Agustín model (Rodolfo Dufo-López & Bernal-Agustín, 2012). Then the wind speed values are obtained in steps of 1 minute following the first-order autoregressive function model used by Meteonorm software (*Meteonorm. Global meteorological database. Handbook part II: Theory. Version 7.1*, 2015).

If load data are not available at 1 minute intervals, the software obtains them from the hourly data using a first-order autoregressive function model similar to that used for irradiation.

In order to consider the effect of ambient temperature on photovoltaic generation and on wind generation (Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016b) the hourly temperature must be known, which, if no data are available, can be calculated from monthly average temperature data (together with the irradiation data) applying the model of Erbs et al. 1983 (Erbs, Klein, & Beckman, 1983).

In the case of lead-acid batteries, the state of charge of the batteries, as well as the maximum current allowed by them can be calculated according to several models, to be chosen by the user: Model Ah (used by Schuhmacher in 1993) (Schuhmacher, 1993), KiBaM model (Manwell and McGowan, 1993) (Manwell & McGowan, 1993), Copetti model (Copetti et al., 1993 y 1994) (Copetti, Lorenzo, & Chenlo, 1993)(Copetti & Chenlo, 1994), Schiffer model (Schiffer et al., 2007) (Schiffer et al., 2007). The calculation of the estimated lifespan of the batteries is very important, since it influences the number of replacements of the batteries during the study period and therefore in the total cost NPC or NPV of the system. It is possible to choose between Equivalent Cycles to failure model and another more complex and precise, the method of the Count of Cycles or Rainflow according to the algorithm of Downing (Downing and Socie 1982)(Downing & Socie, 1982), more accurate(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995)(Green & Manwell, 1995).

For lead-acid batteries, it can be used the method proposed by Schiffer et al (Schiffer et al., 2007), a much more precise model, which includes the ageing by corrosion (a comparison of the different models was studied in (Rodolfo Dufo-López, Lujano-Rojas, & Bernal-Agustín, 2014), where it was verified that the model of Schiffer gives similar results to the real ones, whereas in some cases the other models predict the duration of the batteries of the order of 2 or 3 times superior to the real duration).

In the case of lithium-ion batteries, in addition to the Equivalent Cycle life model and the Cycle Count or Rainflow method, you can choose other three life models specific to lithium-ion batteries: three models for LiFePo4 / graphite batteries, Wang et al, 2011 (Wang et al., 2011); Grot et al., 2015 (Groot, Swierczynski, Stan, & Kær, 2015)); Naumann et al., 2020 (Naumann, Spingler, & Jossen, 2020); and another model for LiCoO2/graphite batteries, Saxena et al., 2016 (Saxena, Hendricks, & Pecht, 2016)).

Once a combination of components and control strategy has been simulated for all the time intervals of a year, MHOGA knows the different parameters that will determine the NPC or NPV of the system over its useful life. With these data, MHOGA can know the annual costs and incomes. It can also be known how long it will take for each component to need to be replaced. Finally, by updating or translating all these costs to the initial moment of the investment, the NPC or NPV of the system is obtained.

2. INSTALLING AND RUNNING THE APPLICATION

2.1 Installation

To run the program you need the Microsoft Windows XP operating system or higher.

A minimum screen setting of 1152x864 pixels is recommended. Lower values will cause some screens of the program not to be displayed in full and the scrollbars will have to be used. It is also recommended that the text size of Windows be medium (if it is large it may not be well visualized the texts of the program, some texts can be mounted on others). These requirements are met by default by most of the computers that were manufactured some years ago.

To install the application double click on the auto-installable file called MHOGA with the version number and build data. If you have problems to install, you can request to the developers the files to be added directly to your computer.

MHOGA software does not run under virtual machines or hypervisors. Even if you do not use it, virtualization is enabled by default in many new computers BIOS. Deactivate virtual machines or hypervisors if, after installing, when you open the software you obtain the following message "Failed to start the trial: The function failed because this instance of your program is running inside a viertual machine / hypervisor and you've prevented the function from running inside a VM." (*it can happen due to the default virtualization activation in the computer BIOS, in this case you must disable it in BIOS, see the last page of the following document*): **How to deactivate virtual machine / hypervisor**

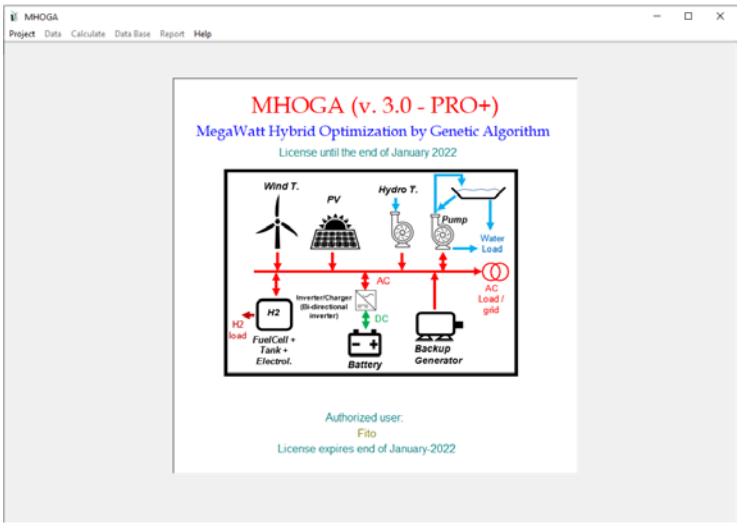
2.2 Running the Application

The application may be started:

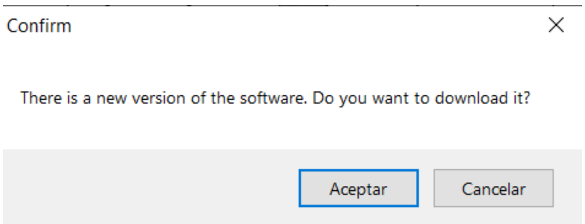
- From the Start button, Select All Programmes, select MHOGA.
- From the Desktop, double click on MHOGA.

3. INTRODUCING DATA

A welcome screen is shown when the programme is open.



When you open the software, it asks if you want to look for updates. If yes, it connects internet looking for a new version. If a new version is ready to be downloaded, it asks you to download it:



It is strongly recommended that you download and install the new available version. After downloading it, you must close the software and install it.

> ***If the version is the same as the one you had installed, but it is a new build****:*
>
> *A)* ***If in the previous version you changed the currency and/or the components of the databases:*** *DO NOT RUN THE INSTALLER, YOU SHOULD ONLY COPY THE EXECUTABLE FILE (folder EXECUTABLE) and replace the original one in the installation folder of the software.*
>
> *B)* ***If in the previous version you did NOT change the components of the databases neither the currency****: Uninstall the current version and install the new version by running the installable file (folder INSTALLABLE). It is not recommended if you changed the currency and/or the components of the database, because you would loss these changes.*

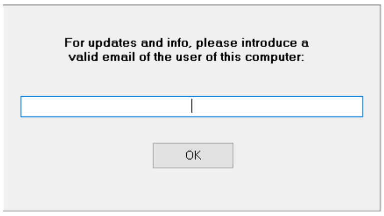
If the version is new (newer than the one you had installed)*:*

A) ***If in the previous version you changed the components of the databases and/or the currency****:*

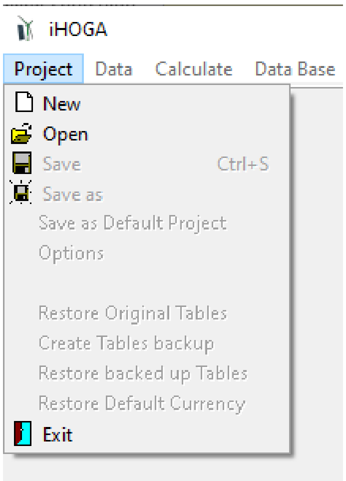
1. ***If you changed the components of the databases****:*
    a. *Before installing the new version, you must make a backup of the database tables (Project->Create tables backup); the backup will be created in the installation folder of the software, with a .back file and a folder with the same name.*
    b. *Copy the .back file and the folder with the same name which was created in the installation folder, to a safe different folder.*
2. *Unisntall the previous version and then delete the installation folder where the software was installed.*
3. *Install the new version by running the installable file (folder INSTALLABLE).*
4. *After installing:*
    a. ***If you changed the currency****: before opening a previous project, you must* ***create a new project*** *and change the currency as you did in the previous version (the software will ask you for doing that).*
    b. ***If you changed the components of the databases****: copy the .back file and the folder with the same name from the safe folder to the installation folder of the new version. Then, restore the backed up tables (Project->Restore backed up tables and choose the .back file).*

B) ***If you did NOT change the components of the databases neither the currency****: uninstall the previous version and install the new one by running the installable file (folder INSTALLABLE).*

The first time you open the software it asks for a valid email address which will be used to inform you about updates and information about the software. Enter the email and click "OK".

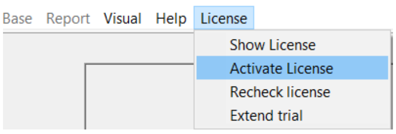


On the Project Menu, there is a choice to create a new project, open an existing one, exit the application or other options (available after a project is created or open).

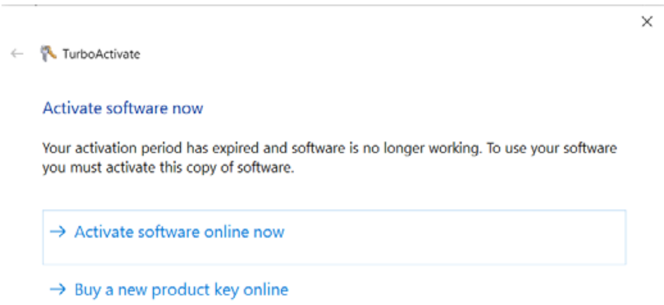


Licensing:

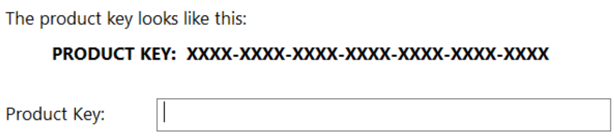
The first time we run MHOGA, after accepting several messages showing that the license is not active, you should click in the upper menu "License" -> "Activate License".



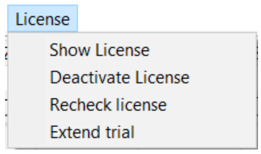
Then a window appears, where you must click "Activate software online now".



Then it asks for the product key (you should have bought the key previously):

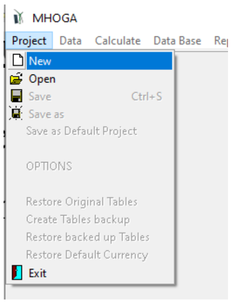


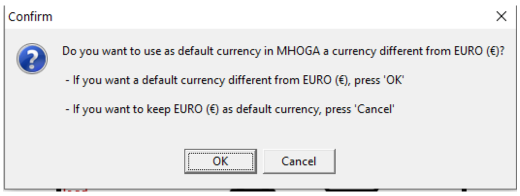
If you just purchased 1 license, you can use the same product key in several computers, but it only can be active in one computer. If you want to use the software in another computer, first deactivate the license in the computer where you were using the software, and then in the another computer activate the license. You can change from a computer to another one whenever you want.



<u>Change the default currency which will be used by MHOGA:</u>

The first time you create a new project (menu Project->New), MHOGA asks if you want to change the default currency, i.e., if you want to use as default a currency different from Euro (€).



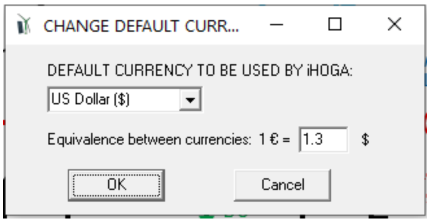


MHOGA will only ask for the default currency this first time we create a project. If it is not changed at this time, the default currency will be the Euro.

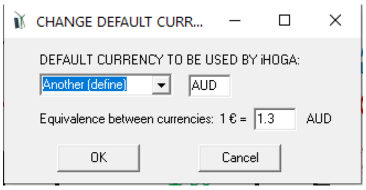
To change the default currency later: In the upper menu <u>Project</u>, select <u>Restore default currency</u>, and accept all the steps. The next time you open the software, it will ask you for the new default currency.

If we want to keep € as the default currency, we must click the "**Cancel**" button. If we want to use another currency by default, we will click "**OK**".

If we click "OK" the following screen appears, where we can choose the new default currency. You can choose between Euro (€), US Dollar (€) or any other to be defined.



If we choose another currency, a text box appears at the right where we must write its abbreviated name. Below we must indicate the equivalence between the Euro and the new currency.



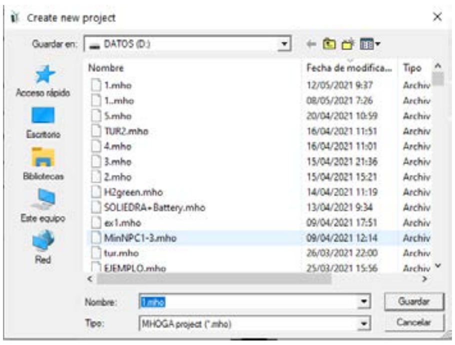
If we click the "**Cancel**" button, the Euro will be kept as the default currency and the default databases and data will not be altered. However, the next time you create a new project or open a project, you will be asked to define the currency.

If we click "**OK**", the new currency will be the one that will use MHOGA by default, and the economic values used by default and the cost data of the databases will be multiplied by the factor we have set as equivalence between currencies. The next time we create a new project or open an existing project, the program will no longer ask for the change of currency. However, in each project, you can define another currency.

Create a new project:

If we click on **Project-> New**, the program will ask for the name of the project and the folder where we want the project to be created.

The Windows save window appears to select the name and folder where the project will be created.



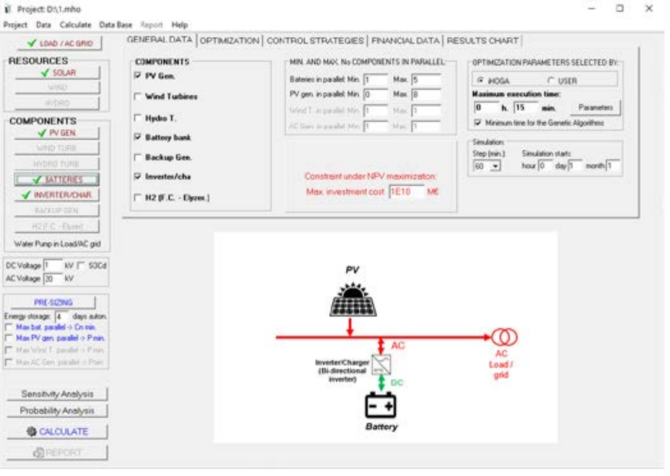
The file of the project will have **.mho** extension. Once pressed "**Save**" button, the program will create a file with the name that we have given to the project plus ".mho", in addition to a folder with the same name, in the same directory where we created the project. In that folder the necessary tables and files for the execution of the project will be placed.

If, after working on the project and closing the software, you want to move or copy the project to another directory, you must not only move or copy the .mho file, you must also move or copy the folder with the same name.

Important: If the path from the root to the project directory is too long, the Paradox tables used by the program do not work, and when we open the project it will give an error message. In that case, place the project in a directory with fewer characters.

If the operating system is Windows Vista or 7 it will not let you save projects directly to C:

The default values are for a PV-battery generating system, with no load and irradiation of Zaragoza, Spain. Of course, the user can change any data.



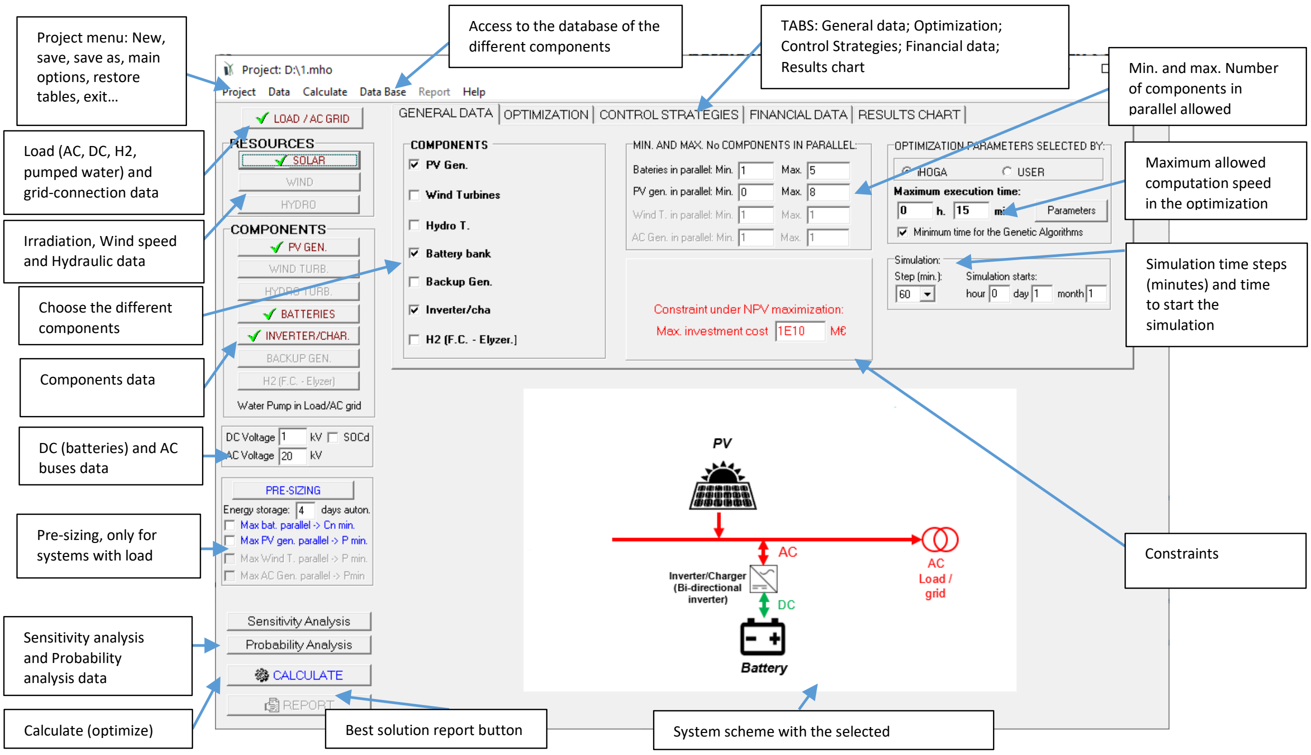
Open an existing project:

If we choose Open an existing Project (**Project->Open**), we must also first select the type of project. A screen will appear where we should look for the folder of the project file that we want to open (with extension .mho).

In the directory where the project file is located, there must also be a folder with the same name, where are the tables used by the program (when a new project is saved, MHOGA creates both the .mho file and the folder with the same name) .

3.1 Main screen and main options of the project

The main screen of the program looks like this:

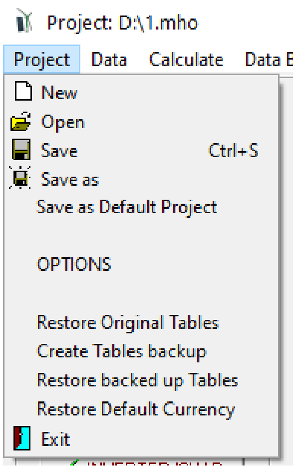


The main screen shows menus and buttons. They provide access to additional screens where the different elements of the system may be selected.

Main options of the project.

The first to decide are the main options of the project.

By clicking on the upper menu **Project-> OPTIONS**:



The next window appears, where we can choose the main options of the project.

We must choose:

Simulation of each combination of components and control strategies:

- **Simulation of just the 1st year** and extrapolate the results.

Or

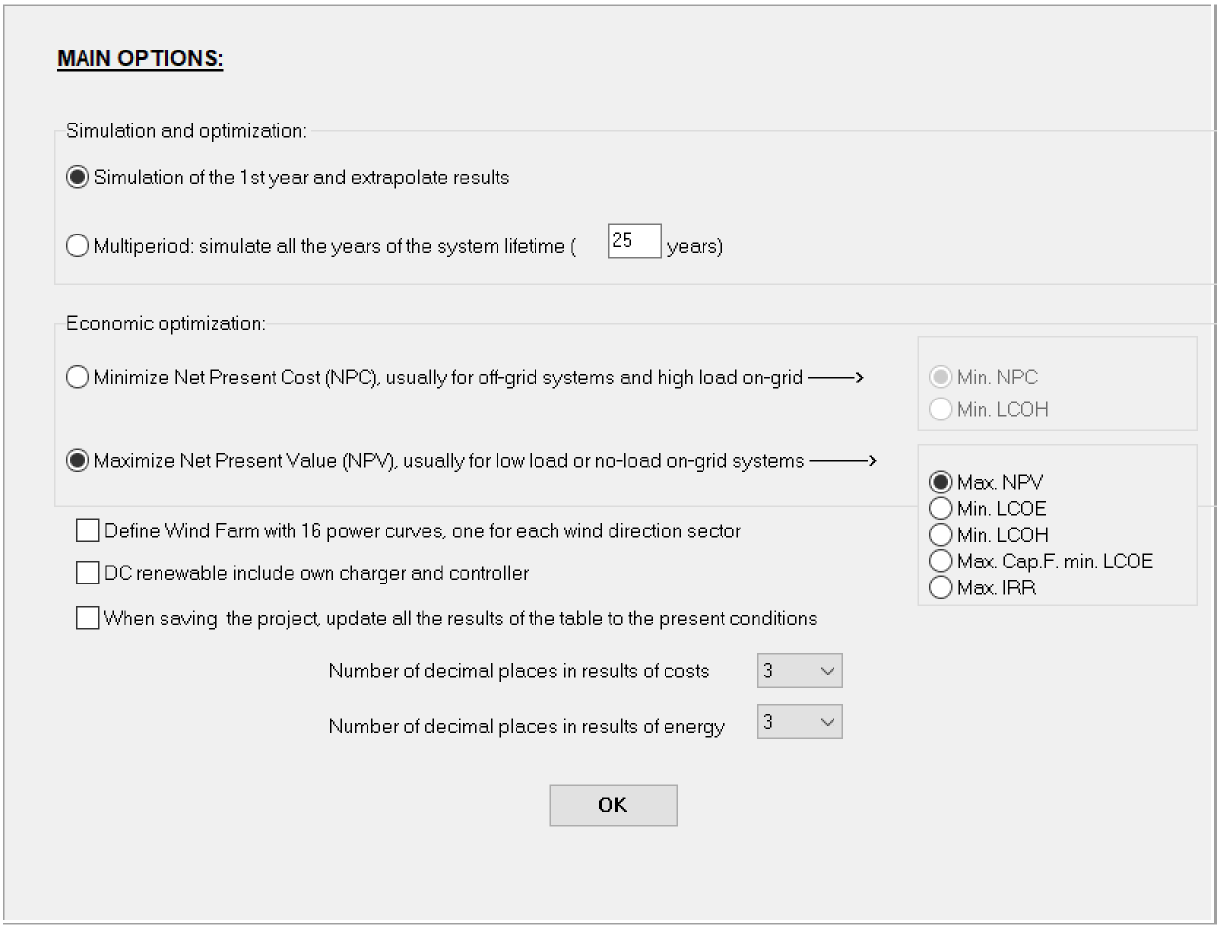
- **Simulation Multiperiod** (simulate all the years of the system lifetime, considering the increase in load and the decrease in PV generation, wind turbine generation,...).

Type of project considering the economic optimization:

- **Minimization of net present cost (NPC)** (typical for off-grid systems or grid-connected systems with high load). We can select minimization of NPC or minimization of LCOH, if there is hydrogen load.

Or

- **Maximization of the net present value (NPV)** (typical for grid-connected generators with low load or without any load, where all the energy or almost all is sold to the AC grid). We can select maximization of NPV or minimization of LCOE or minimization of LCOH, if there is hydrogen generation (a button "Data" appears where a minimum annual amount of hydrogen to be generated can be set). Also is possible the maximization of capacity factor and minimization of LCOE, with weights (a button "Data" appears where a data must be set). Also is possible the maximization of IRR.



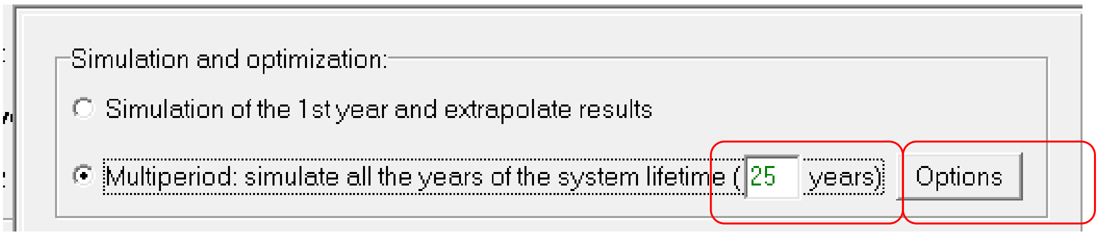
We can also select the option to **Define Wind Farm with 16 power curves, one for each wind direction sector** (by selecting the checkbox). In that case, later, in the Wind resource window we will have to import a file with wind speed and direction data, and in the Wind Turbines window we will have to import the 16 power curves.

We can select the option **DC renewable include own charger and controller** (by selecting the checkbox). In that case, if later you define PV generator and/or wind turbines connected to the DC bus, they will be supposed to include their own charger and controller therefore they will be able to charge the batteries and/or feed the DC electrolyzer, not needing an inverter/charger.

Also the number of decimal places of the results must be settled.

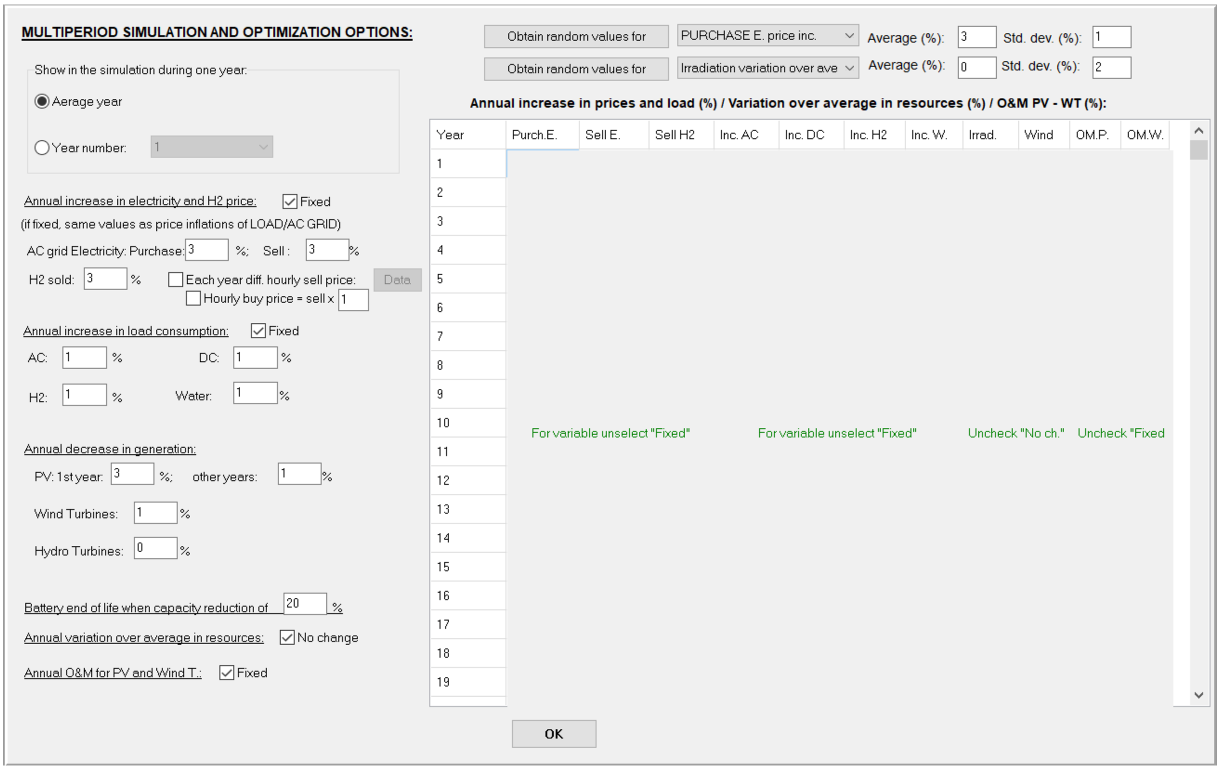
If we select the box "**When saving the project, update all the results of the table to the present conditions**", when you save the project, the results table will be updated to the present conditions, this means that each row of the results table (that is, each combination of the results table) will be simulated again and the results will be updated. Be careful with this option, as if the results table has many results and you are using multi-period optimization and/or time steps of few minutes, the update can take a long time.

By selecting **Multiperiod,** the number of years of the system lifetime must be indicated (by default 25 years) and a button appears to select several options:



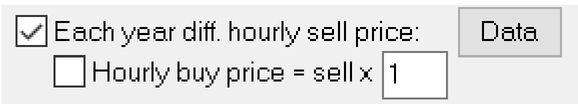
By clicking in **Options** button a new window appears, where we can choose:

- The year to be seen in the simulation (although all the years are simulated, just one can be seen in the simulation screen): the average year or a specific year. Anyway, later, in the simulation screen, the visualisation year can be changed.
- The annual increase (%) in electricity and in hydrogen price. They can be fixed values (if "Fixed" option is checked, as default), that is, same values for all the years, or they can be different for each year (if "Fixed" option is unchecked, appearing the first three columns of the right table where we can introduce the values for each year of inflation of the electricity purchased to the AC gird in "Purch. E." column, inflation of the electricity sold to AC grid in "Sell E." and inflation of the hydrogen sold in "Sell H2").
- The annual increase in load consumption (%). Fixed values for all the years or a specific value for each year in the right table, columns "Inc AC" to "Inc H2".
- The annual decrease (%) for the different technologies of generation.
- The battery end of life capacity reduction.
- The annual variation (%) over average in resources (irradiation and wind speed), if "No change" is checked, all the years will have same resources, however if it is unchecked, in the columns of the right table ("Irrad." and "Wind") we can introduce the variation of each year (%) over the average.
- The annual operation and maintenance (O&M) for PV and for Wind T., which can be fixed (all the years the same) or it can be different for each year (in the two last columns of the table, OM.P. and OM.W, in % of the acquisition cost of the PV and of the Wind turbines). The cash flow of each year will be that percentage, which will be affected by the general inflation.



Random values can be obtained for all the columns (except for the two last ones), by clicking in the upper buttons "**Obtain random values for**" and selecting the item and the average and standard deviation.

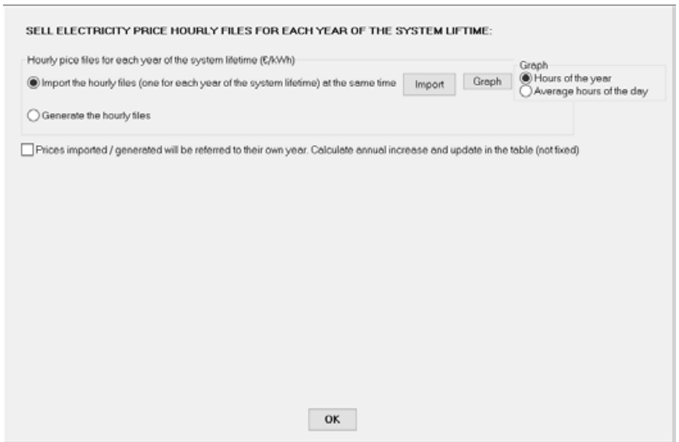
We can use different hourly sell price for each year, by clicking "**Each year diff. hourly sell price**", and later the button "**Data**":



If the checkbox "**Hourly buy price = sell x**" is checked, the hourly buy price for each year will be proportional to the hourly sell price that will be obtained for each year.

After clicking Data button, we can see a new window, where we can choose to:

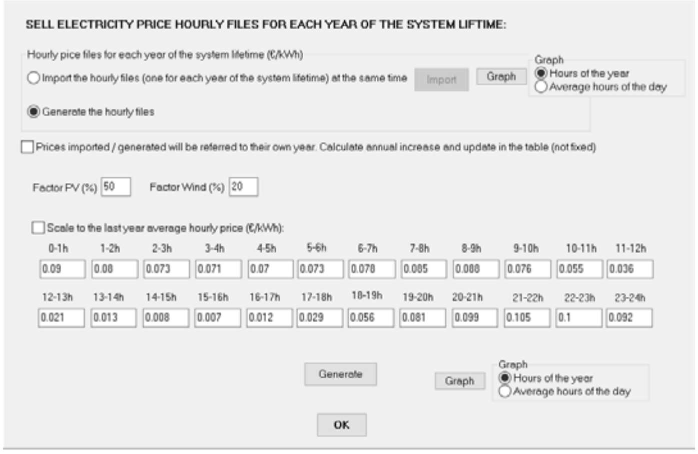
- **Import the hourly sell price files**. We need, in the same folder, one file for the hourly sell price of each year, from the 2nd to the last year of the system lifetime (for the 1st year, the hourly price will be the one previously imported in the LOAD/AC GRID window affected by the sell price inflation, as the imported file is the one of the year 0, the beginning of the system lifetime). The files must have the same name, with the number of the year at the end of the name, before the file extension: for example, you can have the files price2.txt, price3.txt…, price25.txt (if system lifetime is 25 years). Each file must have the hourly price of each hour of the year (8760 rows). Click Import and select the first of them, corresponding to the year 2 (in the example, price2.txt). After importing, you can see the graph for all the years, of the hourly price during all the year, or of the average hours of the day, by clicking the button "Graph".



- **Generate the hourly sell price files**. In this case, we must estimate a PV factor and a Wind factor (%) so that the prices of the year 1 (the hourly price previously imported in the LOAD/AC GRID window affected by the sell price inflation, as the imported file is the one of the year 0, the beginning of the system lifetime) are updated year by year considering the effect of the change in the hourly profile of the day due to the increase in PV penetration ('duck curve') and also the increase in wind penetration (R Dufo-López, Lujano-Rojas, & Bernal-Agustín, 2023):

$$Pr_{Esell}(h,y) = Pr_{Esell}(h,0)\left(1-(F_{PV}G(h,1)+F_w)\left(\frac{y-1}{Life_s-1}\right)\right)\ (1+Inf_{PrE})^y,\ \forall\ 1 \leq y \leq Life_s$$

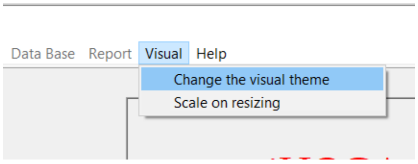
where $Pr_{Esell}(h,y)$ is the selling electricity price of the hour h (0… 8760) in a year y; F_{PV} (default 50%) is the PV factor to consider the price reduction in the future hourly price profile due to an increase in PV penetration, 'duck curve', depending on the average irradiance of hour h of year 1, $G(h,1)$ (W/m2); F_{wind} (default 20%) is the wind factor to consider the price reduction in the future hourly price profile due to the increase in wind generation, and Inf_{PrE} is the annual inflation rate for the electricity price. If the checkbox "**Scale to the last year average hourly price (€/kWh)**" is checked, the previous prices will be scaled so that the last year average prices will be the ones shown below the checkbox.



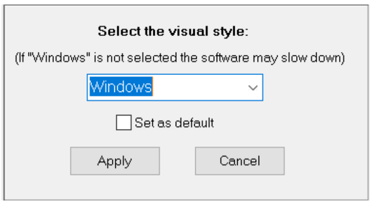
In both cases, if the checkbox "**Prices imported/generated will be referred to their own year. Calculate annual increase and update in the table (not fixed)**" is unchecked (by default), the software assumes that the imported or generated data hourly sell prices for the different years are data referred to the year 0 (beginning of the system lifetime) and therefore the real price of each year will be the imported or generated for that year updated to the year by the inflation shown in the previous window. On the other hand, if this box is checked, the software assumes that the imported or generated data hourly sell prices for the different years are data referred to their own year, so these prices will be the prices of each year (they don't need to be updated), and the annual difference from one year to another one (inflation) is calculated and will be shown in the table of the previous window.

Visual options

In the main screen of the software, upper menu, click in "Visual", if you then click in "Change the visual theme":



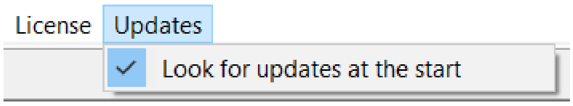
A small window appears, where you can change the visual theme (***if you use a different one from the deault "Windows", the software may slow down***):



In the same upper menu, "Visual", if you click in "Scale on resizing", when you vertically resize the screens of the software, the objects will be scaled. If scale on resizing is not checked, the objects will not be scaled.

Updates

In the main screen of the software, upper menu, click in "Updates", if "Look for updates at the start" is checked (by default), when the software starts it will ask you for looking for updates. If it is not checked, when the software starts it will not look for updates. If you clik in "Look for updates at the start", its status changes.



Main screen tabs.

In the main screen of the software, text fields and check boxes are also available for further input of system details.

On the main screen there are 5 tabs where data must be entered (in the 5th tab we can see the results of the optimization as a graph):

- GENERAL DATA
- OPTIMIZATION
- CONTROL STRATEGIES
- FINANCIAL DATA
- RESULTS CHART

3.1.1 GENERAL DATA tab

In this tab we must enter the most important data:

- Which type of components can be included in the system.

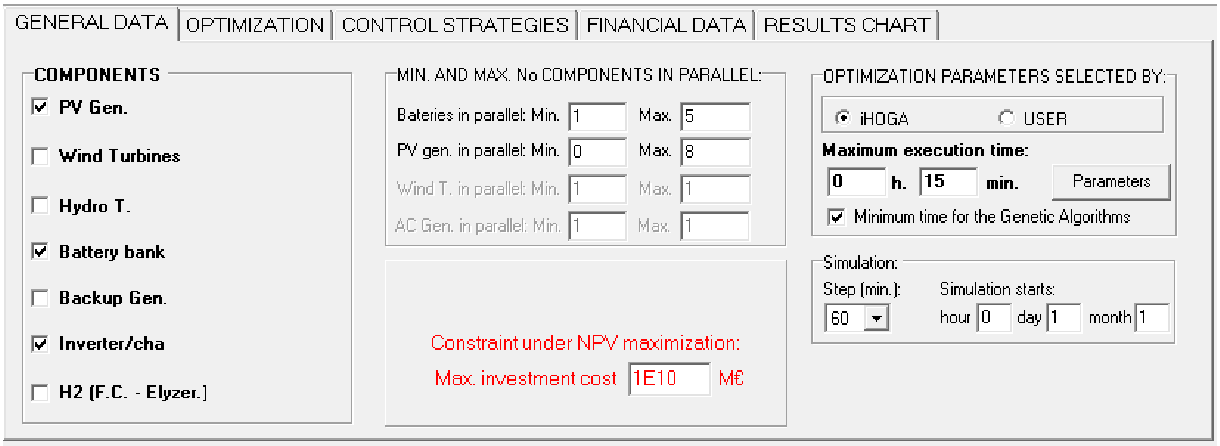
- Maximum and minimum number in parallel allowed for some components.

- Constraints that must be met.

- Maximum execution time and the way to select the optimization parameters (MHOGA or user).

Also indicated:

- The time steps of the simulation and the date and time of the beginning of the simulation.



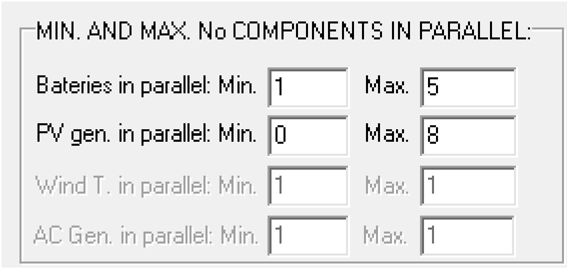
COMPONENTS:

The default hybrid system is a no load, grid-connected photovoltaic generating system, with the possibility of having batteries storage (needed inverter/charger). To add or remove components, select them on "COMPONENTS".

When you add or remove a component, the schematic of the lower part is automatically updated, and the buttons on the left that will introduce us to the screens of the different components are enabled or disabled.

MINIMUM AND MAXIMUM NUMBER OF COMPONENTS IN PARALLEL:

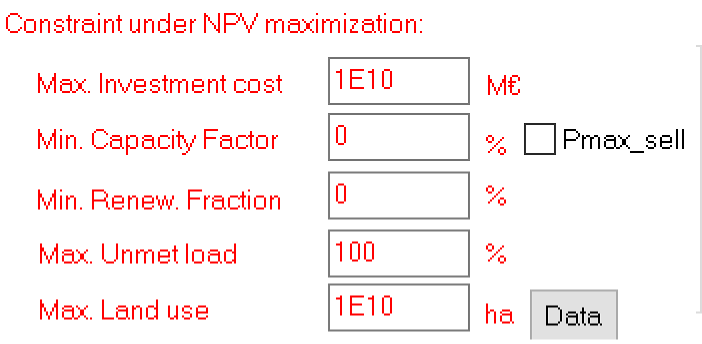
Minimum and maximum number allowed for batteries, PV generators, wind turbines and AC generators (Diesel…) parallel must be provided.



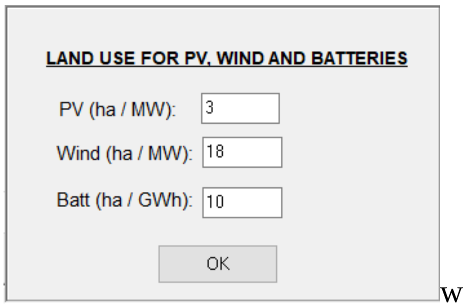
CONSTRAINTS:

In **NPV maximization projects**, where there is typically no load (grid-connected generators so sell the electricity to the AC grid) there can be five constraints:

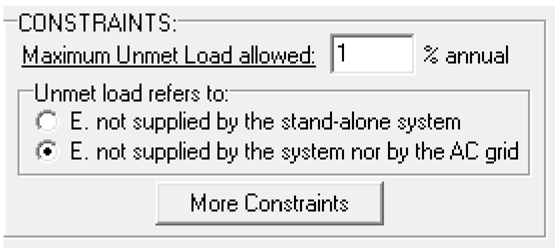
- The maximum investment cost (by default a very high value, that is 1E10 M€, so by default this constraint is not considered).
- The minimum capacity factor (annual energy sold divided by the peak renewable power multiplied by 8760 h) (by default 0%, so by default this constraint is not considered). If you check the box “Pmax_sell”, then the capacity factor will be calculated as the annual energy sold divided by the maximum power that can be exported to the AC grid multiplied by 8760 h.
- The minimum renewable fraction (by default 0%, so by default this constraint is not considered). It is calculated as the annual energy injected to the grid minus the annual energy injected to the grid by the fossil fuel generator, divided by the annual energy injected to the grid.
- The maximum unmet load (load energy not served, by default allowed 100%, so by default this constraint is not considered). This is the unmet load that cannot be supplied by the system nor by the AC grid.
- The maximum land use (by default a very high value, that is 1E10 ha, so by default this constraint is not considered).



By clicking the button "Data" we can edit the land use of PV (ha/MW), Wind turbines (ha/MW) and batteries (ha/GWh).



In **NPC minimization projects**, where a specific load must be supplied, in CONSTRAINTS, user must determine maximum percentage of annual Unmet Load allowed (100 · annual Unmet load / Total annual Energy Required by the system).



The Unmet Load can be refered as:

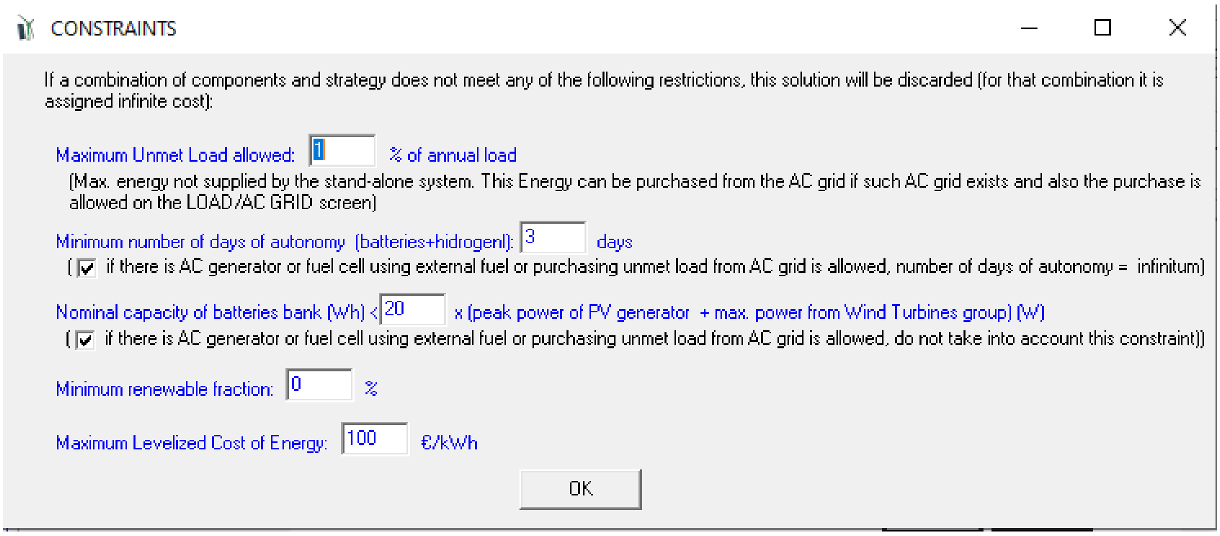
- E. not supplied by the stand-alone system: The energy demanded by the load that is not supplied by the components of the system (energy not served by all the components of the system, including the renewable sources, the batteries, the AC generator and the fuel cell), but not including the AC grid.
- E. not supplied by the system nor by the AC grid (default): The energy demanded by the load that is not supplied by the system (energy not served by the components of the system, including the renewable sources, the batteries, the AC generator and the fuel

cell) nor by the AC gird, if it is available. That is, energy that cannot be covered by any means.

In the case of wanting to cover all the demand, it is not desirable to indicate 0%, but it is recommended to leave a minimum value, for example 0.001%. Leaving this parameter at 0% is not convenient, since sometimes the decimal rounds imply that the software counts small values of unmet load, so if 0% is indicated, it is possible to discard solutions that are correct.

More constraints:

Clicking the "**More constraints**" button a screen appears showing all the possible restrictions to fix:



- Minimum number of days of autonomy (sum of days of autonomy that give the batteries, if any, plus autonomy gives storage of hydrogen, if any, plus autonomy gives the AC generator, if any). If AC generator (e.g. Diesel) exists, it is considered by default that autonomy is infinite (unless you uncheck the "if there is AC generator or purchasing unmet load from AC grid is allowed, number of days of autonomy = infinitum"). The same is seen if fuel cell is used and H_2 is externally purchased. It is also considered infinite autonomy if purchased to AC the unmet load (this is specified in the "LOAD / AC GRID" screen, see section 3.2). If a combination of components and control strategy does not meet the minimum autonomy, this combination is discarded. To calculate the days of autonomy, the energy consumed during one day is considered to be the average daily consumption (energy consumed during the year divided by 365).

- Nominal capacity of the battery bank (Wh) <CR times the peak power of the PV generator + maximum power from Wind Turbines group (W), so that the batteries can be charged properly

by the photovoltaic generator and the wind turbines. For each combination of components and control strategy, if this inequality fails, that combination is discarded. This restriction is only taken into account if there is present in the system a PV generator and a batteries bank.

- Minimum renewable Fraction (%). Minimum percentage of load to be covered by renewable. If a combination does not fulfill this fraction, it is discarded.

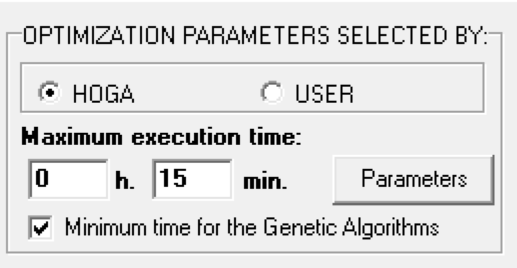
- Levelized Cost of Energy (€ /kWh). Maximum allowed for the kWh price (calculated as the NPC divided by the total energy load supplied during the system lifetime). If a combination does not comply with this maximum value, it is discarded.

In projects of minimization of NPC, MHOGA assigns an infinite NPC value to every element combination that does not meet all the constraints. This indicates that the system is not acceptable, and will not fulfill our requirements.

In projects of maximization of NPV, MHOGA assigns a -infinite value to every element combination that does not meet all the constraints.

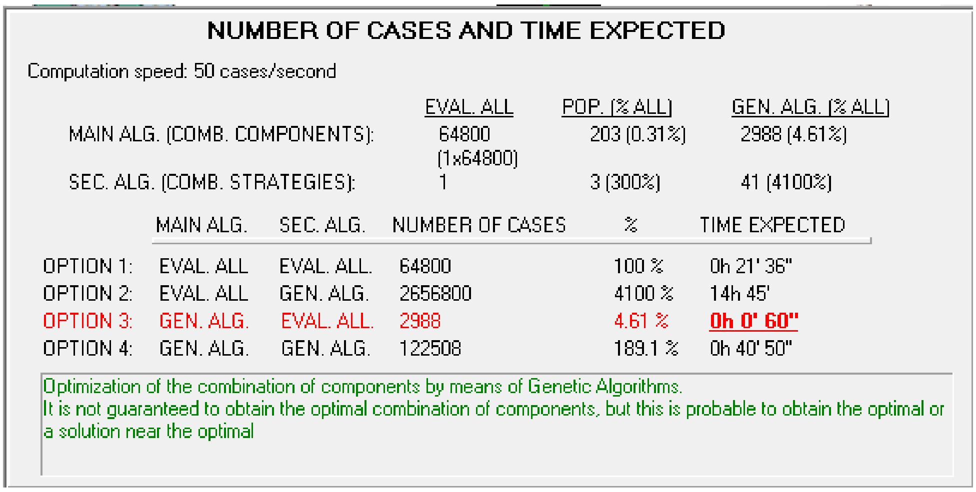
SELECTION OF THE PARAMETERS OF THE OPTIMIZATION.

The parameters of the optimization can be selected by HOGA (default) or by the USER. If the parameters are selected by HOGA, the user must decide the maximum time to execute the optimization (default 15 min).



If in a particular project (for example a project where we have added wind and hydrogen components and the maximum number of components in parallel is high) there are many possible combinations of components and we change the value of the maximum execution time for example to 1 minute, a screen similar to the following appears, where it informs us of the selection of optimization parameters: enumerative method (evaluate all combinations) or genetic algorithms for both the main algorithm (combination of components) and the secondary algorithm (control strategy), and the calculation time used in each case.

In the example (next figure), it is selected genetic algorithms method for the optimization of the combination of components and the enumerative method (evaluate all the combinations) for the optimization of the control strategy (there is only one combination as in this case the control strategy will not be optimized), and the time expected is 60 seconds.



Notes:

If the lead-acid battery model is the Schiffer et al. model, much more accurate than the others (see ref. (Schiffer et al., 2007)*), the calculation time is several times higher, since the simulations cost much more time. This is already taken into account by MHOGA to estimate the calculation time.*

If "Try Both" is checked in the control strategies tab, the calculation time is somewhat higher.

If Multiperiod simulation was selected in the main options of the Project, the calculation time can be 30 or more times higher than if the simulation is just for the 1st year.

If time steps are lower than 60 min. (shown later), the calculation time can be much higher.

This is already taken into account MHOGA.

This screen also appears when we move with the mouse over the area of the parameters of the optimization or the area where we set the minimum and maximum numbers of components or over the area of the control variables, and when changing some data it is updated.

It is advisable to let MHOGA select the parameters of the optimization.

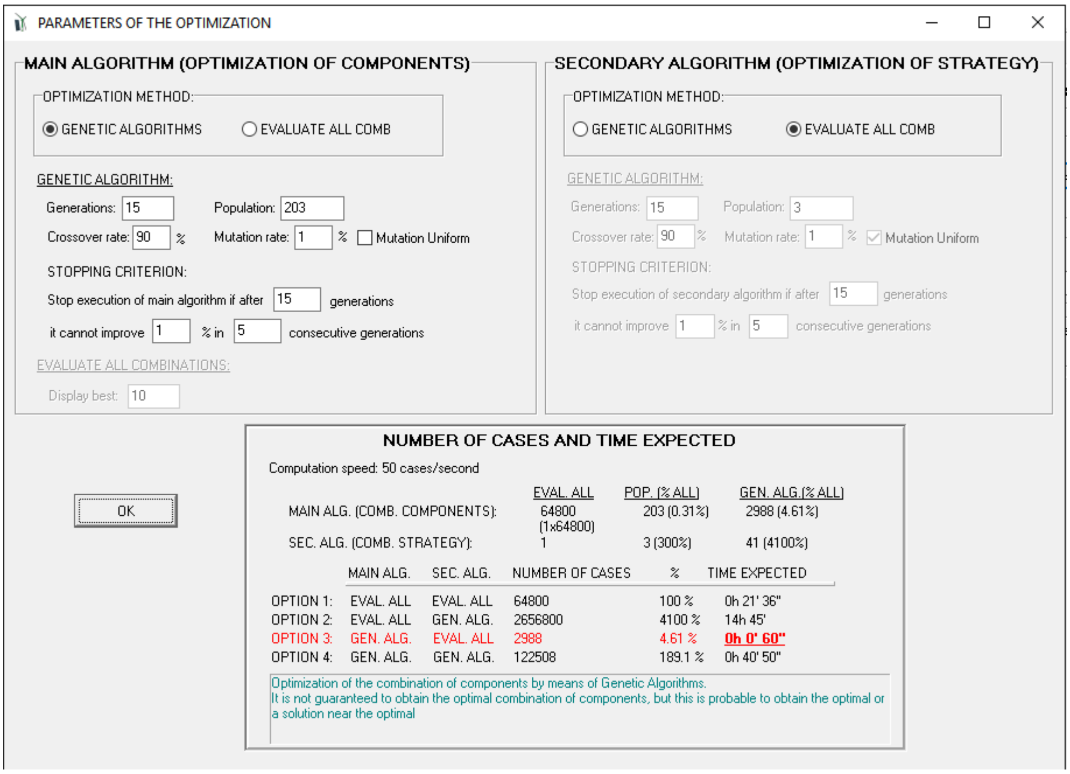
However, if the maximum execution time we allow is too small, MHOGA will inform us of the minimum time needed to finding the optimal solution or to obtain a solution close to the optimal with high probability.

The user can decide himself the parameters of the optimization by selecting "USER" instead of "HOGA".

If the time allowed by us is lower than the time needed for the enumerative method, MHOGA will use the genetic algorithms to optimize the system in the time allowed. However, if the time allowed is so low that it is not enough to ensure a minimum probability of obtaining the optimal solution by mans of the genetic algorithms, MHOGA will take the minimum time that it considers correct to run the genetic algorithms (as, by default, the checkbox 

is selected). If this checkbox is not selected, the time allowed will always be the time used by MHOGA, even if this time is not enough to ensure a minimum probability of obtaining a good result.

The parameters are displayed clicking on "**Parameters**" button.

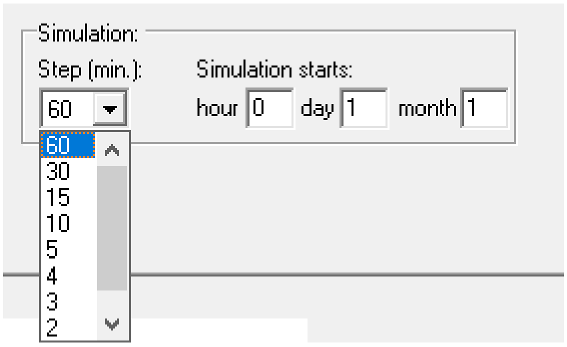


If the number of combinations is very high but we want to perform the optimization in a short time, we must reduce the number of possible combinations. The best way is to eliminate control variables to optimize, since they have less effect than the components.

It is recommended that the user allow the parameters of the optimization to be selected by MHOGA. However, more details about genetic algorithms and selection of optimization parameters are explained in Annex 1.

TIME STEPS OF SIMULATION AND START OF SIMULATION

The time steps of the simulation must be fixed (between 1 and 60 minutes) and also the time and date of the start of the simulation.



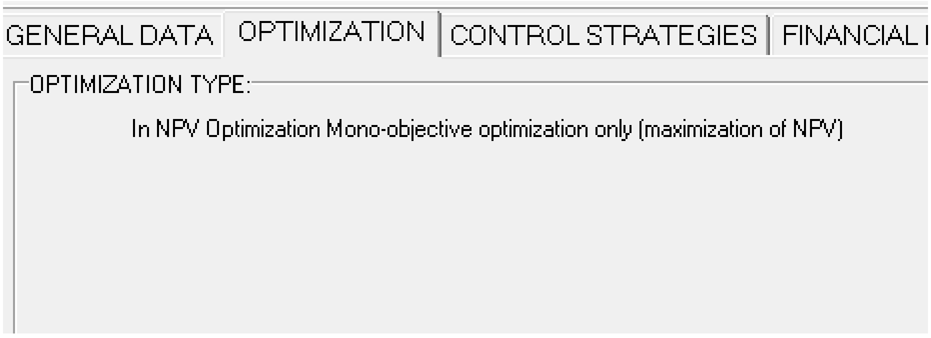
It is common to use the 60 minutes time step, since the simulations are much faster and therefore the optimization is also faster. If you want to give more detail to the simulations you can reduce the time step, up to 1 minute, but that involves much longer calculation time.

At the indicated time and date, the simulation of each combination of components and control strategy will begin, with the simulation performed for one year for each combination (more years if the Schiffer model is selected for the lead-acid batteries; simulation is performed during the system lifetime if Multiperiod is selected in the main options of the project). The batteries (if any) begin the simulation with a percentage of the state of charge that is set on the BATTERY screen (see section 3.10). The hydrogen tank (if any) begins the simulation with a load that is fixed on the screen of the components of the HYDROGEN (see section 3.13) and the water tank (if there is previously pumped water consumption) starts with a fixed capacity fixed in the LOAD / AC GRID screen (see section 3.2). Normally this date in which the simulation starts affects little to the overall expected behavior of the system.

3.1.2 OPTIMIZATION tab.

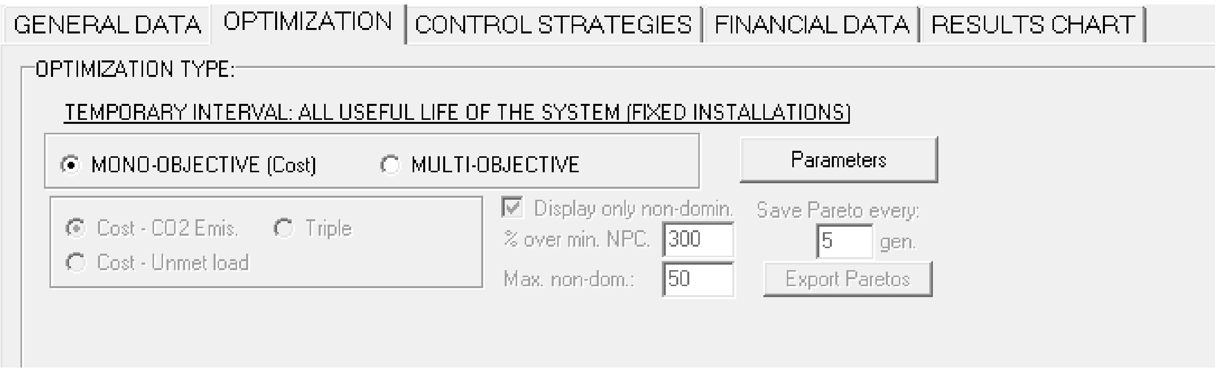
NPV optimization:

In this case, just mono-objective optimization is allowed (minimization of NPV).



NPC optimization:

In that case, you must choose between optimization MONO-OBJECTIVE (economic) or MULTI-OBJECTIVE (several objectives).



Mono-objective optimization:

By default the mono-objective optimization is selected, so the program will seek the most economical solution (lower total cost over the lifetime, NPC). If the method of optimization is by genetic algorithms (and not by the enumerative method), in each generation, the program orders the solutions by cost, so that the least cost are more likely to reproduce, and move to the next generation. In fact, the best always passes intact to the next generation, without mutating (elitism). In the results chart, when the execution of the mono-objective optimization is going on, we will see the graph of the cost of the best solution of each generation, in addition to the table with the characteristics of the best solution of each generation.

Multi-objective optimization:

If we select the "MULTI-OBJECTIVE" option, the optimization will be multi-objective, i.e. there will be two or more objectives to minimize.

Multi-objective optimization (Bernal-Agustín et al., 2012)(Rodolfo Dufo-López & Bernal-Agustín, 2008)(Bernal-Agustín & Dufo-López, 2009b)(Rodolfo Dufo-López et al., 2011)(Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016a)(Coello et al., 2002)(Zitzler & Thiele,

1999) can be NPC - CO_2 emissions or NPC - Unmet load (in this case it will be necessary to place the maximum allowed value of Unmet load in its respective box, already commented previously), or triple.

Objectives may be mutually counterproductive in many situations. Several solutions will be provided by the system, some of them offering the lowest costs, and some others providing the lowest level of emissions or unmet load. Solutions or individuals are sorted by the application, with the best ones at the top. Solutions are better when they are "dominated" by fewer alternative solutions (a particular solution is dominated by others when those provide better objectives; in our case, better solutions offer a lower NPC, and lower levels of CO_2 emissions or unmet load). Thus, the best solutions available will not be dominated by any others, with the next best solutions dominated by 1, by 2, and so on.

All non-dominated solutions will have the same degree of probability to breed, as none of them is better than any of the others. The same argument applies to all solutions dominated by 1 solution, etc. As the multi-objective optimization progresses, a chart and a table are shown. The chart includes the individuals for every generation, the emissions, unmet load or other objective versus NPC for each individual (this is known as a "Pareto" diagram). The table provides a list of individuals, sorted from best to worst. Every time a new generation is obtained, a new chart and table are shown.

A check box is available to "Display only Non-Domin.".

The Multi-Objective algorithm is based on SPEA (Strength Pareto Evolutionary Algorithm), and on SPEA 2.

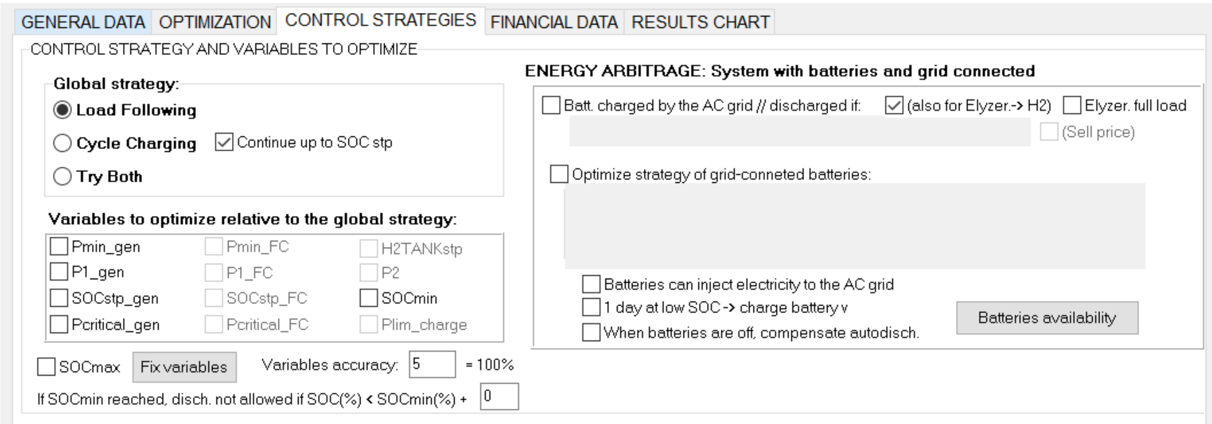
The user must introduce the maximum percentage difference of NPC that may be achieved by any non-dominated solution, as referred to the non-dominated solution with the lowest NPC. The maximum number allowed for non-dominated solutions must also be introduced. This prevents the number of non-dominated solutions from being too close to the population number, which would result in a saturation of non-dominated solutions. In this case, they would be too similar, without a reasonable degree of variability.

As a practical example, let us assume that a non-dominated solution has the lowest NPC value of all, at M€ 100. If the percentage specified by the user is 60%, all non-dominated solutions with NPCs above M€ 160 will be eliminated (provided the total number of non-dominated solutions is larger than the maximum number allowed for non-dominated solutions). After all non-dominated solutions above the specified percentage are eliminated, the number of the remaining non-dominated solutions is checked. If this number is still larger than the maximum number allowed, truncation is applied. For each pair of adjacent non-dominated solutions on the Pareto diagram, a check is carried out of the modulus of the distance between them. The solution is eliminated for the closest pair, where the solution is nearer from its adjacent solution on the other side.

The user must also decide on the number of generations between successive storage of the Pareto diagram, i.e. NPC and other objectives values for the individuals in that generation. The first and the last generations are stored by default. Once the simulation is over, the different Pareto values stored may be exported as an ASCII file, by clicking on "Export Paretos".

3.1.3 CONTROL STRATEGIES tab.

This tab defines the overall control strategy and the variables to be optimized. The strategy can also be optimized in the case of batteries in grid-connected systems (charging of batteries during the hours when the electricity price of the AC grid is low and discharge during the hours when the price is high), also for pumped hydro storage and for the generation of green hydrogen by the electrolyzer.



3.1.3.1 Control strategy and variables to optimize.

For systems with load (off-grid systems or grid-connected systems with high load), the **global strategy** (left part of the tab) can be important if there are batteries and backup generator and/or hydrogen storage. **Global strategy is not used for systems without load consumption (grid-connected generating systems)**

In **Global Strategy** we can choose between two global control strategies (they are used when there is load; if there is no load, for example in grid-connected generating systems without load, these global strategies are not used):

- LOAD FOLLOWING STRATEGY: In this strategy, in systems that include batteries and generator (diesel, gasoline ...), when energy from renewable sources is not enough to meet the whole load, the rest energy is covered by the battery bank. If the batteries cannot meet the whole demand, the generator will run to cover the rest of the load. The same applies for the fuel cell, if present in the system instead of the generator.
- CYCLE CHARGING, with or without the option "continue up to SOCstp": The difference with the previous strategy is that when the generator must run because load cannot be met by the batteries, it will run at its rated power, so that the extra power will be used to charge the batteries. If "Continue up tp SOCstp" is activated, the generator will run at rated power until the State Of Charge (SOC) of the batteries reach the value of the variable SOC setpoint generator, which by default is 100%.

For both strategies, we have the possibility to optimize the control variables, while some do not make sense depending on the global strategy chosen.

The variables to be optimized must be selected here, with a maximum number of 12 (see Annex 2). The exact number of variables will depend upon the system elements selected. For the case shown in the figure below, no fuel cell has been selected (no electrolyzer), so the following variables are disabled: P_{limit_charge}, P1_FC, P2, Pmin_FC, Pcritical_gen, SOCstp_FC and H2TANKstp , as they are no longer required.

Load following strategy:

If you choose the strategy "Load following", Pcrtical_gen and Pcritcal_FC variables are set to 0 W. That is, the generator (or fuel cell) never work at rated power to try to charge the batteries. When it must operate, the power required to operate is the one to strictly meet the demand. This strategy implies that SOCstp_gen and SOCstp_FC are equal to SOCmin.

However, these variables can be optimized, as well as other variables. In case of optimizing these variables, for example, if the software in a particular case chooses Pcritical_gen= 1000 W and SOCstp_gen = 75%, this means:

- For each hour, if the generator has to supply a power greater than 0 but less than 1000 W, it runs at its rated power, charging batteries with surplus power to 75% of SOC (try to reach this value of SOC alone during that time, the following will not). That is, for that time, the strategy really will be "cycle charging" without continue up to SOCstp.

- For each hour, if the generator has to supply a power exceeding 1000 W, it will run at the power needed to supply the demand, without trying to charge the batteries. That is, for that time, the strategy will be "load following".

Cycle charging strategy:

If you choose the strategy "cycle charging", Pcritica_gen and Pcritica_FC variables are set at a very high value, 10^{10} W (thus ensuring that no load will exceed this value). That is, the generator (or fuel cell) will run, when batteries can not meet the load, at rated power, not only to meet the demand, but also trying to charge the batteries to SOCsetpoint_gen (or SOCsetpoint_FC in the case of fuel cell). If the option "continue up to SOCstp" is selected, it will continue the next hours until SOCstp is reached. SOCstp_gen and SOCstp_FC by default are 100%.

However, these variables can be optimized, as well as other variables. In case of optimizing these variables, for example if the software in a particular case chooses Pcritical_gen= 1000 W and SOCstp_gen = 75%, this means:

- For each hour, if the generator has to supply a power greater than 0 but less than 1000 W, it will run at its rated power, trying to charge batteries with surplus power to 75% of SOC (try to reach this value of SOC only during that hour if the "continue up to SOCstp" is not selected, while if this option is on, the generator will run the following hours to reach 75% of SOC). That is, for that time, the strategy will be"cycle charging" with or without "continue up to SOCstp".

- For each hour, if the generator has to supply a power exceeding 1000 W, it will run at a power strictly necessary to supply the demand, without trying to charge the batteries. That is, for that hour, the strategy will really be "load following"

Try both:

If you select "Try both", the software will consider the two strategies. However, in this case, $P_{critical\_gen}$ and $P_{critical\_FC}$ may not be optimized.

Variables to optimize relative to the global strategy.

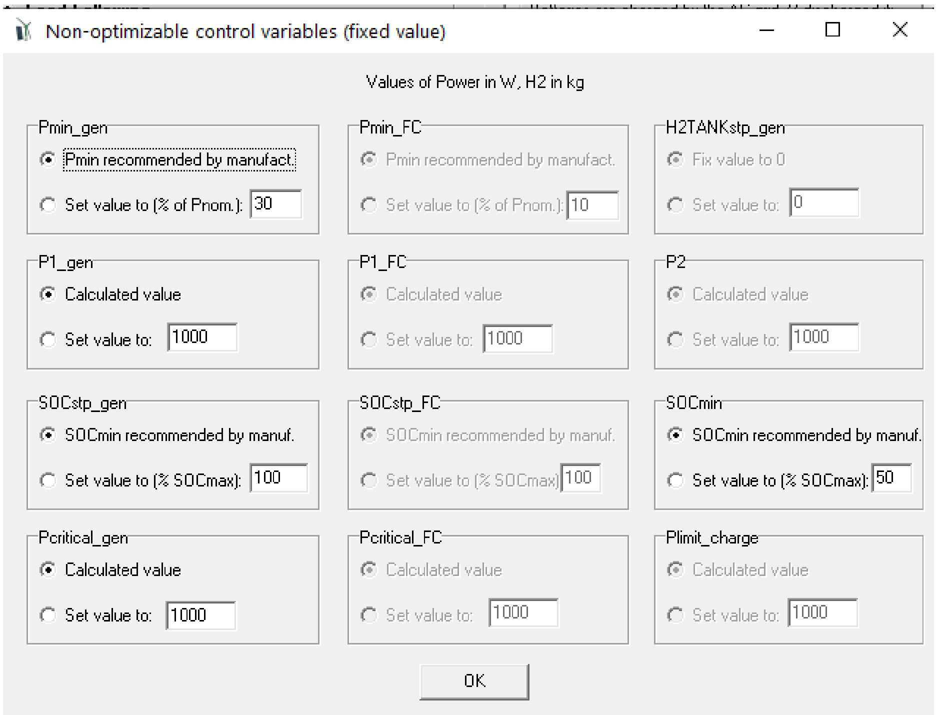
Of the variables allowed to be optimized, we can choose all or only some (in this case the variables we do not choosen will not be optimized). If we do not mark as optimizable the variables Plimit_charge, P1_gen, P1_FC or P2, the correcting factor will remain fixed at 1, that is, we will always remain with the calculation value (or with the value specified in the screen that appears when you press "Fix variables"). If we do not mark as optimizable the variables Pmin_gen, Pmin_FC, SOCmin, Pcritical_gen, Pcritical_FC, SOCstp_gen, SOCstp_FC or H2TANKstp the correcting factor will be fixed to 0, thati is, Pmin_gen, Pmin_FC, SOCmin will be the recommended by the manufacturer while Pcritical_gen, Pcritical_FC and H2TANKstp will be 0; SOCstp_gen and SOCstp_FC will be equal to SOC_{min}.

If the checkbox "SOCmax" is checked (located under the box of the variables to optimize), the maximum SOC limit will be optimized instead of the minimum SOC (SOCmin).

Important: If there are many possible combinations of components and control strategies, MHOGA will need a high time to perform the optimization. Combinations of components are usually more important than control strategies in the NPC or NPV, but not always.

The value of the "Variables accuracy" is the number of possible values that each variable can have. If it is a small number, the precision will be low, while if it is high, it will have great precision, but also many possible combinations of variable values, so optimization can be lengthened.

By clicking on the "Fix Variables" button a new screen appears. This will allow the user to set the values of the variables not checked in the previous screen (i.e. variables not to be optimized). A choice is provided here between a value calculated by the programme, or one assigned by the user.



3.1.3.2 Energy arbitrage: Management of the charge / discharge of the storage in the case of systems with storage and AC grid connection.

In case the system has batteries (also for pumped hydro storage and also it can be applied for green hydrogen generation) and also there is an AC grid connection (purchase or sell of electricity to the AC grid defined in the "CONSUMPTION / AC grid" screen, "PURCHASE / SELL E" tab, see section 3.2), the management of the charging / discharging of batteries can be selected: charging of batteries during the hours in which the electricity price of the AC grid is low and discharge during the hours when the price is high, being able to carry out the discharge only to feed the own load or also to inject to the AC grid. If the difference in prices for charging and discharging is sufficient, it can be worth charging / discharging the batteries and that can imply an economic profitability, saving on the electric bill (or obtaining benefits when batteries inject energy to the AC grid). These savings or benefits can be higher than the cost of cycling the batteries (the cycling, i.e. the charges / discharges of the batteries degrade them, which implies a future replacement cost). On the other hand, if the difference between low and high price is small, the cost of cycling the batteries may be higher than the savings or benefits, so it would not be worth using the batteries.

- There are two options:

- Charge / discharge batteries when the price is lower / higher than certain fixed values.
- Optimize management.

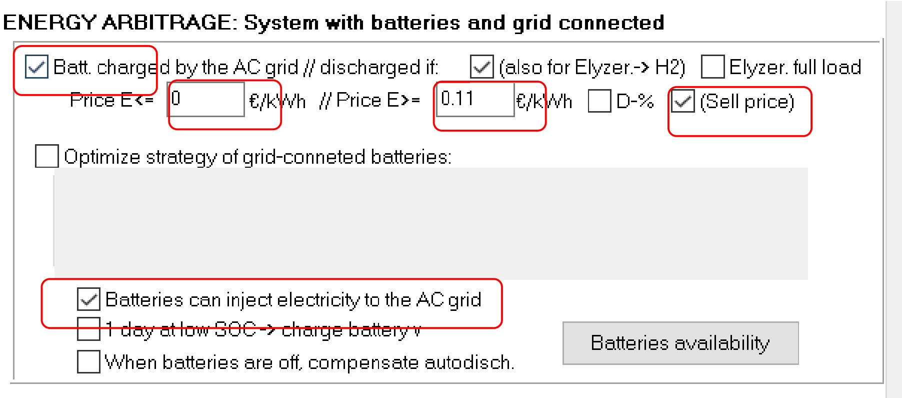
Note that using these strategies of charge/discharge of the batteries by the AC grid, if there is load consumption in the system, it is possible that the load consumption will not be correctly supplied by the batteries and by the backup generator (when renewable sources are not enough to cover the load). The grid-connected batteries management will imply that the load is not correctly covered in some cases, so the load consumption will only be correctly covered by the AC grid. ***Therefore, if there is any load consumption, you must be sure to select the option of PURCHASING ELECTRICITY TO THE AC GRID****.*

Therefore, these options of grid-connected batteries management are only suitable for:

- *Generating systems (without any load consumption)*
- *Systems with load consumption where the option of purchasing electricity to the AC grid is selected.*

Batteries are charged by the AC grid / discharged if electricity price is lower / higher than specific values.

This option is obtained by activating the box "Batteries are charged by the AC grid // discharged if:". The maximum and minimum prices for the charging / discharging of the batteries must be set.



By default, these values are 0 and 0.11 €/kWh (and they are referred to the sell price, that is, to the price we sell electricity to the AC grid, as "(sell price)" checkbox is checked by default). We should change them considering the price of electricity of the different periods (this values must be selected considering the purchase or sell price of the electricity in the "LOAD / AC GRID" screen, "PURCHASE / SELL E ", see section 3.2).

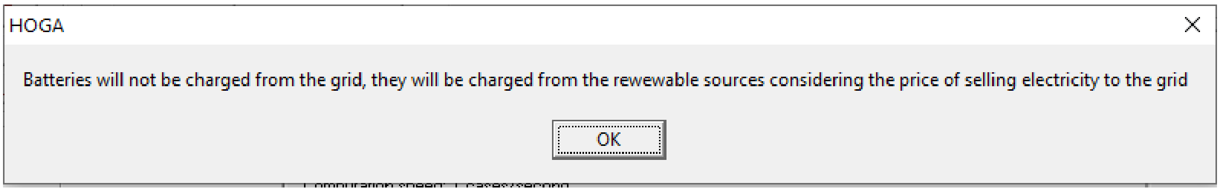
Batteries can inject electricity to the AC grid:

By default, the checkbox "**Batteries can inject electricity to the AC grid**" is selected, in this case, when the control strategy determines that electricity price is higher than the minimum for the discharge, batteries are discharged supplying the load but also injecting the maximum possible of energy to the AC grid (if the injection is allowed to the AC grid, fixed in the window "LOAD / AC GRID ", "PURCHASE / SELL E "tab, see section 3.2.).

Consider sell electricity prices instead purchase prices, and do not use AC grid to charge the batteries:

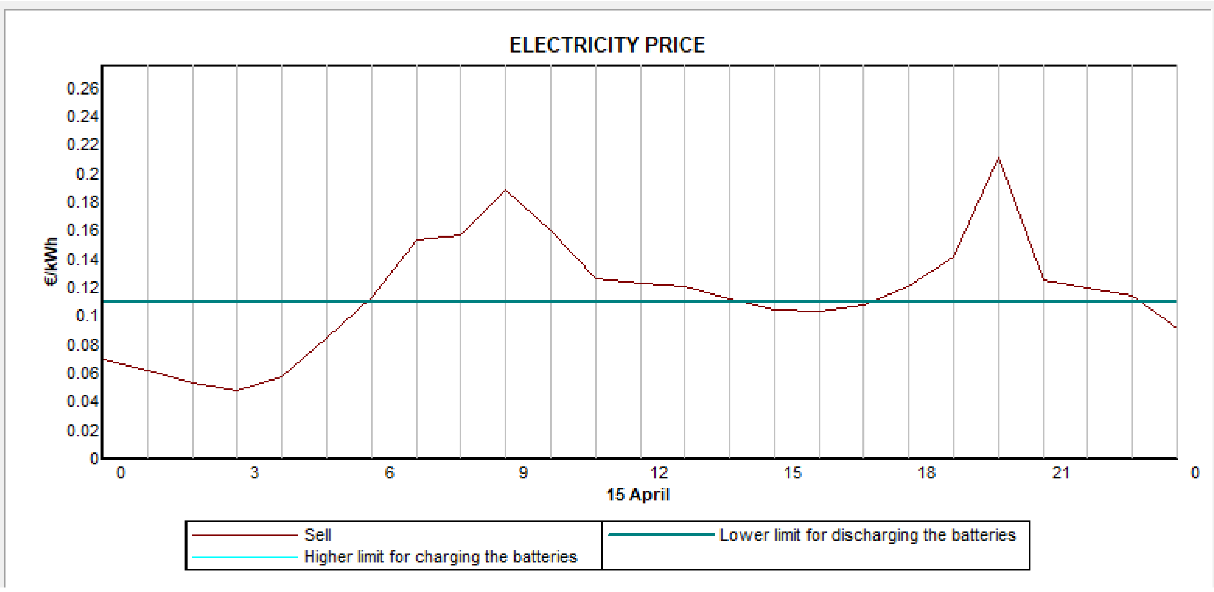
If "**Batteries can inject electricity to the AC grid**" is selected, we can select that the maximum and minimum prices for the charging / discharging of the batteries are the sell electricity prices instead of the purchase prices, by checking the checkbox **"(Sell price)"** (checked by default). Also, if **"(Sell price)"** is checked, the batteries will not be charged by the AC grid, they will just be charged by the renewable sources when the sell price is lower than the limit (or when the power from the renewable sources is higher than the maximum power that can be injected to the grid, then the surplus power is used to charge the batteries). In that case, in the window "LOAD / AC GRID ", "PURCHASE / SELL E "tab (see section 3.2.) we must set the electricity sell prices.

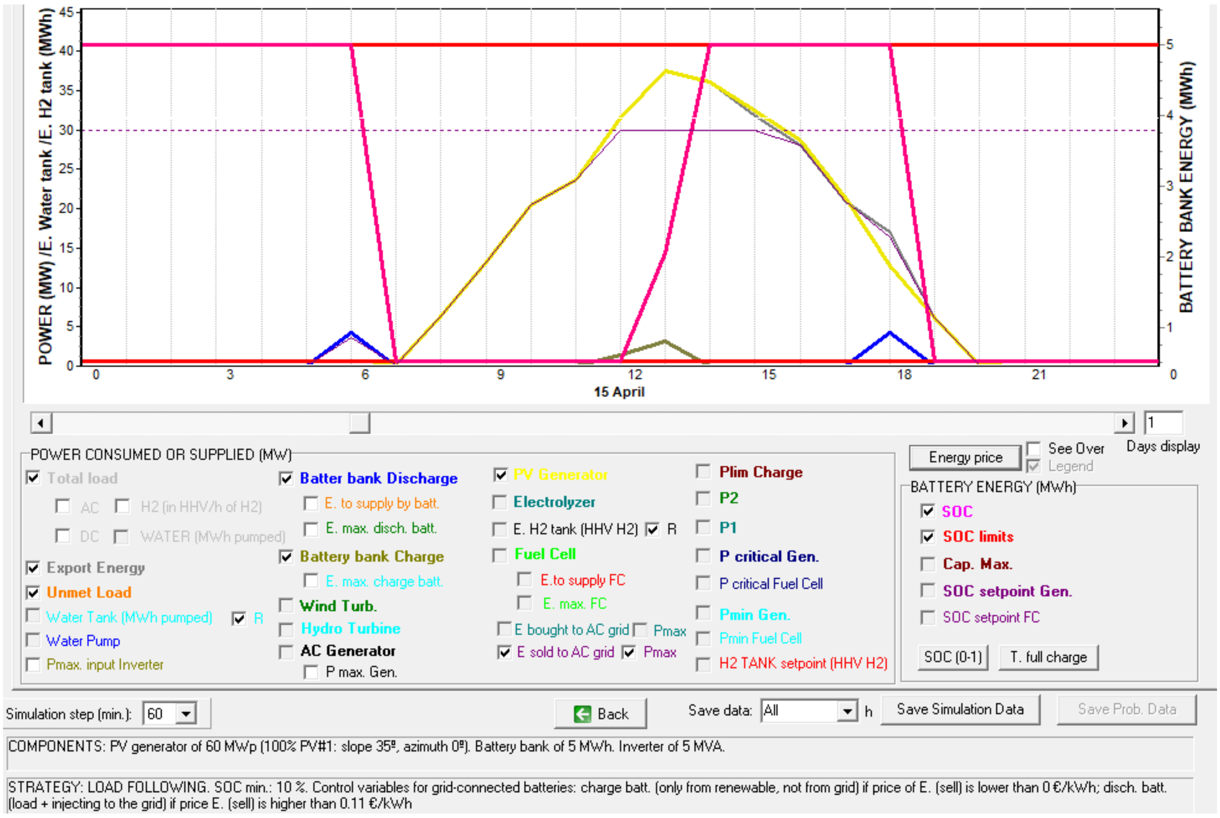
When selecting this option, a message appears telling us that batteries will not be charged from the AC grid.



With the default values, when the sell price (price at which we sell the electricity to the AC grid, which can be variable, for example, hourly price) is lower than 0 (that is, never), batteries will be charged from the renewable sources; if price is higher than 0, renewable sources will inject electricity to the AC grid. When the sell price is higher than 0.11 €/kWh batteries will be discharged, supplying the load (in the case there is load) and injecting the maximum power to the AC grid, selling electricity to the AC grid (because "Batteries can inject electricity to the AC grid" checkbox is checked).

For example, see the simulation of that case, for a system with 60 MW PV, battery of 5 MWh and inverter-charger of 5 MW, without load (just generating system), for a specific day (15^{th} April): this day, from 6 h to 14 h the electricity price is higher than 0.11 €/kWh, therefore batteries must be discharged and sell electricity to the grid, but they are fully discharged in just 1 hour, at 6 a.m. (battery bank is just of 5 MWh and inverter is of 5 MWh). We can see that from 12 to 15 h the PV generation is higher than the maximum power that can be injected into the grid (30 MW), therefore the surplus energy is used to charge the batteries. Later, from 18 to 23 h, the electricity price the electricity price is higher than 0.11 €/kWh, therefore batteries must be discharged and sell electricity to the grid, but they are fully discharged in just 1 hour, at 18 a.m.





The same strategy would be applied if we had pumped hydro storage: when the sell price is lower than 0 (that is, never), water is pumped with the renewable sources to store energy in pumped water; when the sell price is higher than 0.11 €/kWh the hydro turbine works with the stored water, supplying the load (in the case there is load) and injecting the maximum power to the AC grid.

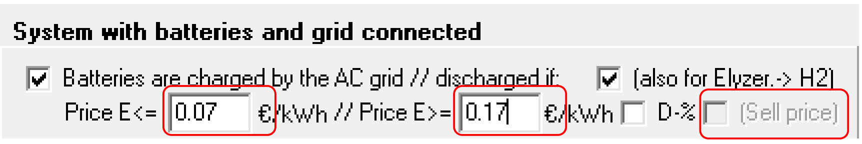
*The same strategy would be applied if we had electrolyzer (and the checkbox "**also for Elyzer->H2**" is selected), for the generation of green hydrogen (when the sell price is lower* *than that the specific value, then electrolyzer consumes electricity from the renewable sources and it generates green hydrogen), in this case if that specific value is 0 it will never run with the renewable sources, unless when their power is higher than the maximum power that can be injected to the grid, then the surplus power will be used to generate hydrogen.*

In this example, as "(sell price)" is checked, AC grid is never used to charge batteries or pump water or generate hydrogen. As the lower price is set to 0, renewable sources are not used to charge batteries or pump water or generate hydrogen, they would be used when the power generated by the renewable sources is higher than the maximum power that can be injected to the AC grid, the surplus power would be used to charge batteries or pump water or generate hydrogen.

<u>Consider purchase prices instead sell prices, and use AC grid to charge the batteries:</u>

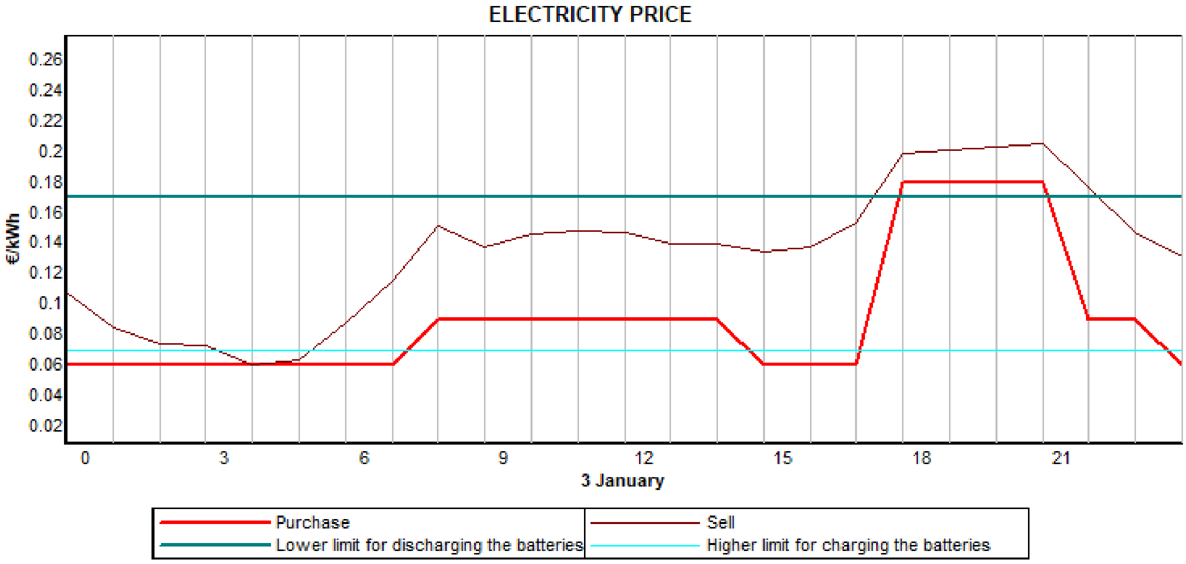
If **"(Sell price)"** is unchecked, the prices considered will be the prices of purchasing electricity to the AC grid.

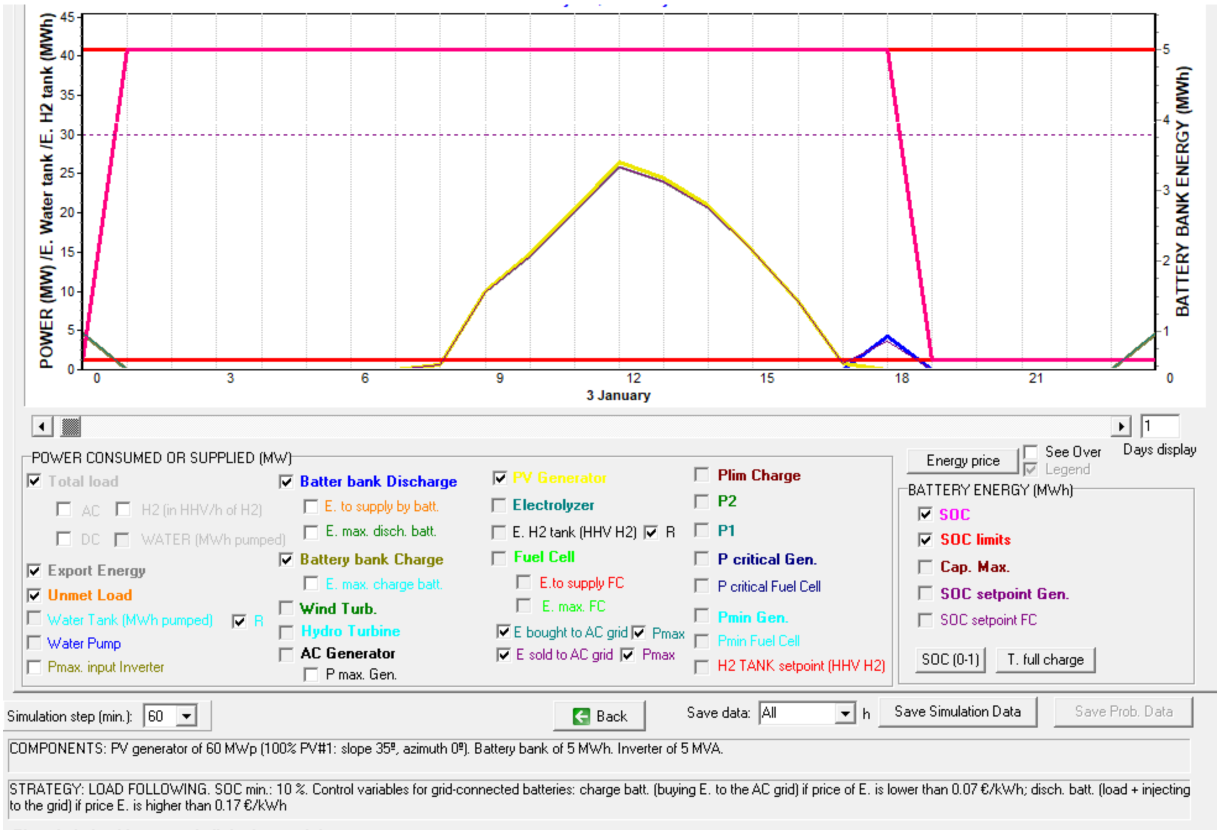
For example, let's suppose that in our case we have three hourly periods for the electricity purchased from the AC grid: P1 (peak) at 0.18 €/kWh, P2 at 0.09 €/kWh and P3 (valley) at 0.06 €/kWh, in this case we could set the first value to 0.07 and the second one to 0.17, and also we must uncheck the "(sell price)" checkbox, as MHOGA by default considers the selling costs. If we want to consider the electricity purchase costs, we must uncheck that checkbox.



Then, in that case, when the simulation of the system is being performed, during the hours of period P3 (valley), as cost is 0.06 €/kWh (lower than the limit settled, 0.07), batteries will be charged from the renewable sources (after supplying the load) and also from the AC grid at their maximum power. On the other hand, during the hours of period P1 (peak), as cost is 0.18 €/kWh (higher than the limit settled, 0.17), batteries will be discharged to supply the load instead of using the AC grid (if "Batteries can inject electricity to the AC grid" checkbox is checked batteries will also inject its maximum power to the AC grid, selling electricity to the AC grid, if it is allowed).

Let's see the simulation of this example, for a system with 60 MW PV, battery of 5 MWh and inverter-charger of 5 MW, without load (just generating system), for a specific day (3rd January): now the important price is the purchase price (in red), we can see that from 0 h to 7 h purchase price is lower than 0.07 €/kWh, terefore batteries must be charged from the renewable sources and also from the AC grid, they are fully charged at 0 h because their capacity is low (5 MWh). We can also see that from 18 to 21 h purchase price is higher than 0.17 €/kWh, therefore batteries must be discharged selling electricity to the AC grid (the option of selling electricity to the AC grid is checked), and in just 1 hour (from 18 to 19 h) batteries are fully discharged.





It could also be applied for systems with load consumption, this methodology is shown in the publication (Rodolfo Dufo-López & Bernal-Agustín, 2015b).

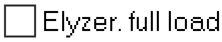
Generating hydrogen by the electrolyzer when electricity price is low:

If, as default, the option "**also for Elyzer->H2**" is selected, this means that the strategy of charging batteries will also be applied to generate hydrogen by the electrolyzer (in the case there is electrolyzer in the system).

If in the system there are batteries and also there is electrolyzer, when the electricity price is lower than the value settled for charge, the priority is to charge the batteries and, after they are at 100% SOC, then the electrolyzer starts to produce hydrogen.

Generating hydrogen by the electrolyzer at full power all the time:

If the option "**Elyzer. full load**" is selected, this means that the control strategy will make the electrolyzer run at full load, using the renewable power and, if not enough, buying electricity to the grid. If there are batteries, when the strategy determines that they must be discharged (at high electricity price), they will supply the electrolyzer load instead of the grid.



<u>Use day difference and percentage instead of considering prices to charge/discharge:</u>

Instead of using the values of maximum price to charge or minimum price to discharge, we can use other values: minimum day difference in prices and percentage over the minimum or under the maximum to charge /discharge. If we select the checkbox "**D-%**", the values are changed:

In the left box we must set the minimum difference in electricity price (maximum of the day minus minimum of the day), in €/kWh so that the control strategy can be applied, and the % around, in %. For example, if we set Day Dif. >=0.1 €/kWh, this means that, for each day, if the maximum price minus the minimum price of the day is lower than 0.1 €/kWh, batteries will not be used for the strategy or charging/discharging. However, if the difference for each day is higher than that value, batteries will be charged during the hours when the electricity price is lower than the minimum plus 10% and they will be discharged during the hours when the electricity price is higher than the maximum minus 10%.

<u>Other options:</u>

If the box 

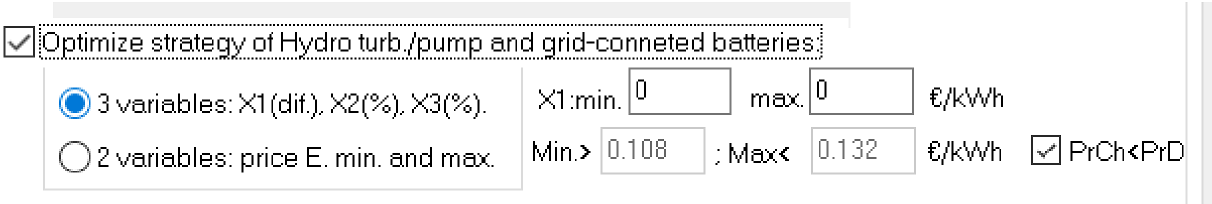
is selected, if the state of charge of the batteries is kept to a minimum during a whole day, the AC grid will be used to charge them.

If the box 

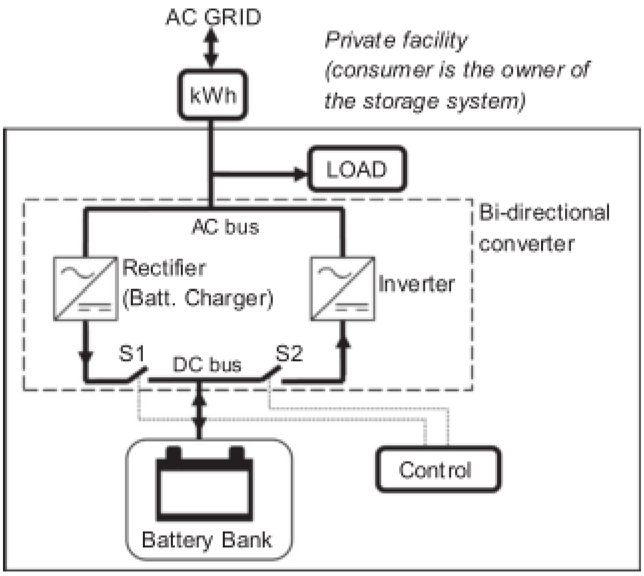
is selected, if the batteries are not charging nor discharging, the self-discharge is compensated.

<u>**Optimize strategy of grid-connected batteries:**</u>

You can also optimize the management, looking for the best limit prices for charging/discharging, in the case of having an hourly price (different for each hour), by selecting the box "**Optimize strategy of grid-connected batteries**".



This optimization can be useful for grid-connected systems where the hourly price of energy (sell or purchase, depending if "(sell price)" is checked or not) is different every hour (real time pricing, RTP). The system will have the batteries and the bi-directional converter (inverter-charger) shown in the following figure, but could also have any other components that MHOGA allows (photovoltaic modules, wind turbines ...).

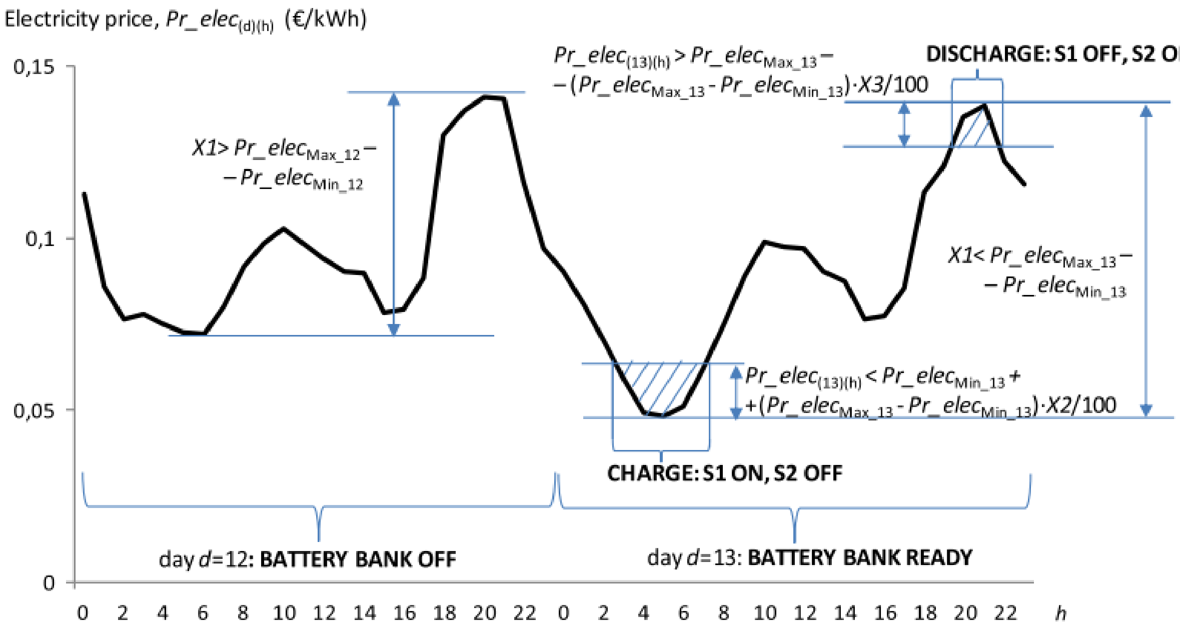


You can choose between optimization with 3 variables: X1, X2 and X3, following the methodology outlined in the article (Rodolfo Dufo-López, 2015), or the optimization by 2 variables (the minimum price for the discharge and the maximum for the charge).

3 variables: X1(dif.), X2(%), X3(%).

In the case of optimization with 3 variables, the following three variables are optimized, in order to minimize the total cost of the system to supply the electric load during its useful life:

- X1: It is the minimum difference between the maximum and minimum price of each day such that it can be profitable to charge and discharge the batteries. If a given day the difference between the minimum price and the maximum price is less than X1, it is not worth charging / discharging the batteries, so they are not used that day. If this difference is greater than X1, the batteries can be charged / discharged. See figure below, which shows the price of electricity for two consecutive days. The first day the difference between the maximum and the lowest price is less than X1, so the batteries do not work. The second day said difference is greater than X1, so the batteries are ready to operate.
- X2: is the percentage of the difference between the maximum and minimum price of the day that is added to the minimum price so that in the hours whose price falls within that range the batteries are charged (see figure below, hours in the CHARGE area).



- X3: is the percentage of the difference between the maximum and minimum price of the day that is subtracted from the maximum price so that in the hours whose price falls within that range the batteries are discharged (see previous figure, hours in the DISCHARGE zone).

2 variables: Price E. min and max.

In the case of choosing 2 variables for the optimization, only two prices will be optimized:

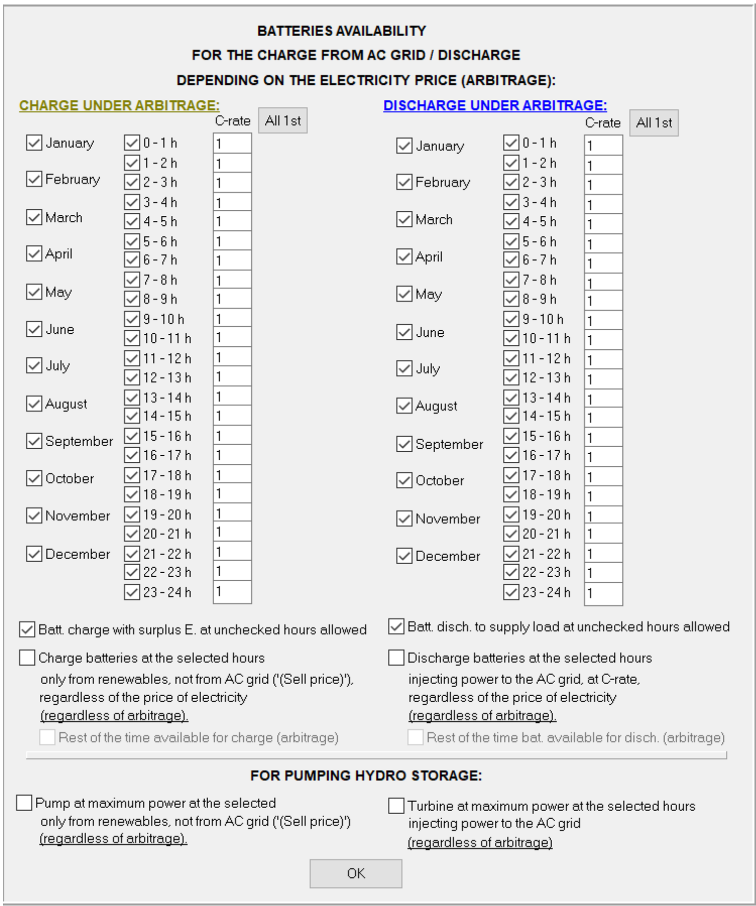
- The minimum price necessary for the discharge. If the price of electricity at a given hour is high enough (above the minimum), the batteries must be discharged, supplying the electricity load, since the cost of cycling the batteries is lower than the economic savings due to avoiding energy purchases to the AC grid at that time. If the price is higher than the minimum, the batteries are not discharged (the cost of cycling is not worth it).

- The maximum price required for the charge. If the price in a certain hour is low enough (less than the maximum), the batteries will be charged, since it will be worthwhile to cycle them. If the price is higher than said maximum, they will not be charged, since it will not be worth it due to the cost of cycling.

If the checkbox “PrCh<PrD” is selected (by default), it will only consider setpoint values for the maximum price required for the charge lower than the setpoint values for the minimum price necessary for the discharge.

By clicking on the button 

the following window appears, where we can deselect the hours when we do not want the batteries to be charged from the AC grid or discharged:



The hours that the CHARGE is NOT marked, the batteries will not be charged from the AC grid, even if the price of the electricity in the network is low. However, they can be charged by the surplus energy (from the renewable sources), if the checkbox "Batt. charge with surplus E…" is checked, as by default

The hours DISCHARGE is NOT marked:

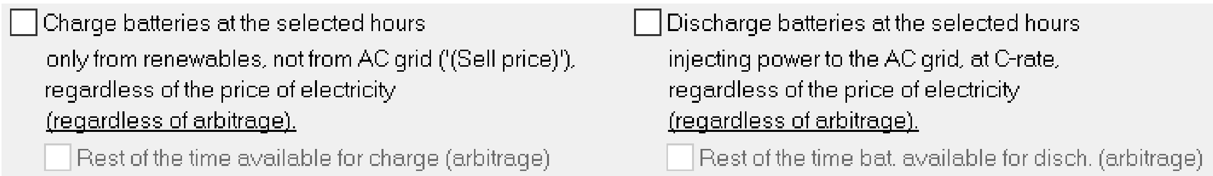
- If the priority to supply the load not covered by the renewables is the AC Grid (consumption screen, Purchase/Sell E tab, see section 3.2): the batteries will not supply the demand not covered by the renewables, although the price of the AC grid electricity is high, this demand will be covered by the AC grid.
- If the priority to supply the demand not covered by the renewables is Storage / AC Gen.: the demand not covered by the renewables is primarily provided by the batteries or the AC generator or the fuel cell, depending on the control strategy, so that the batteries can supply the demand.
- If the checkbox "Batt. disch. to supply load…" is unchecked, batteries will not supply the load.

The maximum C-rate for the charge and for the discharge during each hour is set next to the corresponding checkbox. During a time step, if the strategy is charging /discharging , batteries will be charged /discharged at the rate shown in the table for this hour. Note that the charge / discarge is also limited by the value of the maximum allowed current of the battery (Imax, see section 3.10.1), by the state of charge (SOC) and the maximum /minimum SOC, and by the available power (from the renewable sources and from the grid / to be injected to the grid).

The buttons "**All 1st**" copy the rate of the first hour to all the hours of the day.

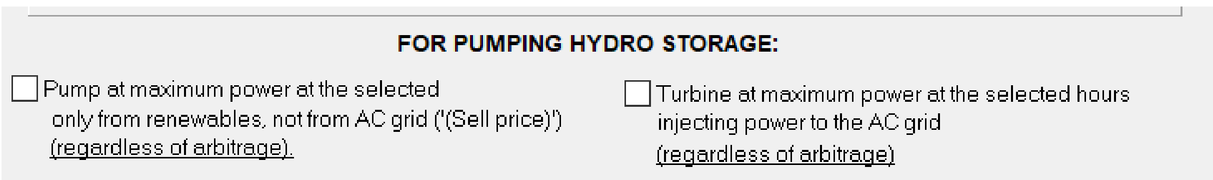
If we check the box "**Charge batteries at the selected hours...**", the batteries will be charged with the AC grid at the scheduled times, regardless of the price of electricity. If it is checked, we can also check the box "Rest of the time available for charge (arbitrage)", which means that the non-selected hours, batteries will be charged if it is ordered by the arbitrage control strategy.

If we check the box "**Discharge batteries at the selected hours...**", the batteries will be discharged (providing load and, if permitted, selling energy to the AC grid) at the scheduled times, regardless of the price of electricity. If it is checked, we can also check the box "Rest of the time available for charge (arbitrage)", which means that the non-selected hours, batteries will be discharged if it is ordered by the arbitrage control strategy.



If a certain hour is both marked for charging and discharging and the two previous boxes are marked, forcing at that time both charging and discharging, the priority is the discharge, that is, batteries will be discharged during that hour.

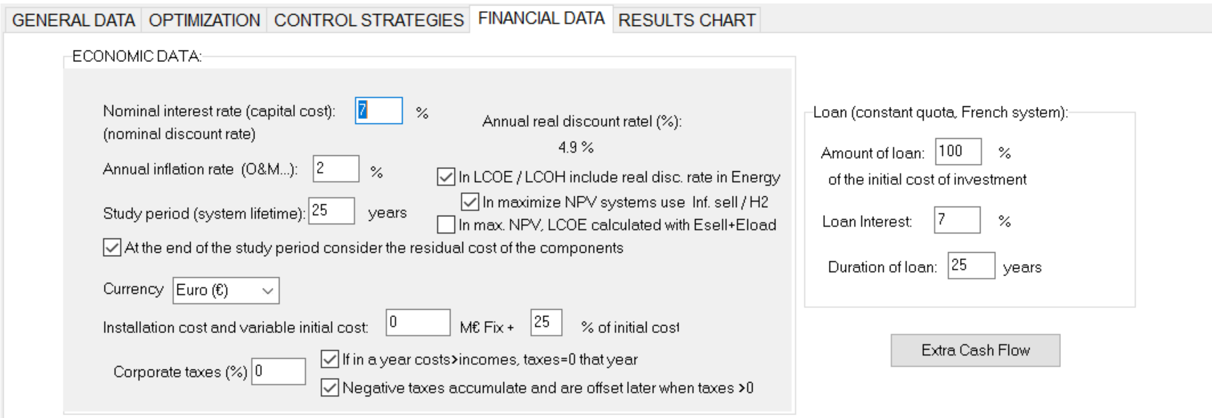
Also, in the lower area of the window, we can set the same for PHS: regardless of arbitrage, we can force to pump or to run the turbine during the selected hours.



3.1.4 FINANCIAL DATA tab.

ECONOMIC DATA:

Data for economic and financial calculations must be provided as follows (see figure below): lifetime of the system or period of study (usually the same as the lifecycle for the PV modules, 25 or 30 years), installation costs and variable initial cost (fix cost + percentage of initial cost), nominal interest rate (nominal discount rate or nominal capital cost, indexed to inflation, I), and expected general inflation rate (Inf_{gen}). The software uses these last two indicators to calculate the discount rate (real discount rate or real capital cost, net of inflation), with a value close to subtracting one from the other [Real Discount Rate (%) = (I-Inf_{gen})/(1+ Inf_{gen}/100)]. This value will then be used to update the different costs affected by the general inflation rate (operation and maintenance costs, as well as the cost of replacing the elements which do not have a specific inflation rate) throughout the whole of the study period, as referred to the initial time of investment, thereby obtaining the NPC or NPV. Other costs have their own inflation rate (for example the electricity price, the fuel price…), the real discount rate for these costs will be calculated considering their own inflation.



If the checkbox 

is checked, LCOE will be calculated as shown in section 1.3, the total present cost divided the total supplied energy during system lifetime, including in the energy the real discount rate.

-If minimizing NPC:

$$LCOE_{i,k} = \frac{NPC_{i,k}}{\sum_{y=1}^{Life_{HS}} E_{load_y} \cdot \frac{\left(1+Inf_{gen}\right)^{y}}{(1+I)^{y}}}$$

-If maximizing NPV:

$$LCOE_{i,k} = \frac{Total\_Present\_Cost}{\sum_{y=1}^{Life_{HS}} (E_{injected\_y} + H2_{sold\_y} \cdot 39.4) \cdot \left(1 + Inf_{gen}\right)^{y} / (1 + I)^{y}}$$

However, if that box is not checked, in the denominator of the equation there will be just the total energy:

-If minimizing NPC:

$$LCOE_{i,k} = \frac{NPC_{i,k}}{\sum_{y=1}^{Life_{HS}} E_{load_y}}$$

-If maximizing NPV:

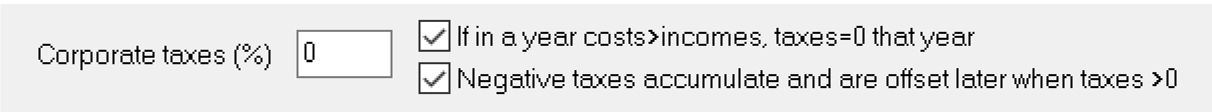
$$LCOE_{i,k} = \frac{Total\_Present\_Cost}{\sum_{y=1}^{Life_{HS}} (E_{injected\_y} + H2_{sold\_y} \cdot 39.4)}$$

In maximizing NPV projects, if the checkbox "☑ In maximize NPV systems use Inf. sell / H2" is checked, the LCOE and LCOH are calculated using electricity sell price inflation and hydrogen price inflation, respectively, instead of general inflation.

In maximizing NPV projects, if the checkbox "☐ In max. NPV, LCOE calculated with Esell+Eload" is checked, the LCOE is calculated considering the energy sold to the AC grid plus the load energy supplied; if it is not checked, only energy sold to the AC grid is considered.

If the checkbox "☑ At the end of the study period consider the residual cost of the components" is checked, it is considered that the residual cost of the different components is obtained when the useful life of the system ends (each component would be sold at a price proportional to its remaining useful life).

Corportate taxes are set in the lower part of the window (default 0%). If you change to a value higher than 0%, the software will calculate the taxes considering EBIT, interest payment, linear depreciation and amortization. Taxes are costs for the system, and are applied to the net incomes (considering also interest payment, depreciation and amortization), and will be added to the total cash flow of the year.



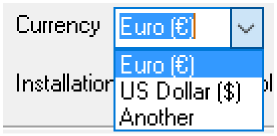
If the checkbox "☑ If in a year costs>incomes, taxes=0 that year" is checked (by default), if in a year costs are higher than incomes, taxes will be 0 that year (that is, taxes will not be incomes). If it is not checked, during that year taxes will be negative costs (that is, incomes).

If the checkbox 

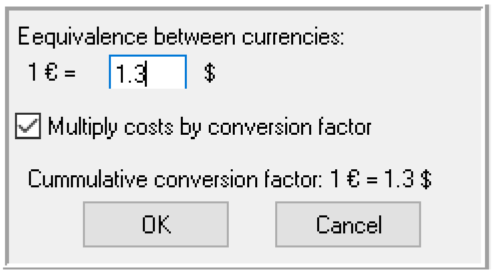
is checked (by default), negative taxes (in the years when costs > incomes) will be accumulated and will be offset in a future year, when taxes of that year are positive.

Currency change:

The default currency was defined the first time you created a project. However, you can change the currency used in each project, selecting in the dropdown menu:



In any case, the change of currency must always establish the equivalence with the previous currency.



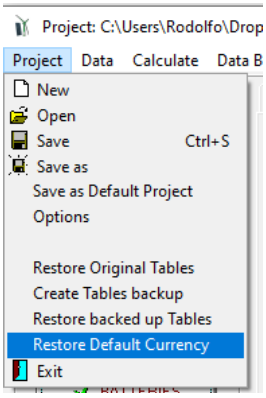
If you check "**Multiply costs by conversion factor**", all costs used by the program, including databases, will be multiplied by this factor, changing the currency. In results, costs also will be changed, if the project has already been calculated (except if the sensitivity analysis has been done, which, in that case, it is mandatory to make the changeover before the calculations). If not checked, numeric values will remain, changing only the currency. The databases also change. If you later want to change back to the default currency, the conversion factor calculated by the program appears, we cannot change it because it is necessary to obtain the initial values in the default currency.

When you close the program, it undoes the change in the database, so that original database values are stored for subsequent projects in euros.

Important: If you have changed the currency in a project, when you have finished the project you must close the program before opening another project or before creating another project.

If the currency has been changed in a project and the program is closed without exiting it (restarting or shutting down the computer without closing the program), the databases will be damaged, so the originals must be re-entered, doing the following:

In Project menu, select Restore Default Currency.



Accept the questions about restoring the currency and restoring the original tables.

After closing the software and restarting it again, you must select the default currency.

Loan:

In the right panel we can indicate the loan to finance the investment. By default, 100% of the total initial investment cost is financed by loan (value that the user can change). Indicate the loan interest and number of years to return. The loan must be on constant quota, French system (every year to pay the same amount).

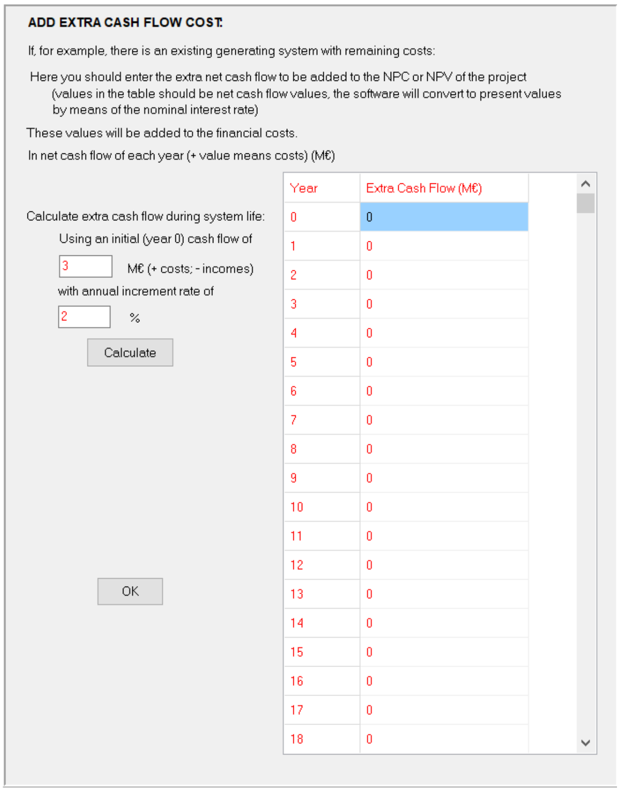
The annual quota (a) is calculated as:

$$a = C_0 \frac{i}{1-(1+i)^{-n}}$$

Where *Co* is the total financed cost, *i* is the interest rate of the loan and *n* is the number of years to return.

Extra cash flow:

By clicking the button "**Extra cash flow**", a window appears where we can add extra cash flow to be added to the NPC or NPV of the project. Positive values in the table are considered costs.

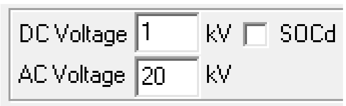


3.1.5 RESULTS CHART tab.

In this tab, once the system is calculated, we see the graph representing the NPC or the NPV of the different solutions, as well as CO_2 emissions. In the case of multi-objective, it represents two objectives (one in X-axis and the another one in Y-axis).

3.1.6 System DC and AC Voltage.

System DC voltage (battery bank) and AC voltage must be introduced on the main screen (bottom left). The DC voltage default is 1 kV.

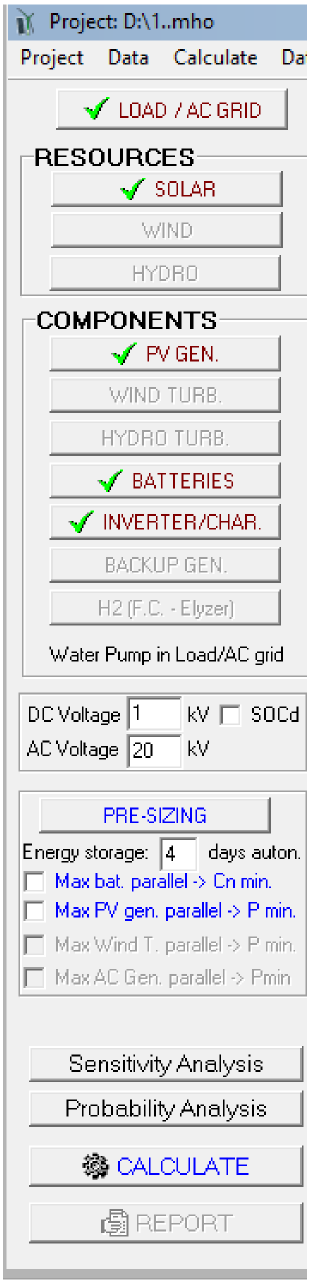


If we change any of these voltages, after having accepted the windows of the different components, a message will appear saying that we must verify that the components are OK for this voltage.

The program will calculate the number of batteries in series as the division of the voltage DC between the nominal voltage of the battery.

The box SOC d. indicates whether we want to consider the dependence of the DC voltage vs. the state of charge (SOC) of the battery bank, just in the case of lead-acid batteries. If this box is unchecked, the DC voltage will be assumed to be constant and equal to the nominal voltage all the time. If the box is checked, the DC voltage will vary depending on the SOC of the batteries (more realistic situation).

3.1.7 Buttons and menus on the Main Screen

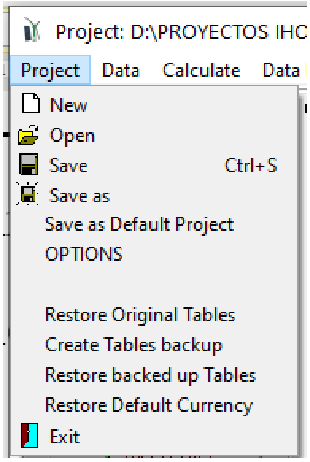


Several menus are available on the main screen (top left): Project, Data, Calculate, Database, Report, Visual, Help, License and Updates.

A number of buttons is available (left) for Load/AC grid (loads and options to buy and sell energy to AC grid and to sell hydrogen), Resources (Irradiation, Wind, Hydro), and Components, as well as for Pre-sizing, HDI and Jobs, Sensitivity Analysis, Probability Analysis, Calculate, and Report (for the best solution, once this has been calculated). Buttons are enabled only for components already selected (see section 3.1.3. above, on Selecting Components).

Once a screen has been accepted, a validation sign is shown for buttons and submenus: ✓ for buttons ✓ for submenus.

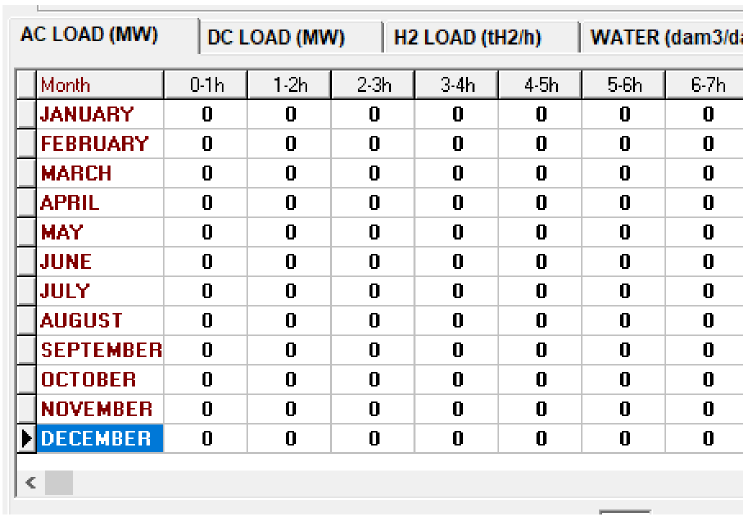
After all the required screens are accepted for all components selected, the Calculate button and menu are enabled. Once the system is calculated, the Report button and menu are enabled (report for the best solution)



The options available under the "Project" menu are: New (create new project), Open (open an existing project), Save (save the current Project, shortcut Ctrl+S), Save As (save the current project with an alternative name), Save as Default Project (save the current project as the default project, that is, the project that will be loaded when a new project is created), OPTIONS (to define the main options of the project, shown in section 3.1), restore original tables, create backups of the tables of the software or restore backup tables, restore default currency and exit.

To save a project with a different name, use the "Save As" button.

The tables mentioned above are the tables used in the windows where the Load, Wind, PV generators, Wind Turbines, Hydraulic Turbines, Batteries, Inverters, AC Generators, H_2 (Fuel Cell and Electrolyzer) are defined, and also the table of results (once the system has been calculated).



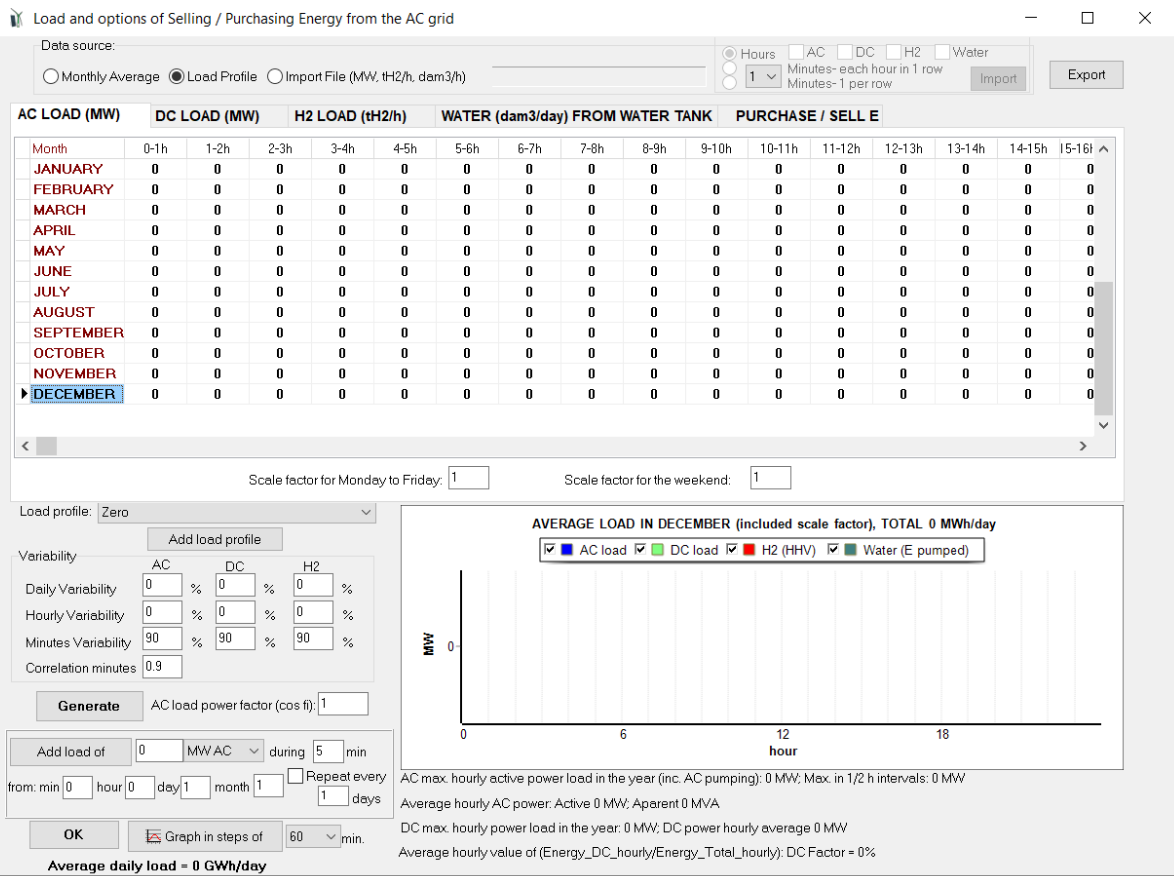
Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h
JANUARY	0	0	0	0	0	0	0
FEBRUARY	0	0	0	0	0	0	0
MARCH	0	0	0	0	0	0	0
APRIL	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0	0
JULY	0	0	0	0	0	0	0
AUGUST	0	0	0	0	0	0	0
SEPTEMBER	0	0	0	0	0	0	0
OCTOBER	0	0	0	0	0	0	0
NOVEMBER	0	0	0	0	0	0	0
DECEMBER	0	0	0	0	0	0	0

Details will be provided below for the screens on load consumption, resources, and components.

3.2 Load and options for purchasing / selling electricity to AC grid

By clicking on the "LOAD / AC GRID" button or by clicking on "LOAD" in the "Data" menu, we access the screen where we must specify the expected load consumption of the installation (AC, DC, hydrogen for external consumption or water previously pumped to tank). Also indicated on this screen are the options for the electricity purchase / sale to the AC grid and for the sale of hydrogen.

The default is the Zero load profile, that is, no load consumption (by default the system is a grid-connected PV generator without any load, where we want to maximize the NPV). There are different tabs, for the different load types and for the options of purchasing and selling energy.



If we want to supply the load of a system (farm, town, building…) in this window we must define the load (usually only AC load) and, in the main screen of the software, Project->Options, you should select the option of minimizing NPC.

All data of the load demand must be referred to OFFICIAL times. In many European countries, official summer time is 2 hours ahead of solar time, whilst official winter time is 1 hour ahead.

3 options are available for introduction of data sources on load:

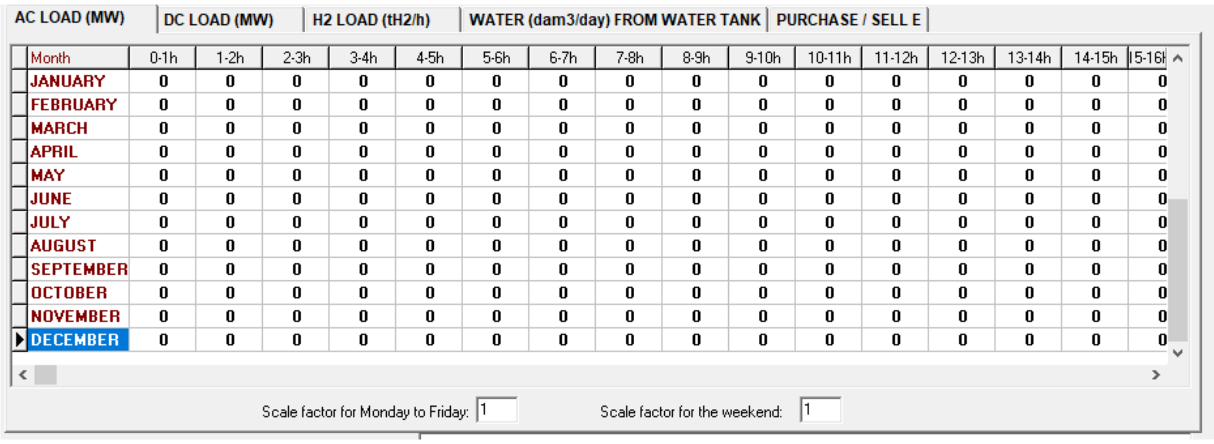
- MONTHLY AVERAGE
- LOAD PROFILE
- IMPORT HOURLY DATA FILE

Monthly Average data:

If we click in "Monthly Average", we can introduce the load data in the tables of the different tabs. This is adequate in case the expected load is known in monthly average hourly values. Data on load must be introduced on the load tables (in MW and t H_2 per hour). Three load tables are available, for AC, DC, and H_2 (click on the tabs to display them). Load profiles are shown for the month under the cursor (bottom right). AC loads are displayed in blue, with DC loads in green, and H_2 loads in red (the latter are shown as power, multiplying by the HHV value of 39.4 MWh/t for H_2). Also, water consumption from water tank previously pumped can be defined.

AC LOAD (W) tab:

In this table you must enter the AC load (MW) values for each hour of the day, for each month.



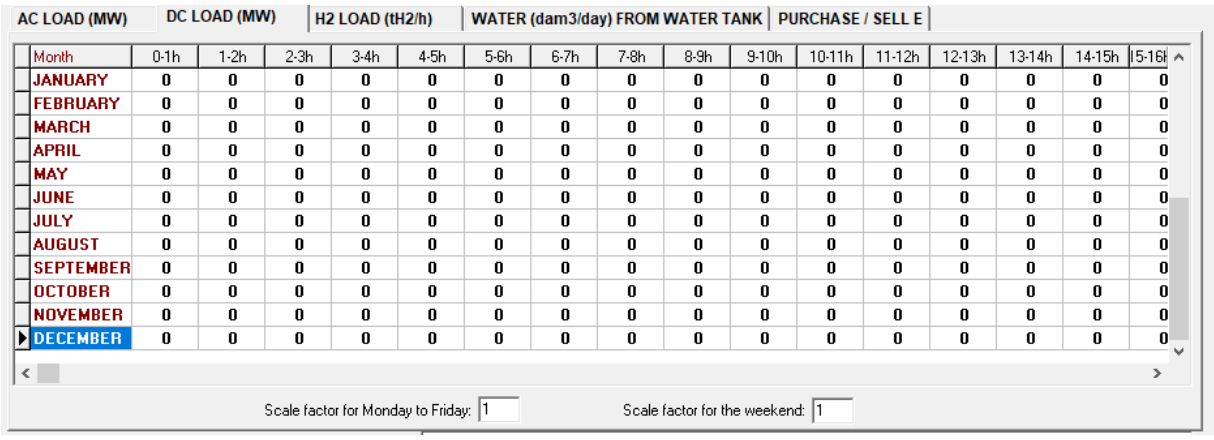
Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEBRUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MARCH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APRIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JULY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUGUST	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEPTEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCTOBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOVEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DECEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

In the tables (AC, DC and H_2 table), data can be written quickly if all the months have the same value for an hour. For example, if the AC load for every month at the first hour of the day (0-1h) is the same, for example 50 MW, you must enter this value of load in the cell JANUARY 0-1h, and then you click your mouse in the cell JANUARY 1-2h, then all the cells of the column

0-1h will take the same value (50 MW). Scale factor must be entered, one for weekdays and another one for weekend.

DC LOAD (MW) tab:

DC load is not usual in high power systems, but in this tab it could be defined in the case there is DC load.

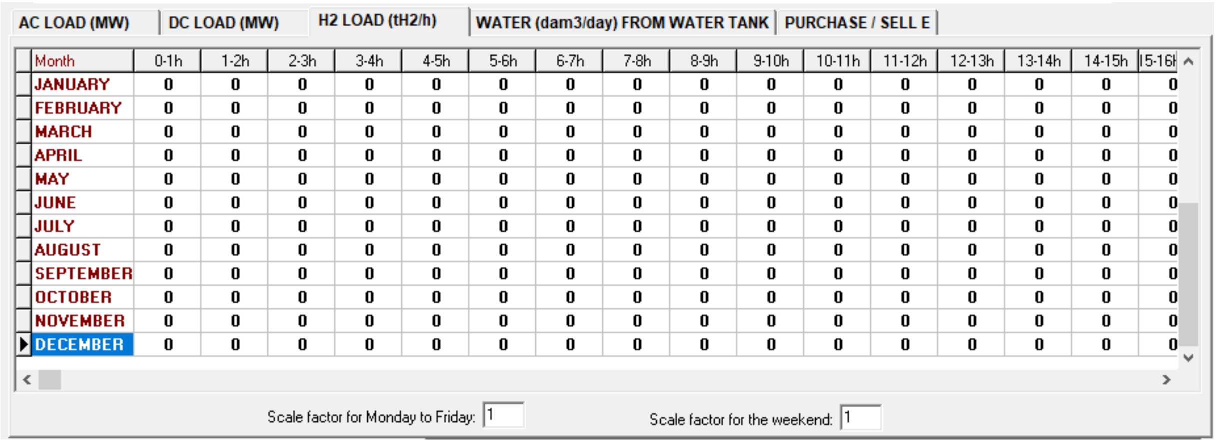


Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16h
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEBRUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MARCH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APRIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JULY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUGUST	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEPTEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCTOBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOVEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DECEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

In this table you must enter the DC load (MW) values for each hour of the day, for each month. Scale factor must be entered, one for weekdays and another one for weekend.

H2 LOAD (kg/h) tab:

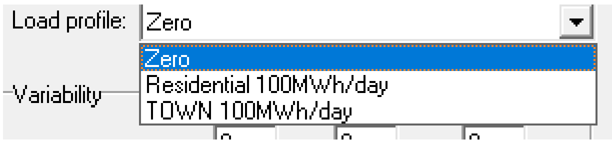
In this table you must enter the H2 load (t/h), i.e., external H2 consumption. It is not the H2 consumption of the fuel cell. Here you must enter the H2 consumption which will be used externally in our company or building (for example, H2 to be used in our hydrogen cars), not to be sold, it will be used by our company without any charge. Scale factor must be entered, one for weekdays and another one for weekend.



Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16h
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEBRUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MARCH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APRIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JULY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUGUST	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEPTEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCTOBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOVEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DECEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Load Profile data:

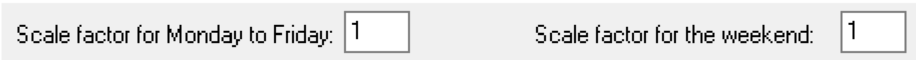
For loads corresponding to profiles predetermined by the system (or created by the user), the adequate option for data source is "Load Profile". When this option is selected, the default profile is charged (the Zero profile). Additional preloaded profiles are available by clicking on the dropdown menu, which is displayed under the tables.



Scale factors:

In the cases of "Monthly average" and "Load Profile" data, a scaling factor must be set for weekdays and another for weekend days. There will be a couple of factors for each type of load (AC, DC, H2 and pumping water).

The factor will multiply to the values that we have placed in the table of the 24 h for all the months of the year.

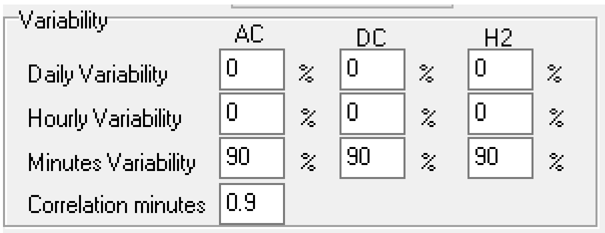


For example, if the expected consumption is equal for all the days of the week, both factors will be 1. If the installation is used only the weekend, the first factor will be 0 and the second factor 1. If the consumption of the weekend is twice that of the week, in the tables you introduce the week days values and the first factor may be 1 and the second factor 2.

Variability:

In the case of "Monthly Average" and "Load Profile" data we can set a percentage of variability or randomness of load (AC, DC and H2), daily, for each hour, and for each minute, for each type of load. The program will randomly calculate the consumption for each hour taking this into account.

To obtain the data of each minute a correlation factor must also be added that will be used to obtain the consumption in time intervals of 1 minute. The software obtains them from the hourly data using a first-order autoregressive function model.



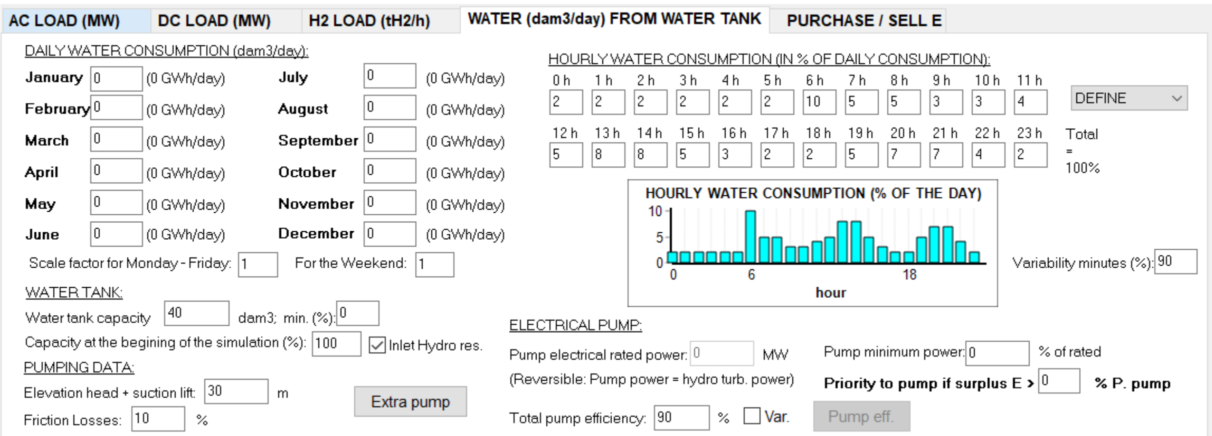
The randomness of the water consumption for time steps of 1 minute is defined in the tab "WATER (dam3/day) FROM WATER TANK (PREVIOUSLY PUMPED)".

AC load power factor:

The user must also introduce a value for the expected AC load power factor:

WATER (dam3/day) FROM WATER TANK (PREVIOUSLY PUMPED):

This tab displays the following:

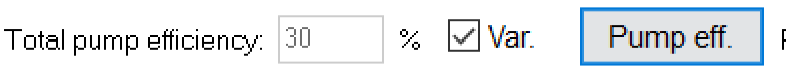


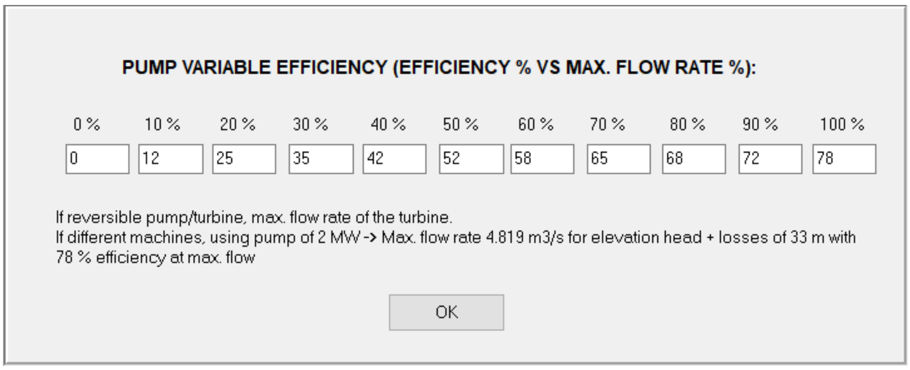
In which we must define different data:

- The DAILY WATER CONSUMPTION of each month (dam3/day)
- Its HOURLY WATER CONSUMPTION (IN % OF DAILY CONSUMPTION) profile, where the sum of the 24 values must be 100%)

- The capacity of the WATER TANK (dam3), the minimum volume (%) and the volume at the beginning of the simulation (%), and the possibility (checking the box "**Inlet Hydro res.**") to consider the water flow defined in the HYDRO RESOURCE window as water flow inlet in the water tank or reservoir.
- The PUMPING DATA: total height (elevation head + suction lift) (m), friction losses (%), pump rated electric power (MW) (in parenthesis the recommended value for pumping the maximum daily flow for 6 hours of pumping appears; note that if you expect to pump for longer hours the power may be lower, higher if fewer hours are expected), pump minimum power (% of rated) and total pump efficiency (%), which could be variable if selected the checkbox "Var".

If pump efficiency is variable (selected "Var"), by clicking the button "Pump eff." we set the variable efficiency % vs. max. flow rate %.





The value of "Priority to pump if surplus E > …. % P. pump" is related to the limit value so that if surplus power from renewable sources is higher than this limit, that surplus will be first used to pump and store water, if it is lower this will be first used to charge batteries (or generate H2 by the electrolyzer).

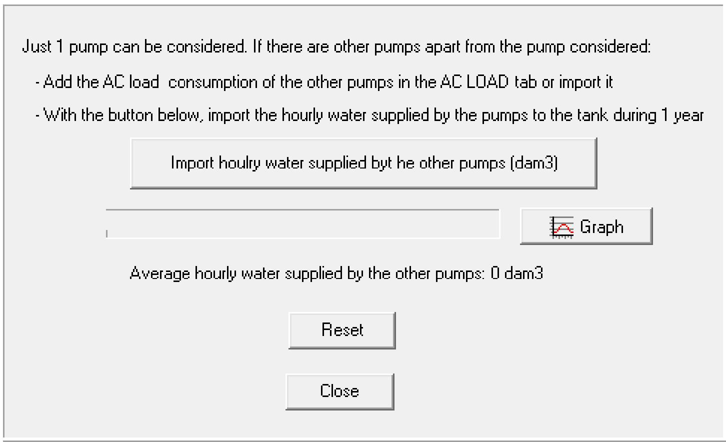
Next to the box of the daily flow of each month appears in brackets the daily energy in GWh/day necessary to pump the daily flow.

It should be noted that in the consumption of water from tank (previously pumped) what really matters in MHOGA is the energy needed to pump that water from the river or well to the tank or reservoir. As the water consumption is normally out of time with respect to the pumping, since the regulator tank is in the middle, the energy consumption cannot be defined directly as

AC or DC loads on their respective load tabs. If it is direct pumping (without going through tank), we can set the water tank capacity to 0 or it could be defined the energy consumption as AC load.

If we only want to calculate a system of pumping water to a tank (without AC, DC or H2 loads), we select the data in the water consumption tab and define zero consumption for the rest of the load (DC, AC and H2), the easiest way is to select the load from profile ("Load profile") and choose the "Zero" load profile.

If we want to consider extra pumps which pump water to the tank or reservoir, by clicking the button "**Extra Pump**" a small window appears, where we can import water pumped by other pumps (and its consumption must be added to the AC load consumption).



Button "Generate":

By clicking on the "**Generate**" button MHOGA generates the load for all the minutes of the year in AC, DC, H2 and water. Below the graph we will see the values of the maximum and average powers both for AC and DC, as well as the value of DC Factor (average value of the relation between the DC load of each hour and the total load of that hour).

Once the hourly and minute values of the year are generated, the tables could be saved as a new profile by clicking on the "**Add Load Profile**" button. In that case, we will be asked for the profile name.

Data from hourly file:

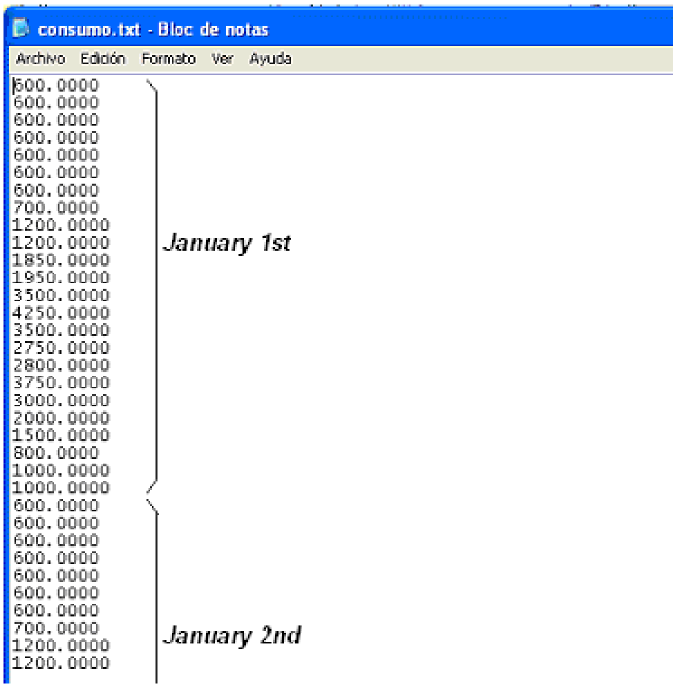
You can import hourly (or in several minutes steps) consumption data for a whole year.

Hourly data:

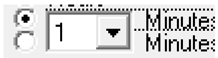
If we have our load perfectly defined and we know (or estimate) the hourly values of the whole year (365 · 24 = 8760 hours), in AC, in DC, in H2 and in water load (we must have them in a text file conveniently sorted as shown below), choose the option "Import File" and keep the "Hours" selection. We can import AC (MW), DC (MW), H2 (t/h) and/or Water load (dam3/h), by selecting their checkboxes.

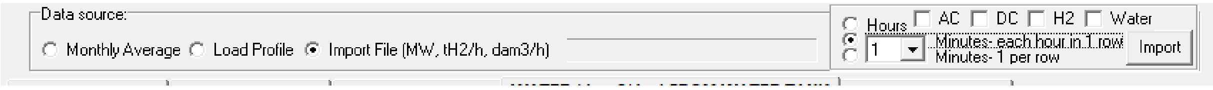
Then click on the "Import" button, opening a dialog where it asks for the location of the file.

The file must have the following format: the hourly consumption values, in MW, must be sorted in rows. If just AC load (for example) is selected to import, the file will have 8760 values, each one in a row. If all the types of load are selected to import, there will be 8760x4 = 35040 rows. Depending on the types of load selected to import, there can be up to 4 groups of 8760 rows, corresponding to the consumption of AC, DC, H2 and water. Anyway, if there are more than one type of load selected, the file must include first the 8760 rows of AC load (if selected), next the 8760 rows of DC load (if selected), next the 8760 rows of H2 load (if selected) and finally the 8760 rows of water load (if selected). The first 8760 rows will be the values of the AC consumption corresponding to each hour (sorted by date and time, i.e. the first row will be the AC load of January 1st, 0h, in MW, the second row is the AC load of January 1st, 1h ... the last row, that is, the 8760th row corresponds to 23 h on December 31), then the 8760 rows corresponding to the hourly consumption DC (MW), then the 8760 rows of hourly consumption of H2 (t/h) and finally the 8760 rows of water consumption from tank (dam3/h). ***The separation decimal point should always be dot (.), not comma.***



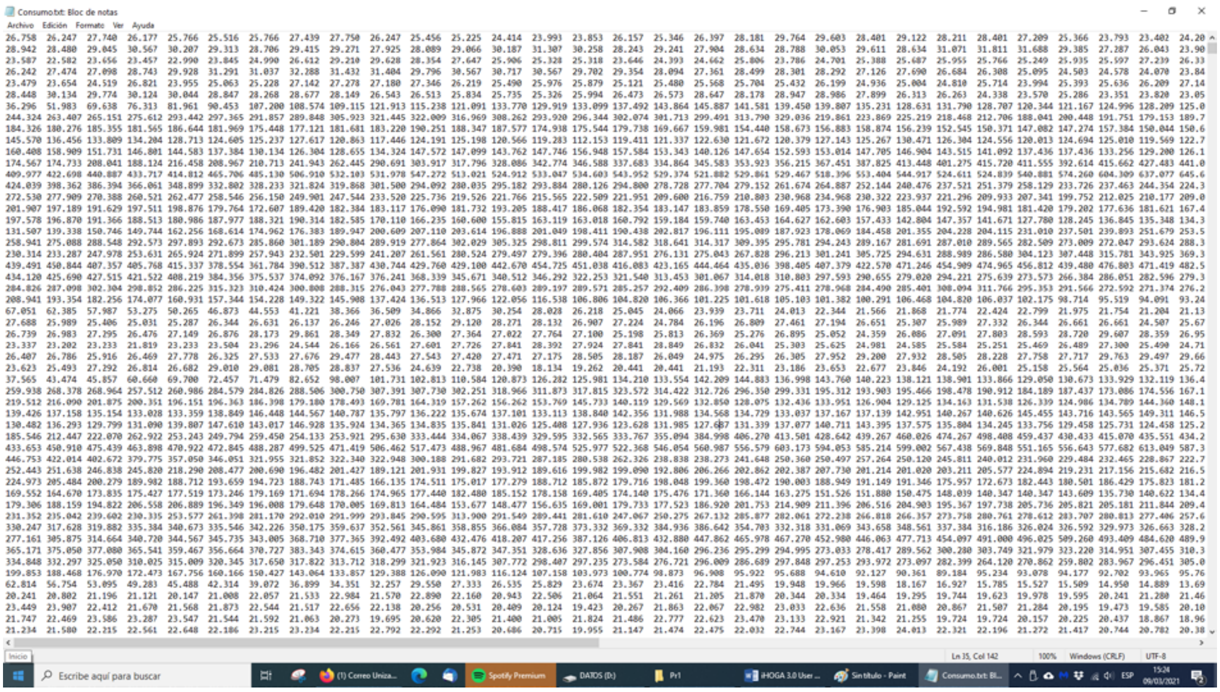
<u>Lower time steps data:</u>

If the data is available in minutes (1 or more minutes per time step), we will select the number of minutes of the time step  (default 1 minute, that is, 60 data per hour) and we can choose "Minutes - each hour in a row" or "Minutes -1 per row", depending on which type of file we have.



If we click in "Minutes –each hour in 1 row" we must have a file in which we have 8760 x M rows, where M is the number of types of data to import (AC, DC, H2 and/or Water), if all are selected, M =4 and therefore the file must have 35040 rows. Each row corresponds to 1 hour, and in each row there are N data corresponding to the number of steps per hour.

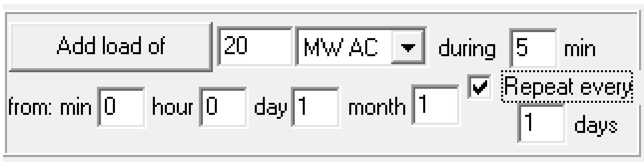
For example, here we can see part of a file where the time step is 1 minute (N=60, therefore 60 tab separated columns).



If we click on "Minutes (1 per row)" we need a file where we have 8760 x N x M, where N is the number of steps per hour (default 1 minute time steps, N=60 steps per hour) and M is the number of types of load selected. If time step is 1 minute (N=60 steps per hour) and we import all the types of load (M=4 types), 2,102,400 rows are needed, every minute in 1 row.

Add load

Once the hourly and minute load has been generated (using the "Generate" button) or the consumption has been imported, you can add either AC, DC, H2 or water consumption, using the button "Add load", where the consumption to be added must be specified (see figure following).



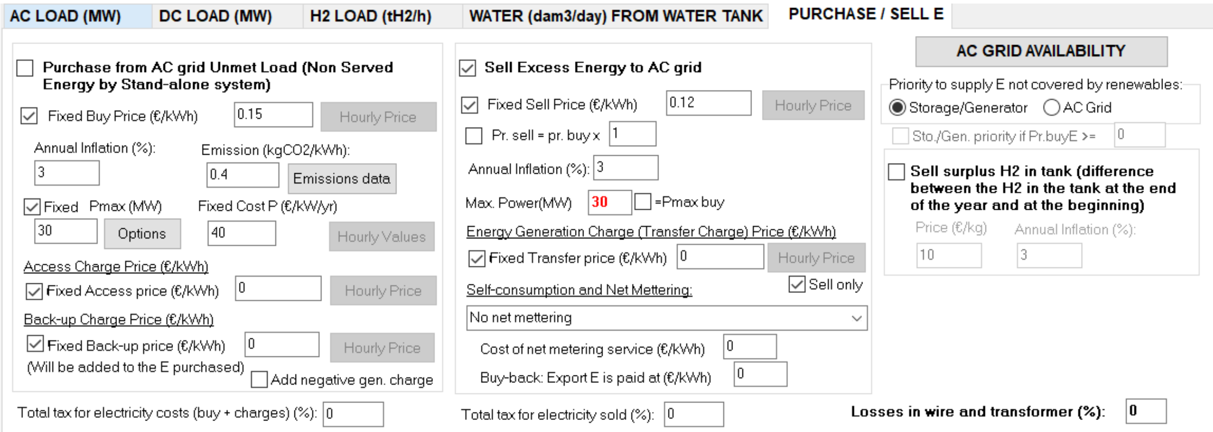
In the example, when you click on "**Add load of**" MHOGA will add 20 MW AC for 10 consecutive minutes from 5 a.m. of January 3rd, and will be repeated every day until the last of the year. If you did not click on "Repeat", it would only be added for January 3rd.

Please, note **that this must be done after the load has been defined and generated** using the "Generate" button **or after the load has been imported**.

PURCHASE / SELL E tab:

This tab defines the options to purchase electric power to the AC grid, availability of the AC grid, priority to supply the energy not covered by the renewable sources, by the storage (batteries / PHS / AC generator / fuel cell) or by the AC grid, sale of surplus electrical energy to the AC grid, and sale of excess hydrogen in the H2 tank (difference between hydrogen at the end and at the beginning of the year).

By default, a generating system is considered without any load, therefore Sell energy to AC grid is allowed but Purchase energy from the AC grid is not allowed. If there is any load that cannot be covered by the generating system, you should allow the purchase of energy from the AC grid.



Electric power is purchased from the AC grid when there is power that the renewable sources and the storage/generator have not been able to supply. Also, in the case of energy arbitraje in systems with batteries connected to the AC grid or pumped hydro storage or green hydrogen generation by the electrolyzer, during the time steps when the price of electricity is low, power can be purchased from the grid to supply the load consumption and charge the batteries and/or pump water and/or generate green hydrogen.

Electric power is sold to the AC grid when there is surplus energy after supplying the load and storing the extra energy in batteries, pumped water and/or hydrogen.

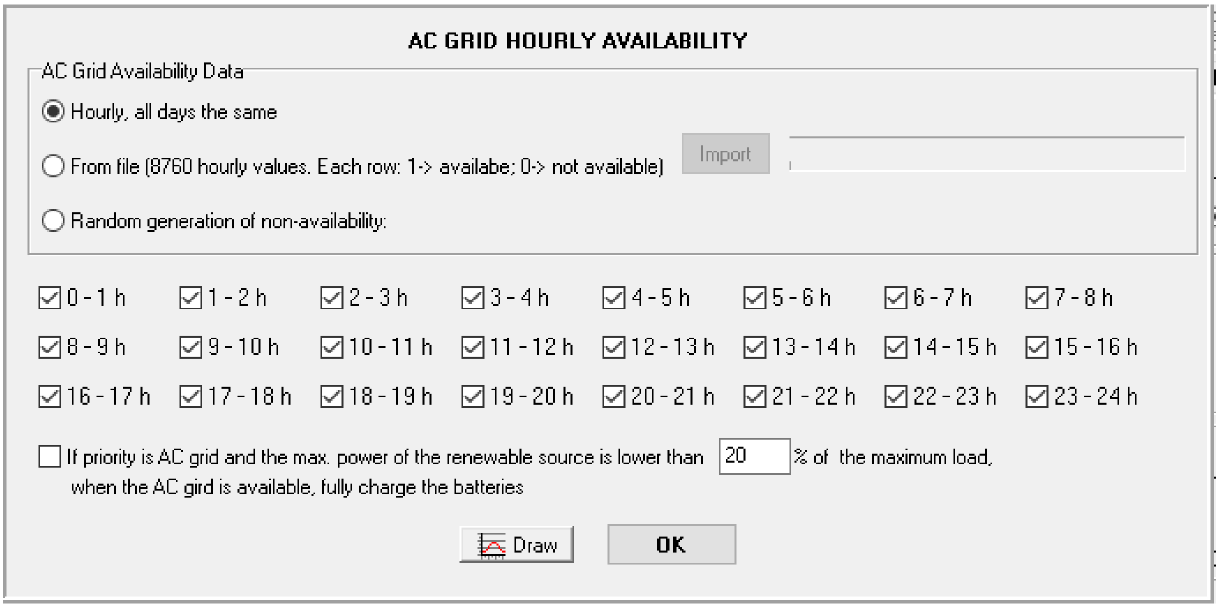
Also, in the case of systems with batteries connected to the AC grid or systems with pumped hydro storage, during time steps when electricity is expensive, batteries are discharged and/or hydro turbine runs with the stored water to supply the load and, if allowed, energy is injected into the grid.

<u>- AC grid availability</u>:

On the right there is the button 

.

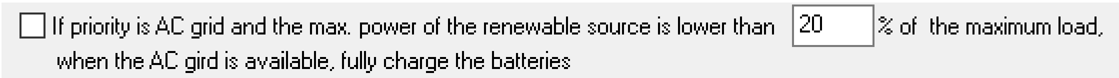
By clicking this button, the next window appears:



AC grid hourly availability data can be:

- Hourly, all the days the same (default): in this case during the hours checked the AC grid will be available; during the hours that are unchecked AC grid will be unavailable.
- Import from file: the file must have 8760 rows (1 for each hour of the year). In each row, value 1 means available; value 0 means unavailable.
- Random generation of non-availability: by choosing this option a text box appears where you must introduce the percentage of non-availability. Then you must click on "Generate" to obtain the random generation.

The checkbox "If priority is AC grid and the max. power of the renewable source…" is checked, that means:



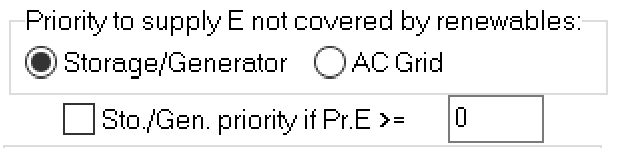
If the priority to supply the load that was not covered by the renewable sources is the AC grid (see below), then, in the case that the maximum renewable power (PV+wind) is lower than a specific percentage of the maximum load, when the grid is available it will charge the batteries. It is a good option when you want to consider systems with low renewable power (or even without renewable power), in this way the AC grid will be available to charge the batteries (the renewable sources will likely not have enough power to do it).

By clicking the button "Draw" the availability of the AC grid during the year is shown.

By clicking the button "OK" the window is closed.

<u>- Priority to supply E not covered by renewables</u>:

Under the previous button, we can select the priority to supply the energy not covered by the renewable sources:



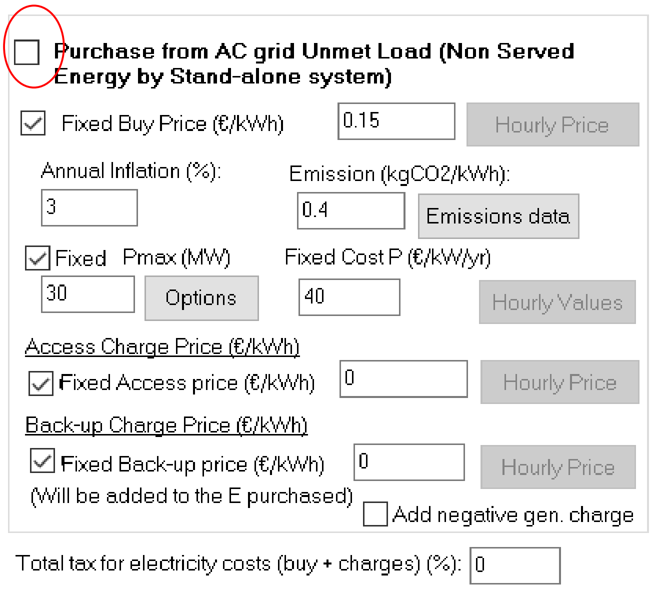
- "Storage/Generator": this means that, during each time step, if the renewable sources cannot meet the whole load, the rest of the load will be covered by the batteries / AC generator / fuel cell. If the storage, generator and fuel cell are not capable to cover the whole unmet load (if there is still unmet load), it will be covered by the AC grid (if it is available and the purchase is allowed).
- "AC Grid": this means that, during each time step, if the renewable sources cannot meet the whole load, the rest of the load will be covered by the AC grid (if it is available and the purchase is allowed). If the AC grid cannot cover the whole unmet load, and there is still unmet load, it will be covered by batteries / AC generator / fuel cell.

If the checkbox 

is checked, the priority will be Storage/Generator when the purchase electricity price is lower than the value defined in the box (in monetary unit / kWh).

- Purchasing from AC grid Unmet Load (Non Served Energy):

By checking this option (unchecked by default), when doing the simulation, if the AC grid is available, all the energy load that cannot be supplied (unmet load) by the system (the renewable sources, the storage, generator and fuel cell) will be purchased from the AC grid. It may happen that the unmet load is greater than the maximum power that can be purchased from the grid Pmax (MW), in that case it will not be possible to cover all the unmet load from the AC grid.

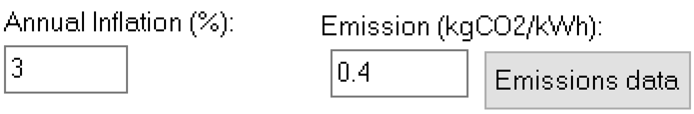


You can choose a fixed price for the cost of the energy purchased from the grid, not including the charges, which are indicated separately (for all hours of the year the same price by ticking the box "Fixed Buy Price (€/kWh)"):

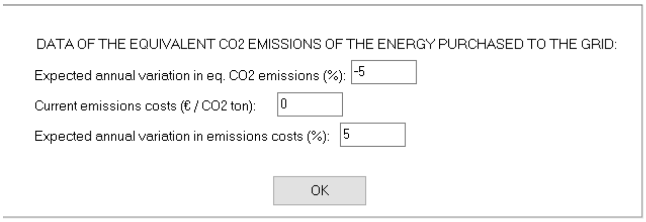
Or set a price for each hour or by hourly periods, if the indicated checkbox is not checked, the button on the right 

is enabled.

Also it must be set the expected annual inflation for the price of electricity, the CO2 emissions due to the energy purchased from the AC grid (depending on the energy mix of the country).

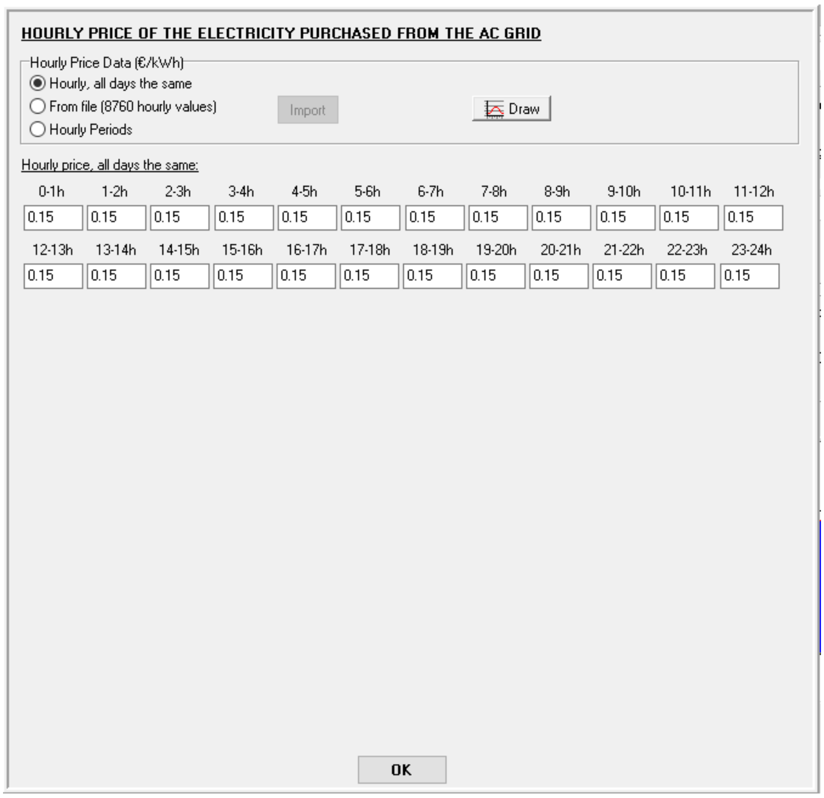


By clicking the button "**Emissions data**" we can define the expected annual variation in the CO2 emissions due to the energy purchased to the grid (depending on the expected future of the energy mix of the country; + increase, - decrease), the current cost of the emissions (€ per CO2 ton) and the expected annual variation in this cost.

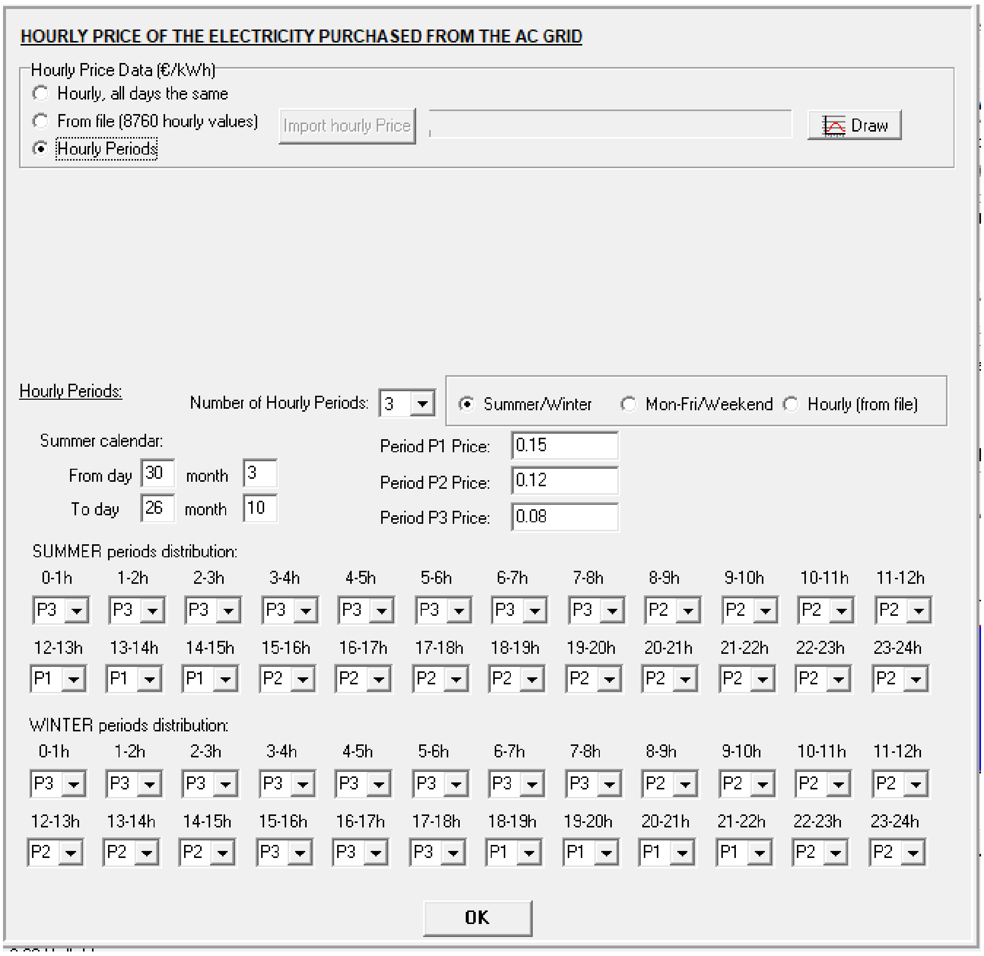


If the "Fixed Buy Price" checkbox is deselected, the button 

is enabled. By clicking on this button a window appears from which you can enter the price for each hour of the day (every day the same) or import from file the prices of the 8760 hours of the year (in the case of importing of file, in the hourly values of the file the decimal separation must always be dot, not comma)**.**



If the option "Hourly periods" is selected, the number of periods (default 3: Peak, Normal and Valley, here called P1, P2 and P3) and the purchase price for each of them must be set. Also it must be defined the type of period for each hour during summer/winter (default) as well as the summer calendar, or the type of period for each hour for Monday-Friday/weekend.



If your period distribution during the year does not match with summer/winter or Monday-Friday/weekend, you can use the option to import an hourly file, you should click in "Hourly (from file)":

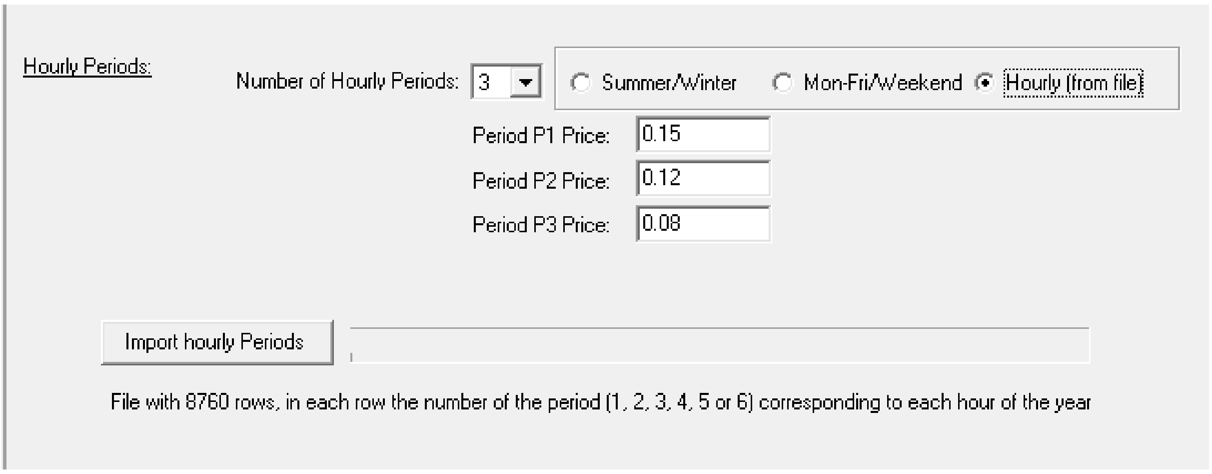
In this case, you must have a file (for example a .txt file) with 8760 rows (1 for each hour), in each row the number of the period. For example, if the first hour of the year (0 h 1st of January) is period P3, the number 3 must be in the first row, and so on. Take into account that MHOGA considers the first days of the year (1st and 2nd January) as weekend.

For example, in the next figure we can see an example of a file with the 8760 rows

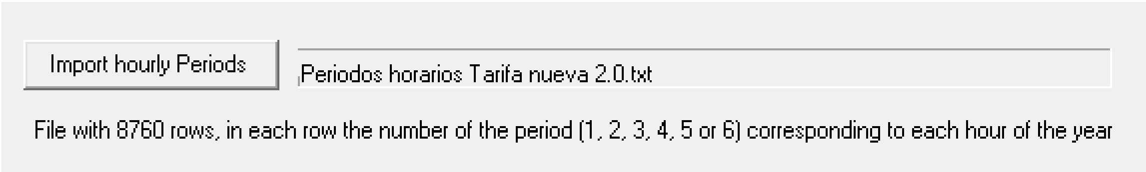
Where, during the weekend we have a valley period (P3), that is, in the file the first 48 rows are “3”.

From Monday to Friday, the periods are 1, 2 or 3, depending on the hour (see next figure, where we can see some hours of the week days).

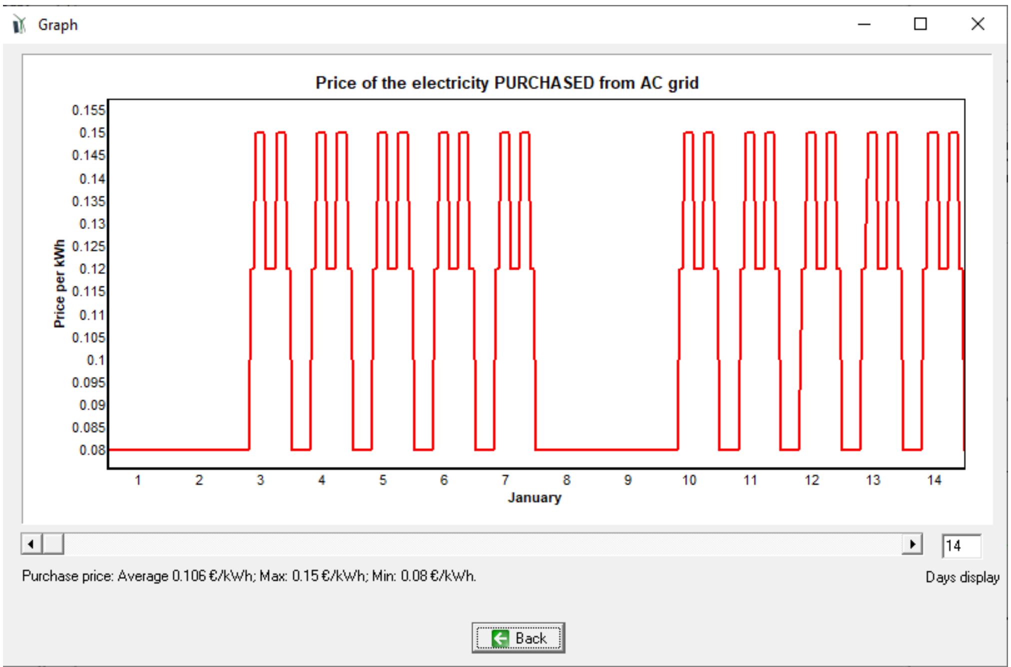
A button “**Import hourly Periods**” is shown, and clicking in this button you must select your file with the 8760 rows of numbers of the period for each hour.



After importing the hourly file with the numbers of the periods, we can see the name of the file imported:



After downloading the file, in the upper right corner of the window, we click in "**Draw**" button and we can see the hourly price of the electricity. In the next figure we can see the hourly price for two weeks (14 days shown), during the weekend (two first days of the year) the period is P3 (valley) and during the weekdays several hours it is P1, other P2 and other P3.



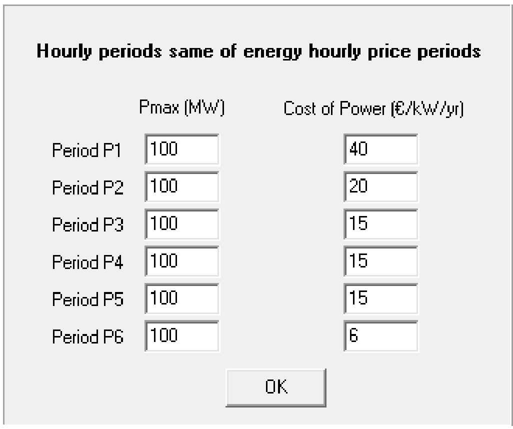
Finally, it is necessary to click on "OK" to save the changes of the hourly price.

Contracted power (maximum power that can be obtained from the AC grid):

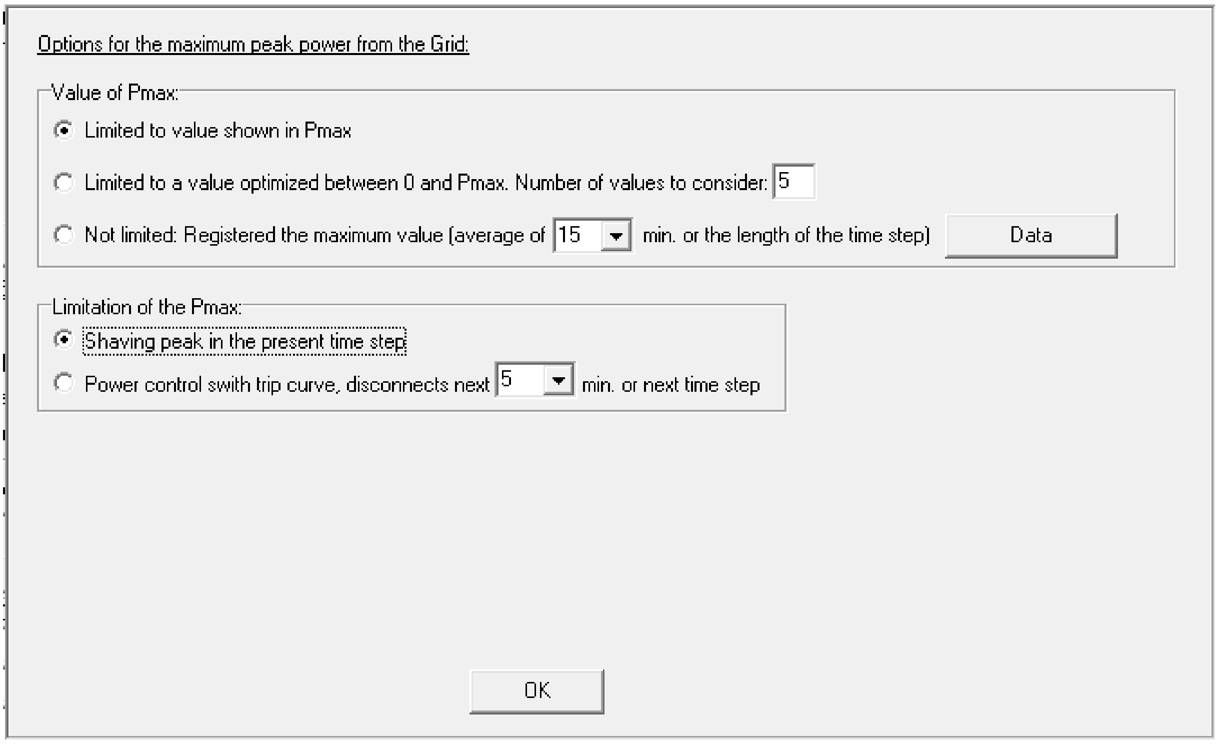
Also it must be set the maximum contracted power Pmax (MW) that can be bought from the AC grid, and the annual fixed cost for the availability of the AC grid "Fixed cost P (€/kW/yr)".

The contracted power can be a fixed value (checkbox checked) or it can have different values for different periods. If the checkbox "Fixed Pmax" is unchecked, the "Hourly values" button is enabled:

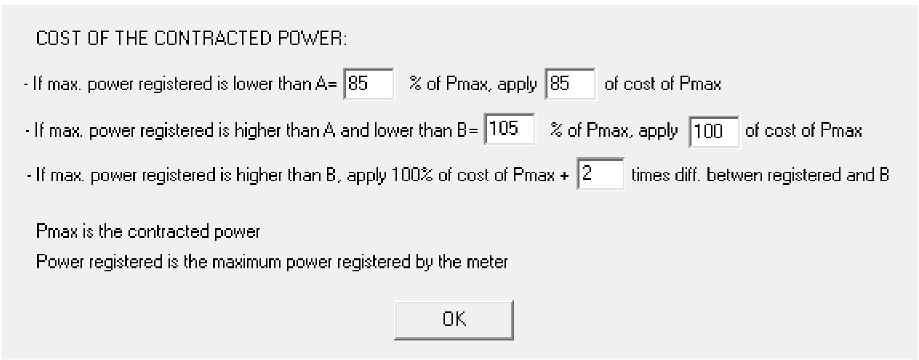
By clicking in the "Hourly values" button we can set the different values of the contracted power and its cost in €/kW/year for the different periods previously defined for the energy purchased from the AC grid.



By clicking in the button "Options", we can set the options of the maximum peak power from the grid. The value of the maximum power from the grid by default is limited to the value shown in Pmax (kW), but it can be optimized (second option) or not limited (the contracted power is the value of Pmax but the maximum to be counted in the electricty bill will be consider the maximum average value registered in 15 minutes steps, third option).

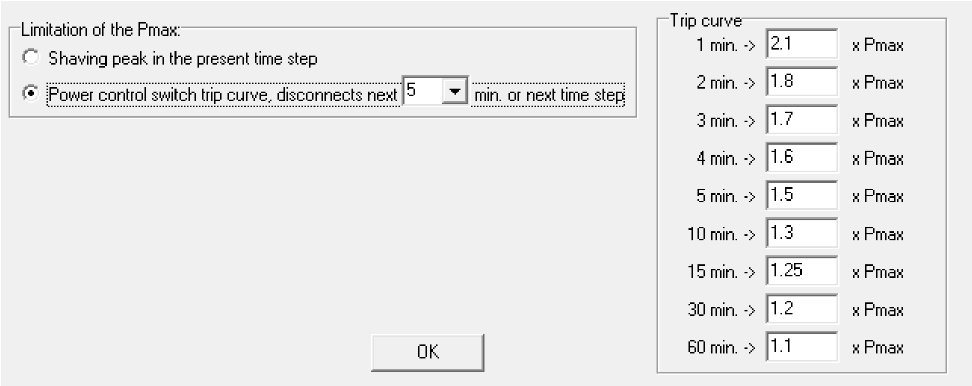


In the third option, if we click "Data" button, we can see how the costs of the contracted power will be calculated, considering the contracted power and the maximum 15-min average registered value (as done in Spain and other countries where the maximum power is registered).



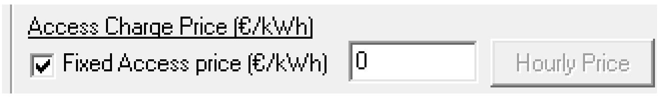
The limitation of the Pmax (1st or 2nd options seen previously) can be by shaving the peak at the present time step (default) or by the power control switch curve, disconnecting the next X minutes (default 5 minutes) or next time step.

If we select the 2nd option for the limitation of the Pmax, the values of the trip curve are shown:



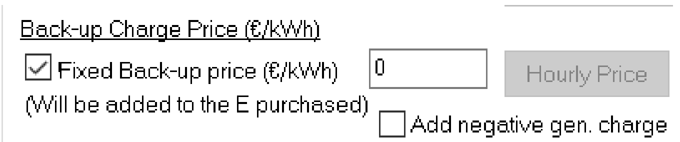
Access charge:

The AC grid access charge will be added to the cost of energy purchased. It is also indicated in this electricity purchase table, being it possible to set a fixed price or an hourly price, just as for the cost of electricity.



Back-up charge:

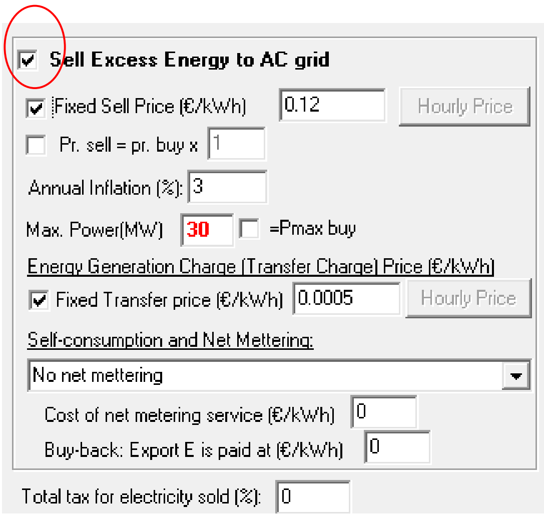
In the case of PV self-consumption with a grid connection, in some countries, it could be necessary to pay for the energy produced by the generators of the installation that is consumed in the installation, called a "back-up charge". This charge will be added to the cost of the purchased energy. It is also indicated in this electricity purchase table, being able to fix a fixed price or a hourly price, as for the cost of electricity.



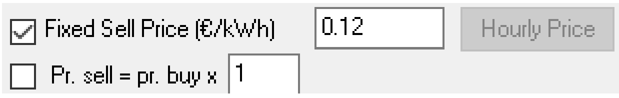
If the checkbox "Add negative gen. charge" is selected: if in the Generation charge (transfer charge), defined later, we define a negative value, that generation charge will not be a charge, it wll be an income, and this income will be added (in negative value) to the back-up charge.

- Sell excess energy to AC grid (excess energy produced by the system components):

If the check box "Sell Excess Energy to the AC grid" is checked (as by default), the electrical energy that can not be used by the system will be evacuated to the AC grid. If the control strategy for grid-connected batteries (or pumped hydro storage) are set, the energy injected to the AC grid will depend on the electricity prices.

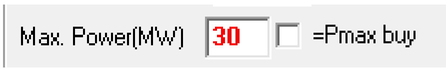


You can choose a fixed price for all hours of the year (check the box "Fixed Sell Price (€/kWh)", marked default), or a price that is proportional to the purchase price (check the box "Pr. sell = pr. buy x ", indicating the proportionality factor), or, if neither option is marked, it will be considered the hourly price that appears in the window when clicking the button "Hourly Price" (in that case you can use hourly periods or import a file with the hourly prices).



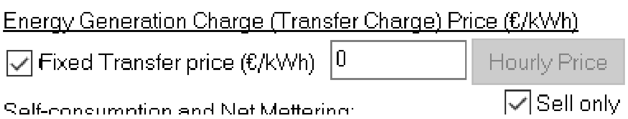
The expected annual inflation for this sell price will also have to be fixed.

If you want to limit the power that can be injected to the AC grid, you must set the corresponding value in the text box to the right of "Max. Power (MW)", which can be the same as the maximum Power limited for the purchase (if checked the "=Pmax buy" checkbox).



Energy Generation Charge (Transfer Charge):

If the regulations of the country require the payment of a transfer charge (generation charge) for the energy injection to the AC network, a fixed value can be indicated for all the hours of the year or you can set hourly values:

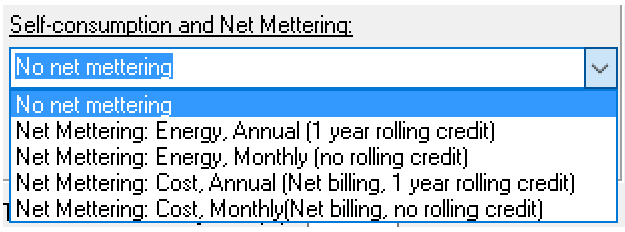


If the ckeckbox "Sell only " is checked, this means that it will be applied only to the energy injected to the AC grid; if it is not checked, the generation charge will be applied to all the renewable production (PV+wind), even if it is not injected to the grid.

We could set a negative value, this would mean not a charge, but extra incomes due to generation of clean energy: the system would receive money due to the renewable energy generated; this will be subtracted from the cost of purchasing electricity to the grid (added as a negative value to the back-up charge defined previously, if its checkbox is checked).

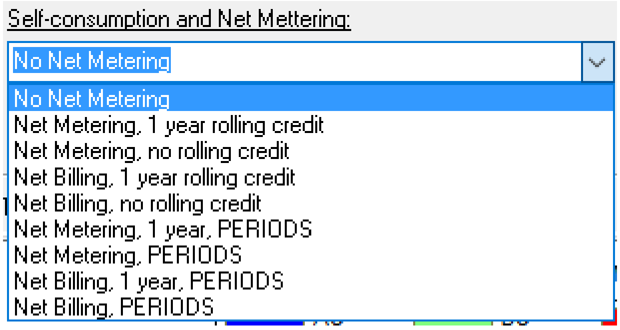
Net metering.

As default, No Net Mettering is selected. However, you can choose up to 4 cases of Net Mettering (Rodolfo Dufo-López & Bernal-Agustín, 2015a).



If it is not allowed to sell more energy annually than to buy, you must select Net metering: Energy, Annual (1 year rolling credit). If it is not allowed to sell more energy to the grid on a monthly basis than to buy, you should select Net metering: Energy, Monthly (no rolling credit). If the annual revenues due to the sale of electricity to the grid cannot be higher than the costs due to the purchase of power to the grid, you must select Net mettering: Cost, Annual (Net billing, 1 year rolling credit). If the monthly income due to the sale of electricity to the grid cannot exceed the costs due to the purchase of power to the grid, you must select Net mettering: Cost, Monthly (Net billing, no rolling credit).

If several hourly periods have been defined, there are 4 more possibilities of Net Metering, just like the previous ones, but with the addition "- PERIODS", in these cases the net balance is allowed only within the same hourly periods, being more restrictive. *These additional cases, taking into account the periods, cannot be defined if there are batteries and the aging model is that of Schiffer*.



The "**Cost of net metering service**", is the price of the energy involved in the net metering (€/kWh) and must be placed in the following box:

For any type of net metering, it is possible to define "buy-back", that is, the energy that has been injected into the grid and that has not intervened in the net balance (the excess energy accumulated at the end of the balance) and that is compensated by the electricity company with a certain price, in that case the price (€/kWh) must be placed in the following box:

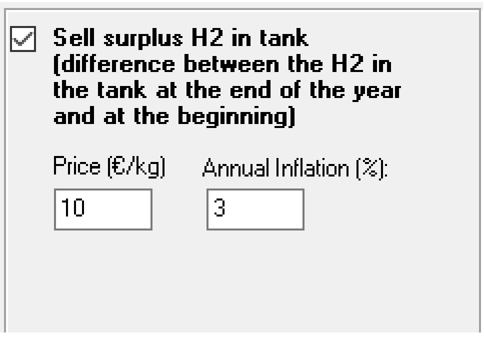
Taxes:

Under the boxes of purchase and sale of electricity two boxes appear where you can indicate:

- Total taxes on the costs of acquiring electricity to the grid (%). This percentage will be applied on all costs: energy, access charge, back-up charge and fixed cost. It will also be applied on the generation charge (costs for the sale of energy to the grid).
- The total taxes on revenues from the sale of electricity to the grid (%): is applied to sales revenue, i.e., to the sale price of energy (the electric company will be invoiced for the price of electricity sold + this tax).

- Selling surplus H_2 in tank:

That is, selling H_2 stored in the H_2 tank, resulting from the difference between the end and the start of the year. Purchase price and inflation rates must be introduced.



- Losses in wire and transformer:

We can consider losses in wires and transformer so that the electricity injected to the AC gird will be reduced in this percentage:

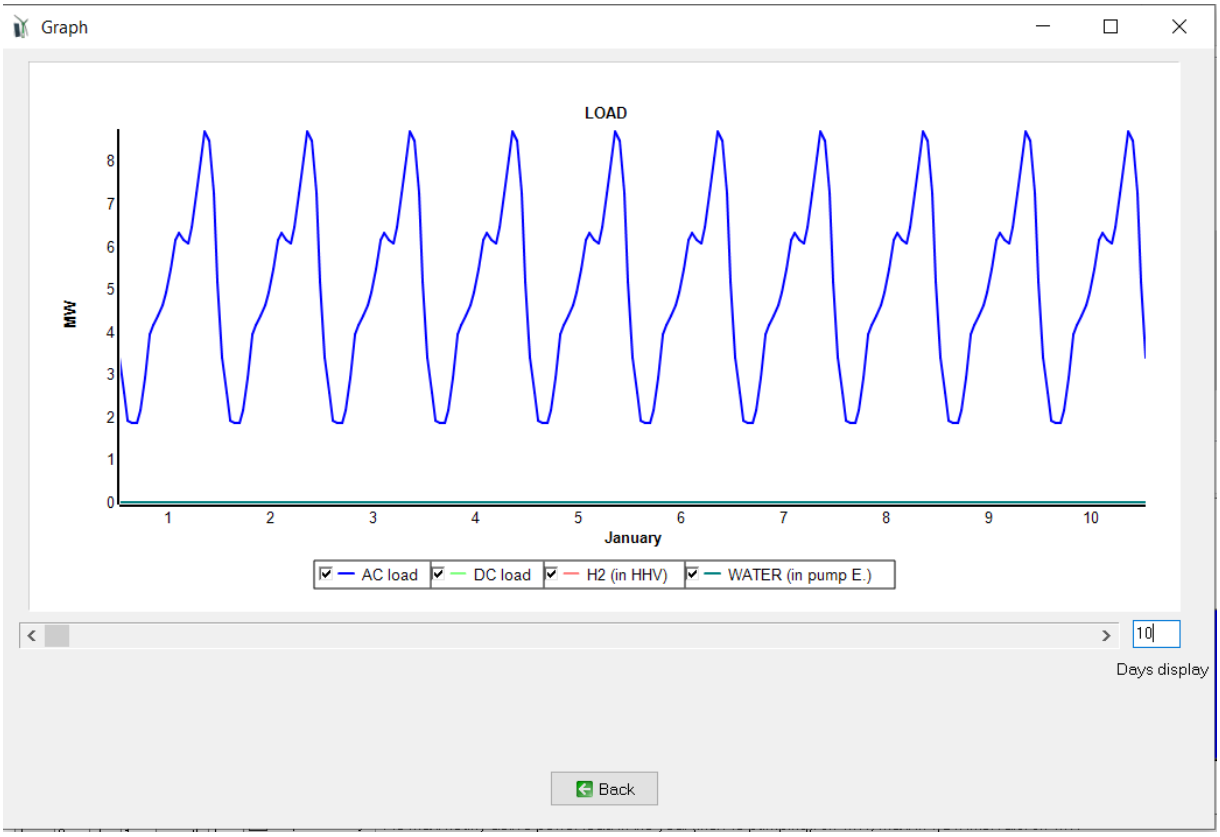
Button "Graph in steps of":

In the LOAD / AC GRID window, at the bottom left there is the button 

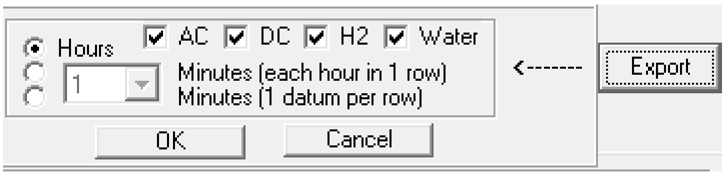
, with which, once the loads of the year are generated (or imported), a screen with the annual load chart appears in MW, dark blue AC, green DC, H2 red and light blue WATER . It can be displayed in steps of between 1 and 60 minutes. With respect to the consumption of H2 (t/h) although the data entered are in t of H2, to be able to represent it together with the electrical consumptions, it is converted to energy (MWh) by multiplying by the Higher Heating Value of H2 (HHV), roughly 39 MWh/t and then divided by the time step in hours it its converted to power in MW. In water consumption (dam3/h), the power that during that interval has previously been needed to pump (from the well or river to the reservoir) the flow of that interval is represented.

You can change the number of days to display (down right). Clicking the right button on the graph shows a menu where you can select "Copy" (to the clipboard) or "Save Picture".

For example, if using the load profile "Residential 100 MWh/day", showing 10 consecutive days:



You can also export the time values generated (or imported) by pressing the "Export" button (up right).



A small window appears where you have to indicate the format of the data to be exported:

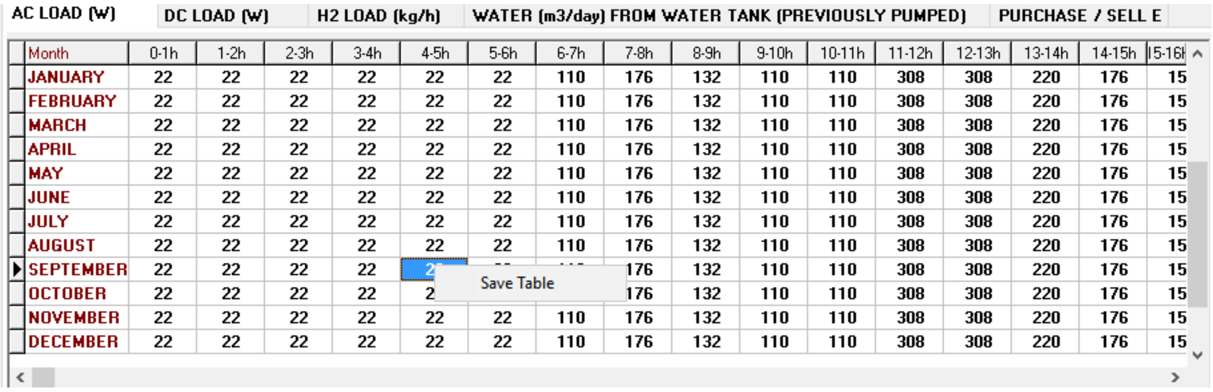
In hourly data: 8760 h rows x M, where M is the load types (AC, DC, H2 and/or Water, depending if they are selected or not). For example, if you select to export just the AC load, the file will have only 8760 rows. If you select to export all the load types, the file will have 8760x4 = 35040 rows (first 8760 rows AC, next 8760 rows DC, next 8760 rows H2 and last 8760 rows Water).

In other time steps data: We must select the time step (by default 1 minute, in this case number of time steps in one hour is N=60).

If we select "Minutes (each hour in 1 row), N time steps tab separated data will be in each row (if 1 minute is selected as time step, 60 tab separated values will be in each row, that is, all the values of each hour), and the number of rows will be 8760 x M, where M is the load types (AC, DC, H2 and/or Water, depending if they are selected or not).

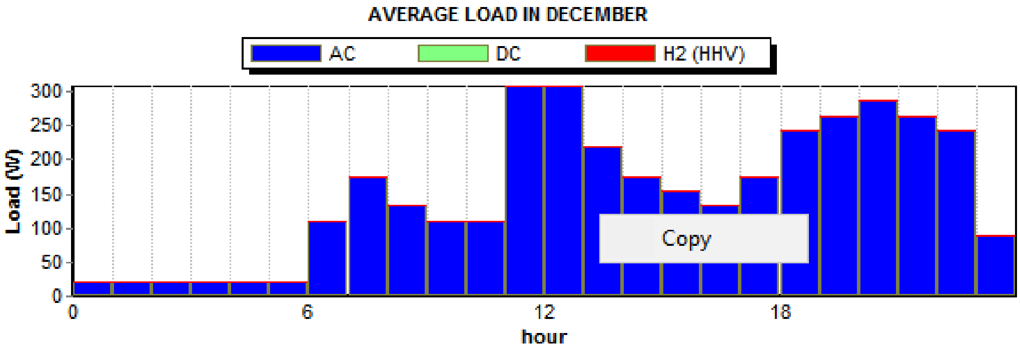
If we select "Minutes (1 datum per row), in each row there will be just one datum, for example, if the time step selected is 1 minute, the first 60 rows will be the values for each minute of the first hour of the year, and so on. If all the data is selected (AC, DC, H2 and Water), 8760x60x4 = 2102400 rows will be in the file.

It is possible to save the data of the consumption tables, both of the AC consumption table as well as the DC and H2 tables. To do this, select a cell with the left mouse button and then right click and "Save Table".



Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16h
JANUARY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
FEBRUARY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
MARCH	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
APRIL	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
MAY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
JUNE	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
JULY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
AUGUST	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
SEPTEMBER	22	22	22	22	[illegible]	[illegible]	[illegible]	176	132	110	110	308	308	220	176	15
OCTOBER	22	22	22	22	[illegible]	[illegible]	[illegible]	176	132	110	110	308	308	220	176	15
NOVEMBER	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15
DECEMBER	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	15

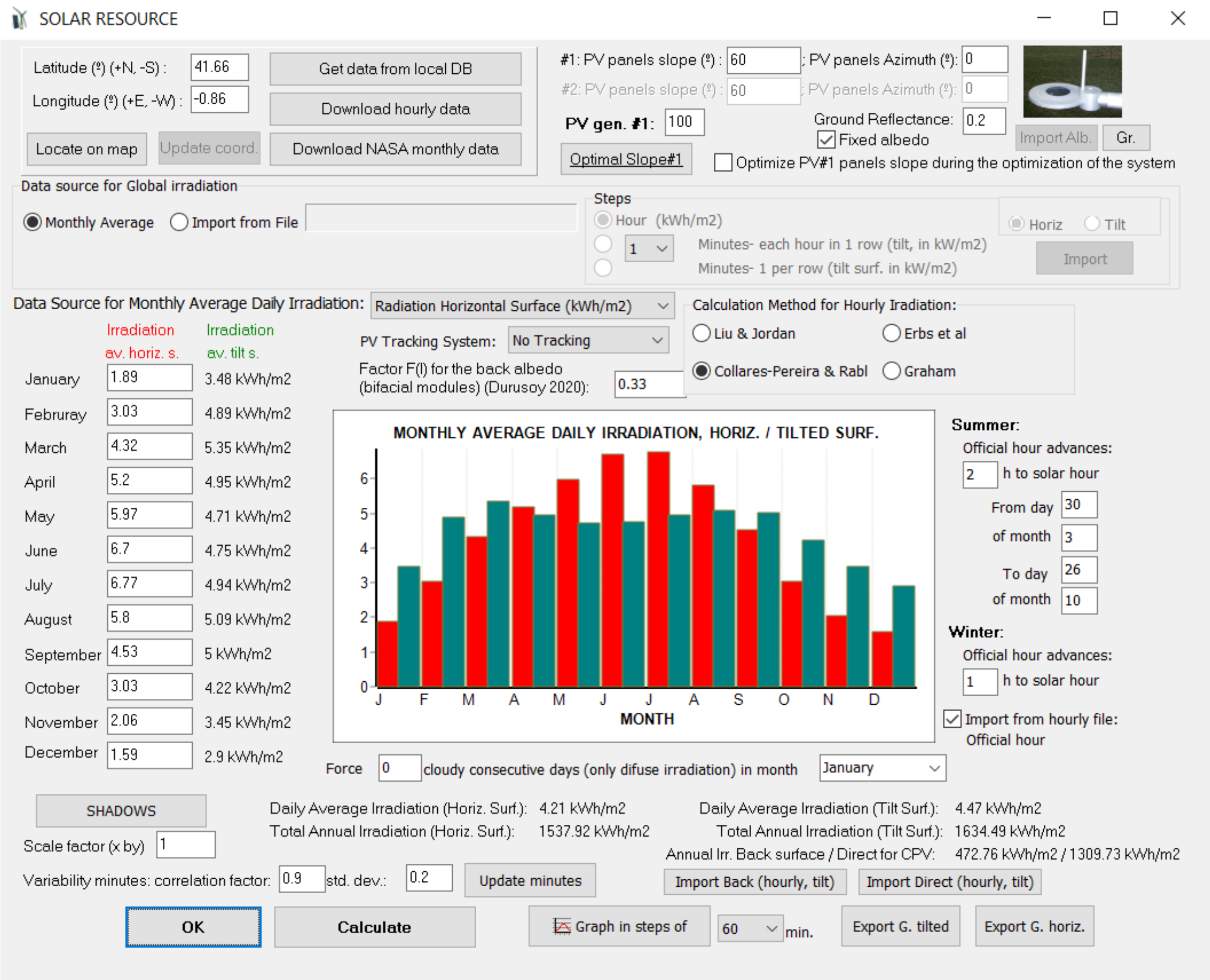
The consumption chart can also be saved. By right clicking on it, we will select "Copy" (to the clipboard). The same can be done with all the graphs of the program.



Once we have defined the consumptions, click on the "OK" button and we return to the main screen.

3.3 Solar resource (Irradiation)

Data on solar irradiation may be introduced by clicking on the "SOLAR" button (RESOURCES), or selecting "Solar" within the "Data" menu. Irradiation data is used for calculation of the energy produced by the PV generators (also bifacial PV or CPV can be defined).

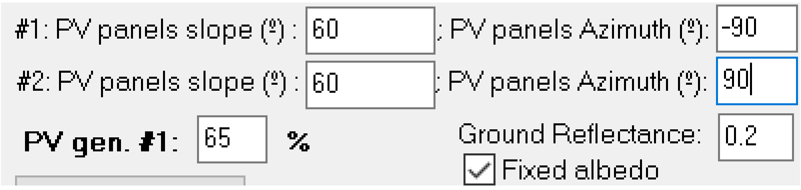


In the upper left zone, it should be indicated **latitude** (+ northern hemisphere, - southern hemisphere) and **longitude** (+ East, - West), as well in the upper right zone the **slope** (º) and **azimuth** (º south) of the modules and **ground reflectance** (fixed value for all the year of "Fixed albedo" or you can import an hourly file with the 8760 hourly values of the albedo, button "Import Alb").

3.3.1. PV generator divided in two zones.

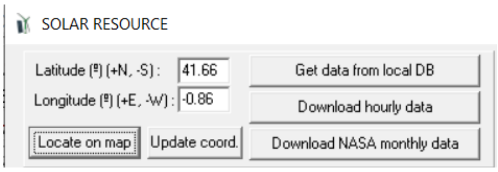
MHOGA allows the **PV generator divided in two zones at different slope and azimuth**.

By default, there is only one zone for the PV generator (zone #1 is 100%). If you want to divide the PV generator in two zones, you must change the value of "**PV gen #1**". For example, if you want 65% of the PV generator power in zone # and 35% in zone 2, you must define **PV gen. #: 65%.** You must define the slope and azimuth for zones #1 and #2, for example, in the following figure it is defined that #1 (65% of the PV gen.) is 60º slope and -90º azimuth (east), and zone #2 (35%) is 60º slope and 90º azimuth (west).



3.3.2. Locate coordinates on the map.

The latitude and longitude can be obtained from a web map (necessary internet connection) by clicking on "**Locate on map**" (top left corner).

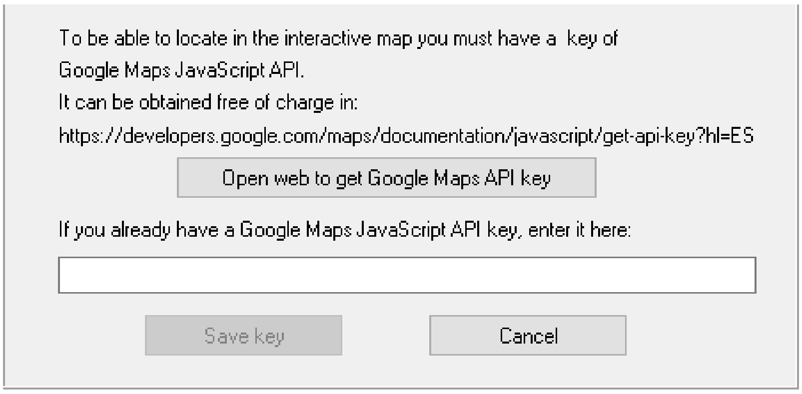


In order to locate a place on the map, it is necessary to have a Google Maps JavaScript API key. If you do not have a key you can get it for free at:

https://developers.google.com/maps/documentation/javascript/get-api-key?hl=EN

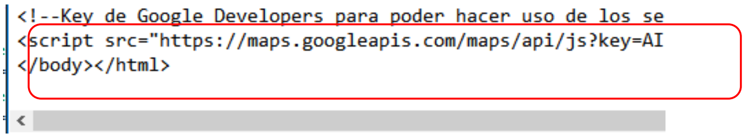
It is important not to include any restrictions on the API key, because if you introduce any restrictions it may not work in MHOGA.

The first time you click on "**Locate on map**" the following panel appears:



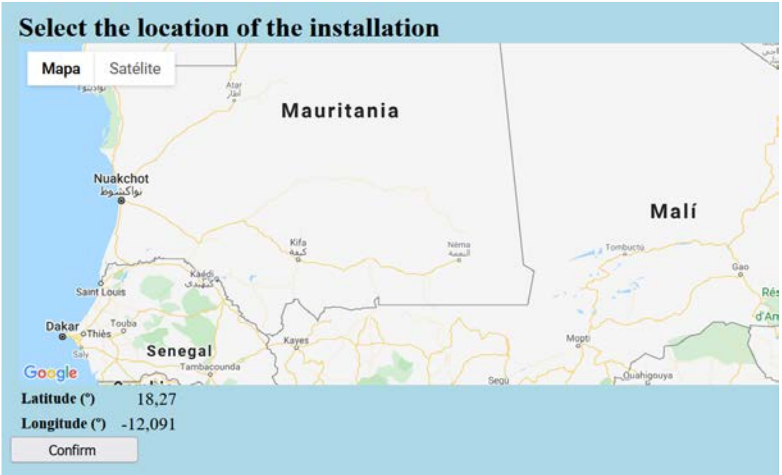
Once a key is available, enter it in the text field and click on "Save key" (you will not be asked for the next times).

If you later want to change the key, open the "Map.html" file located in the "Map" folder (which is in the program's installation directory) with the Notepad and delete the last two lines:

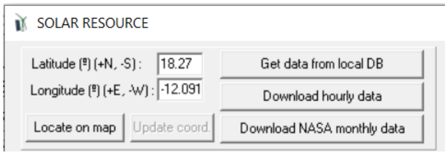


The next time you try to locate on a map, you will be prompted to enter the credential.

Then a window opens in the web browser where we must click on the location that interests us and then click on the "**Confirm**" button (see figure below).



After clicking "**Confirm**" on the web, we return to MHOGA and click on "**Update coord.**", then the latitude and longitude are updated. After that, the “Update coord.” button is disabled.



If you want to obtain new coordinates in the map, click again “Locate on map”, a new web map appears, and you must click in the new web map the new location (do not use the previous web map).

3.3.3. Download resources data.

MHOGA can download resources data (irradiation, temperature, wind speed) from:

- Monthly average data:

    -NASA POWER (https://power.larc.nasa.gov/) for a specific year

    - Local database: monthly average values of 22 years from NASA (if you have installed the database)

- Hourly data:

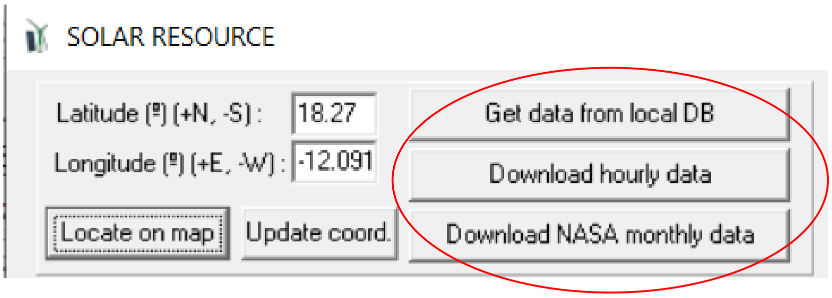
-PVGIS (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html)

-Renewable Ninja (https://www.renewables.ninja/)

- NASA (https://power.larc.nasa.gov/)

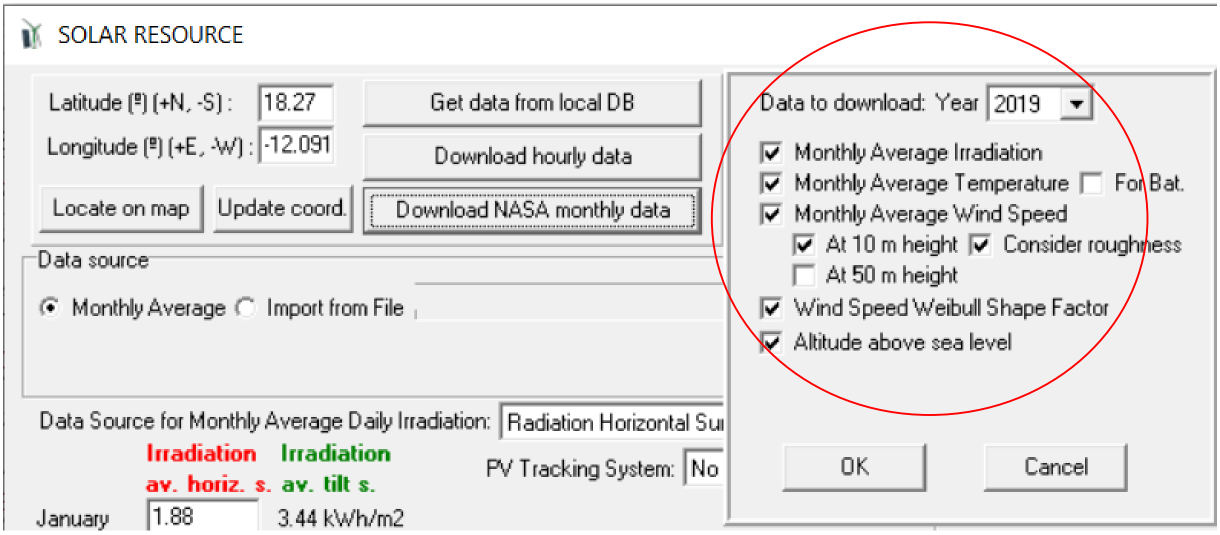
To download data, you can use the buttons:

- **Get data from local DB**
- **Download hourly data**
- **Download NASA monthly data**



3.3.3.1. NASA monthly data

Click in the "**Download NASA monthly data**" button, a small window appears where we can indicate the data that we want to download.



We must indicate the year of the data. Also we can choose the different data to download:

- Average monthly irradiation (kWh/m2) -> The data will be updated on the irradiation screen.
- Average monthly temperature (ºC) -> Data will be updated on the screens of PV generators and wind turbines, to take into account the effect of temperature on photovoltaic and wind

power generation. If "For Bat" is selected, also the downloaded temperature will be considered for the ambient temperature of the battery bank.

- Average wind speed (at 10 m, considering the roughness indicated on the wind screen, or at 50 m) -> The data will be updated on the wind screen.
- Weibull shape parameter of the wind speed (obtained by MHOGA from the wind probability at 50 m) -> The data will be updated on the wind screen. Not available since end of 2018 from NASA. Available from local database (this database can be downloaded from iHOGA / MHOGA web).
- Altitude above sea level -> The data will be updated on the screen of the wind turbines, to consider the effect of the altitude of the location in air pressure and therefore in air density.
- Days of autonomy (maximum number of days without sun in a certain period, default in 14 consecutive days). (*Only available from the local database*) -> The data will be updated in the restrictions screen (minimum number of days of autonomy) and in the main screen, in PRE-SIZING, the number of days of autonomy to predefine storage.

3.3.3.2. Local database monthly data

If NASA database fails (server error), you can use the local database of MHOGA (you must have previously installed the database by downloading from iHOGA / MHOGA web and executing the self-extracting .rar file "RESOURCES-ENG.exe", installing into the MHOGA installation folder, subfolder "RESOURCES". (Availalbe in https://ihoga.unizar.es/Desc/RESOURCES-EDU-eng.exe). To use the local database, click on the button "**Get data from local DB**".

These data were obtained from NASA website, they are 22-year average monthly data.

3.3.3.3. Hourly data

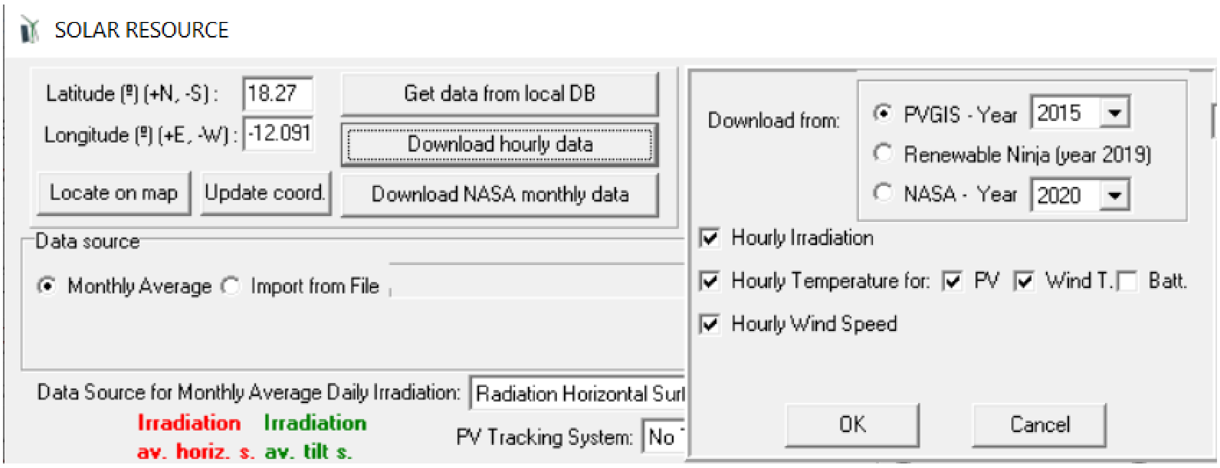
We can also download hourly resources data from:

-PVGIS (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html), years 2007 to 2015.

-Renewable Ninja (https://www.renewables.ninja/), only for year 2019.

- NASA (https://power.larc.nasa.gov/), years 1990 to 2020.

In that case we must click the button "**Download hourly data**", obtaining hourly data of a whole year.



We can download hourly data of irradiation over the tilted surface in the cases of PVGIS and Renewable Ninja or over the horizontal surface in the case of NASA (then these data will be converted to the tilted surface).

Also it can be downloaded temperature data (to be used in the PV generators window, in the wind turbines window and in the batteries window).

Wind speed can be downloaded at the height shown in the wind speed window (any height) in the case of Renewable Ninja but only at 10 m height in the case of PVGIS and 10 or 50 m height in the case of NASA.

Note that Renewable Ninja web only allows 5 downloads per day for anonymous users, and the downloads are only for year 2019 (https://www.renewables.ninja/documentation). Also note that when you download from Renewable Ninja irradiation or temperature it is counted as one download, and for wind it is counted as another one. To increase the number of downloads per day, you can install a free VPN as for example Tunnel Bear (https://www.tunnelbear.com/pricing) and, after the first 5 downloads, you can change the internet connection to another country and you will be able to continue downloading data from Renewables Ninja.

These restrictions are not for PVGIS hourly data download (no limit in the number of downloads, you can download any year data from 2007 to 2015), however there are several areas that are not covered by PVGIS (Argentina, Chile, north of Canada, Alaska, east of Rusia, east of Asia and Oceania), check in https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html.

In the case of NASA, there are no restrictions.

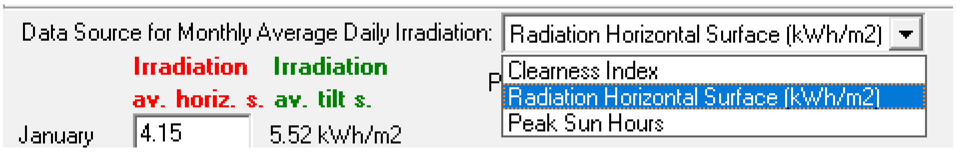
3.3.4. Data source (monthly average or import).

We can also enter the irradiation data without downloading them. In that case there are more possibilities of data formats.

The source of the irradiation data can be in the form of daily average monthly data ("Monthly Average"), or in data of a whole year, in hourly intervals or in minutes ("Import From File").

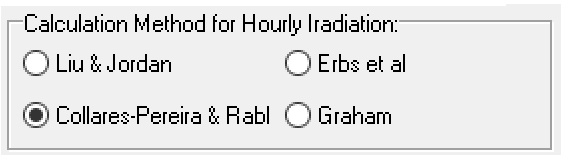
Monthly average data:

In the first case (by default), we can choose the format of the monthly average daily data in the dropdown menu:



The default format is "Radiation Horizontal Surface (kWh/m2)", being able also to be chosen "Clearness Index" or "Peak Sun Hours".

We will also choose if we want to calculate the hourly irradiance on the inclined surface by the method of Graham (1990) (Graham & Hollands, 1990), which includes statistical variability, or through the model of Liu and Jordan, 1960 (Liu & Jordan, 1960) and Hay y Davis, 1978 (Hay & Davies, 1978) and Rietveld (Rietveld, 1978), by using different correlations: Liu and Jordan (1960) (Liu & Jordan, 1960), Collares-Pereira (1979) (Collares Pereira & Rabl, 1979) and Erbs et al (1982) (Erbs et al., 1982).



Once the hourly irradiation data have been obtained, the global irradiance $G_{(t)}$ (kW/m^2) over the tilted surface of the PV generator in 1-minute steps is obtained by using a first-order autoregressive function based on the work (Aguiar & Collares-Pereira, 1992).

First global and diffuse minute irradiance data between hours ($G_{hours(t)}$ and $D_{hours(t)}$) are obtained by means of linear interpolation between hourly values. Then a first order autoregressive (AR) function ($\gamma_{(t)}$) is obtained, which is used to calculate the $G_{(t)}$, that cannot be lower than the diffuse component:

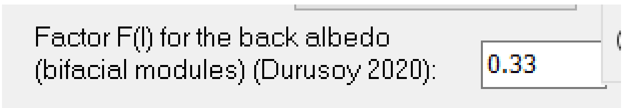
$$\gamma_{(t)} = \phi_{1G}\gamma_{(t-\Delta t)} + N\left(0, \sigma_G\sqrt{1-\phi_{1G}{}^2}\right) \qquad (1)$$

$$G_{(t)} = \max\left(D_{hours(t)}, G_{hours(t)}\left(1 + \gamma_{(t)}\right)\right) \qquad (2)$$

Where ϕ_{1G} is the correlation factor, σ_G is the standard deviation and *N(a, b)* is a random number following normal distribution with mean *a* and standard deviation *b*.

MHOGA calculates the direct normal irradiation over the tilted surface. It will be needed if we consider concentrating PV generators (CPV).

MHOGA calculates the irradiation over the back surface of the PV modules (in the case we use bifacial PV modules, it will be needed), using the methodology shown in (Durusoy et al., 2020), expanded to any azimuth and tracking method. The factor F(l) that multiplies the albedo irradiation over the back surface must be set in the software:

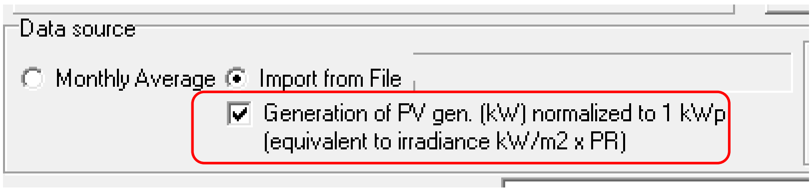


Data from file:

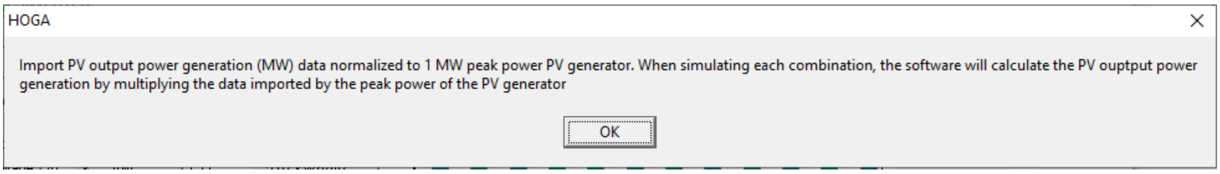
In the case of “**Import from File**” data, we can choose among three format files:

- Hours (horiz. surf. or Tilt surf., depending on the selection in the right  , in kWh/m2): The file must have irradiation values in kWh/ m^2 (that is, irradiance in kW/m^2) and must be ordered in rows, one row for each hour, starting January 1st at 0h. There will be 8760 rows (sorted by date and time, i.e. the first row will be the irradiation on horizontal surface in kWh/m^2 from January 1 from 0 to 1h, the second row the value of January 1 from 1 to 2 h ... all in solar time). Clicking on "Import" appears a dialog where we will specify where the file is. Decimal spacing must be dot, not comma.
- Minutes – each hour in 1 row (tilt, in kW/m^2): There will be 8760 rows (one for each hour), each row will have a number N of columns, one per time step (default time step is 1 minute, therefore N = 60 columns, but it can be changed in the combobox ). The irradiance data for each minute will be for the tilted surface, in kW/m^2.
- Minutes- 1 per row (tilt surf. in kW/m^2): There will be 8760 x N rows (one for each time step of each hour, default time step is 1 minute therefore N=60, but it can be changed in the combobox ). The irradiance data for each time step will be for the tilted surface, in kW/m^2.

If in the "**Import from file**" we select the option "**Generation of PV gen (kW) normalized to 1 kWp**":



A message appears:

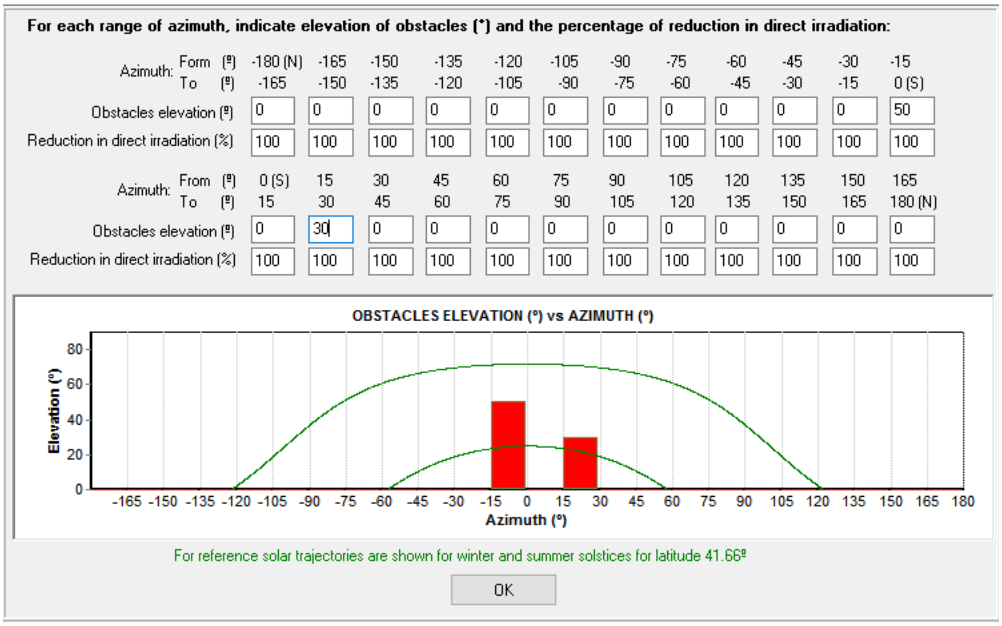


Therefore, in that case we must import form a file (same format as for the irradiation explained before) the output power of a PV generator normalized to 1 MWp. For example, if we have the output power of a PV generator of 100 MWp, these values must be divided by 100 and then we obtain the output normalized to 1 MWp (which, in fact, is the irradiance in kW/m2 multiplied by the performance ratio, that is, including all the losses). Then, this file (in hourly, minutes, 10-minutes… steps) can be imported. Later, when the software is simulating different combinations and optimizing the system, the output power of a specific PV generator of X MWp will be calculated as the imported data multiplied by X.

3.3.5. Shadows button

Shadows must be defined before downloading or calculating the irradiation.

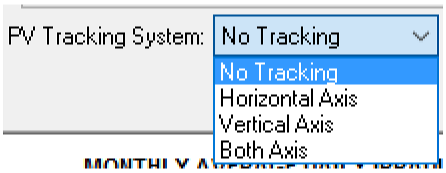
By clicking on the SHADOWS button, a box appears where we can define the elevation of the obstacles (º) vs. the azimuth (º), as well as the reduction factor of the direct radiation (% the obstacles covers the sun, default 100%). In the example two obstacles have been added, one of 50° elevation between azimuth -15° and 0 (southeast) and another one of 30° elevation between azimuth 15 and 30° (southwest). As a reference the solar path curves are shown in the solstices (all solar paths will be between the two ones shown).



Click "OK" to accept the obstacles.

3.3.6. Solar tracking

The user must select the method applied for sun-tracking. The default value is "No Tracking".



If there is no solar tracking system, or only horizontal axis tracking, the **azimuth** of the photovoltaic modules must be specified (orientation towards the south: in the northern hemisphere the optimum is 0º, that is, facing south; Southern hemisphere the optimum is 180º, that is, facing north, the azimuth is positive towards the west, negative towards the east).

If there is no solar tracking system, or only vertical axis tracking, the **panel slope** must be set up.

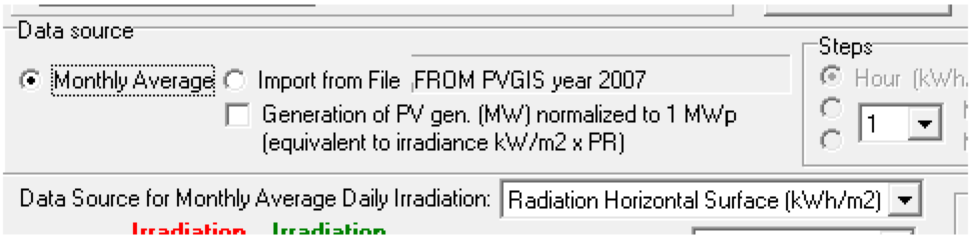
3.3.7. Optimal slope

The optimal slope (to maximize global irradiation) of zone 1 of the PV generator is shown after clicking the button "**Optimal slope#1**".

<u>Note that it can only work if you have the following data:</u>

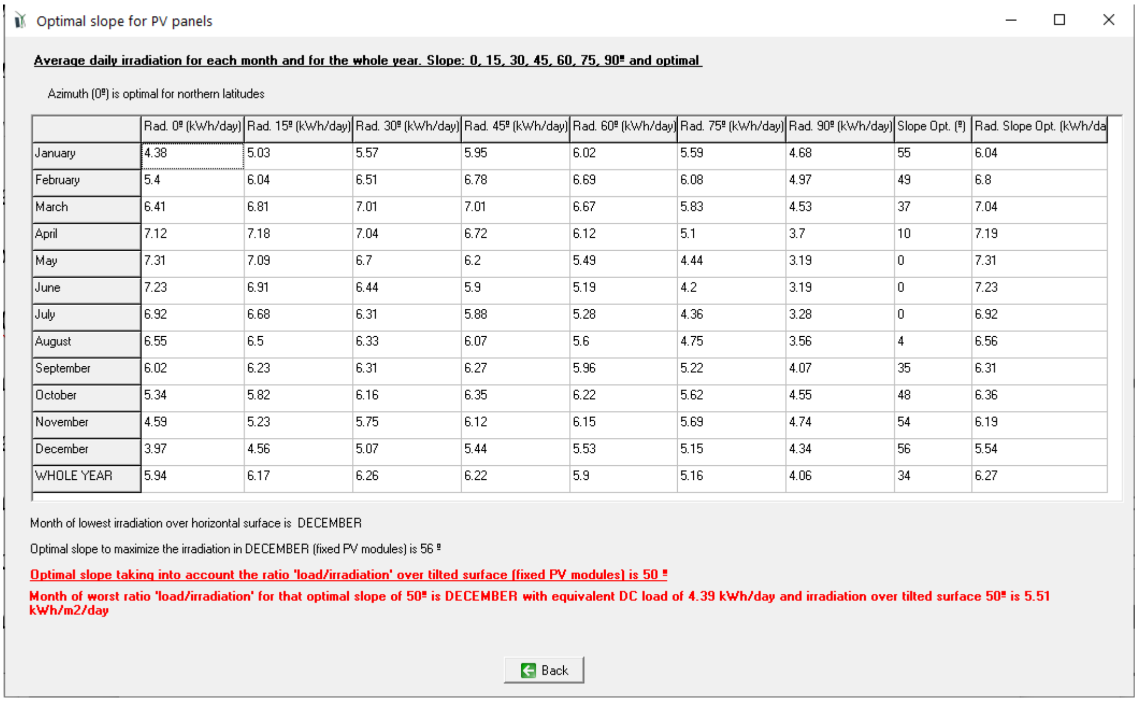
- <u>Monthly average data</u>
- <u>Montly data downloaded from NASA</u>

- <u>Hourly data downloaded from PVGIS, Renewables Ninja or NASA only if #1 PV panels slope is 0º and the whole PV is #1 (100%, as default)</u>. In that case, after downloading irradiation at slope 0º, you must click in "Monthly Average" for the data source, this way the monthly average of the downloaded data horizontal irradiation is considered. Make sure that the data source for monthly average daily irradiation is "Radiation Horizontal Surface (kWh/m2)". Then you can click in the button "**Optimal slope #1**".



- <u>Data imported from file, only if #1 PV panels slope is 0º and 100%</u> Same procedure as with the web downloaded data shown above.

After a time (even 1 minute, please, be patient), the screen shown below is shown.



	Rad. 0º (kWh/day)	Rad. 15º (kWh/day)	Rad. 30º (kWh/day)	Rad. 45º (kWh/day)	Rad. 60º (kWh/day)	Rad. 75º (kWh/day)	Rad. 90º (kWh/day)	Slope Opt. (º)	Rad. Slope Opt. (kWh/da
January	4.38	5.03	5.57	5.95	6.02	5.59	4.68	55	6.04
February	5.4	6.04	6.51	6.78	6.69	6.08	4.97	49	6.8
March	6.41	6.81	7.01	7.01	6.67	5.83	4.53	37	7.04
April	7.12	7.18	7.04	6.72	6.12	5.1	3.7	10	7.19
May	7.31	7.09	6.7	6.2	5.49	4.44	3.19	0	7.31
June	7.23	6.91	6.44	5.9	5.19	4.2	3.19	0	7.23
July	6.92	6.68	6.31	5.88	5.28	4.36	3.28	0	6.92
August	6.55	6.5	6.33	6.07	5.6	4.75	3.56	4	6.56
September	6.02	6.23	6.31	6.27	5.96	5.22	4.07	35	6.31
October	5.34	5.82	6.16	6.35	6.22	5.62	4.55	48	6.36
November	4.59	5.23	5.75	6.12	6.15	5.69	4.74	54	6.19
December	3.97	4.56	5.07	5.44	5.53	5.15	4.34	56	5.54
WHOLE YEAR	5.94	6.17	6.26	6.22	5.9	5.16	4.06	34	6.27

On some occasions, the progress bar stops and it seems that the program does not respond, be patient and wait until the screen shown below appears. If the screen does not appear, but the main screen of the program appears, click on the MHOGA icon in the Windows taskbar (lower part of the computer screen) and the screen shown below will appear.

Irradiation for slope 0, 15, 30, 45, 60, 75 and 90º and for the optimal slope is shown for every month and for the whole year.

MHOGA calculates the optimum angle for each month, reporting the optimum slope to maximize production in the month of lower irradiance (in the example, in Spain, December). It also calculates the optimum inclination considering not only the irradiation, but also the load consumption of each month, giving the ratio load/irradiation for each tilt angle between 0 and 90°. The optimum tilt angle will be the value so that the annual minimum ratio load/irradiation is maximized. (This only makes sense if the slope of the modules will be fixed or tracking system is only using vertical axis. If the tracking system is by using horizontal or both axes, the tilt of the modules is changing during the day.)

If the azimuth we have indicated in the screen is not optimal (0º for northern hemisphere and 180º for the southern hemisphere), a text appears in the top of the screen showing the warning. If load is about the same throughout the year, it will choose the optimum angle for the month of lower irradiance on a horizontal surface. However, if the system is only used in a period of year, for example in summer, we will have to choose the optimum inclination for this period (for example, in the case of the figure, if load consumption was only in summer, choose the angle of about 25 or 30º slope).

3.3.8. Optimize PV modules slope during the optimization of the system

If the checkbox "**Optimize PV modules slope during the optimization of the system**" is checked, the slope of the PV modules will be a variable to be optimized, like the number of modules, panel type, etc.

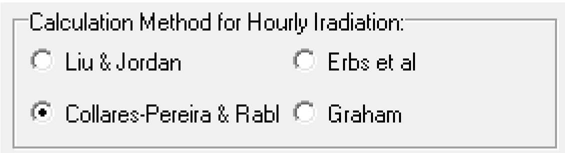
<u>This option will only work if the time step of the simulation is 1 h. The whole PV generator must be #1 (100%, as default). Also, same limitations for the data source as for "Optimal slope#1" button (see above).</u>

This option is interesting for the hybrid systems which include PV array and also available wind turbines or hydro turbine, which electrical production is not stable throughout the year (as usual). In many of these cases the optimum slope will not be the same as if it were a photovoltaic-only system, and a priori it is difficult to know. For example, in a photovoltaic-wind power installed in Spain, if wind production is higher in winter, it is possible that the optimum inclination of the modules is not the usual slope for photovoltaic systems where production is maximized in the month of lower irradiance (December, with optimum inclination around 60°), but it is possible that the PV slope will be the value to maximize production in another month when the wind speed is lower.

Also interesting is the option to optimize the slope together with the system in cases where load is distributed throughout the year and during the day in an unusual way, for example, consumption of irrigation pumps that operate only in summer, only during morning or afternoon hours in the day. In such cases, a priori, it is difficult to know the optimal slope for the photovoltaic modules that feed these pumps, so we can let the software try different slopes and seek the optimal.

The possible slopes to consider in the optimization are between 0 and 90 ° in 10 ° intervals.
It is recommended that, when you use this option, set to 0 the correlation factor and the standard deviation for the variability of the irradiation in minutes step.

Also, do not use the Graham method for the calculation of hourly irradiation (because this method introduces random variability).



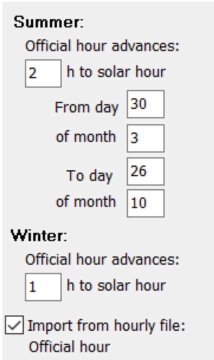
This way, when you open a project where the PV slope optimization has done, the results will not change, as the irradiation obtained for the different slopes (which will be calculated again when the project opens will be the same.

After clicking "**Optimize PV modules slope during the optimization of the system**" checkbox, the software calculates the hourly irradiation for all the slope cases (from 0 to 90º). <u>You mustn't click **"Calculate**" button after that.</u>

The irradiation curve for each case (0 to 90º) can be seen by selecting the slope and then clicking in "Graph in steps of" button in the top bottom of the window (note that only hour time steps are allowed, as minutes are not considered in the case of optimizing the PV slope).

3.3.9. Official hour change

User must select (right of the screen) the official hour change (winter – summer):



The irradiation will be converted to official hour (in the simulation, everything is in official hour).

If the box "Import from hourly file: Official hour" is selected, if you import the irradiation from a file, you must ensure that the irradiation data of the file is in official hour. If it is not selected, when you import irradiation from a file, it must be in solar hour.

3.3.10. Force some consecutive cloudy days

Several consecutive cloudy days can be forced in a given month, so that in those days there will only be diffuse irradiation.

3.3.11. Minute irradiation variability

MHOGA will calculate the hourly irradiation (in case of having the average monthly data) and then the irradiation for each minute. To calculate the irradiation values for each minute, MHOGA uses a first-order autoregressive function model based on the one used by the Meteonorm software (*Meteonorm. Global meteorological database. Handbook part II: Theory. Version 7.1*, 2015), needing to define the correlation factor and the standard deviation:

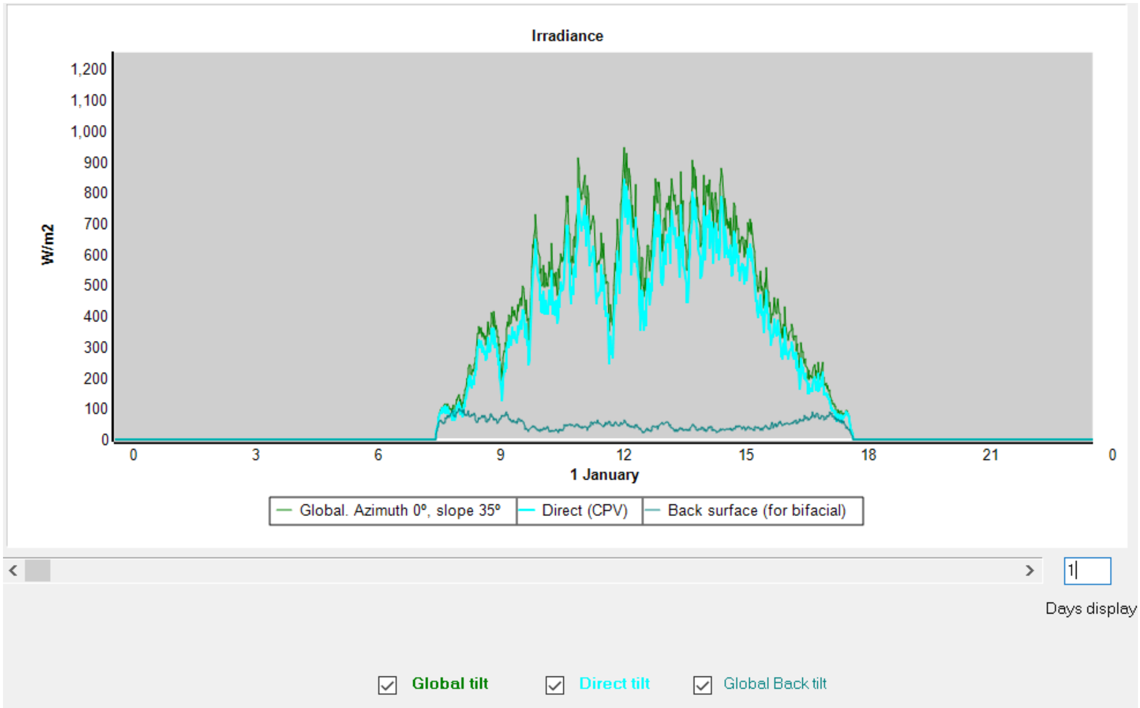
3.3.12. Calculate button

If using **monthly average data** (except for the case of **Optimize PV modules slope during the optimization of the system**, in that case you mustn't click "Calculate" button**)**, once all data are introduced, click on "**Calculate**". The application will generate minute and hourly irradiation values on the plane of the PV modules. Calculated data will be displayed under the chart, referring to daily average hourly irradiation and yearly total values, all of these related to a horizontal surface and to the tilted plane of the PV array. Also back irradiation (for bifacial PV generator) and direct irradiation (for CPV) over the tilt surface are shown.
If you want to consider bifacial PV modules, you need to do that first (use monthly average values and calculate, obtaining the irradiation over the back surface). Then you can download or import hourly values, and the back surface irradiation will remain.

3.3.13. Graph

By clicking on the "**Graph in steps of**" … minutes button we can see the graph of global irradiation on the inclined surface in the temporary steps we defined (between 1 and 60 minutes) that the program has calculated, in thick green line. Also, if monthly average data has been used, and therefore the back irradiation of the PV modules has been calculated (for bifacial PV), it is shown in teal colour. And the direct irradiation over the tilt surface (for CPV) is shown in blue. If we choose the display in time steps of 1 hour, the irradiation on horizontal surface (red) is also displayed.

If we have used the data source "From file" and the hours of advance of the official time regarding the solar are not entered correctly, erroneous results can appear, that are visualized in the graph if in the first or last hours of some days the irradiation on inclined surface is exaggeratedly large (several thousand W/m^2). In that case, modify the hours of advance of the official time with respect to the solar until coherent results appear.



3.3.14. Import hourly irradiation over the back surface or direct irradiation (tilt surface)

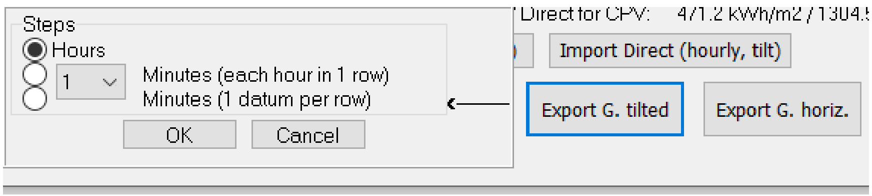
In the lower zone of the screen, there are two buttons:

To import **hourly** irradiation over the **tilted** surface:

- Global irradiation over the back surface of the PV modules (for bifacial PV).
- Direct irradiation over the surface of the PV modules (for CPV).

3.3.15. Export global irradiation

We can export the global irradiation data that MHOGA calculated, using the buttons "**Export G. tilted**" or "**Export G. horiz**".



The first one exports the global irradiation on the tilted surface of the modules, in the form of hourly values or in different time steps values (default 1 minute time step), in the number columns of time steps of 1 hour in each row or 1 datum per row. The second exports the hourly values of irradiation on horizontal surface.

If we want to use the irradiation data to be imported in the Sensitivity Analysis (section 4.8), we must export the irradiation hourly values on the tilted surface of the modules, in hourly format.

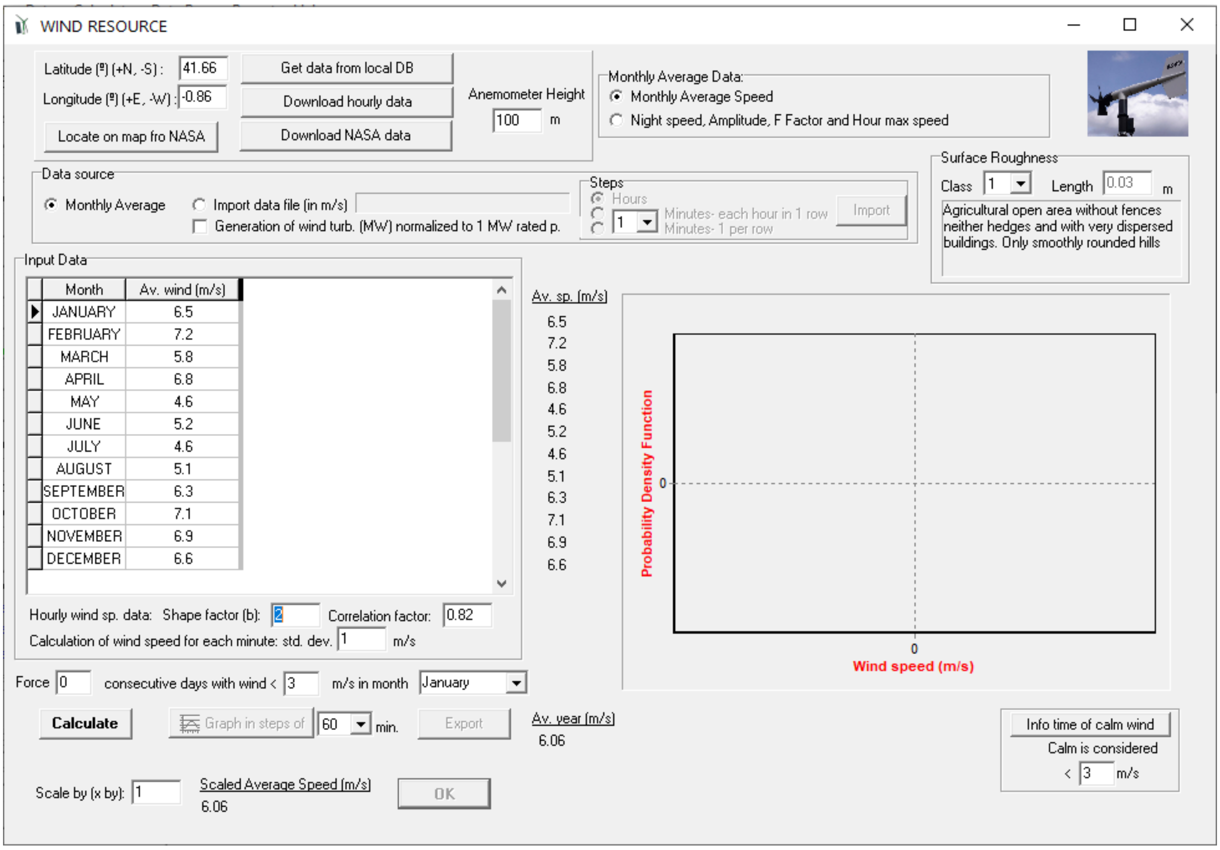
3.3.16. Scale factor

A **scale factor** for the hourly irradiation can be defined (default 1). The hourly and minutes irradiation over tilted surface will be multiplied by the scale factor when we click the “OK” button, the result will be used by MHOGA to calculate the generation of the PV modules.

Finally, clicking on the "**OK**" button we return to the main screen of the program.

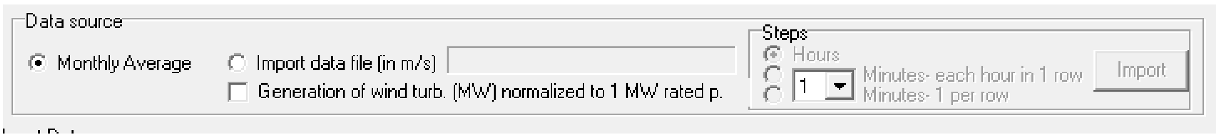
3.4 Wind resource

The Wind resource screen may be accessed by clicking on "WIND" (Resources area), or selecting "Wind" in the Data menu.



Data Source:

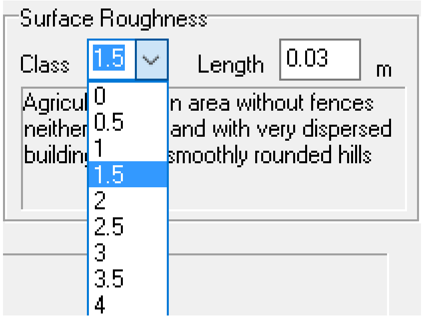
In some cases, it may be difficult to know or estimate wind data for the site where the system will be installed. Two options are available for **Data Source**: "Monthly Average", or "Import Data File". The best choice will always be a file with hourly or minute values, however this is sometimes difficult to obtain, in this case an estimation will be necessary for average monthly values.



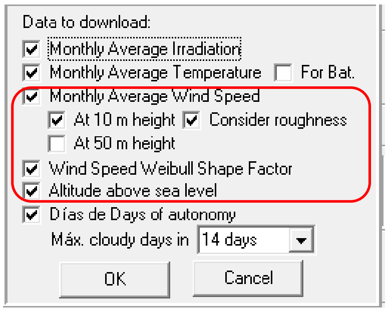
Download wind data:

As in the case of irradiation, you can import the average monthly data from the NASA website (and also the Weibull form parameter) using the button "**Download NASA Monthly data**" (if NASA database fails, click button "**Get data from local DB**" to use local database), of hourly data using the button "**Download hourly data**". Previously, you must have set the latitude and longitude or have been obtained on the web map (see previous section Irradiation).

You must also indicate the type of terrain (roughness), selecting the class in the dropdown menu:

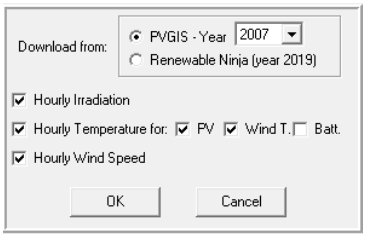


When downloading from the NASA (button "**Download NASA monthly data**"), you can select only wind speed or other parameters, as shown in the irradiation section before. Wind speed Weibull shape factor is necessary to the accurate calculation of hourly wind speed, and altitude above sea level is necessary if we want to consider the fact that wind turbines output power depends on the air density and therefore on the altitude.



Monthly average wind speed can be downloaded at 10 m height (considering or not roughness for the download data) or at 50 m height. After downloading NASA average wind speed, the value of the anemometer height is updated to 10 or 50 m, depending on the downloaded data.

You can also download hourly data from Renewables Ninja (at any height) of from PVGIS (data only for 10 m height), clicking in the button "**Download hourly data**". _Before downloading the data from Renewables Ninja, you must indicate the anemometer height_.



Anemomenter height:

In the case of downloading data from NASA web, the height of the measurement will be placed automatically when downloading (10 or 50 m). In the case of downloading data from PVGIS, the height of 10 m will be shown. In the case of downloading data from Renewables Ninja, before downloading you must indicate the anemometer height, as this database can download hourly data at any height.

In the case of using average monthly data or in case of import a file, the height at which the wind data has been measured must be indicated, since if the wind turbine hub can be at a different height the program must convert the measured data at the hub height.

The software uses the following equation (log law) to convert the wind speed w at the anemometer height (z_{anem}) to the wind speed w_{hub} at the hub height of the wind turbine (z_{hub}), considering the roughness length z_0.

$$w_{hub(t)} = w_{(t)} \cdot \frac{\ln \frac{z_{hub}}{z_0}}{\ln \frac{z_{anem}}{z_0}}$$

Scale factor:

It is also necessary to define the scale factor (lower left), default 1. It is the factor by which the hourly and minutes wind is multiplied, not to be confused with the scale factor of the Weibull distribution.

Data from file:

If we have hourly data (m/s) or even minutes or other time step data, we will introduce them from the file:

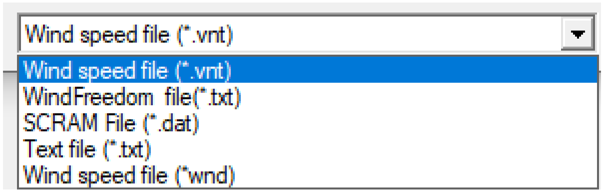
We must choose the file type:

- Hours: 8760 rows of hourly values.
- X Minutes – each hour in 1 row: 8760 rows of N tab separated values, where N is 60/X, for example if X= 1 minute is chosen as time step, as default, N = 60/1 = 60 tab separated values must be in each row, each value corresponding to the wind speed of 1 minute.
- X Minutes – 1 per row: 8760xN rows of values of the wind of each time step.

In the file, decimal spacing must be dot, not comma.

After selecting the data type, by means of the "**Import**" button we select the file to be imported.

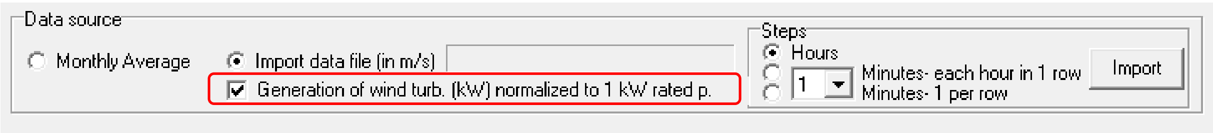
In case the file of hourly values, there are five types of files that can be selected:



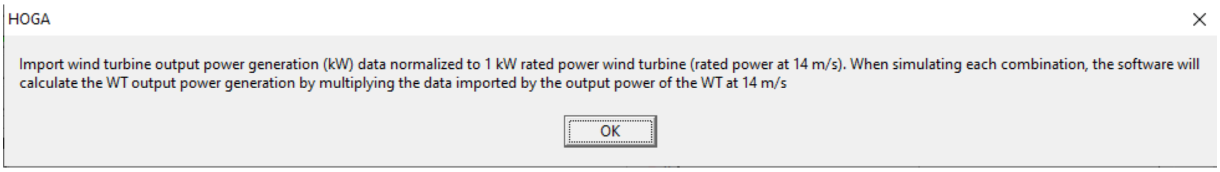
- Files * .vnt: These files are text files generated by the software, the height of the measurement is stored in the first row and in the rest is the sequence of wind speed hour values.
- Files obtained through Windfreedom software, * .txt files: These files are obtained using the free Windfreedom software, with which you can get wind data from many weather stations in the world (downloadable from the website of Joaquin Mur http://www.windygrid.org/software/#page=page1). The wind data for 1 full year must be downloaded using Windfreedom, starting at 0:00 am on January 1st and ending at 24:00 on December 31. This .txt file can be opened directly by MHOGA.
- *.dat files (SCRAM files): These files are available on the US EPA website.
- *.txt or *.wnd files: these files refer to text files containing the 8760 wind speed hourly data (one per line) in m/s, starting with January 1, 0 hour.

When importing the file data, the probability density function (PDF) of imported wind speed is plotted, and below is the value of the shape factor of the Weibull distribution that best fits the imported data.

If in the "Import from file" we select the option "**Generation of wind turb. (kW) normalized to 1 MW rated p.**":



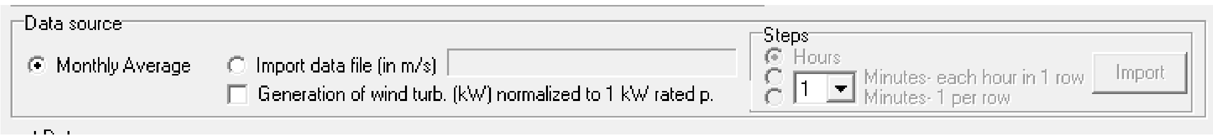
A showmessage appears:



Therefore, in that case we must import form a file (same format as for the wind speed explained before) the output power of a wind turbine or group of wind turbines, normalized to 1 MW of rated power. For example, if we have the output power of a wind turbine of 2 MW or rated power (we consider rated power the output power at 14 m/s), these values must be divided by 2 and then we obtain the output normalized to 1 MW of rated power. Then, this file (in hourly, minutes, 10-minutes… steps) can be imported. Later, when the software is simulating different combinations and optimizing the system, the output power of a specific wind turbine of X MW rated power (rated power the output power at 14 m/s), will be calculated as the imported data multiplied by X.

Monthly average values:

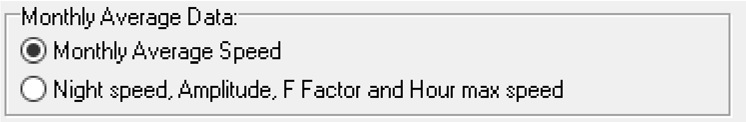
If we do not have the hourly or minutes wind data, we can synthetically generate this from monthly average data.



Monthly values can be:

- Monthly Average Speed Values

- Monthly Average Nigtht speed, Amplitude, F Factor and Hour Max. Speed.

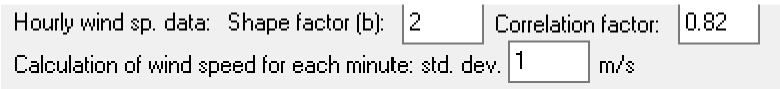


Force some consecutive days with low winds:

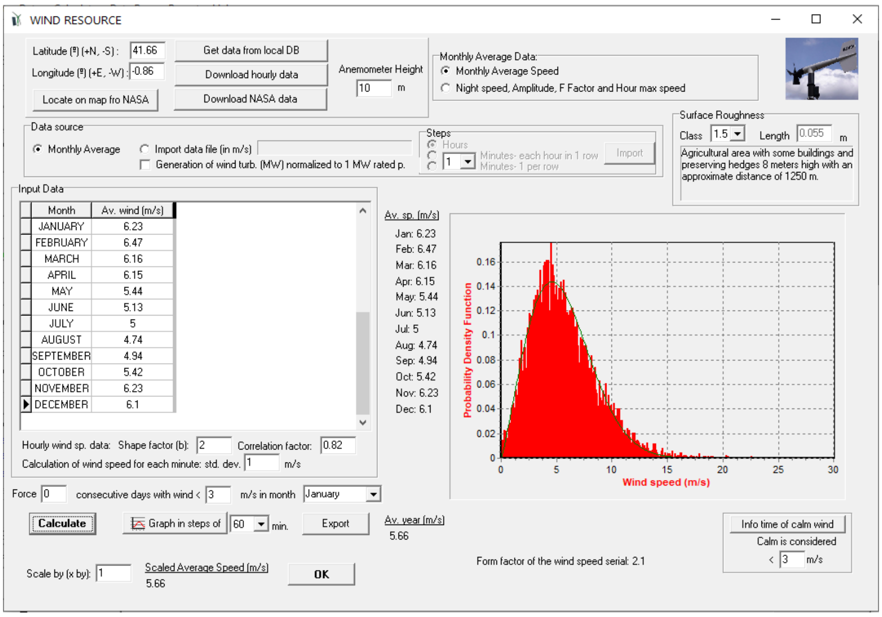
In both cases of monthly average values, a number of consecutive days with low wind in a specified month (or randomly) can be forced (default 0 days).

Monthly Average Speed data:

When “Monthly Average Speed” option is selected, Weibull shape factor and correlation factor are required (under the table of the wind data). Also a correlation factor and standard deviation for the calculation of wind speed for each minute must be set.



When pressing “**Calculate**” button, the software calculates the hourly and minutes wind speed (it takes some seconds).

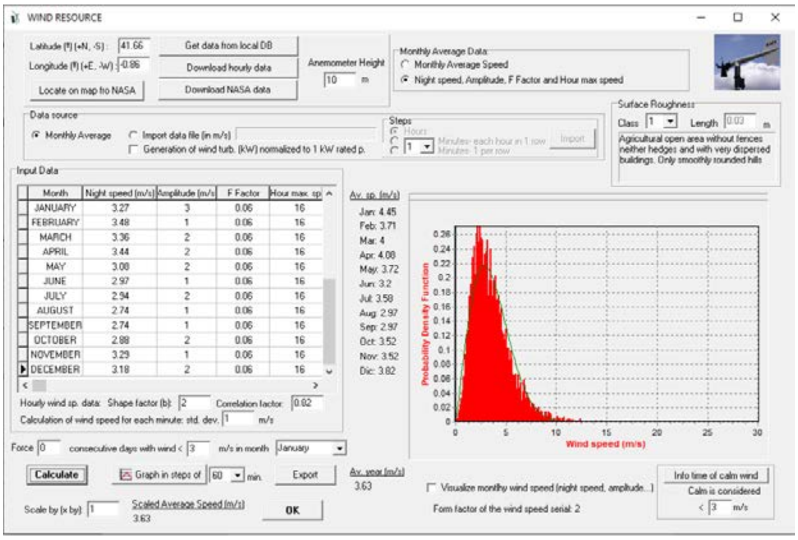


The hourly values (8760 values in m/s) are calculated from the monthly average data, the shape factor (Weibull distribution) and the correlation factor according to the method presented in (Rodolfo Dufo-López & Bernal-Agustín, 2012).

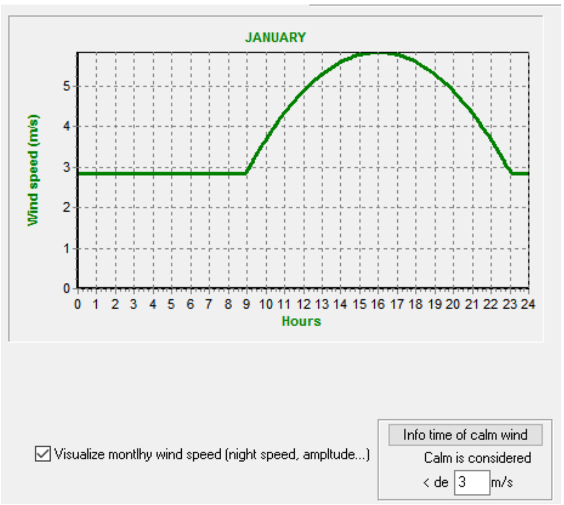
The minute data are then obtained using a first order autoregressive function model using the same correlation factor and the standard deviation within each hour indicated in its box. In the right-hand part of the screen, the probability density function (PDF) of that wind speed range (red color distribution), as well as the PDF Weibull distribution curve (green curve) for the Weibull shape factor that best fits the distribution generated, value shown below the graph.

Night speed, Amplitude, F Factor and Hour max speed data:

Using this option (Gregory, Peterson, Lee, & Wilson, 1994)(Rivas-Ascaso, 2004), the following information is required for the table: Night Speed monthly values (m/s), Amplitude (m/s), F Factor, and the Hour of Maximum Speed, together with the value of the Shape Factor and of the Correlation Factor. Clicking on "Calculate" gives the wind time series as explained in (Rodolfo Dufo-López & Bernal-Agustín, 2012) (it will take a few seconds).



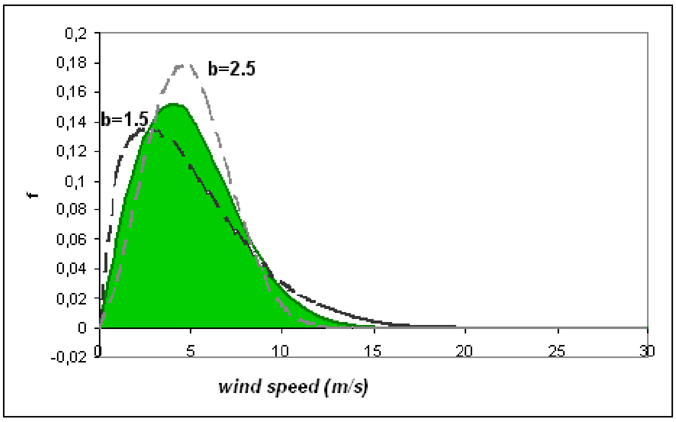
If "Visualize monthly wind speed (night speed, amplitude)" checkbox (bottom, right) is checked, the chart to the right shows the wind profile (m/s) vs. the time of the day for the month selected in the table.



A description is provided below for the parameters mentioned above (Rivas-Ascaso, 2004).

Form Factor

Variations in wind speeds for a given site are usually described using Weibull's probability function. This function is in turn determined by its mean (using also the scale factor), and by its Form Factor. Once the average speed is known for a site, the probability distribution may be deduced for different wind speeds, using the value of this Form Factor. The figure below displays the probability density function (f) for a site with an average windspeed of 5 m/s, and a Form Factor (b) of 2. The dashed line corresponds to the distributions for the same average speed, but with Form Factors of 1.5 and 2.5. Hence, lower b values correspond to wider distributions, as shown below.



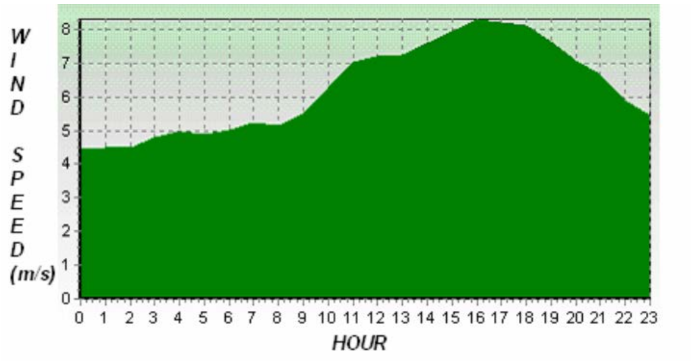
Autocorrelation Factor

This factor is an indicator of the randomness of wind speeds. High values of this parameter show that wind speeds for a given time of the day are largely dependent upon wind speeds for the preceeding time interval. Lower values indicate a more random variation of wind speeds, with a lesser autocorrelation between time of the day and speed readings. This parameter is directly influenced by local land topography. Autocorrelation factors are usually lower for complex local topographic conditions, and higher for more uniform ground.

These two parameters are generic, i.e. applicable to a full year, whereas the parameters described below change every month.

Night Speed (m/s):

This indicates the average wind speed at night for a given month. Wind speeds are higher during daytime for most locations in our planet, since temperature differences between landmasses and oceans are higher during that period. Besides, more turbulences and changes in the direction of the wind are present during daytime. The chart below shows average wind speeds, measured at 1-hour intervals in January for an inland region in China.



The curve may be modelled according to the time at which maximum speed is recorded, so that wind speeds may be higher at night or in the morning.

Amplitude (m/s):

This is the difference between the night speed and the maximum hourly speed.

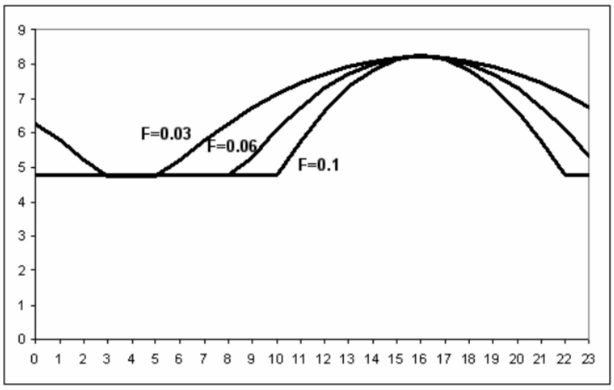
Hour of Maximum Speed

The time of the day when the maximum speed is recorded.

F Factor

This is inversely proportional to the number of sun hours, and directly proportional to the average speed. This parameter provides an indication of the dependency of wind speeds upon the time of the day at which speeds are measured.

Higher F values correspond to narrower variations, centered around the time at which maximum speed occurs, thus with a larger degree of dependency on the time of the day.

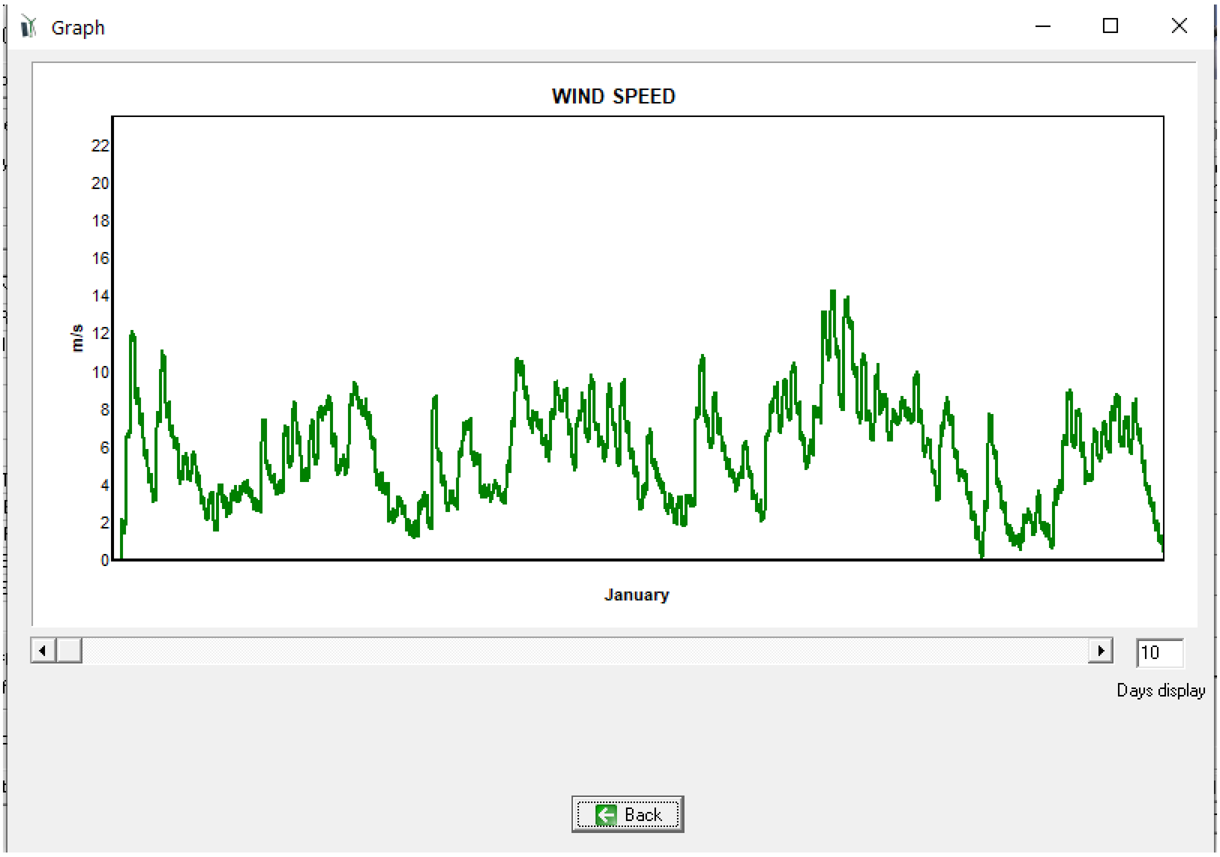


"Export" button:

Click on "Export" button to export hourly or or different time steps values (default 1 minute time step), in the number columns of time steps of 1 hour in each row or 1 datum per row.

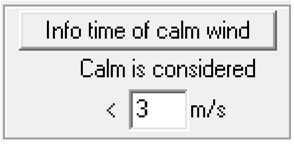
"Graph in steps of" button:

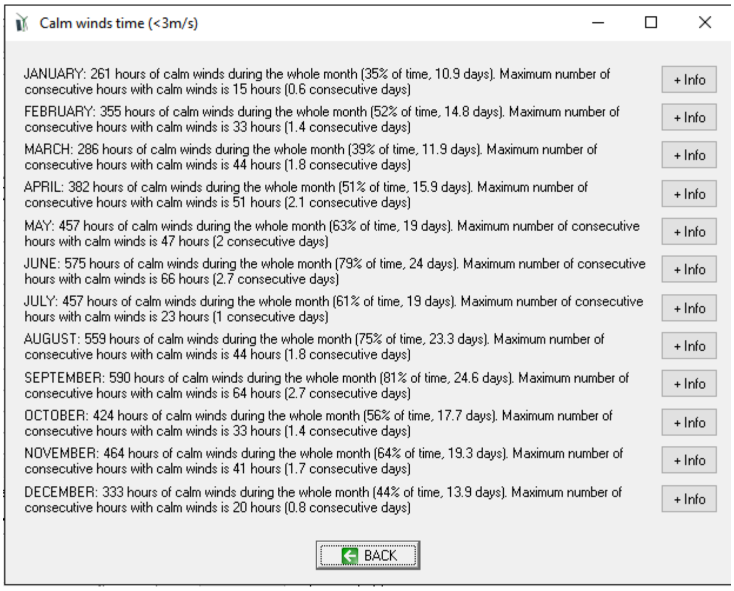
By clicking on "**Graph in steps of"…** minutes we can see the wind speed during the whole year in the steps defined.



Info time of calm wind:

Click "**Info time of calm wind**" to see the information about calmness (low wind speed periods) for each month.

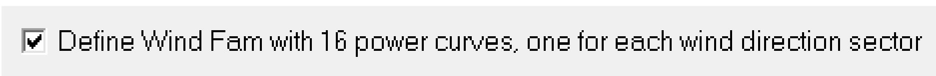




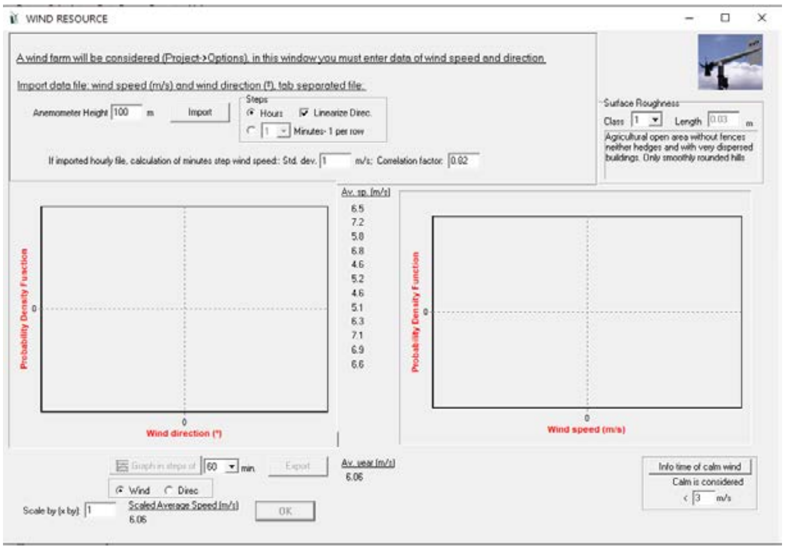
More info can be seen clicking the button "+Info" for each month.

Case of wind farm with 16 power curves, one for each wind direction sector, defined in the main options of the software:

If, in the main window of the software, in the menu Project->OPTIONS, we have defined Wind Farm with 16 power curves, one for each wind direction sector:

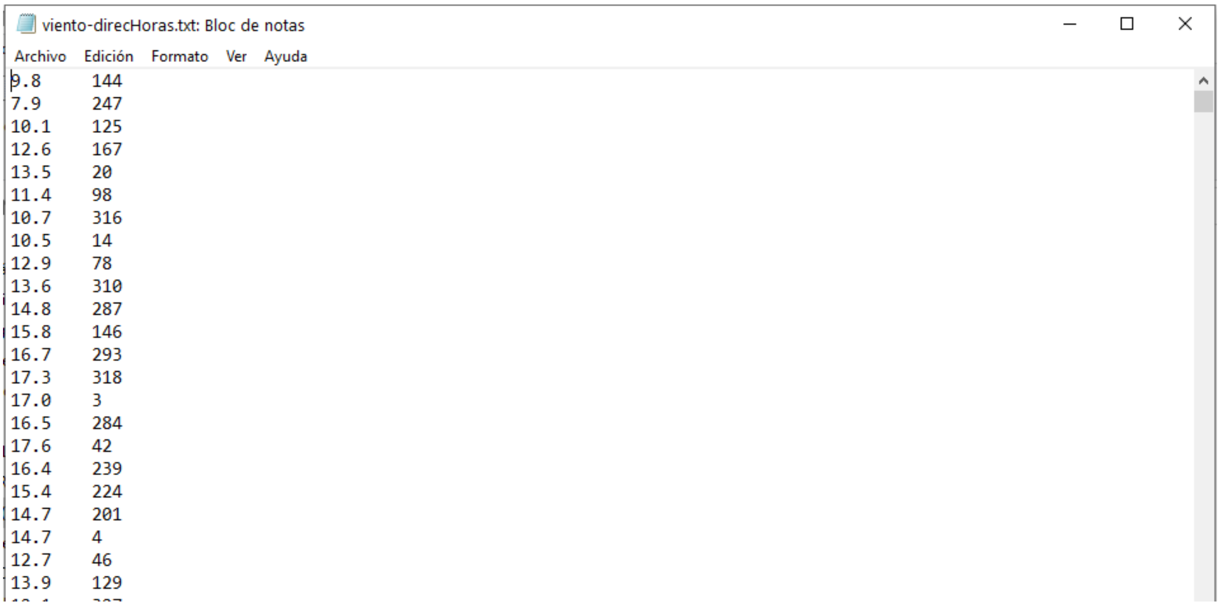


In that case, in the wind resource window, we must import wind speed and direction (see next figure).



You must import the data of the whole year, from a file in hourly or minutes steps, where the first column must be the wind speed (m/s) of each time step at the height set in Anemometer Height (default 100 m) and the second column (tab separated) with the wind direction (º) of each time step.

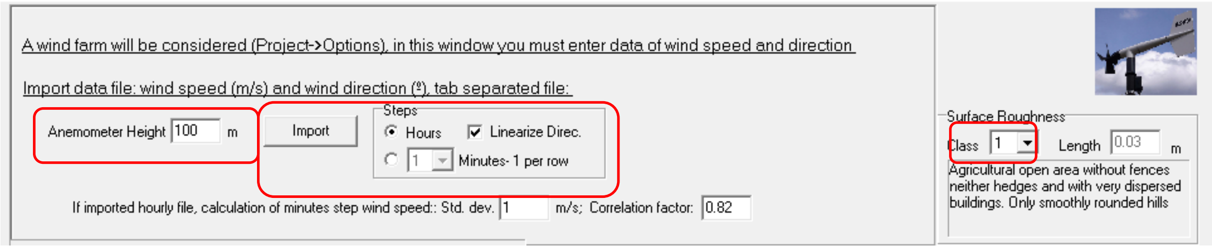
Next figure shows an example of the file in hourly time steps (8760 rows with two columns, first column wind speed in m/s and second column wind direction in º). *Remember, decimal spacing must be dot (.).*


viento-direcHoras.txt: Bloc de notas

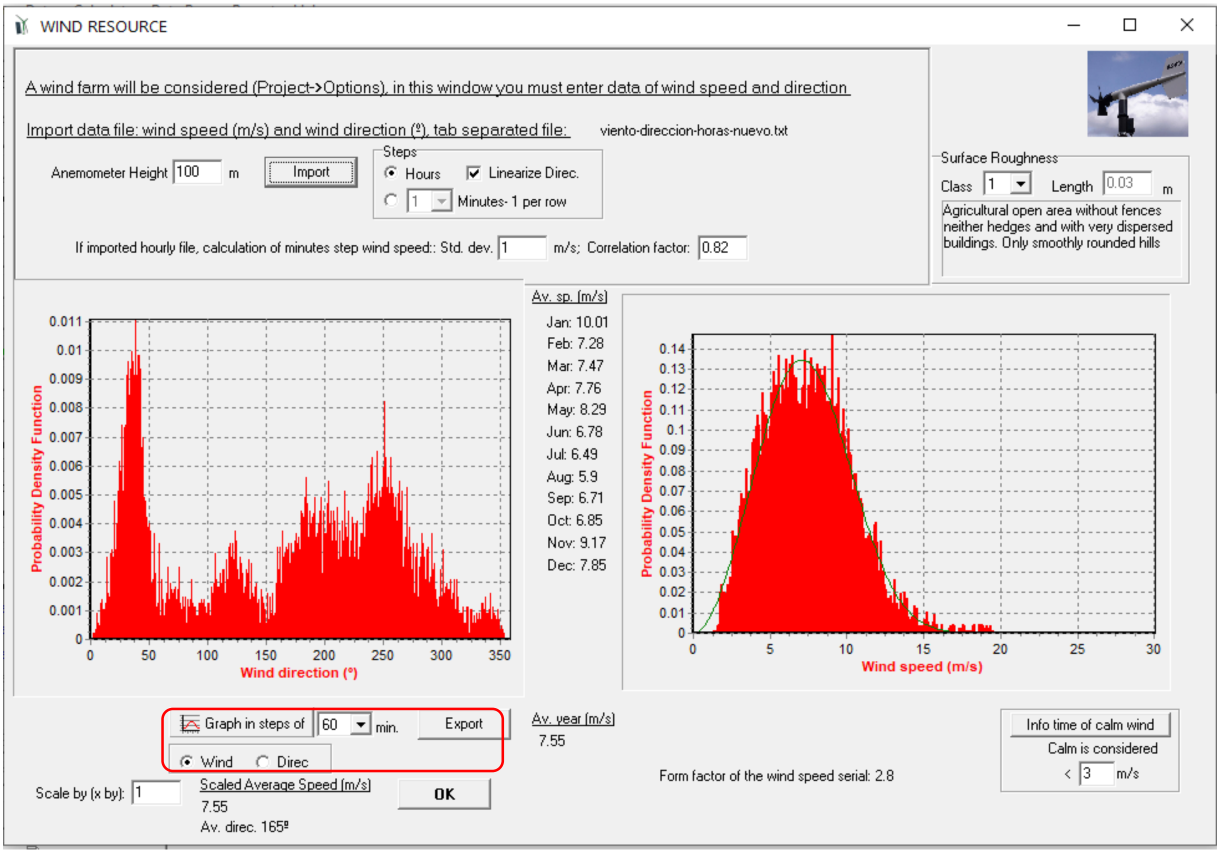
Archivo Edición Formato Ver Ayuda

```
9.8	144
7.9	247
10.1	125
12.6	167
13.5	20
11.4	98
10.7	316
10.5	14
12.9	78
13.6	310
14.8	287
15.8	146
16.7	293
17.3	318
17.0	3
16.5	284
17.6	42
16.4	239
15.4	224
14.7	201
14.7	4
12.7	46
13.9	129
```

Surface roughness must also be defined, in the case the anemometer height is different to the hub height of the wind turbines.



After importing the data, wind speed PDF is shown in the right graph and wind direction PDF is shown in the left graph.

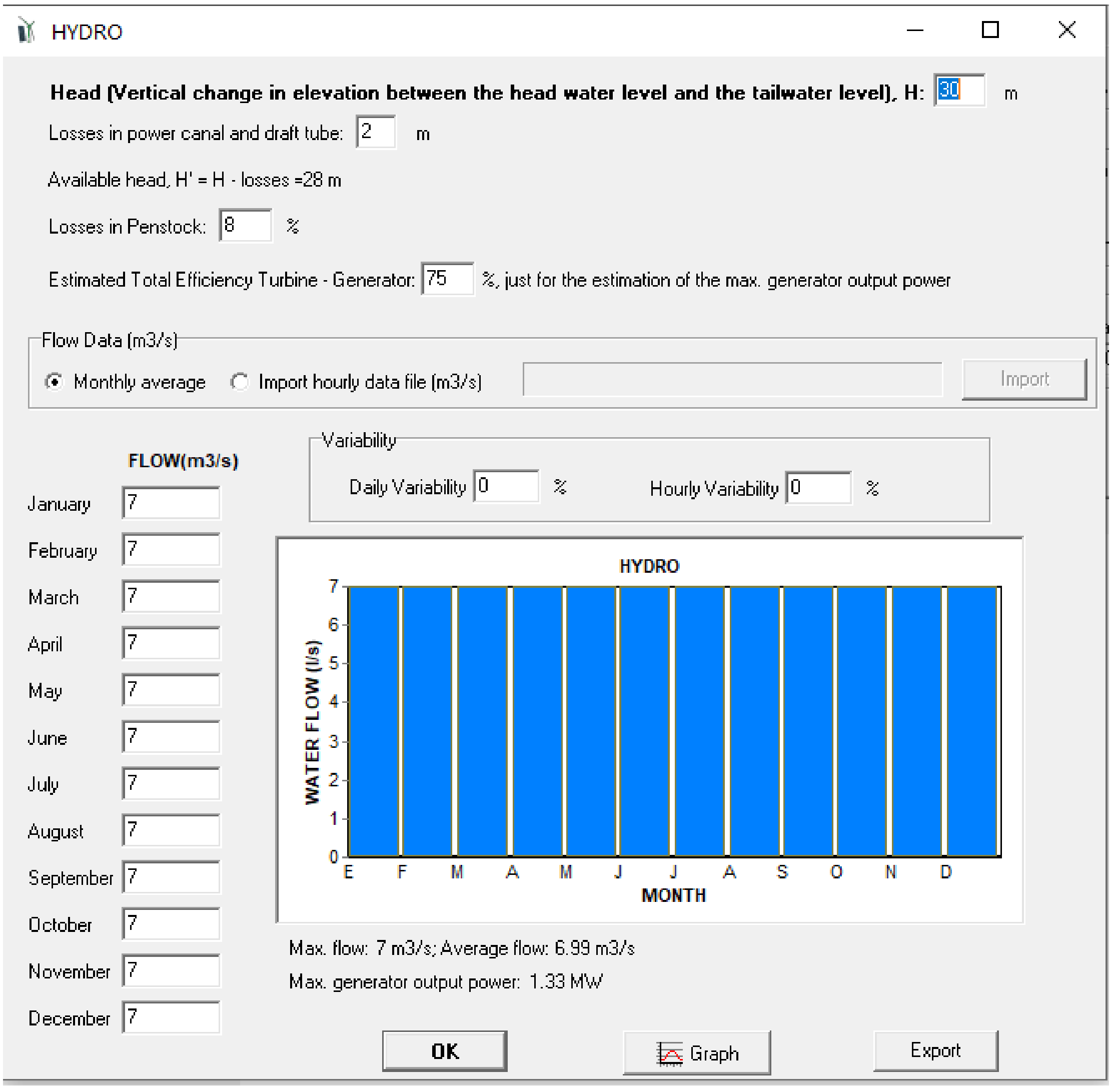


After downloading the data, you can see the graph of the wind speed or of the wind direction, by selecting "Wind" or "Direc" under the graph button. Also you can export wind speed or wind direction, depending on the selection.

Click on "OK" to return to the main screen.

3.5 Hydraulic resource

The Hydraulic resource screen may be accessed by clicking on "Hydro" (Resources area), or selecting "Hydro" in the Data menu.



The following data must be introduced:

- Total Head, H, the difference in elevation between the head water level and the tailwater level, expressed in m.
- Pressure losses in the power canal and draft tube, in m.

MHOGA uses the data described above to calculate the Available Head, H', which indicates the difference between the two.

The value of losses is needed for the penstock water mains (penstock) and for the turbine, in order to obtain the Net Head, H''. Data must be introduced separately for losses in the penstock, and on turbine-generator performance. The latter is used by the application to provide an estimate for the maximum power available for any given waterfall, based on head and flow. Data on turbine-generator performance will not be used for hourly calculations of energy produced by the turbine, since more accurate performance data will be utilized when turbine data is available in the hydro turbine screen.

Data Sources for the flow (expressed in m^3/s), can be in Monthly Average data or an Imported Hourly Data File.

In the first case (Monthly Averages) the user must introduce values for each month on the left side of the screen. These values will be displayed in the chart, with additional indicators for maximum and average flow, and maximum power available from the waterfall, calculated as follows: P_{max} (MW) = 9.81 · H'' (m) · Q_{max} (m^3/s) · η_{mains} · $\eta_{turb\text{-}gen}$ /1000.

Data must also be introduced on daily and hourly flow variability (as a percentage).

The chart and the information displayed will be updated whenever changes are introduced for any of the data described above.

Click on "Draw" to display a chart for hourly flow throughout the year. Click on "Export" to save hourly flow values as calculated by MHOGA.

Click on "OK" to return to the main screen.

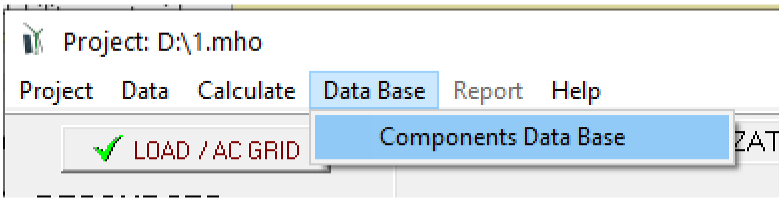
3.6 Data bases

MHOGA includes a comprehensive database of components that can be incorporated into the screens of the components. The components contained in the databases can be used in the optimization or not, the databases are just storages of commercial or generic components. Later, when defining the different components used in the optimization, the user may incorporate some of the components of the database, if the user wants it.

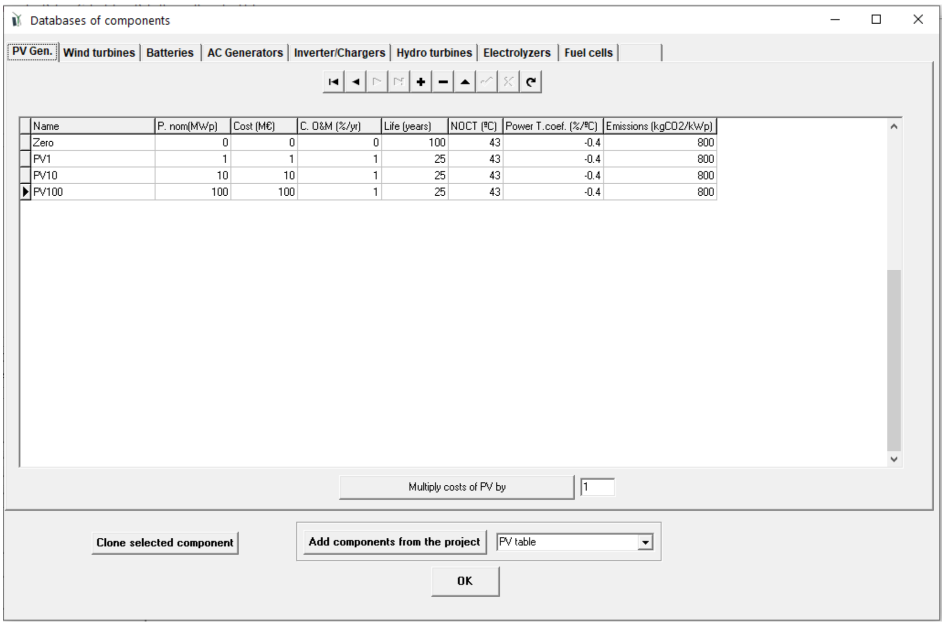
In the databases the user can edit, add or remove components.

<u>Access to databases:</u>

At the top of the main screen you can access the menu "**Data Base**".



Then, clicking on "**Components Data Base**" MHOGA shows the database of the components. The components are in tables, each type in a tab.

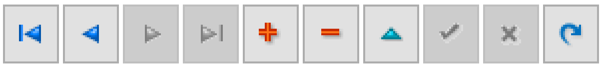


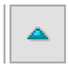
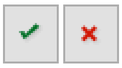
<u>Component "Zero":</u>

In each table there is a component called "Zero", to be able to take into account the non existence of this component.

Edit, add or remove components of the database:

You can edit, add and remove components of the database, using the browser buttons table at the top:



To access the table at a certain box of a component, click on it with your mouse. Once inside the table, we can pass from one to the other boxes using the arrow keys on the computer keyboard. We can also move through the ranks with the table browser. This browser can also add (+) or delete (-) rows. Also, when we edit any box (changing its value), we can click on it twice, so the number moves to the left side of the box, and appears with a blue background, or by clicking on . When a cell is being edited, the components  are enabled in the browser. The first serves to validate, while the second is used to cancel editing and restore the previous value. If we do not press anything, when we finish editing it is automatically validated.

Arrange by families:

Components "PV Gen", "Wind Turbines" and "Batteries" can be arranged by families, because, in this way, then you can import entire families when you define the components used in the optimization. For MHOGA to understand that a component belongs to a family, first should be the name of the family, then ":" and then, after a space, the name of the component.

Multiply the costs:

For each table, costs of all components of the table can be multiplied, by a factor defined, if pressing button "Multiply costs of .... by factor"

Calculate battery cycles vs. DOD:

In the batteries table tab, there is a button "Calculate Cycles vs DOD from the value at 80%", clicking in this button the values of cycles to failure vs. depth of discharge (DOD) of the battery selected are calculated from the value at 80% DOD. That is, the input necessary is the cycles to failure at 80% DOD (usually provided by the manufacturer) and the rest are obtained from this value, considering that the overall energy the battery can cycle during its lifetime is the same for any DOD.

Clone the selected component:

A component can be cloned and later changed some characteristics. To clone a component, select it in its table and click the button "Clone selected component" in the lower left corner. At the end of the table a new component will be added, exactly the same as the one cloned but with the name added "-C". Then you can change any of its characteristics, including the name.

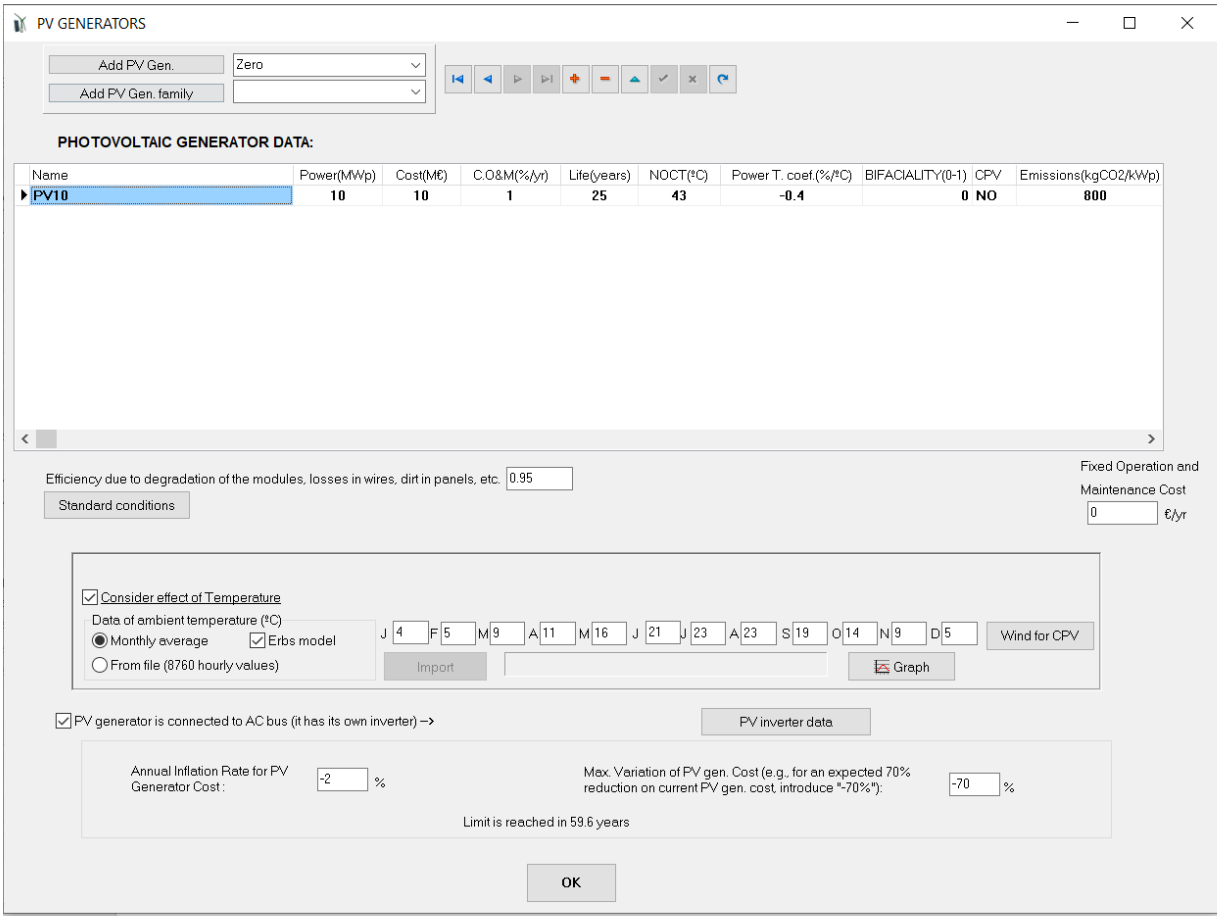
Add components used in the project:

Components used in the component screens, once defined as shown below, can be added to the database tables, pressing the button "Add components from the project".

3.7 Photovoltaic generator

The photovoltaic generators screen may be accessed by clicking on "PV GEN." (Components area), or by selecting "PV gen." in the Data menu.

The software allows the user to modify, eliminate, or add PV generators of different size to be considered in the optimization.



By default there is a single PV generator, which can be modified or deleted, or you can add other ones.

PV generator data:

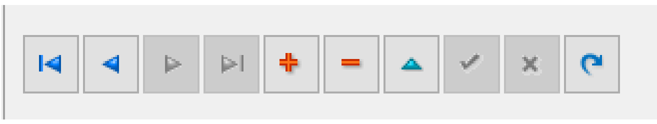
Each PV generator that will be considered in the optimization is parameterized in a line of the table. The parameters are:

- Name
- Peak nominal power under standard test conditions (STC), Pn (MWp)
- The acquisition cost or CAPEX (M€), including all the costs related to the PV generator (mounting structure, tracking system, etc.) and including its inverter.

- The unit cost of operation and maintenance (O&M or OPEX) (cost per photovoltaic generator, apart from the fixed cost, in % of the acquisition cost per year)
- Expected life (usually 25 years)
- NOCT (normal operating temperature of the cell, in °C).
- Coefficient of variation of the power with the temperature, Ct (%/ºC).
- BIFACIALITY (0-1): in bifacial PV modules, it is the ratio of the nominal efficiency at the rear side, with respect to the nominal efficiency of the front side, that is, the ratio of the rear power with respect to the front power of the PV module, measured under standard test conditions. If PV modules are normal, it is 0. If they are bifacial, it is a number higher than 0 (typically > 0.6). In bifacial modules, the peak nominal power under STC Pn (Wp) set in the table must be the values for the front surface.
- CPV: if the PV generator is the type "Concentrating PV", it must be "OK", if not "NO". CPV converts only direct irradiation in electricity.
- Emissions of CO_2 in manufacturing, transport and recycling (kg CO_2 equivalent per kWp of power, depending on modules technology, the country's electrical mix where it was manufactured, transport distance, etc., is usually between 700 and 1500 kgCO_2 / kWp). This value is only necessary if we want to calculate the life cycle emissions of the system.

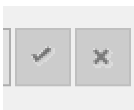
<u>Navigation toolbar:</u>

The user may click on any table cell to edit the contents, move through the table using the arrow keys on the keyboard, and the table navigation toolbar (see figure below), or use this bar to Add or to Remove cells.



To edit cells, use the button shown below or double click on the cell.

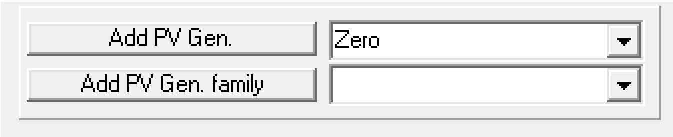
When the user edits a cell, the components shown in the image below are enabled:



Clicking on the first symbol validates all changes to the cell, whereas clicking on the second one cancels all changes. When nothing is selected, any changes to the cell will be automatically validated.

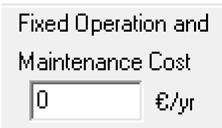
Add PV generators from database:

PV generators can be added from the database: individually or a whole family, by selecting the generator from the drop-down menu and clicking the button "Add PV gen." or by selecting the family and adding it by clicking in the lower button.



The added components from the databases cannot be modified. To modify them, it must be done in the database. However, if you add a component of the database and you rename it (changing its name in the table), then you may change the rest of its data.

Fixed Operation and Maintenance (O&M) cost:



Additional data must be introduced for fixed operating and maintenance (O&M) costs (€/yr). These costs are independent of the number and the type of the PV generators selected by the software during the optimizations. Fixed operator cost and costs for maintenance material are included, regardless of the size of the generator.

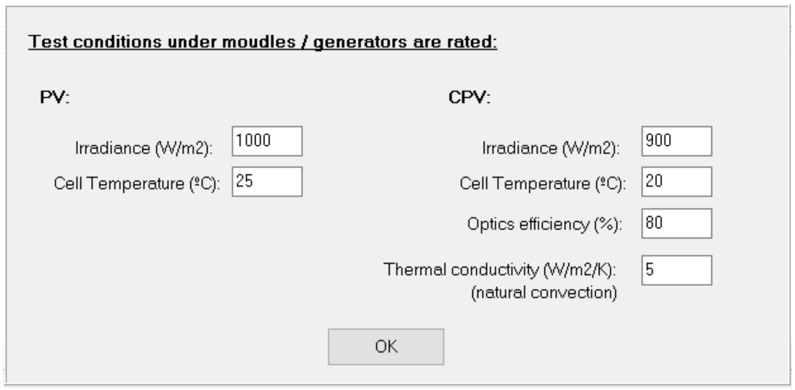
The total cost for operation and maintenance of the whole PV generator will be the fixed costs plus the individual cost of PV generator multiplied by the number of PV generators in parallel.

Standard conditions

By clicking in the button "Standard conditions" a small window appears, where we must set the standard conditions under the modules or generators were tested.

For PV, the global irradiance (*Gref*) and cell temperature (*Tc_ref*) must be set (default STC, irradiance 1000 W/m^2 and cell temperature 25ºC).

For CPV, direct irradiance (*Bref*) and cell temperature (*Tc_ref*) (default direct irradiance 900 W/m^2 and cell temperature 20ºC); and also the optics efficiency η_{opt} (default 80%) and the thermal conductivity in natural convection μ (default 5 W/m^2/K) must be defined so that the cell temperature can be calculated for each time step, knowing the direct irradiance and the wind speed.



Efficiency due to degradation, wires, dirt…:

During the simulation, the program calculates the power generated by the photovoltaic modules at each time interval as a function of or peak power. However, a efficiency (*Eff*) must be applied which takes into account degradation of the modules, losses in wires, dirt in modules, that is, the de-rating factor. If you have selected in the main options of the software the multi-period optimization, this efficiency must not consdier the degradation of the modules, as this will be considered in the simulation during the years.

Output power:

PV generator:

It is assumed that the inverter includes MPPT, so at each instant the PV generator generate the maximum possible power, depending on the irradiance. The PV power is calculated as follows, if the effect of the ambient temperature is not taken into account:

$$P(t)=Pn*G(t)/Gref*Ngen\_parallel*Eff$$

Where *Pn* is the nominal power (peak power, MWp) of the PV generator, *G(t)* is the global irradiance over the tilted surface of the PV generator, in kW/m^2, *Gref* (kW/m^2) is the global irradiance under the PV were tested and *Ngen_parallel* is the number of PV generators in parallel.

If the PV generator is bifacial, the power generated in the rear surface $P_{back}(t)$ will be added to the power generated by the front surface:

$$P_{back}(t)=Pn*Bif*G_{back}(t)/Gref*Ngen\_parallel*Eff$$

Where *Bif* is the bifaciality (0-1) and $G_{back}(t)$ is the global irradiance over the back surface of the PV generator (kW/m^2).

CPV generator:

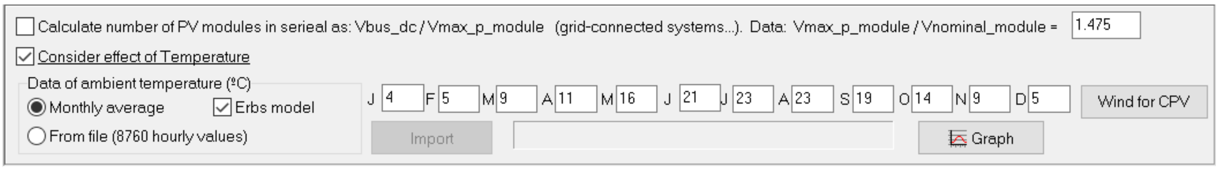
If the effect of temperature is not considered, the CPV output power depends on the direct irradiation over the surface of the CPV, *B*(t), in kW/m^2:

$$P(t)=Pn*B(t)/Bref*Ngen\_parallel*Eff$$

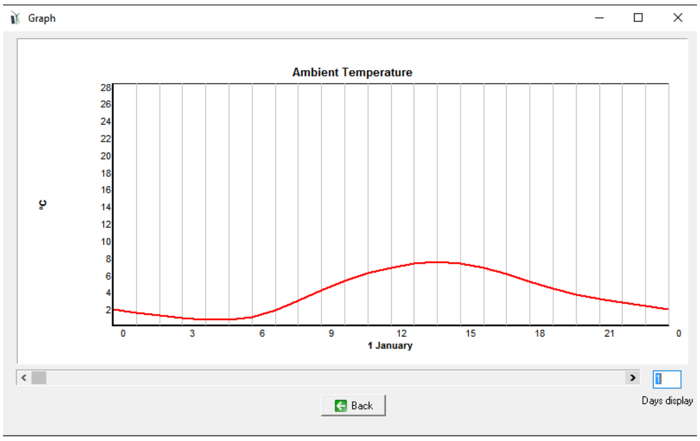
Where *Bref* (kW/m^2) is the direct irradiance under the CPV were tested.

Efect of ambient temperature:

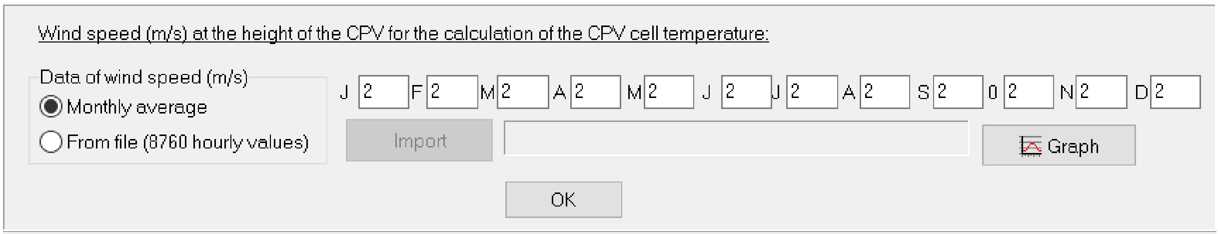
The effect of ambient temperature Tamb (°C) can be taken into account by checking the box “Consider effect of Temperature” (checked by default) and entering monthly average data or by importing data from file (8760 values) or importing hourly data from PVGIS or Renewables Ninja (when downloading data from the irradiation or wind speed windows).



If average monthly data are entered and the "**Erbs model**" box is checked, the temperature of each hour is calculated according to the model proposed by Erbs et al. 1983 (Erbs et al., 1983). (Figure below) using irradiation data (you must have previously calculated the hourly irradiation on its screen).



By clicking the button "Wind for CPV" a small window appears where we can set the wind speed at the height of the CPV which will be used to calculate the CPV cell temperature. Monthly average values or hourly values from file can be used:



PV generator:

Considering the effect of temperature, the internal cell temperature Tc for PV is calculated by:

$$Tc(t)=Tamb(t)+G(t)*(NOCT-20)/0.8;$$

Where *Tamb(t)* is the ambient temperature of the PV modules (°C) and *NOCT* is the (normal operating temperature of the cell (°C).

After calculating the internal temperature of the cell, the power generated by the PV generator is calculated by:

$$P(t)=Pn*G(t)/Gref*(1+Ct/100*(Tc(t)-Tc\_ref))*Ngen\_parallel*Eff$$

Where *Ct* is the Power Temperature coefficient (%/ºC) and *Tc_ref* the cell temperature under the conditions the PV were tested.

If the PV generator is bifacial, the power generated in the rear surface $P_{back}(t)$ will be added to the power generated by the front surface:

$$P_{back}(t)=Pn*Bif*G_{back}(t)/Gref*(1+Ct/100*(Tc(t)-Tc\_ref))*Ngen\_parallel*Eff$$

CPV generator:

Considering the effect of temperature, the internal cell temperature Tc for CPV is calculated by (Leloux, Lorenzo, García-Domingo, Aguilera, & Gueymard, 2014):

$$Tc(t)=Tamb(t) + B(t)*1000*\eta_{opt}*0.75/\mu(t) + 5$$

Where η_{opt} is the optics efficiency and $\mu(t)$ is function of the coolant, of the exchange surface, and of the wind speed (Ws).

$$\mu(t) = \mu + 2.5*ws(t)$$

where μ is the thermal conductivity in natural convection and *ws*(t) the wind speed at the height of the CPV.

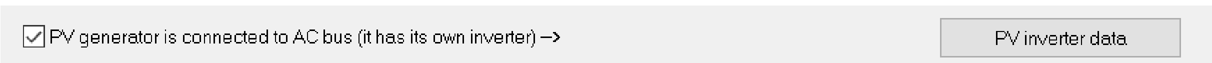
After calculating the internal temperature of the cell, the power generated by the CPV generator is calculated by:

$$P(t)=Pn*B(t)/Bref*(1+Ct/100*(Tc(t)-Tc\_ref))*Ngen\_parallel*Eff$$

Where *Ct* is the CPV Power Temperature coefficient (%/ºC) and *Tc_ref* the cell temperature of the conditions the CPV were tested.

PV generator connected to AC bus (by default):

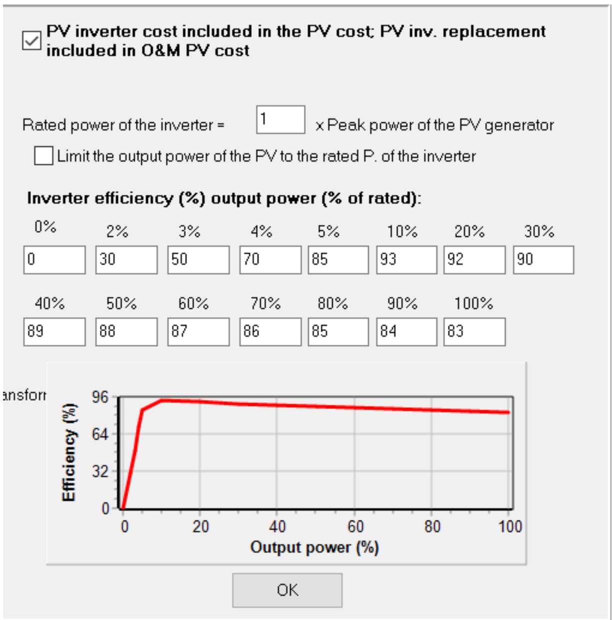
By default, the PV generator is connected to the AC bus (by means of its own grid inverter) as the following checkbox is selected:



If not selected, PV generator will be connected to the DC bus.

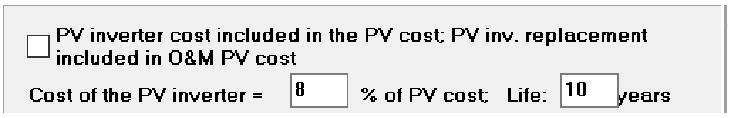
PV inverter data:

The PV generator is connected to the AC bus by its own inverter. The data of the own inverter of the photovoltaic generator are shown with the button "**PV inverter data**":



By default, the cost of the inverter must be included in the photovoltaic generator.

If you uncheck the box "**PV inverter cost included in the PV cost;…**", the following appears:

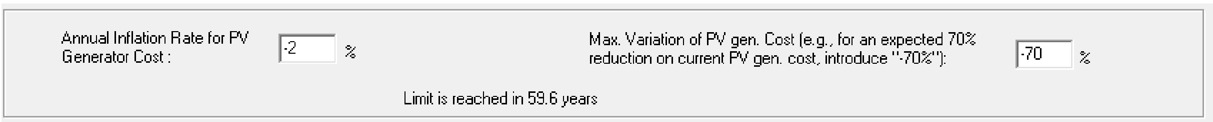


Where you must set the cost of the PV inverter (in % of the PV cost set in the table of the PV) and the PV inverter lifetime (in years). In this case, the total CAPEX of the PV system (including the inverter) will be the cost of the PV (of the table) plus the percentage set here; the inverter replacement (by default, every 10 years) will be added to the OPEX cost of the PV.

The ratio between the power of the inverter and that of the photovoltaic generator (inverse of the inverter load ratio ILR) must be indicated, in addition to the efficiency versus the percentage of the nominal power.

PV generator price inflation:

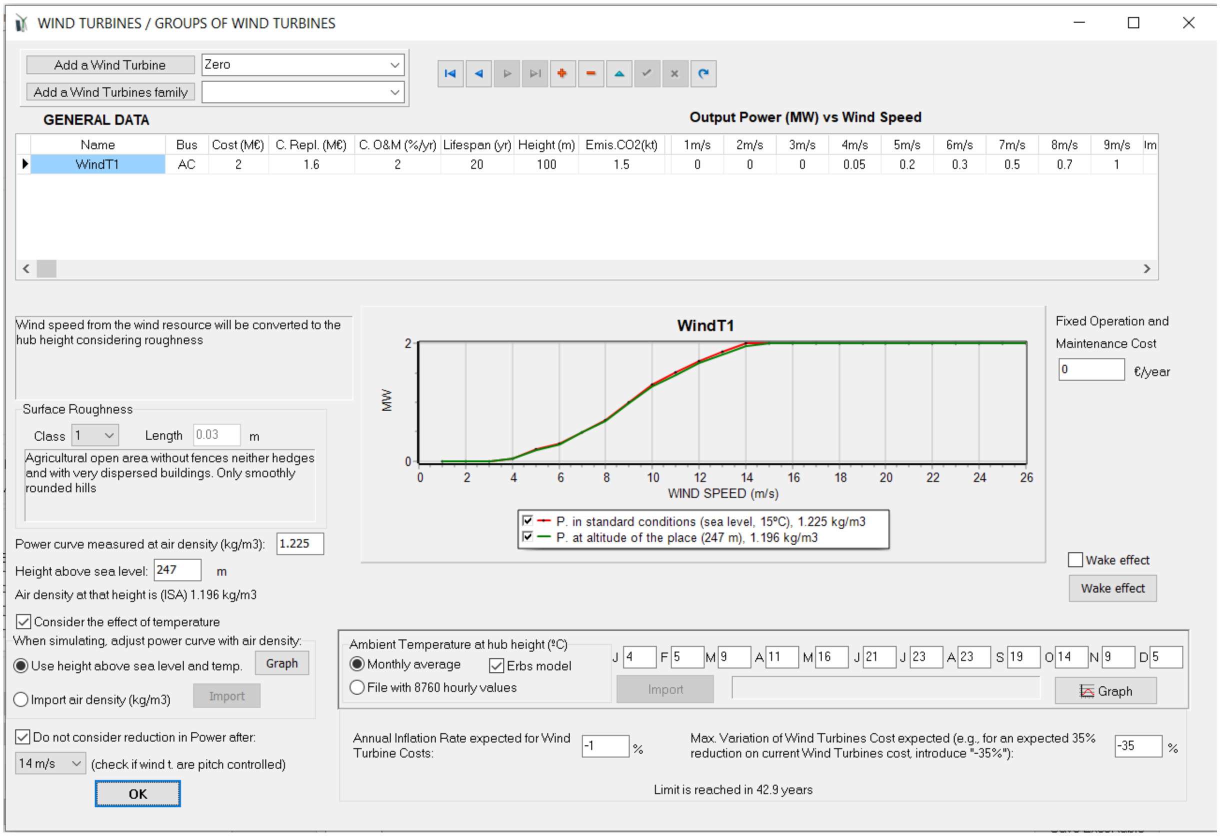
Acquisition cost (CAPEX) for PV generators may be expected to increase (or decrease) at a rate different from that of generic inflation figures (the same can be applied for wind turbines, batteries, and H_2 components). Therefore, an estimation must be made of specific price increases for PV generators, including an upper limit for those. MHOGA will then use this data to calculate the number of years required to reach the price limit. Once this value has been reached, PV generators will be assumed to see their prices increased in line with general inflation. This calculation is used to estimate the price (CAPEX) of the PV generators when they must be replaced (when their expected lifetime ends), however, if using the default lifetime values (25 years for the system lifetime and also 25 years for the PV modules lifetime), they will never be replaced so these calculations will not be used. If, for example, we set that system lifetime is 40 years, as in the year 25 the PV generator will be replaced, the replacement cost will be calculated using the explained procedure.



Clicking on "OK" we return to the main screen of MHOGA.

3.8 Wind turbines

The Wind Turbines screen may be accessed by clicking on "WIND TURBINES" (Components area), or selecting "Wind Turbines" in the Data menu.



Data are available in a table for each type of wind turbine. The table may be accessed as explained in previous section 3.7.

<u>Wind turbines data:</u>

General data are: Name, Bus (default AC, but it can be connected to DC bus, if all are DC in the scheme of the system it will be seen in DC), Acquisition Cost (CAPEX, in M€), Replacement Cost (at the time of replacement, at the end of its useful life, but expressed in the currency referred to the time of the initial investment), Operation and Maintenance Cost (OPEX) for each generator (% of CAPEX/yr), Useful Lifespan (yrs), Height of the Hub (m) and CO_2 emissions in manufacturing, recycling etc. (kilotons, kt).

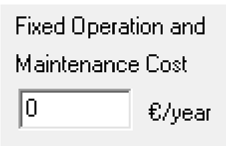
Additional data must be introduced for Output Power as a function of wind speed, from 1 up to 26 m/s, i.e. the output power curve, as shown in the graph. This curve is usually given by the manufacturers for sea level conditions (altitude 0 m) and temperature 15°C, which corresponds to standard conditions and a density of 1,225 kg / m^3. However, it can be defined this curve with another density, that is, if the curve was measured in different conditions than standard, we can define the air density when it was measured (shown at the left of the curve 

). This curve is represented in the graph at the bottom, in red color.

Add or remove wind turbines:

We can add or remove turbines, as shown for photovoltaic generators in previous section. We can also add individual turbines from the database or entire families.

Fixed Operation and Maintenance (O&M) cost:



Additional data must be introduced for fixed operating and maintenance (O&M) costs (€/yr). These costs are independent of the number in parallel and the type of the wind turbine. Fixed operator cost and costs for maintenance material are included, regardless of the total number of turbines.

The total cost for operation and maintenance of the group of wind turbines will be the fixed costs plus the individual cost of wind turbine multiplied by the number of wind turbines in parallel.

Roughness:

Surface roughness class is the same as in the wind resource window, but it can be changed here.

Use the pop-up menu on the left to select the type of ground rugosity (Class 1 by default). MHOGA will then automatically display the corresponding length (m), and a description of the class.

Height above sea level:

In the bottom left area we put the altitude above sea level of the geographic location, and the program gives information of the air density at this altitude. In addition, the power curve for that altitude (green curve) is shown.

The density is calculated according to the International Standard Atmosphere (ISA, earth atmospheric model created by the International Civil Aviation Organization), assuming that in an altitude up to 11,000 feet above sea level the temperature decreases linearly with altitude according to the equation:

$$T = T_o - L{\cdot}H$$

where T is the temperature (K) at the altitude avobe sea leve H (m), T_0 is the standard temperature at height of sea level (288.15 K) and L is the variation rate of temperature vs. height, L=0.0065 K/m.

Atmospheric pressure and air density are calculated as follows:

$$P = P_o \left(1 - \frac{L{\cdot}H}{T_o}\right)^{\frac{gM}{RL}}$$

$$\rho = \frac{P{\cdot}M}{1000{\cdot}R{\cdot}T}$$

where:

T	Temperature (K)
P	Pressure (Pa)
ρ	Density (kg/m^3)
H	Height above sea level (m)
P_o	Standard pressure at sea level, 101325 (Pa)
T_o	Standard temperature at sea level, 288.15 (K)
g	9.80665 (m/s^2)

L	the variation rate of temperature vs. height 0.0065 (K/m)
R	Ideal gas constant, 8.31432 (J/mol·K)
M	Molecular weight of dry air, 28.9644 (g/mol)

Considering the ideal gas law:

$$\frac{\rho}{\rho_0} = \frac{P}{P_0} \cdot \frac{T_0}{T}$$

where ρ_0 is the air density at sea level (1.225 kg/m^3).

Is obtained by substituting the relationship between the density of the height H and the density at sea level:

$$\frac{\rho}{\rho_0} = \left(1 - \frac{L \cdot H}{T_o}\right)^{\frac{gM}{RL}} \cdot \frac{T_0}{\left(T_0 - L \cdot H\right)}$$

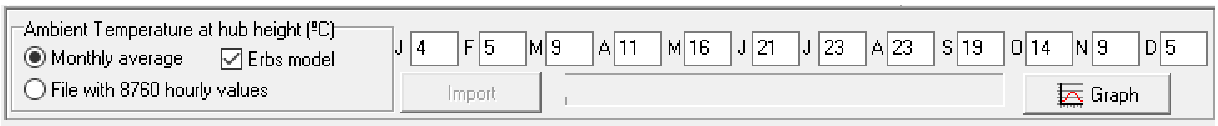
The output power of the wind turbine at the height above sea level H would be the output power at sea level (given by the power curve) multiplied by the ratio ρ/ρ_0. If the wind turbine is pitch controlled, it will be able to maintain its rated power (usually above 14 m/s) even if density is lower than standard density, therefore there is an option (see below) to not consider the reduction in power due to the air density after a specific value of wind speed.

Effect of Ambient temperature:

During the simulations, if we want to consider the effect of ambient temperature on air density, the ckeckbox 

must be checked (checked by default). In the right there is a box where we must enter temperature data. We can choose Data monthly average temperature (Tamb), or, better, if you have a file with 8760 hourly data on ambient temperature, import (in the values imported the decimal spacing must be dot). These data can be different to the used in the screen of the photovoltaic generators, as in the wind turbines we must provide the temperature at hub height, while for the photovoltaic modules we should indicate the temperature at the height that are placed. If the data from NASA, PVGIS or Reneable Ninja has been previously downloaded, the temperatures imported in the PV modules screen and in the wind turbines screen are the same.

In the case of average monthly data, the model of Erbs et al. 1983 (Erbs et al., 1983) can be used to obtain hourly values (we must have previously calculated the irradiation on its screen).

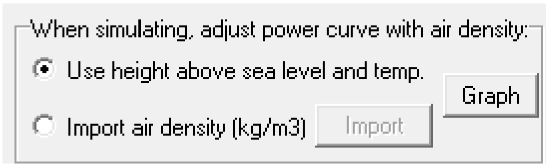


Taking into account ambient temperature, ρ/ρ_0 is calculated as follows:

$$\frac{\rho}{\rho_0} = \left(1 - \frac{L \cdot H}{T_o}\right)^{\frac{gM}{RL}} \cdot \frac{T_0}{T_{amb}}$$

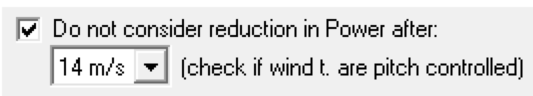
Options to adjust the power curve during the simulation:

During the simulations, the power curve will be adjusted with the air density by multiplying by the relation ρ/ρ_0. The air density during each time step can be calculated considering the height above sea level and (if selected) the temperature, or it can be used the air density imported in an hourly file (in that case the **Import** button will be enabled and you will have to import the hourly file of 8760 rows with the air density in kg/m3). In any case, with the **Graph** button, we will see the air density during the year that will be used in the simulations.



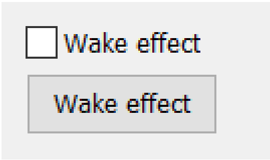
Do not consider reduction in power after a specific wind speed limit:

If the wind turbines can obtain the maximum power (with the pitch control and torque control) for any density (that is, the maximum power is limited by the wind turbine and, even if the air density decreases, the wind turbine can limit it to the same value), check the box "Do not consider reduction in P after" (checked by default) and select the limit in m/s (wind speed at which rated power is reached in the curve). Then, the output curve of the wind turbines after that limit in m/s will not be multiplied by the ratio ρ/ρ_0 and the original output power values of the curve will remain.

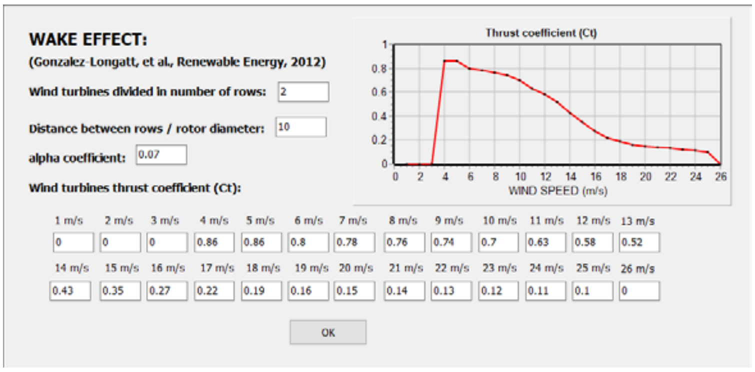


Wake effect for wind turbines in differen rows:

If "Wake effect" is selected, this effect will be considered in the wind farm.



By clicking in the "Wake effect" button, we can see the window with the data for the wake effect, as shown in (González-Longatt, Wall, & Terzija, 2012). It will be assumed that the wind turbines are distributed in the number of rows shown.

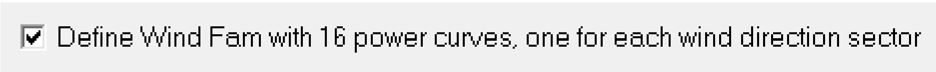


Wind turbines price inflation:

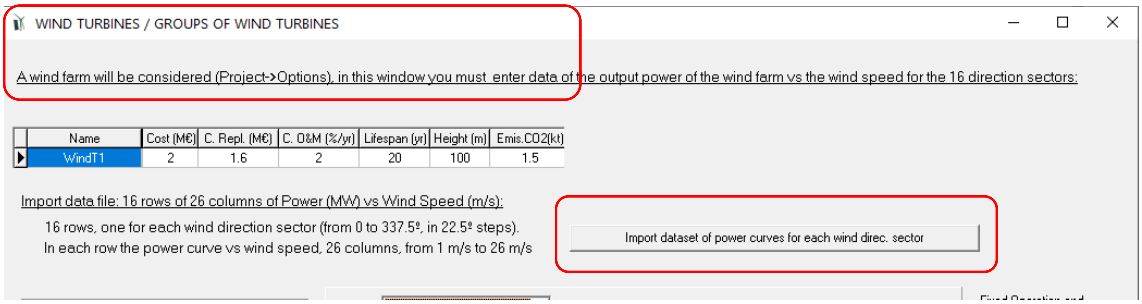
As explained in the screen of the PV generators, in the bottom of the screen we must enter the expected inflation rate of the wind turbines and the limit, to take them into account to calculate the replacement cost if the useful life of the system or study period exceeds the wind turbines lifespan.

Case of wind farm with 16 power curves, one for each wind direction sector, defined in the main options of the software:

If, in the main window of the software, in the menu Project->OPTIONS, we have defined Wind Farm with 16 power curves, one for each wind direction sector:



In that case, in the wind turbines window, we must define the cost, replacement cost, O&M cost (%), lifespan, hub height and emissions. We also must import the output curves of our wind farm vs wind speed for the 16 direction sectors (from 0 to 337.5º in 22.5º steps).



The file to be imported must have the 16 curves, it can be a .txt file similar as the following (you can create it in Excel, copy and paste in Notepad, obtaining a .txt file):

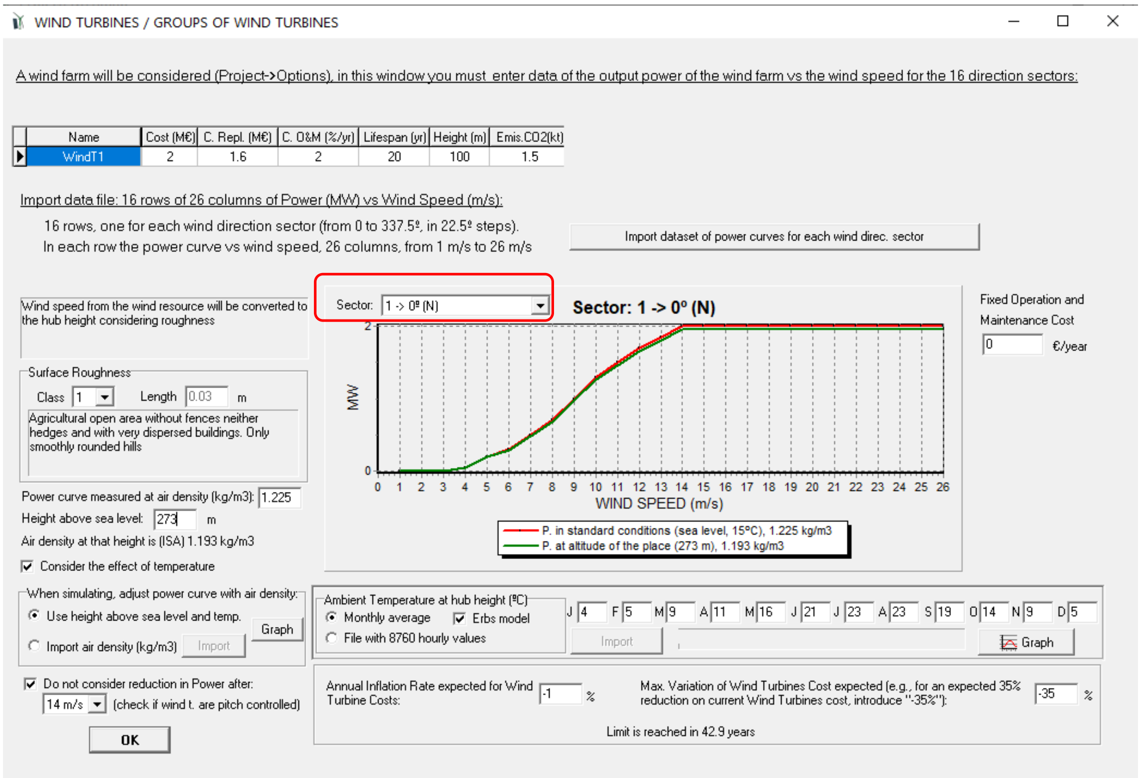
curvasSectores7y16distintos.txt: Bloc de notas
Archivo Edición Formato Ver Ayuda

0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1.3	1.5	1.7	1.85	2	2	2	2	2	2	2	2	2	2	2	2	2
0	0	0	0.05	0.2	0.3	0.5	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Where each row is the output power curve for each wind sector. The first row is for 0º, the second for 22.5º, the third for 45º, and so on, the 16th is for 337.5º.

There must be 26 columns, with the output power in MW, for 0, 1, 2, 3, 4, …. 26 m/s.

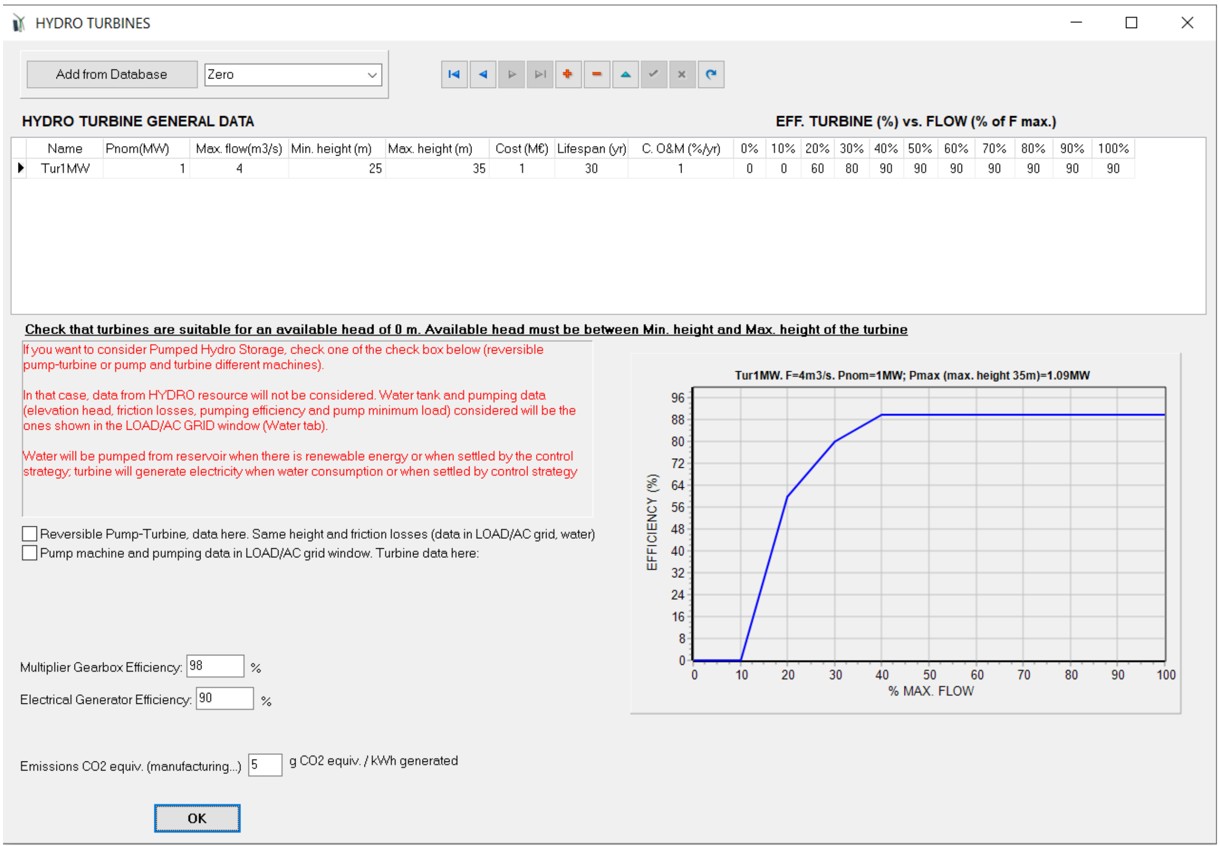
You must import the file with the "**Import dataset of power curves for each wind direc. sector**" button. After importing, it is shown the graph of the power curve for 0º direction (sector 1), but you can see the different curves by selecting the sector in the combo box.



Press “OK” to return to the main screen.

3.9 Hydro turbines

The Hydraulic (hydro) Turbines screen may be accessed by clicking on "HYDRO TURB." (Components area), or selecting "Hydro Turbines" in the Data menu.



The table may be accessed as explained in previous sections.

<u>Hydro turbines data:</u>

The general data for each turbine include: Name, Maximum Flow (m^3/s), Minimum pressure height (m), Maximum pressure height (m), Acquisition Cost (CAPEX, M€), Useful Lifespan (years) and Operation and Maintenance Costs (OPEX, in % of CAPEX per year) for each hydro turbine.

Additional data must be provided on turbine efficiency (%) as a function of load, i.e. versus percentage of maximum flow. Turbine performance is displayed in the chart.

We can add individual turbines from the database.

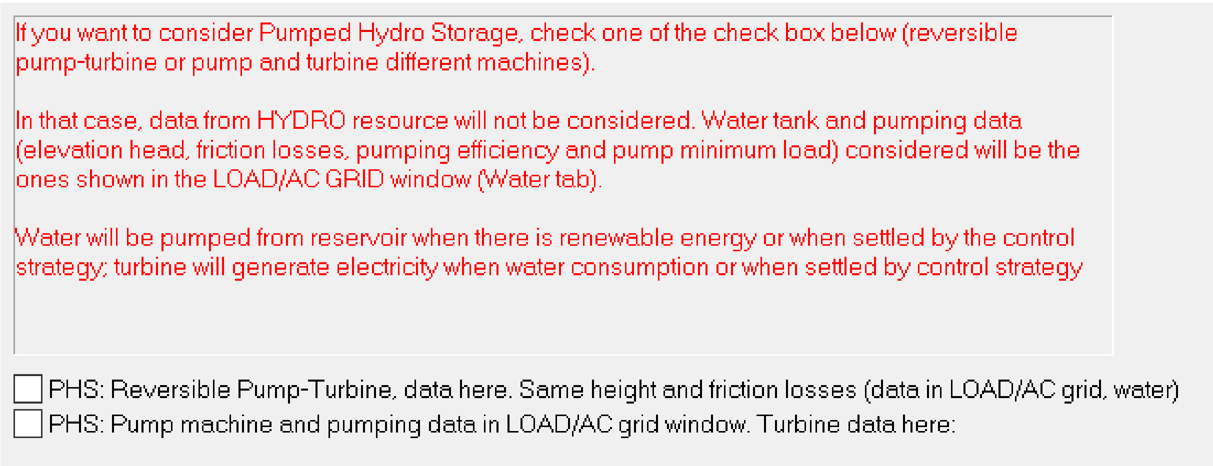
The hydro turbine must be suitable for the available head settled in the HYDRO resource window, it is reminded under the table:

<u>Check that turbines are suitable for an available head of 28 m. Available head must be between Min. height and Max. height of the turbine</u>

If the turbine is not suitable for the available head, when closing the window a message will tell us that we should consider to delete this turbine and change to another one.

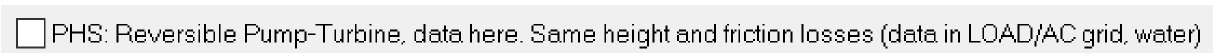
<u>Pumped hydro storage (PHS):</u>

Under the table, we can read the red text:

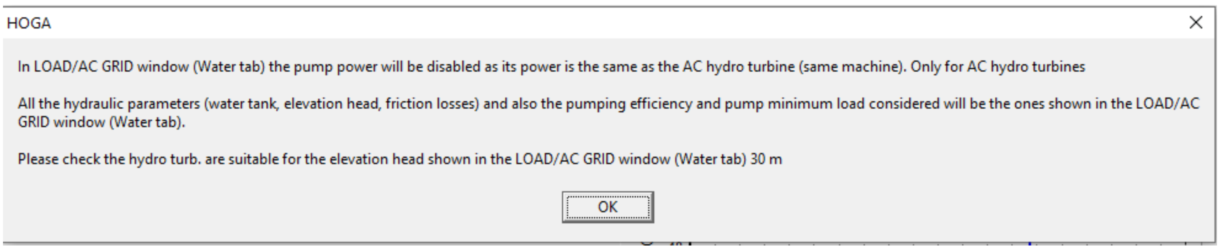


We can select one of the two options below the text for pumped hydro storage. Anyway, <u>for the two options, the data of the HYDRO resource will not be considered, that is, in this case THERE IS NO HYDRO RESOURCE TO RUN OUR TURBINE</u>. Instead, there is a tank or water storage where we pump water when there is energy from the renewable sources (or when settled by the control strategy similar as the grid-connected batteries control strategy), and when there is water load consumption (or when settled by the control strategy), water flows from the tank running the turbine. <u>The data of the tank, height and friction losses will be the ones of the LOAD/AC GRID window, tab "Water…".</u>

- We can consider a **Reversible Pump-turbine,** checking the checkbox **"PHS: Reversible Pump-turbine, data here. Same height…."**

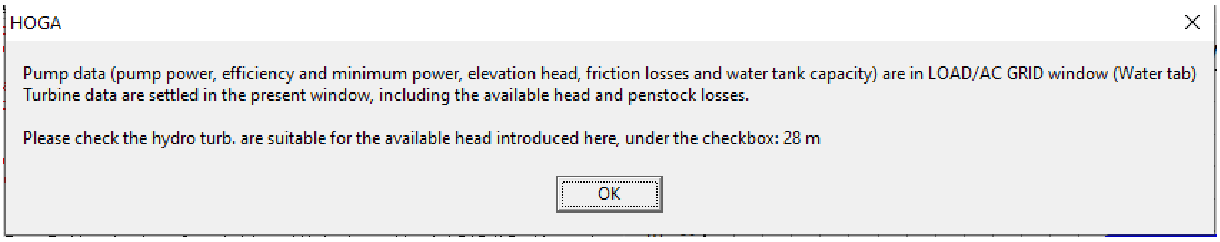
  When checking the checkbox, this message appears:

The data of this machine will be the data shown in the table of this window. As it is a unique machine, which can be operated as pump or turbine, it has same height and friction losses, and these data (height and friction losses) will be the ones shown in the LOAD/AC GRID window, tab "Water…".

- We can consider **two different machines, a pump and a turbine** for the pump hydro storage**,** by checking the checkbox **"PHS: Pump machine and pumping data…"**

When checking the checkbox, available head and penstock losses for the turbine appears under the checkbox. Also, this message appears:

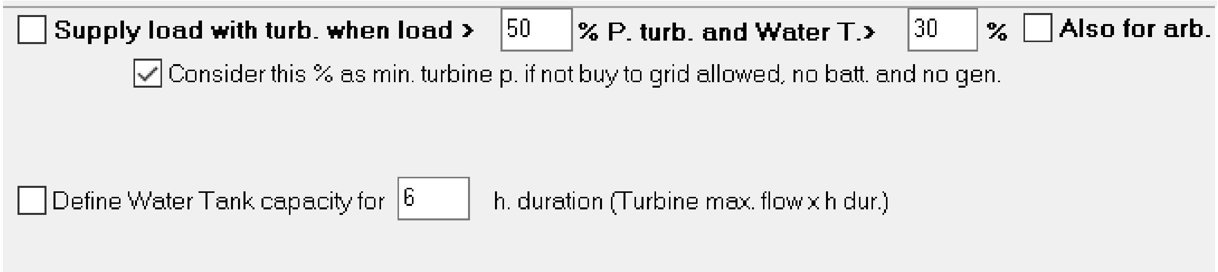


The data of the turbine will be the data shown in the table of this window, however the data of the pump is the data shown in LOAD/AC GRID window. As turbine and pump are different machines, there can be different values for height and friction losses: for example, the pump can obtain water from a reservoir at a certain height and losses and the turbine can run with the water load with a different height from the tank and different losses. The height and losses of the turbine are settled under the checkbox. The tank data and the pump data (power, height, friction losses…) will be the ones shown in the LOAD/AC GRID window, tab "Water…".

If we check one of the two boxes (reversible pump-turbine or two machines), that is, if we are using PHS, a new the checkbox "**Supply elec. load with turbine when load >…. % P turbine and water tank > ….. %**" appears. If we check it, we will force the turbine to work to supply the electrical load of the system when load and water tank are higher than these percentages.

If the checkbox "**Also for arb.**" is checked, it means that it is alos applied for the turbine when it is in the "discharge" mode of the PHS in energy arbitrage.

If the checkbox "**Consither this % as min. turbine…**" is checked, that percentage will be considerd as the minimum output power of the turbine when supplying the load in stand-alone systems (no AC grid), without battery and without backup generator. In these cases, if we didn't consider this, when the renewable sources cannot meet the whole load, if the net load is low, the turbine would supply the load with low efficiency, needing a high amount of water stored to convert it in electrical energy. However, considering this, the turbine will run at a minimum power with high efficiency.



If we check the box "**Define Water Tank capacity for …. h duration (Turbine max. flow x h duration**", this means that, in pumped-hydro-storage (PHS), the water tank or reservoir capacity will be calculated, for each combination of components, as the turbine maximum flow multiplied by the duration wanted (so the value of the water tank capacity of the LOAD/AC GRID window, WATER tab, will not be considered).

More data:

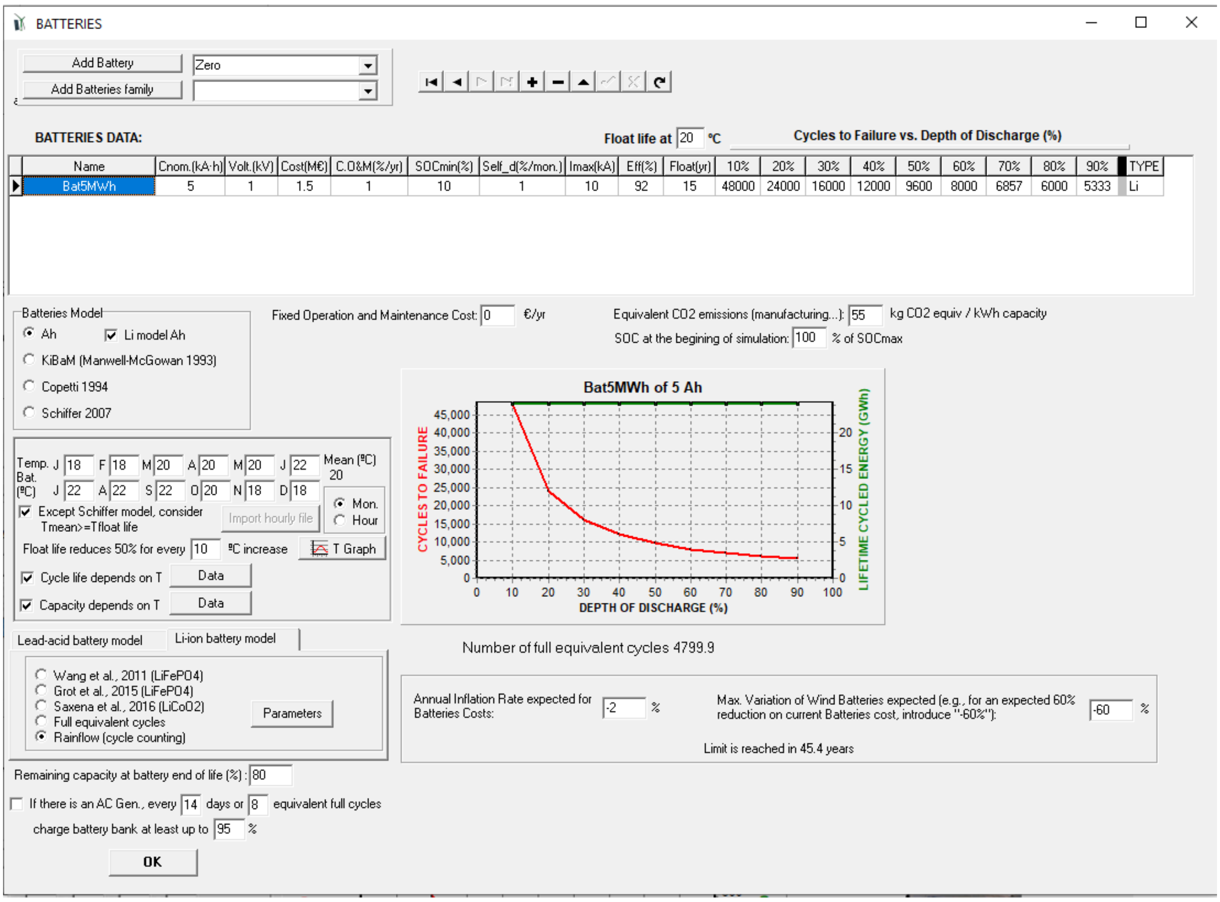
Additional data must be set: the efficiency of the multiplier gearbox, and of the electric generator.

Above the graph, the nominal power and its maximum power, calculated in MW [9.81*Available_head(m)*Flow_max (m^3/s)*efficiency/1000], are reported for the selected turbine. Efficiency includes losses in turbine, multiplier gearbox and in the electric generator.

As explained for modules and wind turbines, if we are interested in the calculation of life cycle emissions, we must introduce equivalent CO_2 emissions due to turbine manufacture, in g of CO_2 equivalent per each kWh of energy generated. However, this value is usually very low, close to 0.

3.10 Batteries

The "Batteries" screen may be accessed by clicking on "BATTERIES" (Components area), or selecting "Batteries" in the Data menu.



As usual, data for each component type is displayed in rows in the table.

Both lead-acid batteries and lithium-ion batteries can be considered in the table. Also, any other type of battery can be modelled if we know its cycle life.

3.10.1. General data

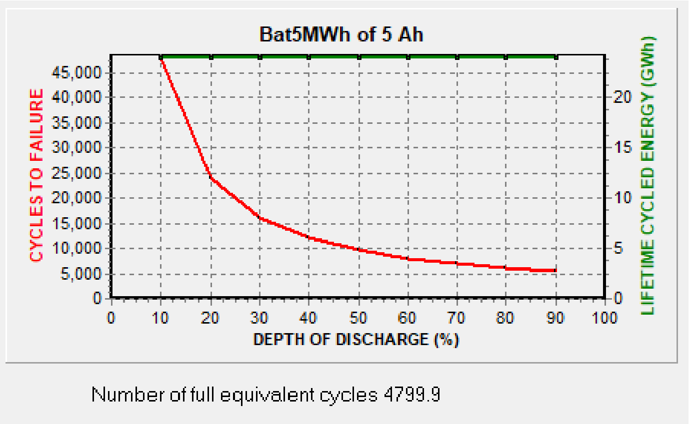
General data for batteries includes:

- Name
- Nominal Capacity (Cn) in kA·h. The manufacturers usually give the nominal capacity for discharge in 100 h (C100), the nominal capacity for discharge in 10 h (C10), etc. It will be necessary to choose as Cn the most suitable. For example, if the load consumption is such that the batteries are expected to perform 1 full charge/discharge cycle per day, the value to choose would be C10. If the batteries are expected to be

discharged at a slower rate (the usual in PV off grid systems), we would choose C20 or even C100.

- Nominal Voltage, Volt. (kV).
- Energy rated (nameplate) capacity, in MWh, will be: Cn(MWh) = Cn(kA·h)·Vn(kV)
- Acquisition Cost CAPEX (M€)
- Operation and Maintenance Costs OPEX (% of CAPEX per year) for each unit
- Minimum State of Charge (SOCmin), as a percentage of maximum SOC. The value of SOCmin (%) equals 100-DODmax, where DODmax is the maximum permissible discharge depth (%). SOCmin is usually from 10 to 50%, depending on the type of battery.
- Self-Discharge Coefficient (monthly %)
- Maximum allowed current (Imax) for each battery, in kA. The maximum power (for charge and for discharge) will be Pmax (MW)=Imax(kA)·Vn(kV).
- Global (roundtrip) Efficiency (%). Charge and discharge efficiencies are square root of roundtrip efficiency.
- Floating Life (indicate the temperature at which floating time is defined, usually 20ºC).
- Cycles to failure vs. depth of discharge.
- Type (Lead-acid batteries denoted by "LA" or "Pb" or Lithium-ion batteries "Li"). For other type of battery, if you know the cycles to failure vs. depth of discharge, select "LA" or "Li", and in the ageing model, select "Rainflow" (explained later).

Data must be provided for each battery on the number of life cycles to failure ($Cicles_i$) for each depth of discharge percentage (DOD_i en %), displayed in red.



Some manufacturers of lead-acid batteries usually indicate the curve cycles to failure vs. depth of discharge. If it is not known, and we know the cycles that the battery can perform at a certain discharge depth, for example we know $Cicles_k$ = 2000 for DOD_k = 80% (k = 8), the rest of the data of $Cicles_i$ (i = 1 ... 9) can be obtained according to:

$$Cicles_i = Cicles_k \cdot DOD_k \ / DOD_i$$

In this example:

$$Cicles_1 = Cicles_8 \cdot DOD_8 \ / DOD_1 = 2000*80/10=16000$$

$$Cicles_2 = Cicles_8 \cdot DOD_8 \ / DOD_2 = 2000*80/20=8000$$

$$Cicles_3 = Cicles_8 \cdot DOD_8 \ / DOD_3 = 2000*80/30=5333$$

$$Cicles_4 = Cicles_8 \cdot DOD_8 \ / DOD_4 = 2000*80/40=4000$$

$$Cicles_5 = Cicles_8 \cdot DOD_8 \ / DOD_5 = 2000*80/50=3200$$

$$Cicles_6 = Cicles_8 \cdot DOD_8 \ / DOD_6 = 2000*80/60=2666$$

$$Cicles_7 = Cicles_8 \cdot DOD_8 \ / DOD_7 = 2000*80/70=2285$$

$$Cicles_8 = Cicles_8 \cdot DOD_8 \ / DOD_8 = 2000*80/80=2000$$

$$Cicles_9 = Cicles_8 \cdot DOD_8 \ / DOD_9 = 2000*80/90=1777$$

In the database (main screen of the software, upper menu, Database, Batteries tab) you can just indicate the cycles at 80%DOD and then press the button to calculate cycles vs. DOD from the value at 80%, see section 3.6.

MHOGA calculates the cycled energy throughout battery lifetime for each DOD:

$E_{cycled\_i}\ (MWh) = Cn\ (kAh) \cdot Vn\ (kV) \cdot DOD_i\ (\%) / 100 \cdot Cycles_i$

This value is displayed in green.

The number of equivalent cycles is calculated as:

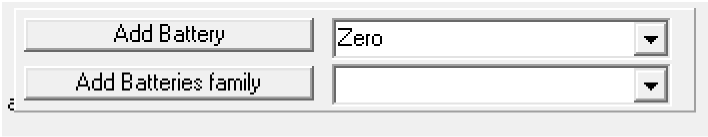
$N_{eq\_cycles} = E_{cycled\_average}\ (MWh) / (Cn\ (kAh) \cdot Vn\ (kV))$

Where:

$E_{cycled\_average} = \Sigma\ E_{cycled\_i}\ (MWh)/9;$

This value is displayed under the chart.

We can import individual batteries or entire families from the database.

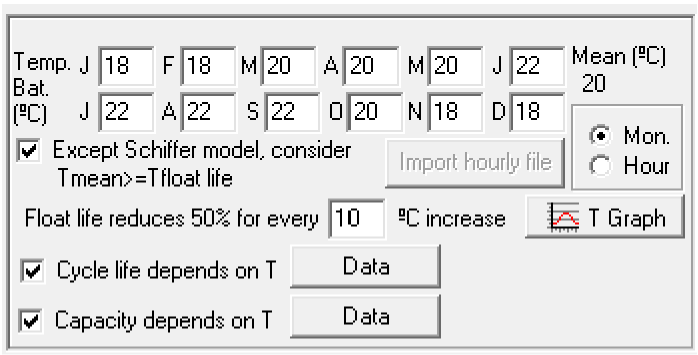


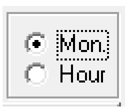
An estimation can be carried out of fixed Operation and Maintenance Costs (€/yr) for the battery set to be used by the system (regardless the number of batteries, that is, the fixed O&M cost). These costs must include the operator and the fixed material, regardless of the final number of batteries included.

Auxliary consumption for cooling, heating, BMS, etc.

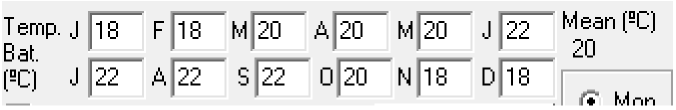
Auxiliary consumption can be defined as a percentage of the maximum power of the battery (Pmax=Imax·Vn), this power will be consumed during all the time. By default, a 0% is considered. By default, this auxiliary consumption is in AC, to define it in DC you must check the "DC cons." checkbox.

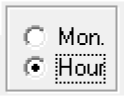
Battery temperature:



If we have selected "Mon", 

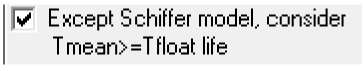
we must indicate also the average temperature of the batteries during each month of the year as this will be taken into account in Copetti and in Schiffer models (lead-acid batteries models) and also in any model to calculate the floating lifetime taking into account Arrhenius law. It is also used to obtain the capacity dependence on temperature and the cycle life dependence on temperature.



If we select "Hour" 

it is possible to download the hourly ambient temperature data of the location with PVGIS or Renewables Ninja (in the windows of solar resource or wind) and use these values as the battery ambient temperature, or it is possible to import an hourly file (button "Import hourly file").

The floating life that the battery manufacturer indicates for a given temperature (generally 20°C) is converted to the floating life corresponding to the average temperature of the batteries according to the Arrhenius law, being necessary to indicate the Celsius degrees needed to reduce the float lifetime in 50% (default 10ºC) 

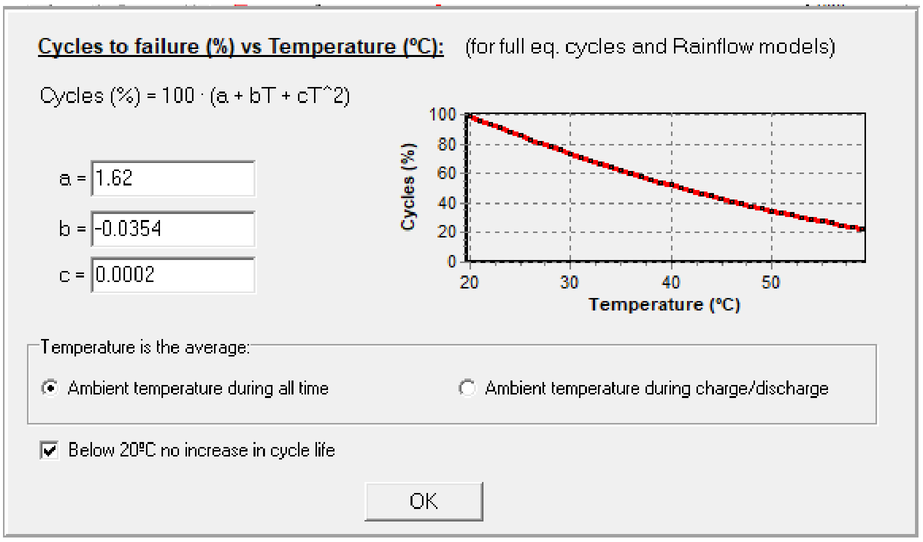
If the average temperature of the batteries is lower than the manufacturer indicates, the floating life obtained by Arrhenius law can be very high (not real). To avoid this, by default the checkbox 

is checked. For aging models other than the Schiffer, this marked box implies that if the average temperature of the batteries is below the indicated temperature at which the manufacturer supplies the float life, the average temperature shall be considered to be equal to that indicated for the floating life and therefore the actual floating life will not exceed that indicated by the manufacturer.

<u>Cycle life dependence on temperature:</u>

If the checkbox 

is selected, the number of cycles to failure (% related to the nominal value, 100% at 20ºC) will be calculated as dependant on average temperature (considering ambient temperature during all time or ambient temperature just during charge/discharge, depending on the user selection in the data window), and it will be obtained considering the data shown by clicking button "**Data**":



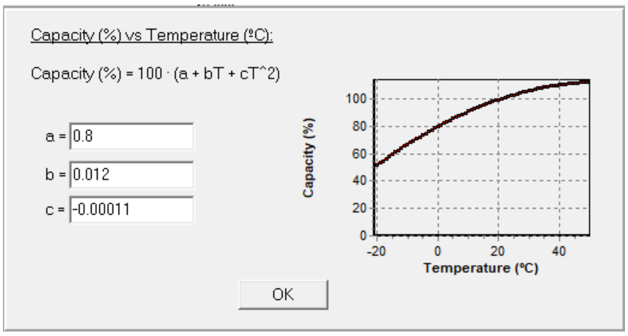
<u>It is very important that you select this option when using Li-ion batteries or for lead-acid if you do not use Schiffer model, as temperature is very important in the degradation.</u>

This curve were obtained from the values shown in https://midsummer.ie/pdfs/fronius-performance-solar-battery.pdf

<u>Capacity dependence on temperature:</u>

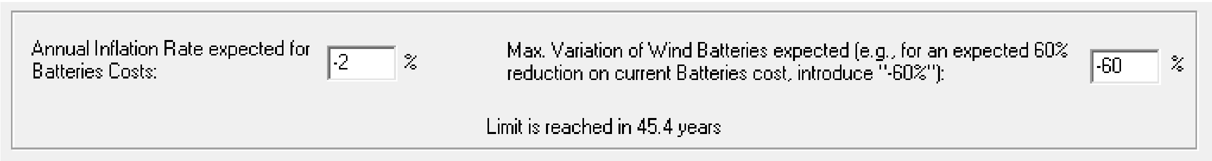
If the checkbox 

is selected, the available battery capacity for each hour will be obtained considering the data shown by clicking button "**Data**":



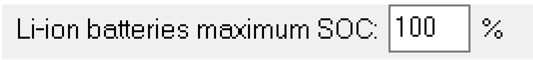
As explained in the previous sections, if you want to know the overall life cycle emissions, you must introduce (above the graph) equivalent CO_2 emissions due to the manufacture of the batteries, in kg of CO_2 equivalent per kWh of capacity.

As explained in the PV modules screen, the lower part of the screen shows the expected inflation of the price of the batteries and their limit, to be taken into account to estimate the replacement cost (in case they have to be replaced during system lifetime).



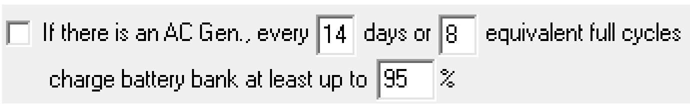
Above the cycles to failure graph, you must enter the percentage of the SOC at the beginning of the simulation.

Also you can set the maximum allowed state of charge, for Li-ion batteries (default 100%, but in many cases it should set to 90%):



At the top bottom of this screen, we must indicate the remaining capacity at battery end of life, by default 80%.

Also we can select an option so that the controller can start the diesel generator automatically to charge the batteries up to 95% of the SOC (by default, can be modified) every certain number of days or each given number of equivalent full cycles. In that case, check the box at the bottom:

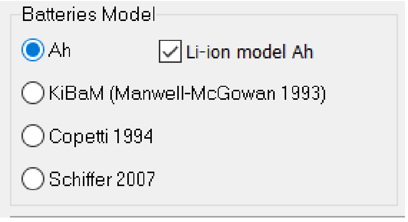


Finally, after defining all the batteries that we want the program to take into account, with "OK" button we can return to the main screen.

3.10.2. Models of batteries

In the case of lead-acid batteries, the state of charge of the batteries, as well as the maximum current allowed by them can be calculated according to several models, to be chosen by the user: Model Ah (used by Schuhmacher in 1993)(Schuhmacher, 1993), Model KiBaM (Manwell and McGowan, 1993) (Manwell & McGowan, 1993), model of Copetti (Copetti et al., 1993 y 1994) (Copetti et al., 1993)(Copetti & Chenlo, 1994), Model of Schiffer (Schiffer et al., 2007) (Schiffer et al., 2007).

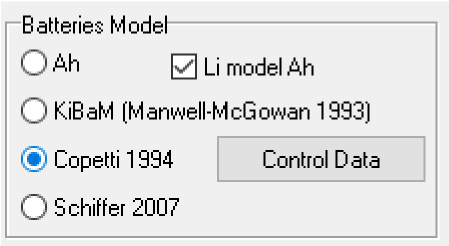
By default the battery model is the Ah model, the simplest one.

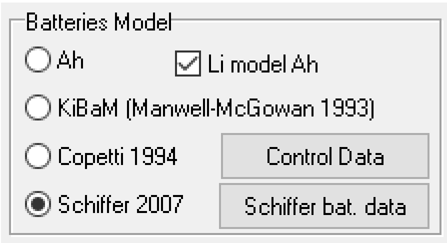


If "Li-ion model Ah" is marked, it means that if Lithium-ion batteries are being considered in a combination of components, the Ah model will be used even if another model is marked here (which would be used for lead-acid batteries).

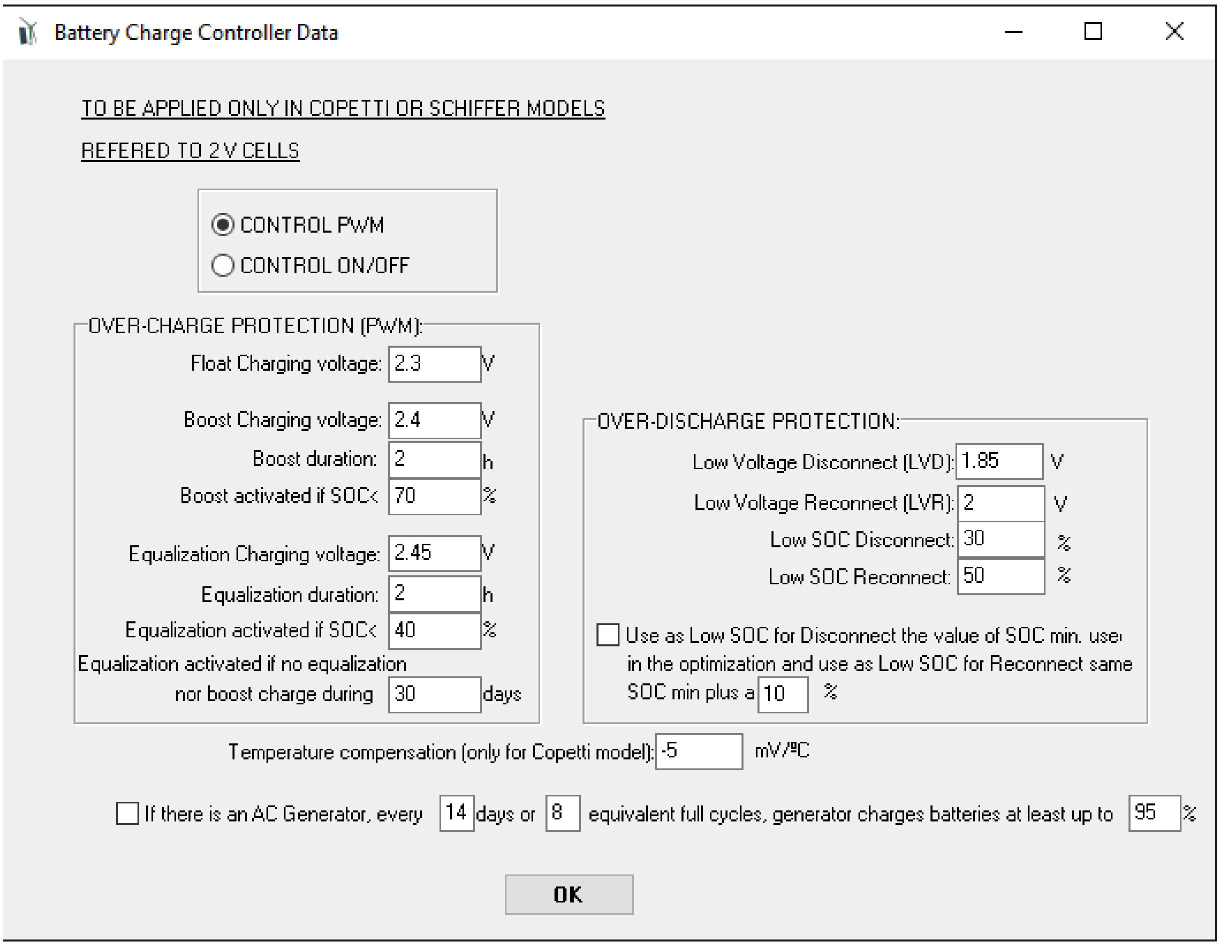
Models Copetti and Schiffer:

If we choose the models Schiffer or Copetti (they are models for lead-acid batteries), the button "**Control Data**" appears" to set up the characteristics of the controller for the charge/discharge of the batteries. If we use Li-ion batteries, these data will not be used.





By pressing the "**Control Data**" button, the screen of the data that will be used by the charge controllers of the batteries (which in some cases are included in the inverter-charger) will be displayed (all the charge controllers must be of the same family since the characteristics are the same for all).



The characteristics of the control of the charge and discharge of the batteries must be indicated: if the controller is PWM type or ON/OFF type. Both devices, charge controller and rectifier (AC/DC converter) are assumed to perform the same control.

Once the type of PWM or ON/OFF control is chosen, the parameters of the controller must be defined. **These parameters must be suitable for the lead-acid batteries that we define in the batteries screen**.

In the case of PWM control, the data for the charge in several stages, typically 3 stages: bulk, boost (absortion) and float, and also the data of the equalization or compensation charge must be set.

In the case of the Copetti model we must also define the coefficient of variation of the voltage with the temperature (mV/ºC).

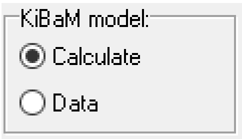
Control of the charge of the batteries by the diesel generator:

If the controller can start the diesel generator automatically (usually in the case of bi-directional converters or inverter-chargers), some types allow the generator to charge the batteries up to

95% of the SOC (by default, can be modified) every certain number of days or each given number of equivalent full cycles. In that case, check the box at the bottom (changes in this box and these values are updated on the main screen of the batteries):

3.10.3. KiBaM battery model

When the KiBaM model is selected (for lead-acid batteries), the table widens, and the chart shrinks to accomodate an additional graph. Select “Calculate” to make MHOGA obtain the parameters needed for the model, or “Data”, for direct data introduction.



New columns are displayed when “Calculate” is selected (see figure below, right hand side): C100, C20, and C10 (all of them in kAh). These values correspond to battery capacities for 100-, 20-, and 10-hour discharge regimes. The longer it takes a battery to discharge, the more energy is provided, so C100 will be larger than C20, which will in turn be larger than C10. This data is supplied by the battery manufacturer. MHOGA calculates discharge intensities (in kA) for the 3 discharge regimes provided (e.g., for a 100-hour regime, this will be C100/100). Discharge intensity is then displayed versus battery capacity. Additional values are shown under the chart for the parameters required by the KiBaM Model, as calculated from C100, C20, and C10. The required parameters are represented by c, k, and Cmax.

There is a last column in the table, which is also new (C. charge), in A / Ah, which represents the Maximum Battery Charge Rate or Maximum Battery Charge Current Coefficient, which is an additional limitation of Maximum charge current using the KiBaM model.

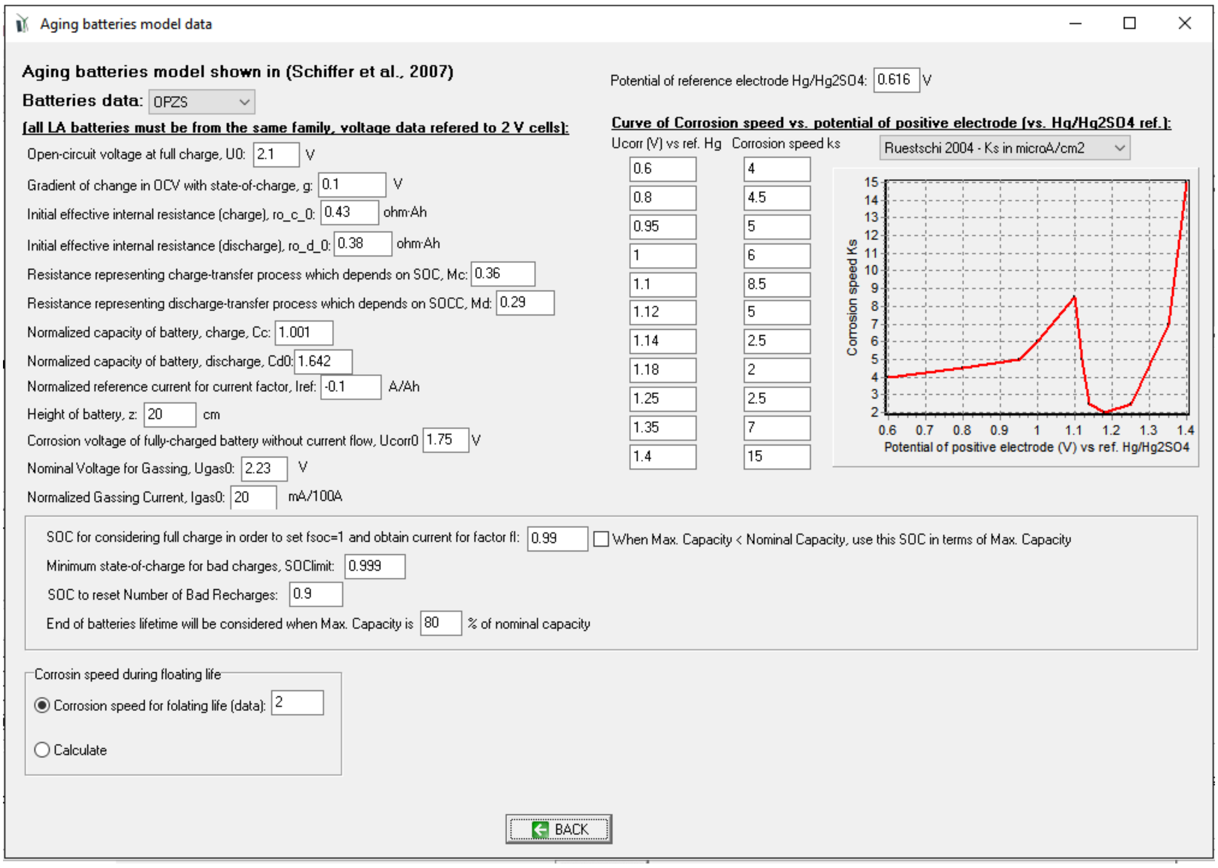
If in the KiBaM model we choose "Data" instead of "Calculate", the new graph disappears and instead of the colums C100, C20 and C10, we will have k (1/h), c and Cmax (kAh), besides the fourth column, which is maintained. In this case, the battery manufacturer should have provided these values.

3.10.4. Schiffer model.

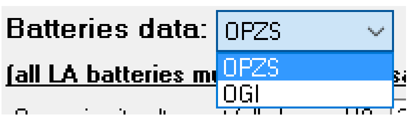
Using lead-acid batteries, we encourage you to use Schiffer model, as it is the most accurate.

If the Schiffer model is chosen, the lead-acid batteries defined in the table must be of the same family, i.e. they must have similar parameters, changing only the "size".

If we have chosen the Schiffer model, the "**Schiffer Bat. Data**" button appears under the "Control Data" button. By clicking on it shows the next window.



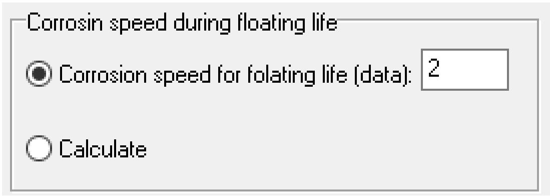
The first option is to choose the type of the lead-acid battery, OPZS (tubular optimized for photovoltaic applications, long service life) or OGi (flat plate, open, use in uninterruptible power supply systems, emergency lighting, telecommunications, can also be used for starting machines, and in photovoltaic systems)



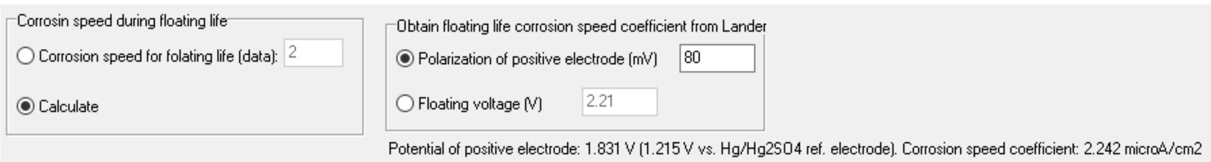
The software loads the data of the batteries used in the article (Schiffer et al., 2007) (Schiffer et al., 2007), however, it should be noted that these data are for certain families of OPZS and OGi batteries, which may not match the family of batteries we are using. We should update these data with those of the family of batteries that we are using (we should know the data of our batteries or test them to obtain data). In many cases many parameters are usually unknown as they are not published by the batteries manufacturers. The default parameters were obtained from the publication of Schieffer et al., 2007. You should not change any value unless you know this. It is important that all the battery models considered in the battery screen table are of the same type, OPZS or OGI, and you select in this window only the type of battery, if you do not know the specific parameters.

In the right part we must select the curve of the corrosion rate against the potential of the positive electrode, Ruetschi 2004 (Ruetschi, 2004) or Lander 1956 (Lander, 1956). It should be noted that the actual curve for each battery family is different, so we should define the curve for the battery family being considered, obtained from the manufacturer or by testing and modifying the values of the curve of Lander or Ruestschi. If you do not know the data of your specific batteries, leave the Ruetschi 2004 model.

At the bottom, the parameter of the corrosion rate for floating life must be set (in the units marked in the corrosion rate curve versus the potential of the positive electrode):



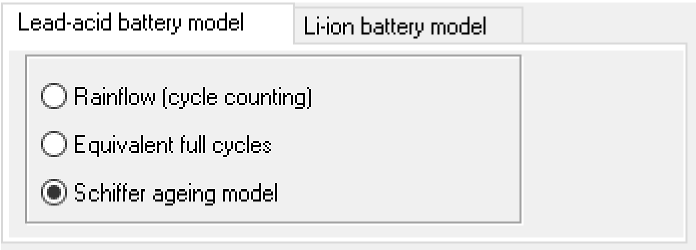
Or calculate the parameter of the corrosion rate for floating life:



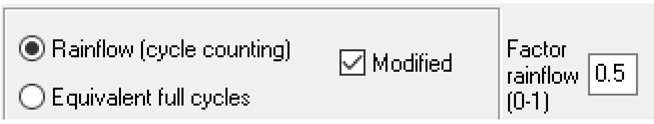
3.10.5. Lifetime models for lead-acid batteries

The calculation of the estimated lifespan of the batteries is very important, since it influences the replacement costs of these and therefore in the total cost of the system. It is possible to choose between the Equivalent Full Cycles model and another more complex and precise, the method of the Cycle Counting or Rainflow according to the algorithm of Downing (Downing and Socie 1982)(Downing & Socie, 1982). Schiffer model (Schiffer et al., 2007) is much more precise model, which includes the aging by corrosion (a comparison of the different models is shown in (Rodolfo Dufo-López et al., 2014), where it is verified that the model of Schiffer gives results much more similar to the real ones, whereas in some cases the other models predict the duration of the batteries of the order of 2 or 3 times higher than the real duration).

For lead-acid batteries, you can choose the lifetime estimate of the batteries according to the Equivalent Full Cycles or according to the Rainflow model, or according to the Schiffer aging model (this only if the Schiffer model has been selected in the model of batteries).



In the case of Rainflow, if you check the box "Modified", a box appears where "Factor rainflow (0-1)" should be indicated.

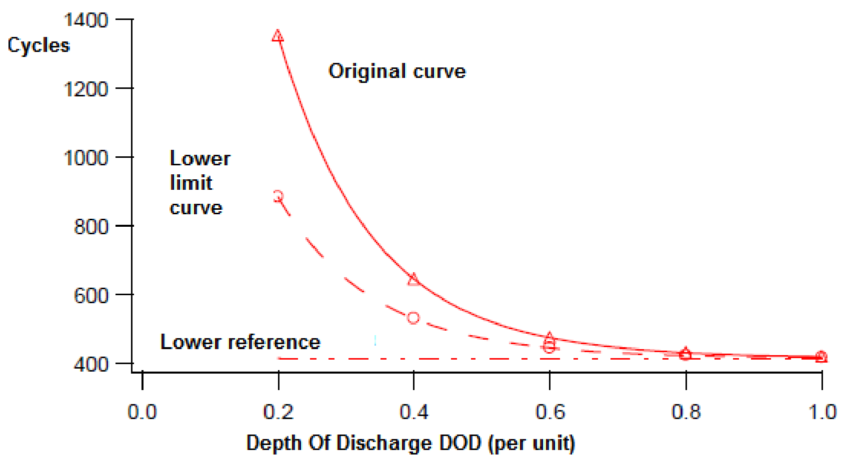


The modified method intends to take into account the average SOC of the batteries during each cycle. The original cycling curve of the following figure is that supplied by the manufacturer (discharge cycles C_F versus depth of discharge) and is assumed to be for batteries starting each cycle being fully charged. However, if a battery starts a certain cycle with a SOC <100%, the wear will be higher. This method is intended to take account of increased wear (fewer life cycles) if each cycle does not start with fully charged batteries.

With the factor rainflow (F), a lower limit curve is obtained, which would be for the cycles that begin and end at the lowest possible state of charge for those cycles. The lower limit curve is calculated according to:

$$C_{F,L} = F\left(C_F - C_{F,R}\right) + C_{F,R}$$

Where $C_{F,R}$ is the reference line of the figure.

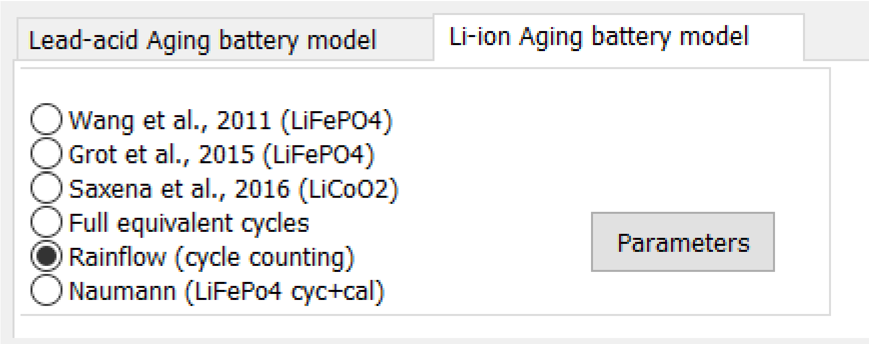


For each cycle, this method takes into account the average SOC of the batteries during the cycle, and obtains the number of life cycles from the curve for that SOC, which will be between the original and the lower limit.

3.10.6. Lithium-ion batteries lifetime models.

In the case of lithium-ion batteries, in addition to Equivalent Full Cycle life model and the Cycle Counting or Rainflow method, you can choose other three cycle ageing life models specific to lithium-ion batteries. There are two cycle aging models for LiFePo4/graphite batteries (Wang et al., 2011 (Wang et al., 2011); Grot et al., 2015 (Groot et al., 2015)) and another one which includes cycle aging Naumann et al., 2020 (Naumann et al., 2020) and calendar aging (Naumann, Schimpe, Keil, Hesse, & Jossen, 2018). There is another model for cycle aging of LiCoO2/ graphite batteries (Saxena et al., 2016 (Saxena et al., 2016)).

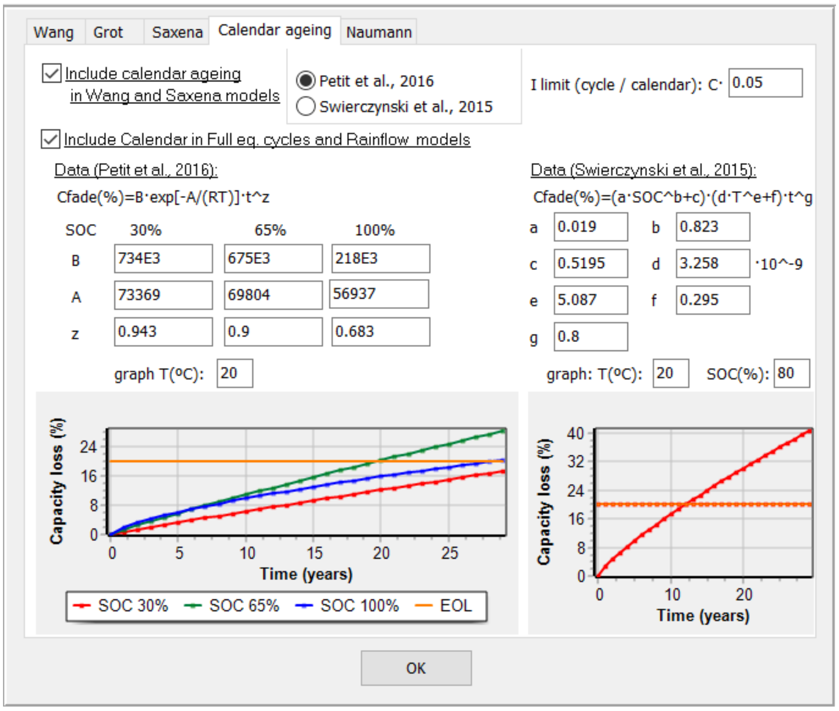
It is important to say that Wang, Grot, Saxena and Naumann models were obtained by researchers by testing specific commercial batteries, so these models are only adequate for those commercial batteries tested and for the conditions they were tested. If you are not sure about if your battery is similar to the ones tested by these models, it would be better to select a generic model (Full equivalent cycles or Rainflow).



If the Grot et al. model is selected, the box "Rate lower than 1C-> 1C" indicates that charges / discharges at rates lower than 1C will be considered as 1C. Where 1C means the charging or discharging rate such that the battery is fully charged or discharged for 1 hour, i.e. the current in A equals the capacity in Ah.

In the case of selecting the Wang et al. model, selecting the "Rate lower than limit" box means that the limits of the model (to use the specific equations) are upper limits, if no such box is selected the limits are intermediate.

By clicking on "**Parameters"**, a window appears where you can see (in different tabs) and edit the parameters of the different models (Wang, Grot, Saxena, Naumann and calendar models) and it is shown the graph of the capacity loss (%) vs full equivalent cycles or vs time.



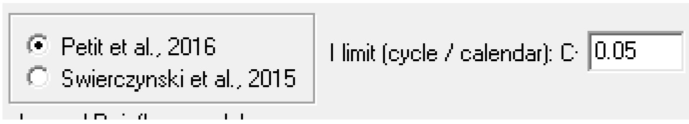
The default tab shows the calendar ageing model included in Wang and Saxena models (it can be included or not, by default included):

There is another tab that shows the calendar ageing model or not in full eq. cycles model and in Rainflow model (it can be included or not, by default included):

There are two models for calendar ageing:

- The model shown in (Petit, Prada, & Sauvant-Moynot, 2016)
- The model shown in (Swierczynski, Stroe, Stan, Teodorescu, & Kær, 2015)

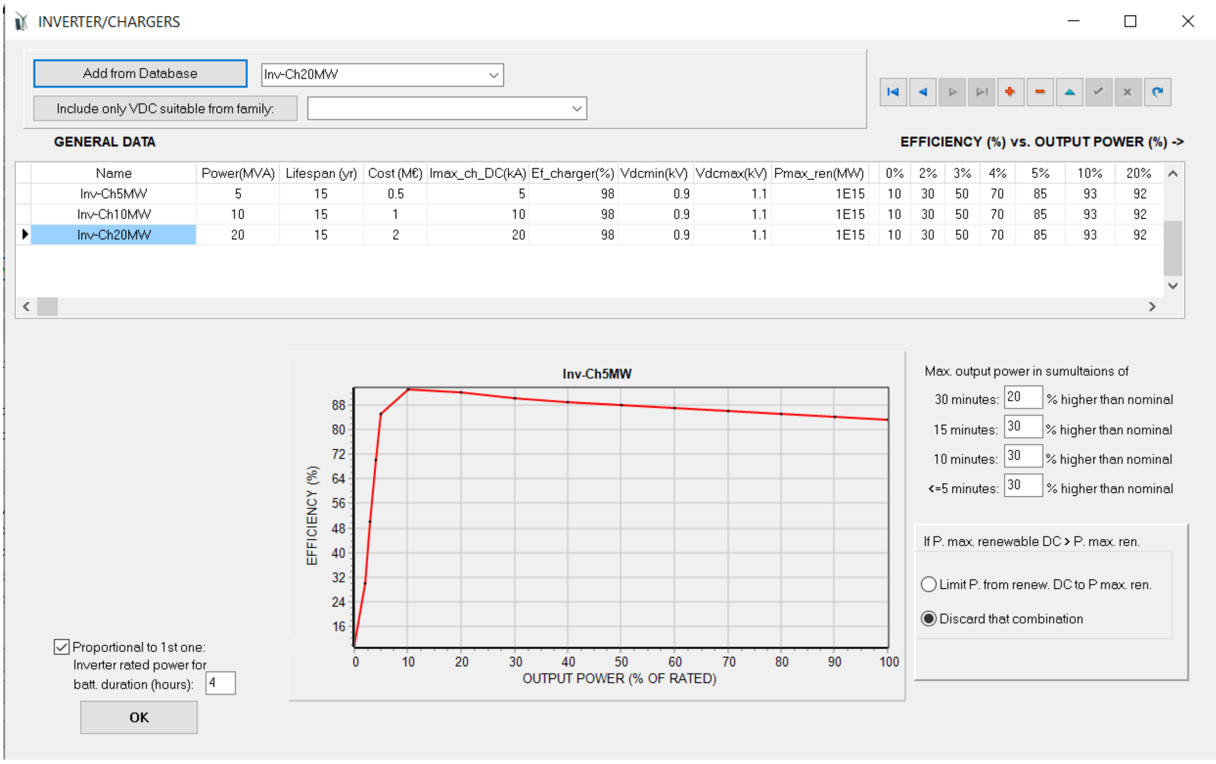
You can choose to use one or another. You must also set the limit current so that when the current of the battery is lower than the capacity multiplied by a specific value (default 0.05), calendar ageing will be considered, and when the current is higher than that value cycle ageing will be considered.



3.11 Inverter-chargers (bi-directional converters).

The "Inverter-chargers" screen may be accessed by clicking on "INVERTER/CHAR." (Components area), or selecting "Inverter-chargers" in the Data menu.

The inverter-charger is needed if there is battery storage to convert AC power to the DC bus of the batteries and vice-versa. Inverter performance is dependent upon power.



<u>Data of inverters and inverter-chargers:</u>

The following data must be included for each inverter or inverter-charger to be considered in the optimization:

- Name
- Output apparent power (MVA)
- Lifetime (years)
- Acquisition cost CAPEX (M€)
- Maximum charge current that can be supplied to the batteries must be set in the following column "Imax_ch.DC (kA)" and the efficiency of the charger in the next column.

- Minimum and maximum operating DC voltage (kV). The nominal DC voltage of the system set in the main screen must be between these two values.
- "Pmax_ren (MW) is the maximum input power allowed from the photovoltaic generator and wind turbines

In addition, for each type, the efficiency (%) vs. the output power (in % of rated power, from 0 to 100%) must be defined. This is reflected in the graph.

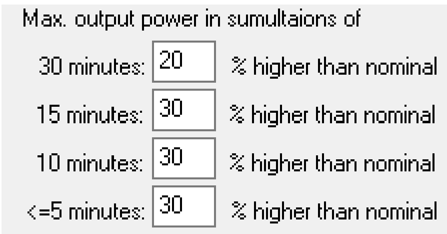
You can add inverters individually from the database using the "Add from database" button.

You can also force that only the inverters suitable for the rated voltage DC of the system and a particular family, by clicking on the button "Include only VDC suitable from family:", where they will be selected only those of the family that comply with the nominal voltage of the system.

Maximum output power in the simulation:

Permissible overloads can be defined in the case of simulations with time steps of less than 60 minutes.

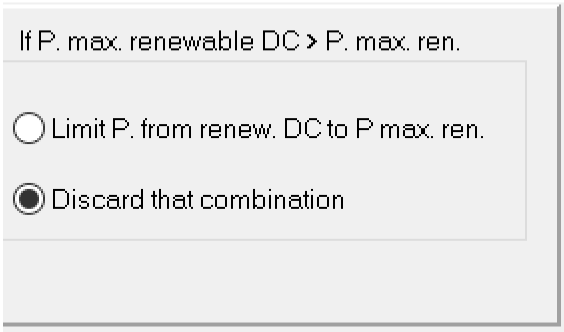
The maximum output power of the inverter must be settled, depending on the time step of the simulation:



Limitation of the power of the renewable DC generators:

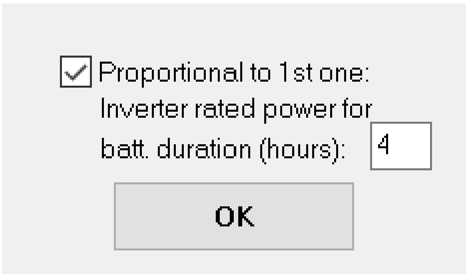
If "Discard that combination" is marked (default), the combinations in which the nominal power of the renewable sources in DC is higher than the maximum allowed input power "Pmax_ren (MW)" will be discarded (infinite cost will be assigned).

We can mark “Limit P. from renew. DC to Pmax. Ren”, in that case the combination will not be discarded, instead of this the power generated by the DC renewable sources is limited to said value.



Define the inverter-charger power depending on the battery duration wanted.

If you check the box "Proprtional to 1st one: Inverter rated power for batt. duration (hours)", for each combination of components, the inverter will be proportional to the 1st one of the table (the rest will not be considered), with a power for the number of hours duration of the battery (that is, the power in MVA will be the battery capacity in MWh divided by the number of hours you set). The CAPEX, the maximum charge current and the maximum input power allowed will be proportional to the 1st one of the table.

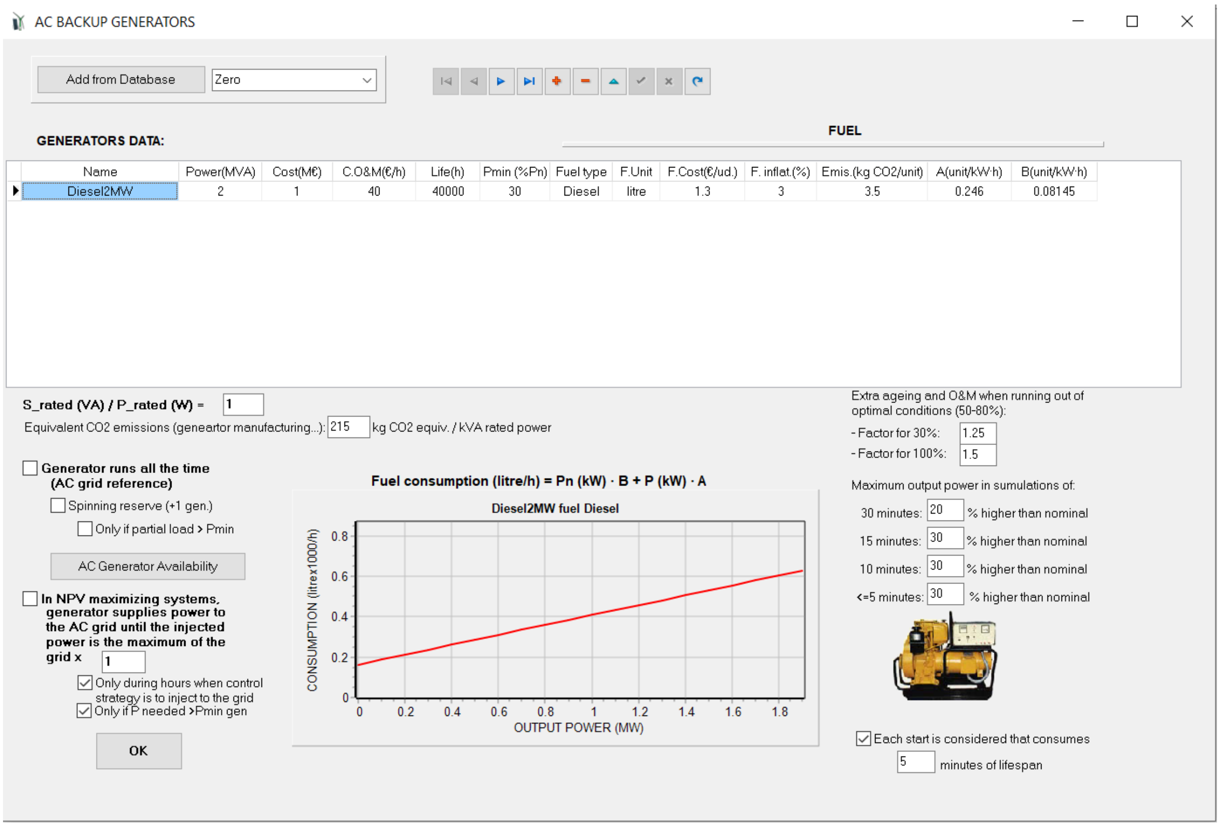


3.12 AC backup generators (diesel or other types)

By clicking on “BACKUP GEN.” (Components area), or selecting “AC Generators” in the Data menu the screen of the AC backup generators appears.

AC backup Generators include all sorts of fossil fuel generating sets, operated with diesel, petrol, biomass, hydrogen, and other fuel types, which are connected to the AC bus.

Generators can be added from database.



AC Generators data:

The following data must be introduced for each generator: Name, Rated Apparent Power (MVA), Acquisition Cost CAPEX (M€), Operation and Maintenance Cost (€/h), Expected Lifespan (h), Minimum Recommended Power (by manufacturer, as a percentage of nominal power), Fuel Type (choices provided include: Diesel, Petrol, Ethanol, Methanol, Natural Gas, Propane, Biogas, or H_2), Fuel Units (litre, kg, m^3 Normal), Fuel Price (€/unit), Annual Inflation Rate for Fuel Prices (%), CO_2 emissions (kgCO_2/fuel unit), and Consumption Parameters: A (fuel unit/kWh), and B (fuel unit/kWh). Default values for A and B are referred to a Diesel generator, as shown by Skarstein and Ullen (1989) (Skarstein & Ulhen, 1989).

The chart shows fuel consumption for the generator selected:

$$Consumption\ (fuel\ unit/h) = P_n(kW)\cdot B + P(kW)\cdot A,$$

where P_n is the nominal power in kVA, although active power is used for consumption; P is the output power.

The annual inflation rate for fuel prices (Inf_{fuel}) is an important parameter, and can be different to the general expected inflation rate (Inf_{gen}) shown in the main screen (see section 3.1.4). Most fuels are affected by higher inflation rates than those affecting components and labour costs. Fuel inflation rates must therefore be dealt with separately.

The relation between the apparent rated power and the real rated power must be set (default 1, but it is usually 1.2):

Data for the calculation of life cycle emissions must be set: equivalent CO_2 emissions in the manufacturing of the generator, recycling, etc. (kg CO_2 per kVA of rated power).

Force the generator to run all the time:

We can force the generator to run all the time to create the AC grid, in this case you should select the checkbox:

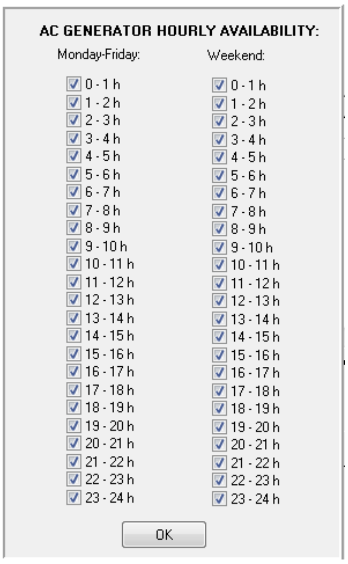
If you check the box 

, during each time step an extra generator will be on (to increment spinning reserve). If the checkbox 

is checked, the mentioned extra generator will be connected only if the partial load of all the generators (including the extra one) is higher than the minimum output power.

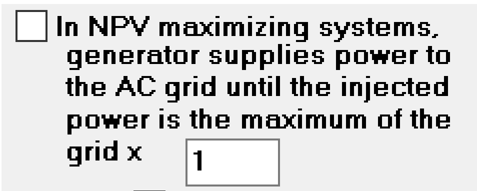
Time availability AC generator in the hybrid system:

We can set the time availability of the AC generator, both during the week and on weekends, clicking the "AC Generator Availability". By default, availability is total. If you want some hours to be not available, you must deselect the checkboxes for the corresponding hours.



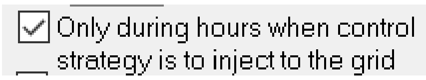
Inject power to the AC grid:

In NPV maximizing systems (systems where the generators inject electricity to the AC grid, and their incomes are from the electrical energy sold to the grid), the fossil fuel generator can be forced to inject power to the grid to be added to the electricity injected by the renewable sources and by the storage. The generator will try to inject the power needed so that the total power injected to the grid is the maximum allowed power that can be injected multiplied by a factor (default factor 1).



For example, if the maximum power allowed to be injected to the grid is 30 MW (LOAD/AC GRID window -> PURCHASE / SELL E tab -> Max. power of Sell excess energy to AC grid section), and the factor is 0.6, this means that the fossil fuel generator will try to inject power so that the total power injected to the grid (renewables + storage + fossil fuel generator) is 30·0,6= 18 MW.

Note that the maximum power that can be injected to the grid can have different values for each hourly period, if in LOAD/AC GRID window -> PURCHASE / SELL E tab -> section of Sell excess energy to AC grid, you select the checkbox "=Pmax buy" and in the section of Purchase from AC grid unmet load, you unselect "Fixed buy price" and *define hourly periods for the purchase of electricity and you unselect “Fixed Pmax” and define the power of the different periods for the purchase of electricity (see section 3.2).*

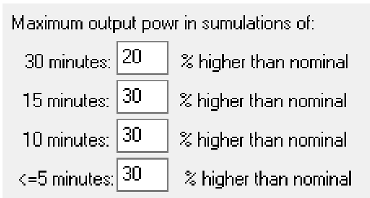
If the checkbox 

is selected, fossil fuel generator will only inject power to the AC grid during the time steps when the control strategy for the management of the storage is to inject to the grid (see section 3.1.3.2).

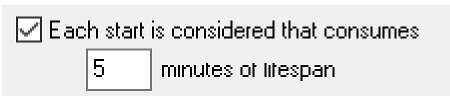
If the checkbox 

is checked, the generator will only inject power to the grid if the needed power to be injected to the grid (maximum allowed by the grid minus renewable power injected minus storage power injected) is higher than the minimum output power.

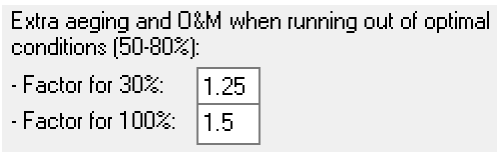
Permissible overloads for temporary steps of less than 60 minutes can be indicated:



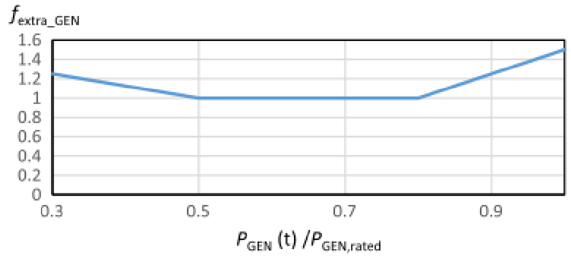
We can also count a penalty on the consumption during each start, default equivalent to 5 minutes running at full load:



In addition, it is possible to specify a penalty in the costs of operation and maintenance and in the useful life (extra ageing) for operating outside the optimal range:



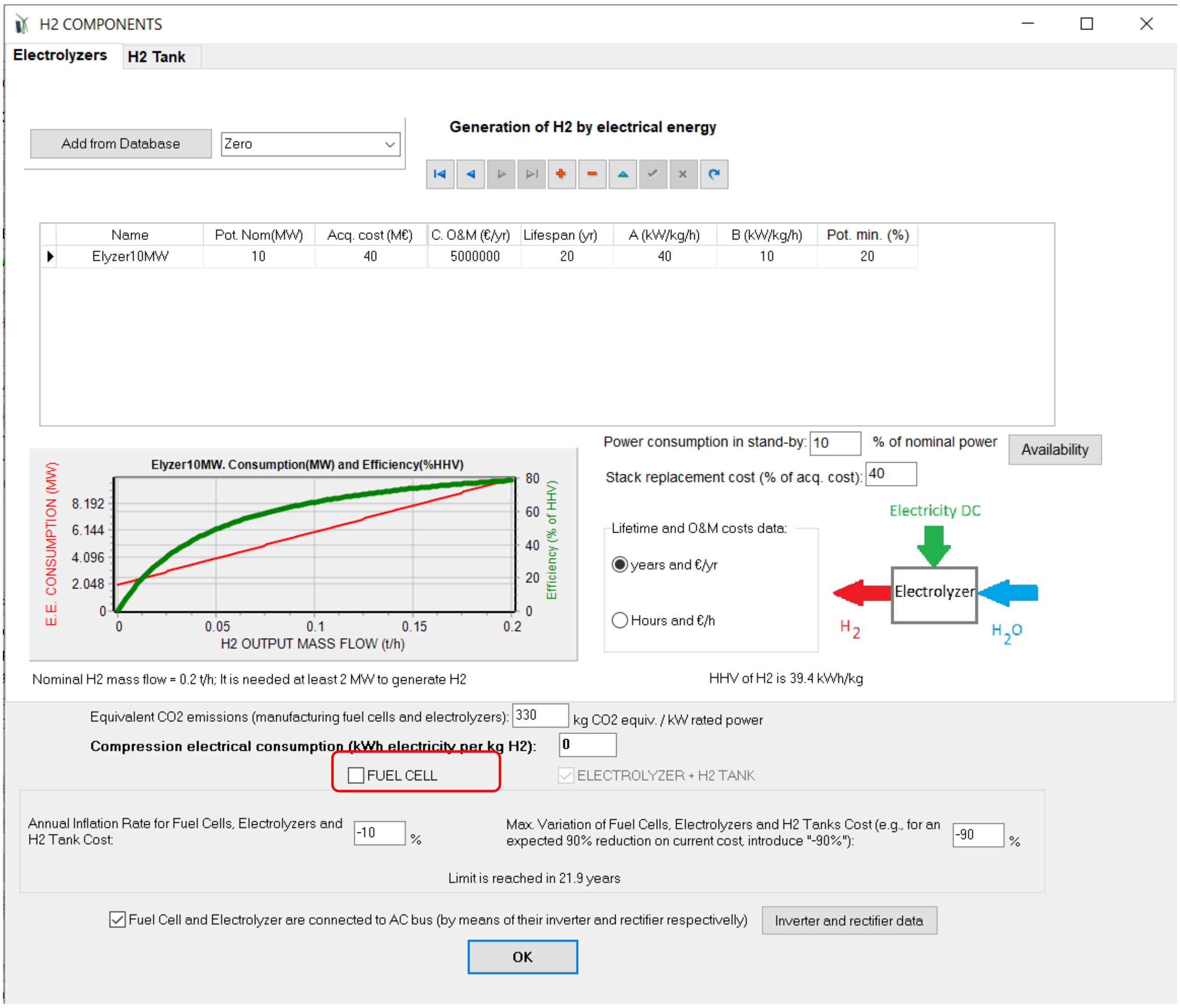
These factors are based on the work of (Rodolfo Dufo-López et al., 2017), where the following graph is shown indicating the extra maintenance and aging factor.



3.13 Fuel Cells and Electrolyzers.

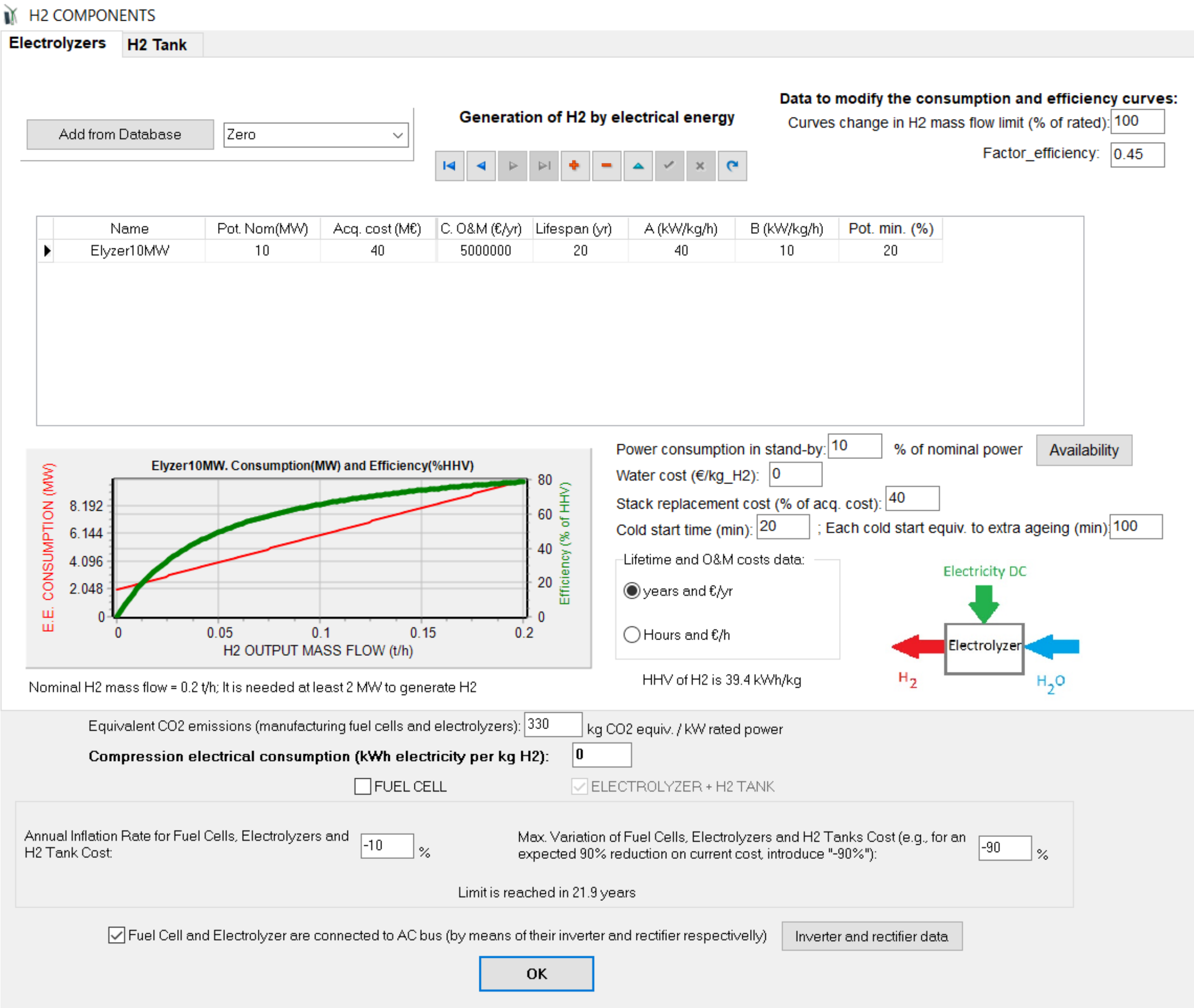
By pressing the button "H2 (F.C. - Elyzer.)" or in the Data menu "H2 (Fuel Cell –Electrolyzer)", we access the data screen of the Fuel Cells, the Electrolyzers and the H2 Tank. This screen has three tabs (by default only two), i.e. there are three screens in one. By default, fuel cell is not considered (just electrolyzer and H2 tank, for generating green hydrogen to be sold), but fuel cells can be considered by clicking the "FUEL CELL" checkbox under the graph.

By default, fuel cell and electrolyzer are connected to the AC bus.



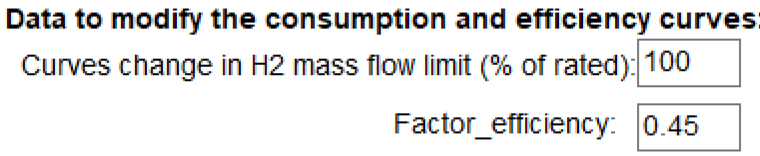
3.13.1 Electrolyzer

By clicking on the tab "Electrolyzers" the electrolyzer window appears.



Data that must be introduced: Name, Nominal Power (MW), Acquisition Cost CAPEX (M€), Operation and Maintenance Cost OPEX (€/year or €/h, depending on the option shown below), Expected Lifespan, Consumption Parameters A (kW/kg/h) and B (kW/kg/h), and Minimum Operating Power (as a percentage of nominal power).

In the upper right zone of the window, you can change the values of the H2 mass flow limit (%) and Factor_efficiency, which will affect the efficiency curve (of course, A and B parameters also affect).



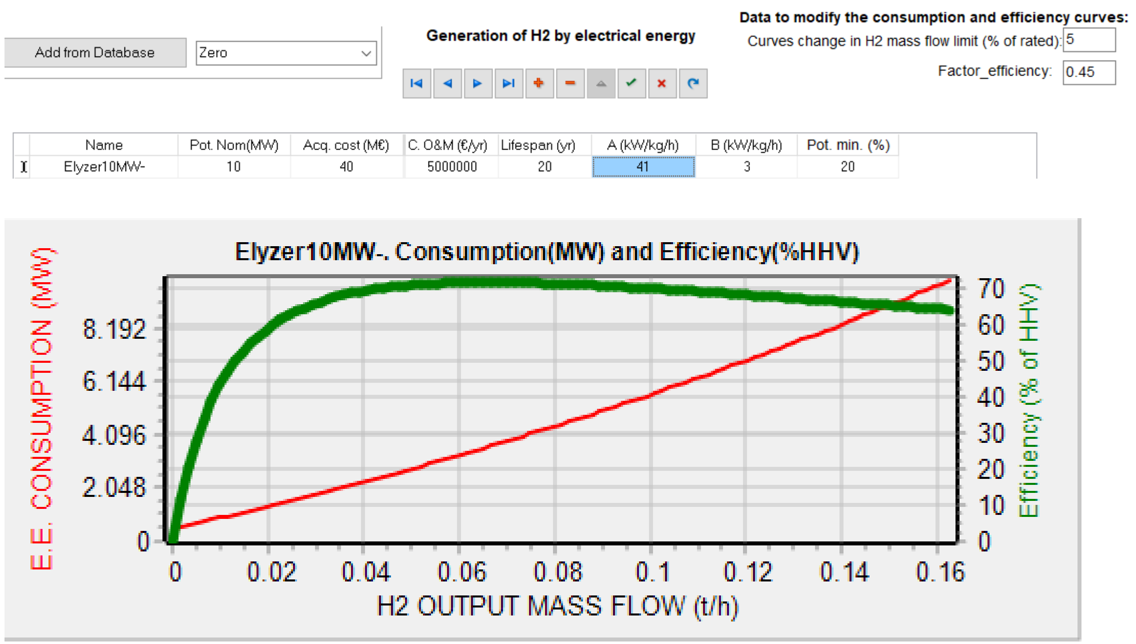
The electricity power consumption of the electrolyzer, P_E (kW) depends on the hydrogen production $H2_{prod}$ (kg/h) following the next equation, where Δt is the time step in hours, $\dot{H}2_{prod\_rated}$ is the rated hydrogen mass flow of the electrolyzer (kg/h), $\dot{H}2_{prod\_limit}$ (kg/h) is the limit defined (% defined multiplied by the rated hydrogen mass flow) and F is the Factor_efficiency defined (R Dufo-López et al., 2023)(https://doi.org/10.1016/j.ijhydene.2023.08.273).

$$P_E(t) = \frac{H2_{prod}(t) \cdot A}{\Delta t} + \dot{H}2_{prod\_rated} \cdot B, \qquad \forall\ H2_{prod}(t) \leq \dot{H}2_{prod\_limit} \cdot \Delta t$$

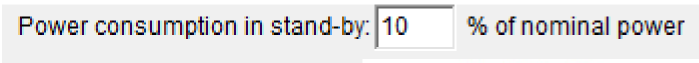
$$P_E(t) = \frac{H2_{prod}(t) \cdot A \cdot \left(1 + F \cdot \left(\frac{\frac{H2_{prod}(t)}{\Delta t} - \dot{H}2_{prod\_limit}}{\dot{H}2_{prod\_rated}}\right)\right)}{\Delta t} + \dot{H}2_{prod\_rated} \cdot B\,,$$

$$\forall\ H2_{prod}(t) > \dot{H}2_{prod\_limit} \cdot \Delta t$$

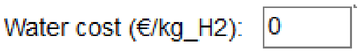
For example, if you change the values to: A = 41 kW/kg/h, B = 3 kW/kg/h, $\boldsymbol{\dot{H}2_{prod_{limit}}}$ = 5% of rated hydrogen mass flow and factor $\boldsymbol{F}$ = 0.45, values which fit with the real 4 MW PEM electrolyzer tested in the publication of Kopp et al. (Kopp et al., 2017), you obtain the following efficiency and consumption curves:



By default, when the electrolyzer does not work, it is in stand-by, which means that it will consume electricity (default 10% of its nominal power): in the simulations you will see that there is a load consumption by the electrolyzer that must be supplied by the rest of the system, it this load is not covered it will be counted as unmet load. You can change the percentage:

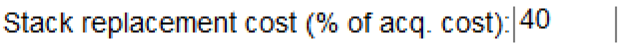


Water cost (in monetary unit divided kg of H2 generated in the electrolizer) can be defined in its box (by default, 0, not considered this cost):

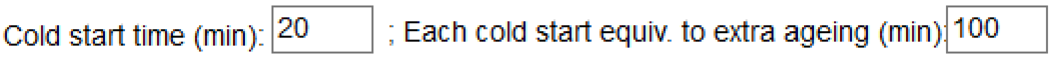


You can change the water cost in its box. For example, if the water price is 4 €/m3 and the consumption of water to produce hydrogen is 15 L/kg, a cost of 4 €/m3·0.015m3/kg = 0.06 €/kg of H2 should be set in the box. This cost is supposed to be increased each year with the general inflation.

The stack replacement cost (% of electrolyzer CAPEX) must also be defined in its box (when electrolyzer lifespan is reached, the stack will be replaced). By default a 40% of CAPEX is considered:

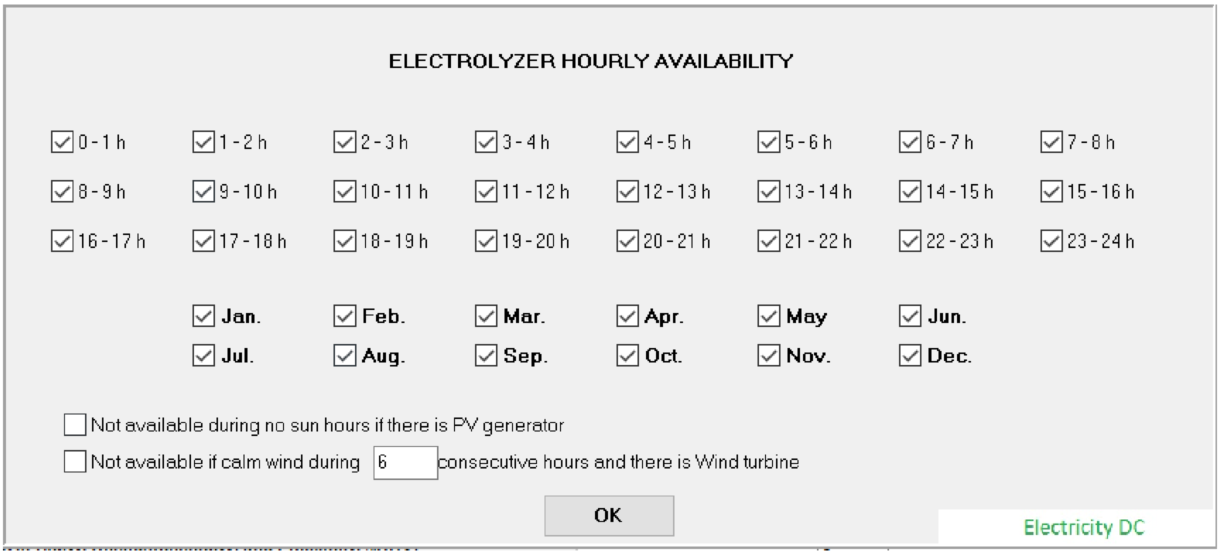


Cold start time (minutes) and equivalent extra ageing (minutes) due to each cold start must also be set:



With the button 

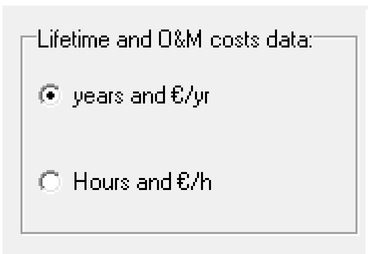
you can select the months and the hours of the day the electrolyzer is available:



In the lower zone of the window, if you click the first checkbox ("**Not available during no sun hours**…"), in PV systems, during night time the electrolyzer will be off. If you check the second checkbox ("**Not available if calm widn during…. consecutive**…"), in wind systems, the electrolyzer will be off if there are the number of hours hours consecutive with low wind speed (calm wind, defined in the WIND window). Be careful: if the number of hours set for the wind calm is high, the simulation and optimization time will be increased, as the software must evaluate during the whole year if the condition is met, and a high number of hours implies a lot of calculations.

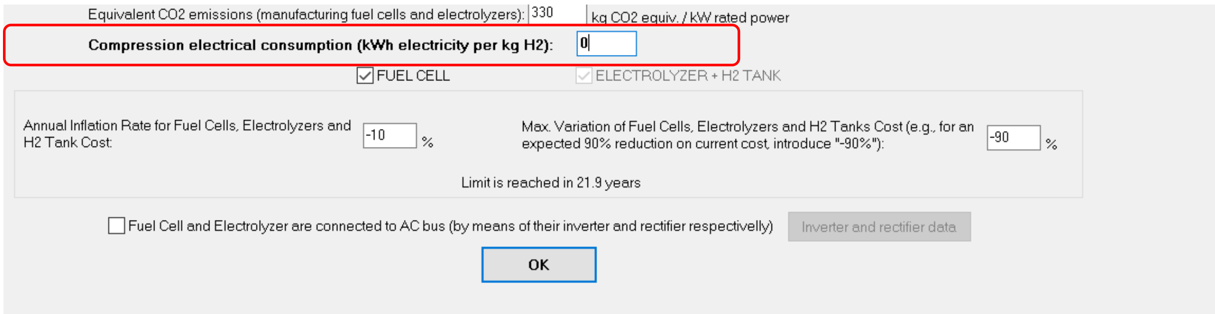
In PV+wind hybrid systems, if both checkboxes are checked, the electrolyzer will be off only during hours when both conditions are met (night and also number of hours in calm wind).

You must select the most appropriate units (bottom centre) for Expected Lifespan and Operation and Maintenance Costs (yrs and €/yr, or hours and €/yr):



Graph represents the electrical consumption and efficiency of the electrolyzer that is selected in the table. Below the graph it shows the nominal H2 mass flow (t/h) and the minimum electrical power needed to start generating hydrogen. In the case of the figure, the electrolyzer needs at least an electric power of 2 MW to begin generating hydrogen. In the simulation, if during a given time no more than 2 MW of power is available to operate the electrolyzer, it cannot generate hydrogen during that time (and therefore it will not work generate H2 that time).

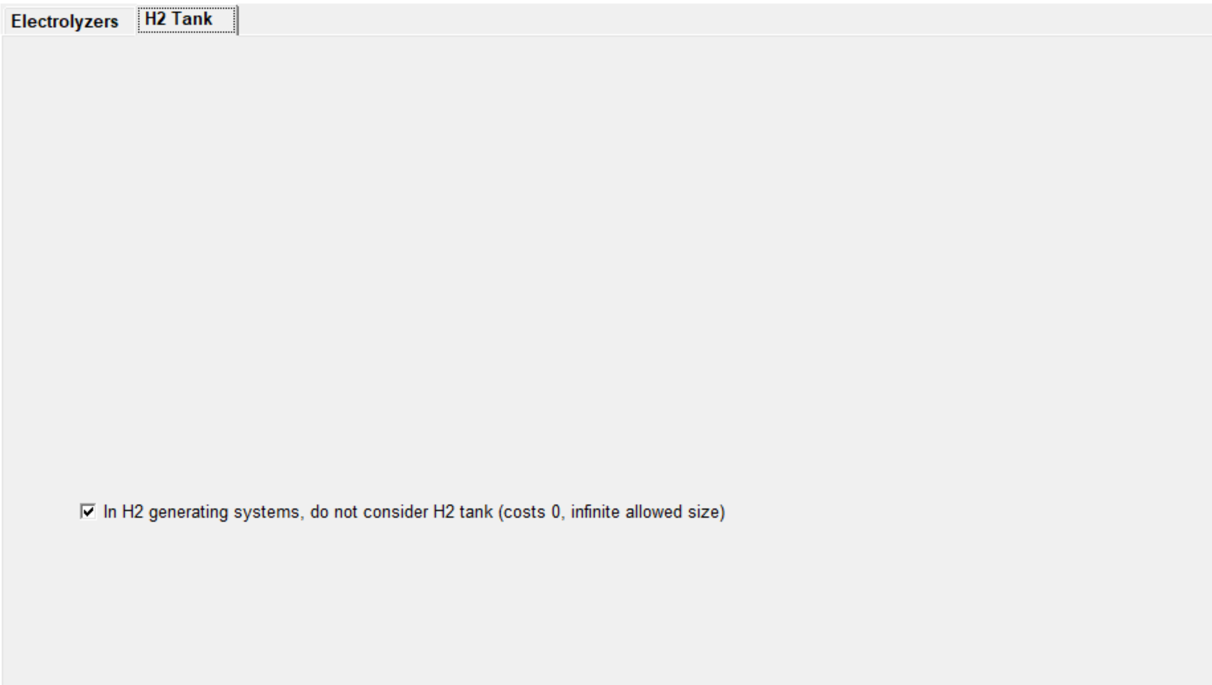
In the lower part of the screen we can see "Compression electrical consumption (kWh electricity per kg H2)". By default, it is 0, but we can change to the value corresponding to the energy needed by the compressor to compress 1 kg of H2. It depends on the output pressure of the electrolyzer and the pressure of the tank where we will store the hydrogen. For example, from 15 to 200 bar, around 2.4 kWh per kg H2.



3.13.2 H_2 tank.

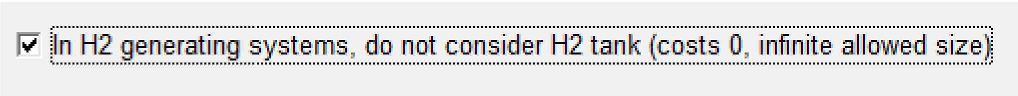
When MHOGA performs the simulation of each combination of components and control strategy, the H2 generated by the electrolyzer is stored in the tank, and it provides the H2 consumption and the H2 required by the fuel cell (in the case it is included in the system). Once the full year simulation is concluded, MHOGA selects the H2 tank size as the maximum tank capacity obtained during the simulation.

By clicking in the "H2 Tank" tab, we can see:



Green H2 generating systems:

If the following checkbox is checked (default in high power projects), no more data is shown for the H2 tank:



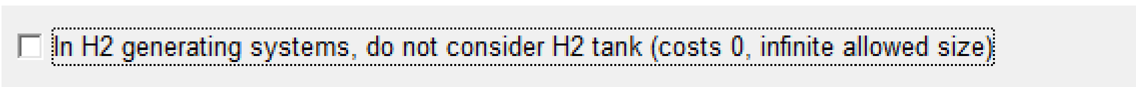
This checked box is used for green H2 generating systems, when we want to produce H2 by renewable sources in the electrolyzer and hydrogen will not be stored in our system (it can be stored temporally before selling it, but it will not be considered), hydrogen will be sold to external use and it will not be used by our system (typically there will not be any fuell cell nor internal H2 consumption). Maybe the H2 produced can be stored during a time, but finally it will be sold and it will not be used by our system.

In that case, no tank will be considered (really there can be a tank for temporal storage before selling the hydrogen, but the size and cost of this tank will not be calculated by MHOGA, size and cost of the tank will be known and we should include the tank cost into the electrolyzer cost). Therefore, as the tank will not be calculated by MHOGA, we will consider no cost of the H2 tank and infinite size will be allowed for the simulations. That is, in the simulations we will see how the H2 in the "virtual tank" is increasing as it is produced by the electrolyzer, without any limitation by the tank, because we want to sell all the H2 produced by the electrolyzer. Remember, if you want to allow the selling of the H2, in the "LOAD / AC GRID" window, tab "PURCHASE / SELL E" you must check the box "Sell surplus H2 in tank….", and you must indicate the H2 sell price (€/kg) and its annual inflation (see end of section 3.2).

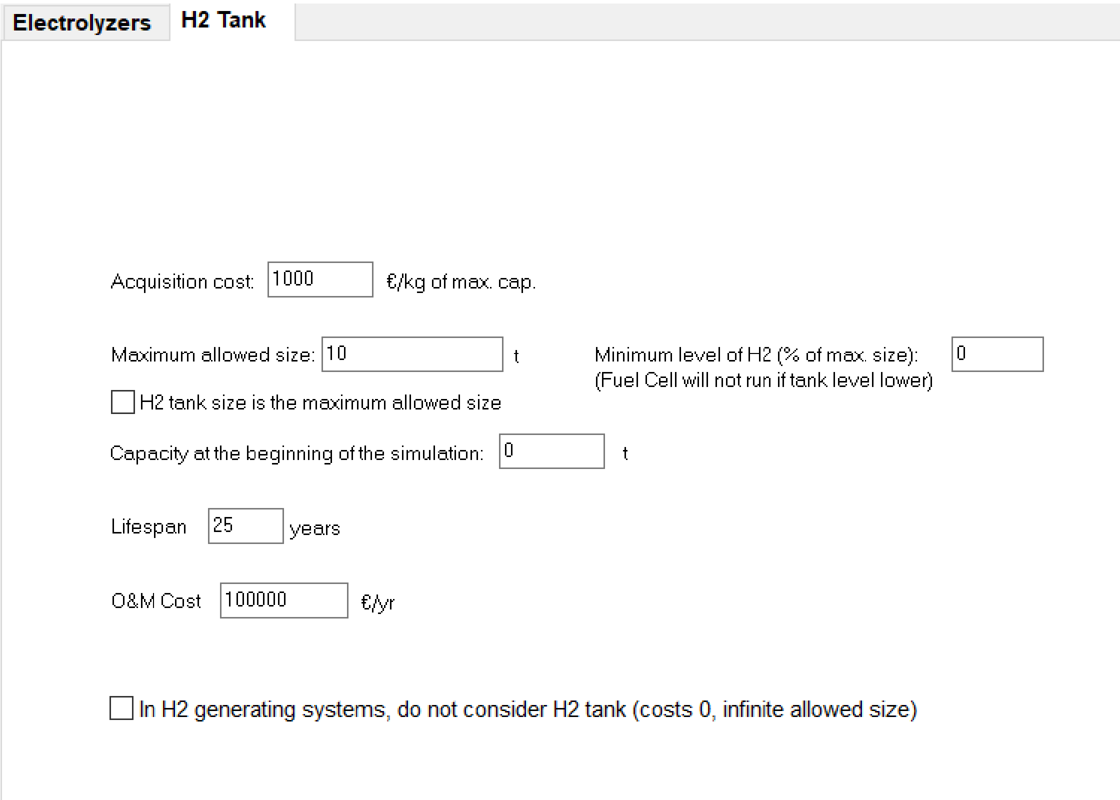
H2 tank for systems with fuel cell or with H2 load consumption:

In the case there is a fuel cell or there is H2 load consumption, as previously said, the H2 generated by the electrolyzer is stored in the tank, and it provides the H2 consumption and the H2 required by the fuel cell (in the case it is included in the system). Once the full year simulation is concluded, MHOGA selects the H2 tank size as the maximum tank capacity obtained during the simulation (unless you select the option "H2 tank size is the maximum allowed size", in that case the tank size will be always the maximum value set).

We uncheck that option:



And the H2 tank data appears:



The tank cost must be estimated, in €/kg of capacity, and a maximum allowed tank size must be set (default 10 t). Note that when simulating, during a time step, if the tank capacity has reached the maximum allowed tank size, the hydrogen generated by the electrolyzer during that time step will not be taken into account as the system will not be able to store it. Therefore, the maximum allowed tank size must be correctly settled.

Also the minimum level of the hydrogen tank (in % of the maximum size) must be set. By default, it is 0, but it can be changed to a different percentage. If the tank is below that level, fuel cell will not work.

If you select the checkbox "**H2 tank size is the maximum allowed size**", in that case the tank size will be always the maximum value set, the software will select H2 tank size as the maximum tank capacity obtained during the simulation.

Additional estimations must be made of the initial tank quantity of H2 (i.e., H2 at the beginning of the simulation), in t, as well as of the expected lifespan and the operation and maintenance costs for the tank (€/year).

3.13.3 Fuel Cell

By clicking in the checkbox 

, the Fuel Cell tab appears.

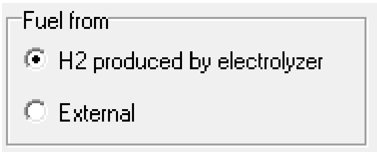
By clicking on the tab "Fuel Cells", the window of the fuel cells appears, where we can add, delete or change data.

You can define the months and hours of the day when the fuel cell is available with the button 

.

In the "Fuel Cells" tab, you can choose several configurations for the fuel cell fuel consumption:

- Fuel cell that consumes the H2 produced in the electrolyzer (and accumulated in the H2 tank).
- Fuel cell that consumes external H2. In that case there is no need for an electrolyser nor the H2 tank. In this case electrolyzer and tank will be required only if there are loads of H2.



At the bottom of the screen we can choose whether or not we want fuel cell and whether or not we want an electrolyzer and H2 tank.

Note that when we have selected that we want fuel cell and in addition the origin of the fuel is H2 produced in the electrolyser, there must be an electrolyzer and H2 tank where the H2 is stored, so the electrolyzer and tank are mandatory (they cannot be deselected).

If there is any element that we do not want, deselecting its checkbox will disappear the corresponding tab.

<u>Data of the fuel cells:</u>

In the table of the fuel cells we must introduce the following data for each fuel cell to be considered: Name, Nominal Power (MW), Acquisition Cost (€), Operating and Maintenance Cost (€/h), Consumption parameters: A_{FC} (kg / kWh) and B_{FC} (kg / kWh). P_{max_ef} (%) is the power of maximum efficiency, it is applied the correction factor F_{ef} (for consumption penalty to adjust to the actual curves of consumption and efficiency of the fuel cells). The fuel consumption curve for output power P (kW) is obtained as follows:

If $P/P_{N\_FC} \leq P_{\ max\_ef}$ (%):

$$Cons_{FC} = B_{FC} \cdot P_{N\_FC} + A_{FC} \cdot P$$

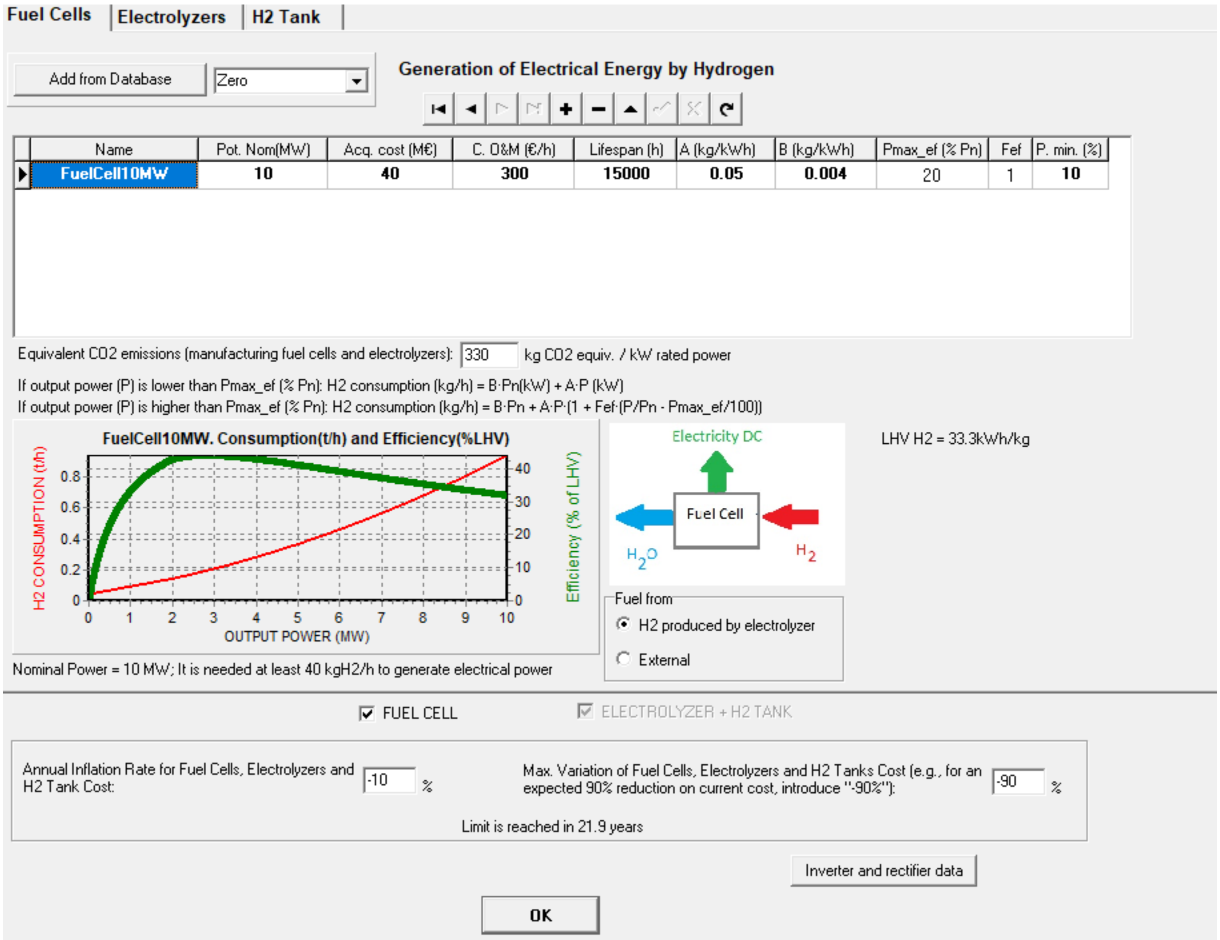
If $P/P_{N\_FC} > P_{\ max\_ef}$ (%):

$$Cons_{FC} = B_{FC} \cdot P_{N\_FC} + A_{FC} \cdot P \cdot \left(1 + F_{ef}\left(\frac{P}{P_{N\_FC}} - \frac{P_{max\_ef}(\%)}{100}\right)\right)$$

Where P_{N_FC} is the nominal power in kW.

It must also be set the minimum output power (%).

The graph shows the consumption and efficiency curves (in % of the LHV of the H2) versus the output power of the fuel cell that we have selected in the table. The H2 Lower Heating Value (LHV) is 33,000 Wh / kg, while the High Calorific Power (HHV) is 39400 Wh / kg.

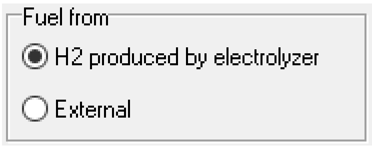


The graph of consumption and efficiency of the fuel cell that is selected in the table is represented. Below the graph it shows the nominal power of the fuel cell (MW) and the minimum amount of H2 required to start generating electricity. In the case of the figure, the fuel cell needs at least a hydrogen mass flow rate of 40 kg/h to enable it to generate useful power. If the fuel cell uses H2 from the tank previously generated by the electrolyzer, in the simulation, if for a given hour there is no more than 40 kg in the tank, the fuel cell will not be able to generate any electricity during that hour (and therefore will not work during that hour).

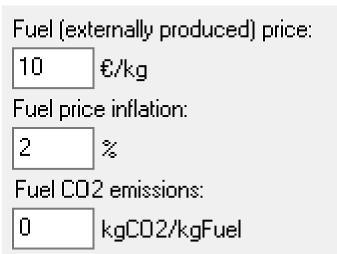
As explained in the previous sections, if we are interested in the calculation of the life cycle emissions, we must enter (below the table) the equivalent CO_2 emissions due to the manufacture of the fuel cell and of the electrolyser, in g of equivalent CO_2 per kW of nominal power. It depends on the technology.

<u>Origin of fuel used by the fuel cell:</u>

Click on the check boxes (bottom right) to select the origin of the fuel to be used by the fuel cell. The default value is "H_2 produced by electrolyzer". This implies that an electrolyzer is in the system and it will generate H_2 with the excess energy. H_2 is stored in the tank, and is used by the fuel cell to produce electricity when necessary.

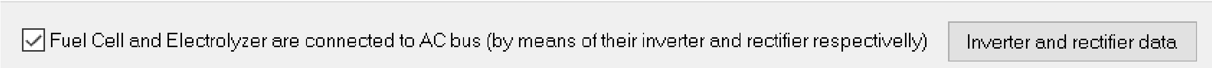


If the origin of the fuel is "External", no electrolyzer will be required. In this case, use of a tank will depend upon the fuel supplier (this is not the H_2 tank), and the check box is enabled to include/exclude an electrolyzer and an H_2 tank. In this case, the fuel used by the fuel cell (H_2 or other fuel as methane with reformer) is purchased externally, and additional data must be estimated, as shown below (bottom right):



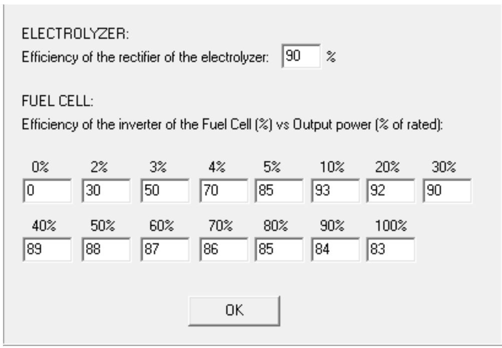
Fuel Price (€/kg), (note that fuel is estimated in kg, even for a gas, as weight does not vary with pressure and temperature), expected annual **Fuel Price Inflation** rate for the fuel to be used by the fuel cell (%), and **CO_2 emissions** from the fuel used by the fuel cell ($kgCO_2$ / kgFuel).

By default, fuel cell and electrolyzer are **connected to the AC bus**:

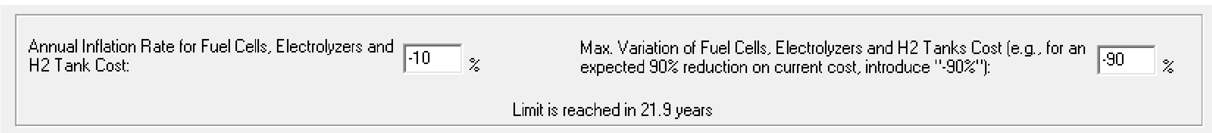


At the right bottom of the window there is the button "**Inverter and rectifier data**":

By clicking it a small window appears, where we must introduce the efficiency of the rectifier needed to supply the electrolyzer and the efficiency of the fuel cell inverter:



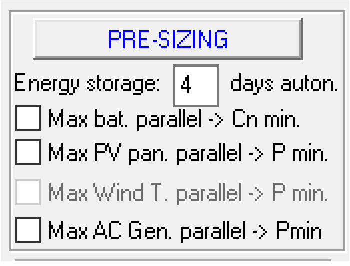
As explained in the PV generators screen, the expected inflation of the price of hydrogen components and their limit appears in the lower part of the screen, in order to take them into account in case they have to be replaced during the system lifetime.



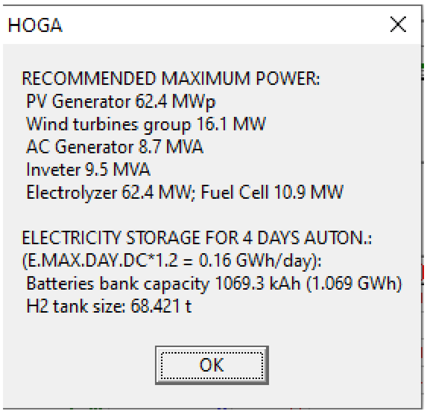
3.14 PRE-SIZING.

After setting the load, resources and types of PV generators, wind turbines, batteries and AC generator (if any), we can perform the pre-sizing.

It can be used only if there is any load in the system. If there is no load in the system (generating systems), using PRE-SIZING will have no sense.



By clicking on the "PRE-SIZING" button button it displays a window with information of the maximum power recommended for the different components:



The following recommendations are for systems that must cover a specific load consumption. If the system sells electricity and/or H2, these recommendations can be not suitable.

- MHOGA knows the energy demand load of the system and the irradiation, so it calculates approximately the peak power of the PV generator to cover that demand only with photovoltaic (estimating an average value of inverter efficiency of 80%, losses in batteries of 20%, assuming all the energy goes through the batteries and adding the efficiency due to degradation of the PV modules, losses in wires, etc. defined in the PV window). This peak power (in the example 62.4 MWp) should be the maximum power of the photovoltaic group that MHOGA can be allowed for optimization. For example, if we use 10 MWp generators, in the main screen, where we select the maximum allowed number of PV generators in parallel, we should not put a number much higher than 62.4 / 10 = 6.24 -> 7 in parallel, for example, we could set 7 as the maximum number of parallel PV generators allowed.

-MHOGA knows the energy demand and the wind speed throughout the year, so it can roughly calculate the power of the group of wind turbines to cover the total demand. In the example, this value is 16.1 MW, so if in the wind turbine screen we consider wind turbines of around 2 M, it would not be necessary more than 8 in parallel to cover the load demand.

- The maximum recommended power for the AC backup generator is the one needed for it to supply the entire demand load, taking into account an efficiency of 90% for the rectifier.

- The maximum recommended power for the inverter is the necessary power to cover the AC load.

- The maximum recommended power for the electrolyzer is the maximum between the maximum recommended power of the PV generator, that of the wind turbine group and that needed to cover the maximum demand for hydrogen (if applicable).

- The maximum recommended power for the fuel cell is the one needed to cover the maximum power, taking into account an inverter efficiency of 80%.

In these calculations the following starting data have been used: 90% rectifier efficiency, inverter efficiency 80%, electrolyzer efficiency 70% of HHV of H2, fuel cell efficiency 40% of LHV of H2, minimum SOC allowed for batteries 20%. In calculations of the maximum recommended power for the photovoltaic generator and for the group of wind turbines an oversize factor of 1.2 has been considered, taking into account the losses in storage (note that this factor is too low if the storage is performed in hydrogen).

In addition, the capacity of the battery bank and the size of the hydrogen tank are shown to have a number of days of autonomy set under the PRE-SIZING button, 4 days by default. It takes into account the day of maximum consumption of the year converted to DC taking into account an efficiency of the inverter of 80% and with a factor of oversizing of 1.2.

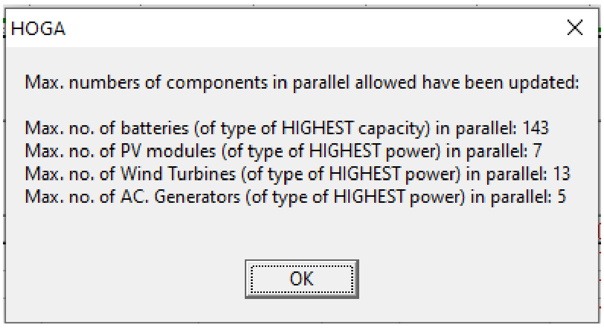
MHOGA calculates the maximum number of batteries in parallel of the type of HIGHEST capacity of those fixed in the battery screen, so that the batteries can supply the load during the days of autonomy fixed (the nearest upper integer is shown). It must be taken into account that the battery of greater capacity can cover the days of autonomy if the number in parallel is the maximum. However, it is possible that the other batteries cannot cover all the days of autonomy.

If the box "Max. bat parallel -> Cn min." is checked, the maximum number in parallel is calculated according to the type of battery of LOWEST capacity. Thus all the batteries would be able to cover the autonomy, if the number in parallel was the maximum.

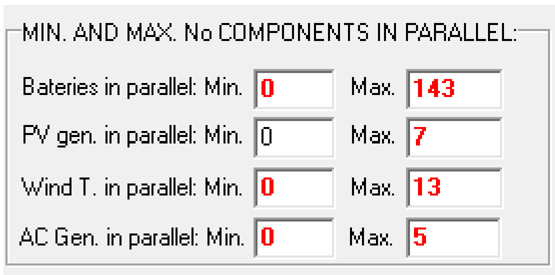
It also calculates the maximum number of PV modules, wind turbines and AC generators. The number of PV modules in parallel is obtained as the upper integer of the division of the maximum photovoltaic power recommended by the DC voltage of the system and by the power of the panel type of HIGHEST power. If the box "Max. PV pan. Parallel -> P min." is checked, the maximum number of PV modules in parallel is calculated according to the panel type of LOWEST power.

Similar calculation is performed for the maximum number of wind turbines in parallel and for the maximum number of AC generators.

By clicking on the "OK" button, MHOGA informs you of the maximum numbers of allowed components being updated on the main screen.

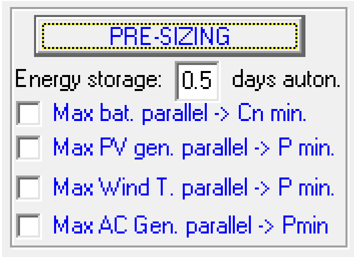


The updated values appear in red:

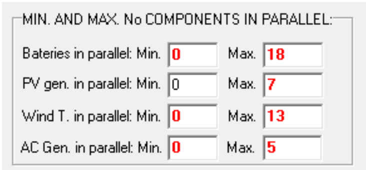


In this example, 143 batteries in parallel would be no-sense, but that value has been selected because we wanted 4 days of autonomy: as the batteries selected are of 5 MWh, to cover 4 days the load demand of 100 MWh/day, including losses and considering minimum SOC, 143 batteries in parallel would be needed.

It is not normal that batteries must cover 4 autonomy days in MW systems, you could change the number of autonomy days for example to 0.5 and click in PRE-SIZING again.



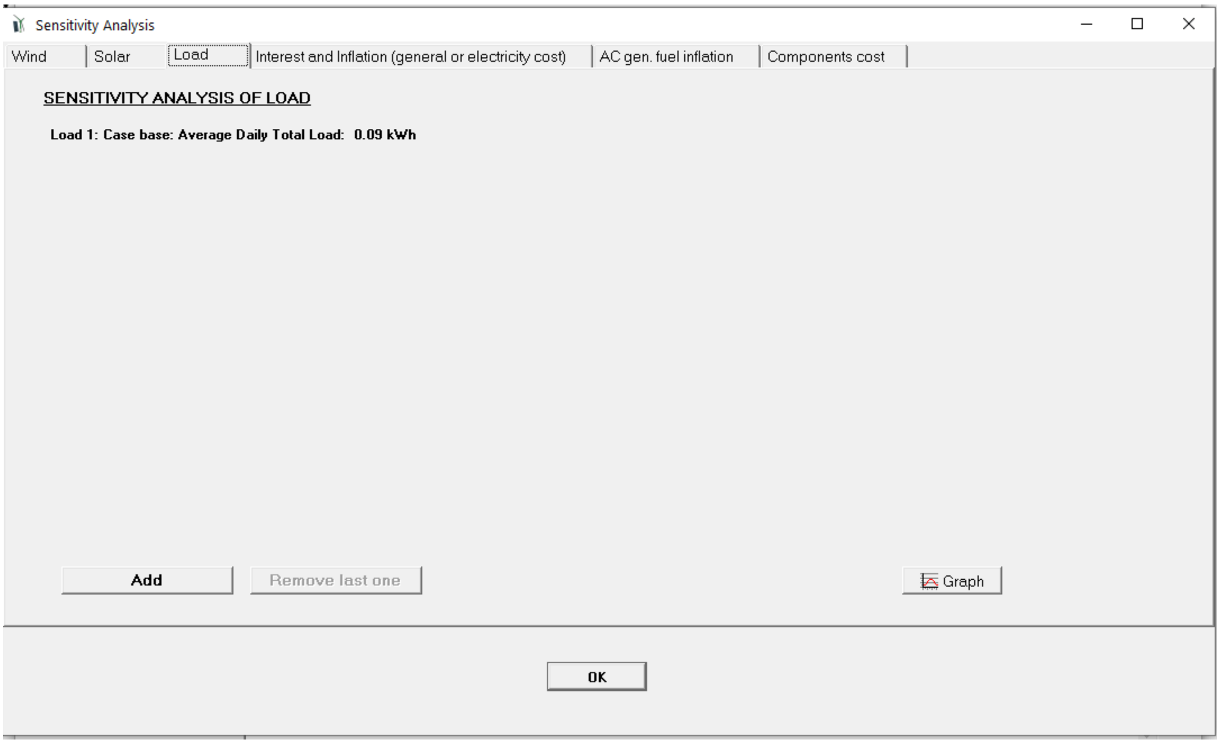
We obtain now 18 batteries in parallel as the maximum allowed. Obviously we can change this value and the rest, if we want.



3.15 Sensitivity analysis.

Sensitivity analysis can only be performed for 60 minute simulation steps.

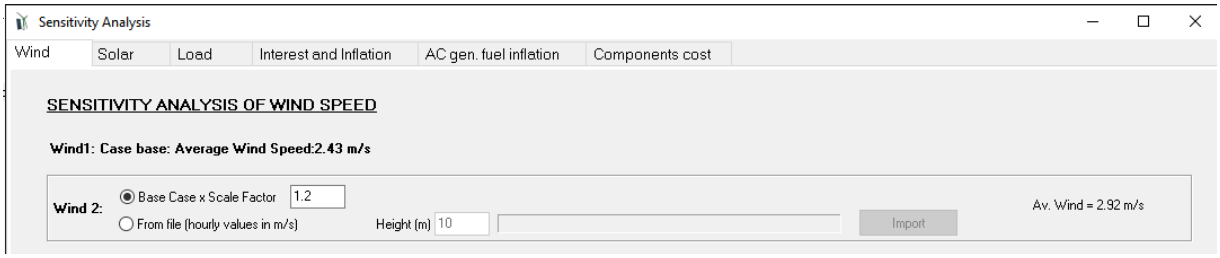
After entering all the data of resources and components, the button of the main screen "**Sensitivity Analysis**" is enabled. When you click on it, the following screen appears (if you have not entered all the consumption data and resources, a message will appear saying that you have to enter the data first):



The screen has 6 tabs where you can enter the data so that MHOGA performs the sensitivity analysis..

Sensitivity of wind speed (Wind.x).

In the first tab, the base case (the wind obtained in the wind screen, if wind is used in the system) is called Wind.1 and it is shown the average speed of the year. Clicking on the "**Add**" button you can add another series of 8760 hourly values of wind speed to consider them as the case Wind.2. You can choose to calculate the series Wind.2 as the base case (Wind.1) multiplied by a scaling factor or to import a series of 8760 values in m/s from file. If you import from file, if the file is .vto it incorporates the measurement height. If another type of file, we put in the height field (m) the value of the height above ground at which the measurement was made. At the right of the case Wind.2 the annual average wind speed is reported.



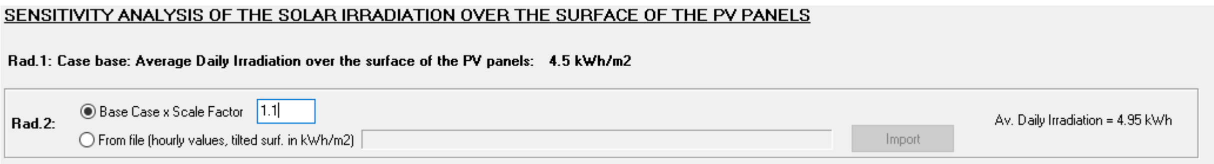
You can add up to a total of 5 cases of wind for sensitivity analysis (base case and four others). The last introduced case can be deleted by clicking "Remove last one". By clicking on the button on the bottom right "Graph" the different series are plotted. Each case will be considered in a different optimization, i.e. MHOGA performs the optimization of the system for each case Wind.x. If we have 3 cases of wind (the basis Wind.1, Wind.2 and Wind.3) MHOGA considers three different cases to optimize (3 sensitivity analysis). If there are more variables considered for the sensitivity analysis (other tabs), then the number of optimizations that will run MHOGA includes all possible combinations. For example, if we have 3 cases of wind for the sensitivity analysis and 2 cases of irradiation (introduced in the 2nd tab) the number of optimizations that will run MHOGA are 3x2 = 6 optimizations. Adding more variables in the analysis of sensitivity, the number of optimizations will be multiplied by the number of cases of each variable.

Sensitivity of global irradiation over the surface of the PV modules (Rad.x).

In the 2nd tab we accede to cases of sensitivity analysis of irradiation. As in the case of wind, using the "Add" button you can add up to 5 cases and you can delete the last entered using the button "Remove last one". Each case is called Rad.x, Rad.1 being the base case, case 2 is Rad.2, etc.

Each case can be defined by a scale factor multiplying the base case or importing in 8760 kWh/m2 hourly values from file. Irradiation imported must be on the tilted surface of the PV modules, not on a horizontal surface.

If a sensitivity analysis of irradiation is done, the optimization of the PV modules during the optimization of the system is not possible.



By clicking on the button on the bottom right "Graph" the different series are plotted.

Sensitivity of Load (Load.x).

In the 3rd tab we accede to cases of load sensitivity analysis. As for the other variables, we can add up to 5 cases. Each time we add a new case, we are reminded that if we chose on the screen of inverters the option in which the inverter is selected to cover the maximum power load, it is possible that, in some cases, the peak consumption is higher than the peak base case, and the system could not meet the demand because the inverter selected can be too small. In that case, deselect this option on the display of Inverters. In the case of import from file, this should be 8760 * 4 = 35040 rows. The first 8760 hourly values should be AC load in W, 8760 following DC load values in W, the following 8760 data are the hydrogen load in kg/h and 8760 last data is the volume of water consumption in m3/s for each hour (the height of pumping losses, pump data, etc. are the same as in the base case).

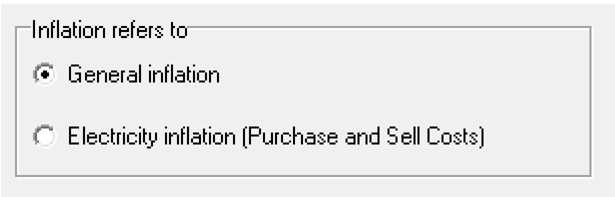
By clicking on the button on the bottom right "Graph" the different series are plotted.

Sensitivity of interest rate (I) and inflation rate (general or electricity cost), (I-g)x.

In the 4th tab we accede to cases of sensitivity analysis of the economic parameters to calculate the NPC: annual interest rate, I (%) and annual inflation g(%). Inflation can be:

- General inflation (%), used for the price of several components (for when you have to replace them) and costs of operation and maintenance
- Electricity cost inflation (%)

You can select which inflation refers to by selecting in the box "Inflation refers to":



Sensitivity of the inflation rate of the fuel consumed by the AC generator (Inf.F.x).

In the 5th tab we accede to cases of sensitivity analysis of inflation in the cost of fuel of the AC generator. The base case (Inf.F.1) uses the values in the table of the AC generators of the screem where they are defined (not specified here as there may be several cases, as there may be several generators that use different fuels: diesel, gasoline, etc..). The cases we add we set a specific value in % annual increase for different fuels (all the same). For example, if 15% Inf.F.2 means in this case all fuels increase their price by 15% every year.

Sensitivity of acquisition cost of the most relevant components (Pr.x).

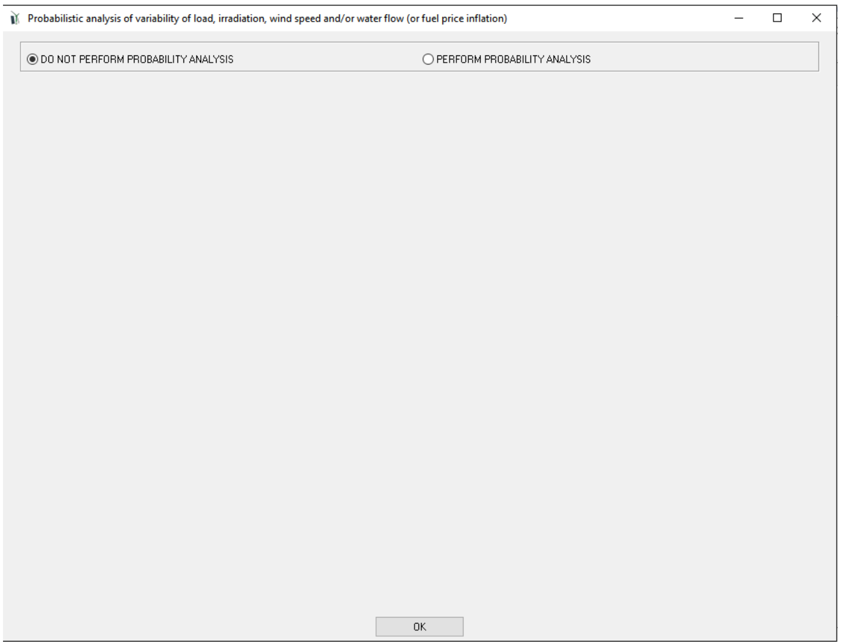
In the 6th tab we accede to cases of sensitivity analysis of the acquisition price of photovoltaic modules, wind turbines, batteries and hydrogen components.

For each case of the sensitivity analysis, we will set a scale factor for each type of component that will multiply the purchase price of each component (acquisition cost) at their screens. For example, in the case Pr.2 we can considered the costs of the PV modules to be the 50% of what we have set on their screen, the same in wind turbines, batteries to 70% of the price set on their screen, and hydrogen components (fuel cell, electrolyzer and hydrogen tank) 30% of the fixed on their screens.

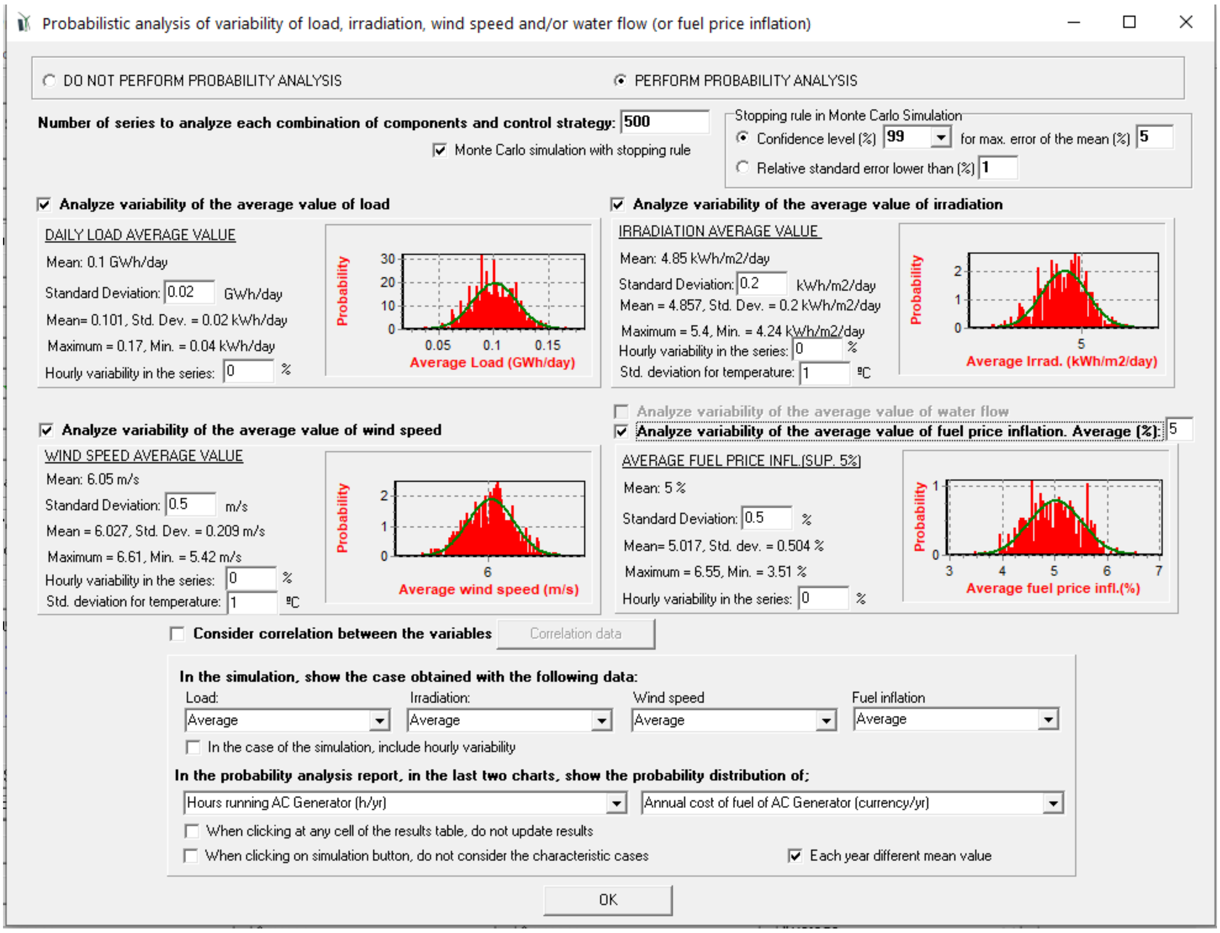
3.16 Probability Analysis.

Probability analysis can take a long time if the steps of the simulation are of less than 60 minutes, so steps of 1 hour are recommended.

Once the data of resources and components have been fixed, the data of the study of the probability analysis can be accessed by means of the button **"Probability Analysis**" of the main screen. The next screen appears:



By default the probability analysis is not ready. To indicate we want probability analysis, click on "PERFORM PROBABILITY ANALYSIS" and the following screen appears, in which the checkboxes "Analyze variability of the average value of load", "Analyze the variability of the average value of irradiation", "Analyze the variability of the average value of wind speed " and "Analyze the variability of the average value of fuel price inflation " have been checked.



With this analysis, for each combination of components and control strategy to be studied, N combinations of different time series of load and resources (and fuel inflation) will be performed using Monte Carlo Simulation, according to the methodology presented in the works (Rodolfo Dufo-López, Pérez-Cebollada, et al., 2016)(Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016b). Each time series of load and resources will be obtained from the original series, but its mean value will be obtained according to a Gaussian probability distribution, with mean the original mean value and standard deviation (also called standard deviation) the value fixed in this screen.

N, the number of series to calculate for each combination of components and control strategy (default 500) must be set. If a very low value is set, the distribution that is obtained may not look much like a Gaussian distribution.

The probability analysis can be performed taking into account the Gaussian distribution of the mean annual values of:

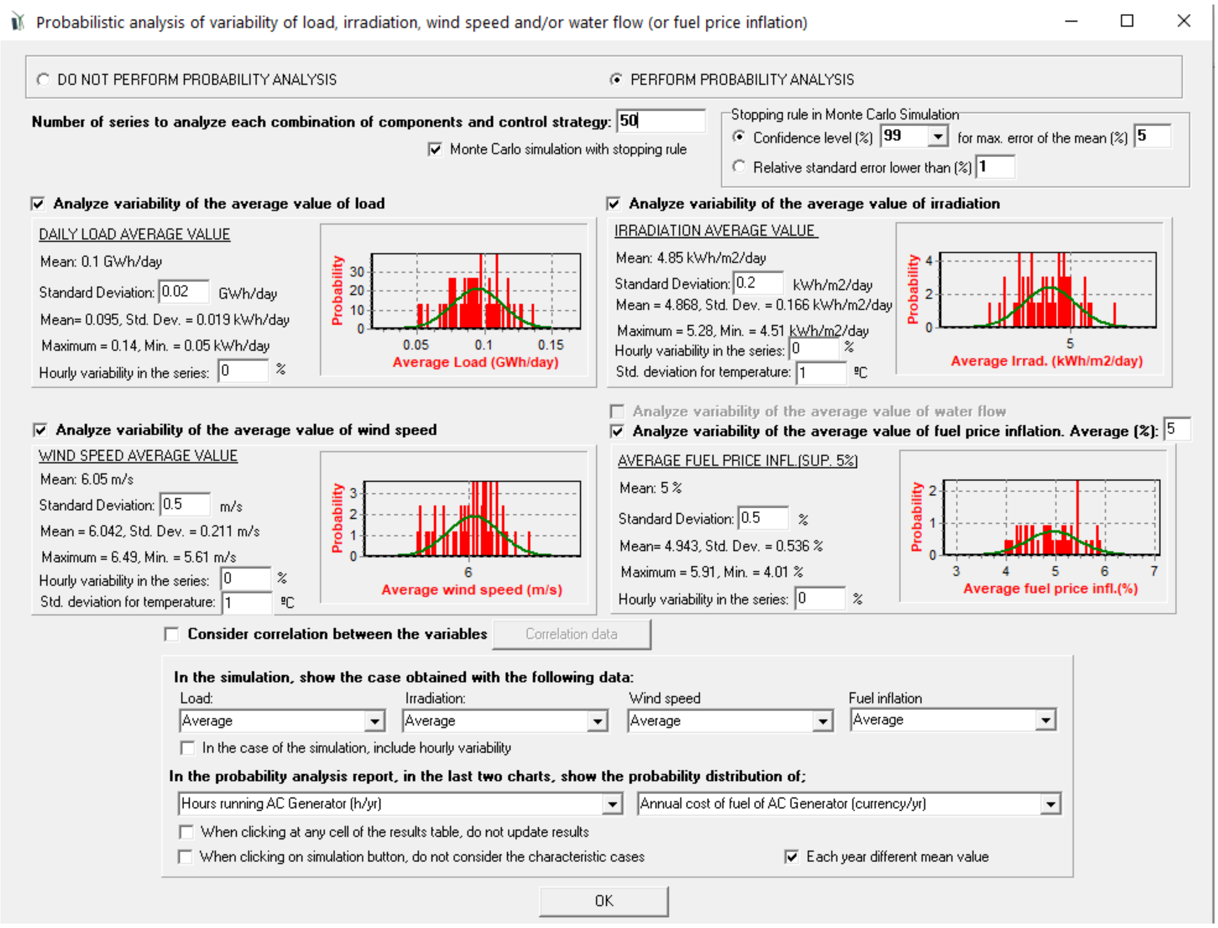
- Average load

- Irradiation (only if photovoltaic modules have been selected in the system)

- Wind speed (only if it has been selected that there may be wind turbines in the system)

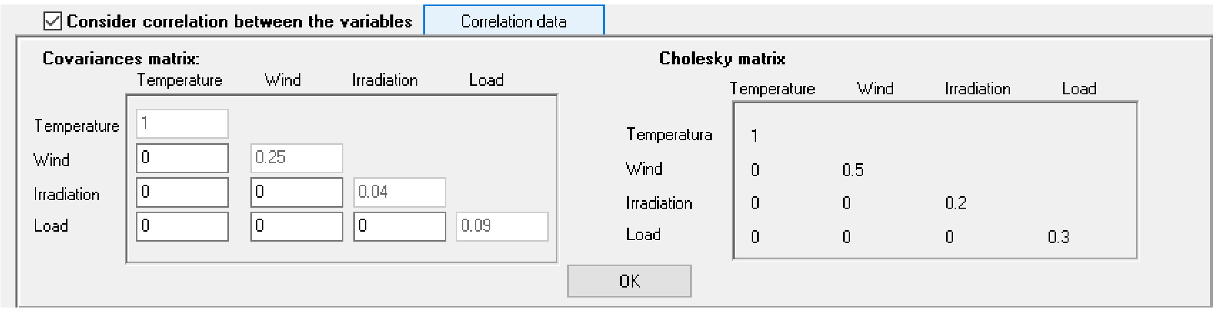
- Water flow (only if water turbine has been selected in the system) or fuel price inflation (if there is an AC bakcup generator).

The average values are those that have been fixed in the screens of load and resources. Standard deviations should be set for each case on this screen. For each case the probability distribution curve is shown in red, taking into account the number of N series that has been set (default 500) and in green the ideal Gaussian probability distribution curve. If a small value is set for the number of series (for example, N = 50), it is observed that the actual distribution may be very different from the ideal one (figure below), which is not recommended:



Each one of the N time series of a full year (and also in 1-minute time steps) (load, irradiation, wind speed and water flow, if any) will be generated according to the mean value randomly obtained following the Gaussian distribution, multiplying that value by the hourly values of each original series obtained in their respective screens and dividing by the original average value. That is, each time series will be proportional to the original. We can also consider hourly variability in the series, default 0%.

If you click on the "Consider correlation between the variables" box, and click on "Correlation Data" button, a small screen with the data of the covariance matrix that relates the load and the meteorological data appears. Then the Cholesky matrix is obtained which will then be used to obtain random data following the indicated correlations (Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016b).



If the box 

is selected (down right), and the Schiffer model of batteries is selected, as the simulation is done for several years, each year will have a different mean value, as was done in (Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016b).

During the optimization of the system, each combination of components and control strategies is simulated N times. Each of these simulations includes a random series of load (following its mean and its standard deviation), a random series of irradiation (in case there are modules, and following its mean and its standard deviation), a random series of wind speed (if there are wind turbines, and following their mean and standard deviation) and a random series of water flow (if there is a turbine, and following its mean and standard deviation) or a random value of inflation of fuel price. These random data follow normal distributions according to the indicated data.

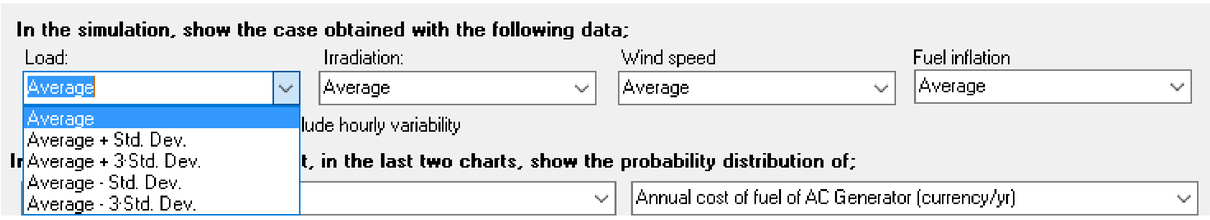
Each of these N simulations will give results of total cost (NPC) or NPV, CO_2 emissions, unmet load, photovoltaic generation, wind turbines generation, etc. For each result the mean of all these simulations is obtained, and this will be the value that the program will take into account to compare with other combinations of components and strategies, and that will be shown in the results table and in the reports.

If a Monte Carlo simulation stopping rule is selected (by default), for each case of combination of components and strategy N or less simulations can be evaluated, depending on whether or not the stopping conditions are reached.

The default stopping rule (confidence level for maximum error of the mean) was used in the article (Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016b), while the stopping rule considering the relative standard error was used in (Rodolfo Dufo-López, Pérez-Cebollada, et al., 2016).

Once the optimization is completed, for each result of combination of components and control strategy, the simulation (see section 4.6.1) can be visualized for the desired case for each series of load, irradiation, wind speed and wáter flow (or fuel inflation) among the cases AVERAGE, AVERAGE+STANDARD_DEVIATION, AVERAGE+3·STANDARD_ DEVIATION, AVERAGE-STANDARD_DEVIATION or AVERAGE-3·STANDARD_ DEVIATION.

MHOGA calculates all these characteristic cases (combinations of each case of AVERAGE, AVERAGE+STANDARD_DEVIATION, etc. for each variable considered in the probability analysis). You can choose which combination of cases (which characteristic case) to be visualized in the simulation screen.



By default the simulation of the average case will be displayed, but other cases can be set to visualize its simulation. For example, we can set the AVERAGE + STANDARD_DEVIATION for load, and for the irradiation, wind and wáter flow data, the AVERAGE-STANDARD_DEVIATION. This combination would be quite pessimistic, since it would be considered that the consumption is somewhat higher than the average, while the resources are somewhat smaller, and, when visualizing the simulation, it will be possible to see if the demand is covered every day of the year, etc., . You could set a more extreme combination to visualize in the simulation, for example, to set the AVERAGE+3·STANDARD_DEVIATION for load, and for the irradiation, wind and wáter flow data, the AVERAGE-3·STANDARD_DEVIATION, this case would be the worst one, since it is almost impossible to have values greater than the average + 3 * standard deviation nor lower than the average - 3 * standard deviation.

If the box 

is selected, in the case to visualize in the simulation screen the hourly variability will be considered. If it is not considered, no hourly variability will be considered in the case visualized in the simulation screen.

Once the optimization is completed, for each result of combination of components and strategy, in the report (see section 4.6.1), probability distribution graphs of different results will be displayed and, in the last two graphs, you can choose which results to display:

After finishing the optimization, if we click on any box in the table of results (main screen), the results are updated (the N random combinations of load, irradiation ... and the average values of the results are updated, which can be different since the N combinations may have been different). If the box 

is checked, the results will not be updated.

If the box 

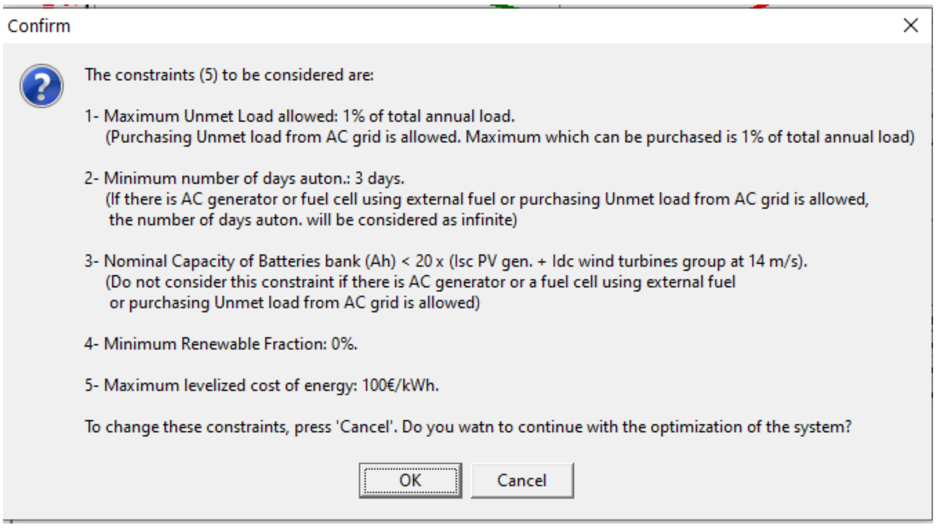
is checked, when the simulation button (results table, main screen) is clicked, only the N cases of the Monte Carlo simulation will be considered, not the additional ones of the characteristic cases.

4. OPTIMIZATION OF THE HYBRID SYSTEM

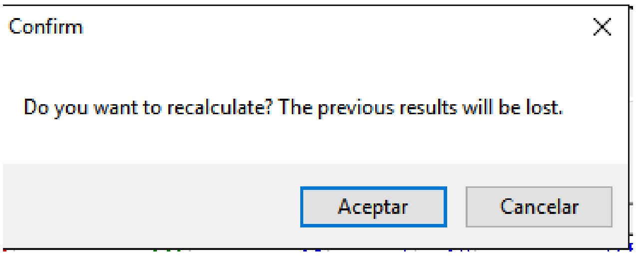
Once all data in our system have been entered, the "**CALCULATE**" button on the main screen is enabled.

If Maximization of NPV was selected as project type, no confirmation of constraints is needed.

If Minimization of NPC was selected as project type, a message box shows the restrictions are indicated. If we agree, click OK and start the optimization.



If it had already been calculated, it asks if we want to calculate, since the previous results will be lost.



If we accept, the program begins to perform the optimization.

It should be noted that if there are results (we have previously optimized the system), clicking on "CALCULATE" and accepting the confirmation requested by MHOGA, the results table will be deleted, and a new one will be obtained with the new results. Even if we click on the "Cancel" button, the original table will be deleted. Therefore, if we want to preserve the original results values, before re-calculating, save the project with another name, with the upper menu Project-> Save As, and from then on we will use this new project, leaving the old one saved.

A panel appears at the bottom of the main screen, with a progress bar indicating the progress of the optimization. Below it we are informed of how many cases have been evaluated so far, the time elapsed and the remaining time.

The system chart disappears and a table appears where the results of the optimization will be collected. If the genetic algorithm method is used (because not enough time has been allowed to evaluate all the possible combinations), in the case of mono-objective optimization, the best solution of each generation is collected in each row (the best obtained is shown in the last row), whereas in the case of multi-objective the solutions or the Pareto front (only non-dominated or all) of each generation are collected in the table. In addition, you can see the graph (when the first generation is complete) where you see the evolution over the generations, in the case of mono-objective optimization, or the Pareto diagram of the latest generation evaluated in the case of multi-objective optimization.

If all combinations are evaluated (enumerative method), the table and graph appear at the end of the calculation, with the combinations ordered from best to worst.

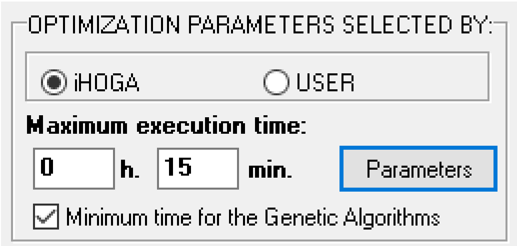
During the simulation you can press the "Cancel" button, to the right of the progress bar, to stop the execution of the program. If you then press the “CALCULATE” button the calculation can not be resumed, but a new calculation must be started.

4.1 Mono-objective optimization by the enumerative method.

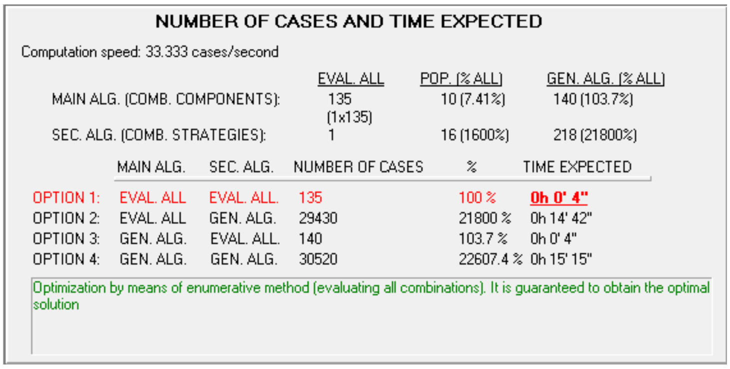
In the case of the mono-objective optimization there is a unique objective: minimize NPC or maximize NPV.

The optimization can be performed by means of the enumerative method (evaluating all the combinations) or by genetic algorithms (heuristic technique that does not evaluate all the combinations and can obtain the optimal or a solution near the optimal in low time). In the case of indicating the option "METHOD ENUMERATIVE" in the window that is obtained by clicking on the "Parameters" button of the tab "GENERAL DATA" of the main screen (or if it is determined by the software when the allowed maximum execution time is higher than the one that would cost to evaluate all the combinations), the genetic algorithm will not be used, but all the possible combinations are evaluated (enumerative method), and the best N solutions will be displayed in the results table and in the graph, N being the number marked in the box "Display best".

In this example we will optimize a generating system (without any load) composed by photovoltaic generator, batteries and inverter/charger. Just 135 possible combinations will be evaluated, which will be done in about 4''. In this case all the combinations will be evaluated (enumerative method), as the needed time is lower than the maximum execution time allowed by the user (default 15').

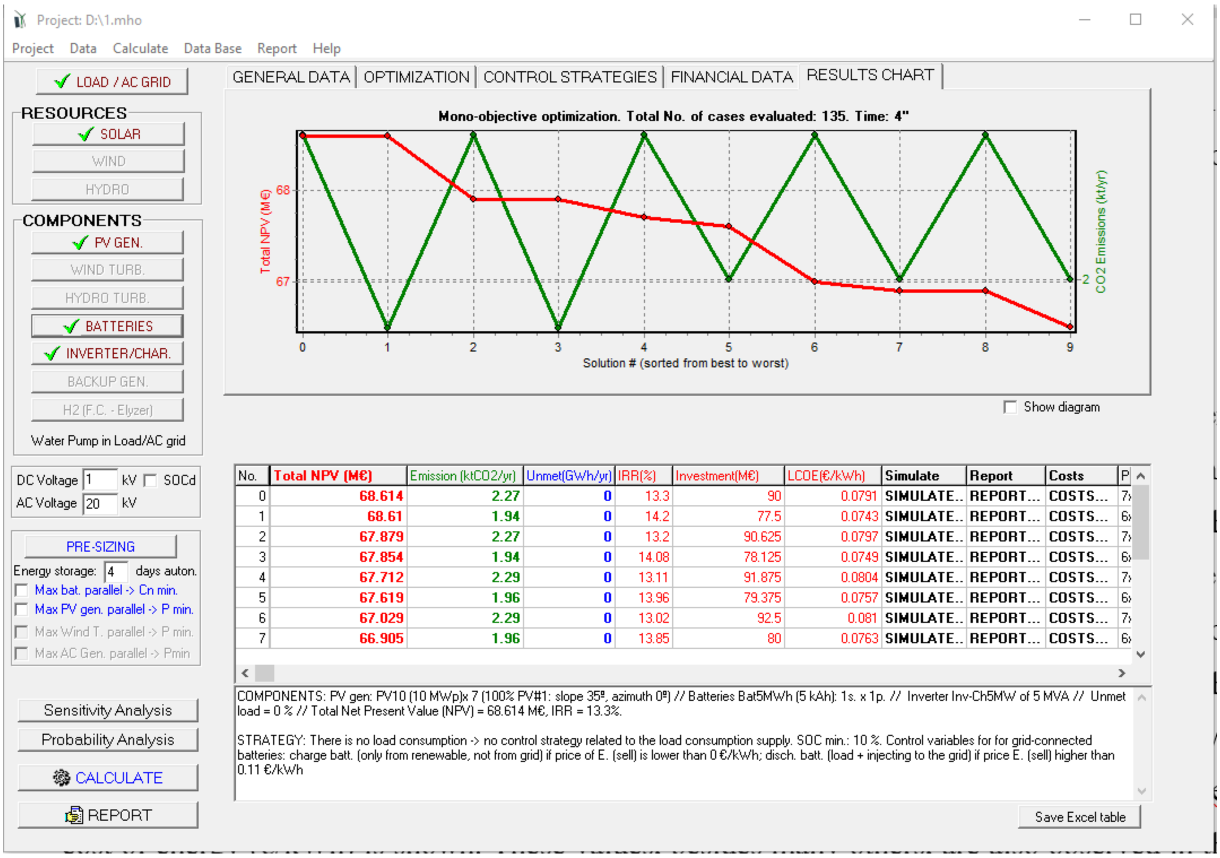


If the estimated execution time was higher than the maximum execution time allowed, the genetic algorithm method would be used to find the optimum without evaluating all combinations, and the best solution found for each generation would be shown during the optimization, seeing how the best solution is improved as the generations appear.

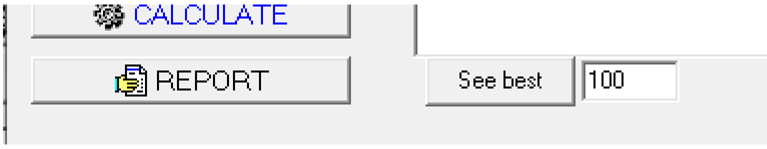


In our case all the combinations will be evaluated.

When clicking the button "CALCULATE", it starts running. At the bottom of the screen a progress bar appears, and under it the evaluated cases, elapsed time and remaining time. You can cancel the execution at any time by pressing "Cancel".



In the top corner of the screen, you can change the number of the best solutions shown, and then you click the "**See best**" button.



After the optimization is performed (in this case just in 4''), the software shows the best combinations found, sorted from best to worst, in a table. Also it shows in the upper graph the total NPV (in red) and the total annual equivalent emissions of CO_2 (including diesel emissions, if any, and manufacturing emissions of the components, spread over their lifetime) (in green).

If the optimization type was the minimization of NPC, the graph would have shown in red the total NPC.

At the end of the simulation the panel disappears with the progress bar and instead the description of the best solution found appears.

The first row of the table shows the best combination found (with the highest NPV).

In the table, it is shown the total NPV (first column, in red) and the total annual equivalent emissions of CO_2 (in green). In blue it is shown the unmet load (in GWh/year). In red it is also shown the Internal Rate of Return (IRR, %), the total investment (M€) and the levelized cost of energy LCOE (€/kWh) is shown.

If the optimization type is Minimization of NPC, the NPV column is replaced by the NPC, some restriction columns appear in blue (the unmet load in %, the days of and the value of the division between the nominal capacity of the battery bank and the current from renewable sources) and the columns of IRR (internal rate of return) and Investment disappear.

In the maximization of NPV, in the case of any row (or all) in the column of Total NPV (M€) the -INF value is shown, it means that this combination of components and control strategy does not comply with the constraints (maximum allowed investment cost, minimum renewable fraction and maximum land use) and MHOGA penalizes that solution, giving it -infinite NPV (-1E15).

In the minimization of NPC, in the case of any row (or all) in the column of Total NPC (M€) the INF value is shown, it means that this combination of components and control strategy does not comply with the constraints we have indicated (the maximum unmet load, the minimum autonomy, the relation between nominal battery bank capacity and current from renewables, the minimum renewable fraction or the maximum cost of energy) and MHOGA penalizes that solution, giving it infinite cost (1E15). If any row has this value, it means that in its generation no solution evaluated comply with all the constraints. It is represented graphically with total cost (NPC) (€) = 0.

By selecting or deselecting the "Show diagram" checkbox (right of the screen), we will see the schematic of the components or the results table 

.

Calculation with probability analysis:

If probability analysis was selected, each combination of components and strategy is analyzed N times, where N is the number of sets set on the probability analysis screen (unless the stop rule of the Monte Carlo simulation is reached). In this case, the results displayed in the table and those saved in the Excel table (see below) will be the average values of the N series.

Save Excel Table:

At the end of the simulation it is enabled in the lower right corner the "**Save Excel table**". If you click it, an Excel file with the values of the result table will be generated.

Note that the Excel table will show the results of the optimization. If, after the optimization, you change any data and click in any row of the results table of the software, the results of that row will be update to the new data, but if later you click in "Save Excel table", the original results will be saved in Excel, not the updated ones.

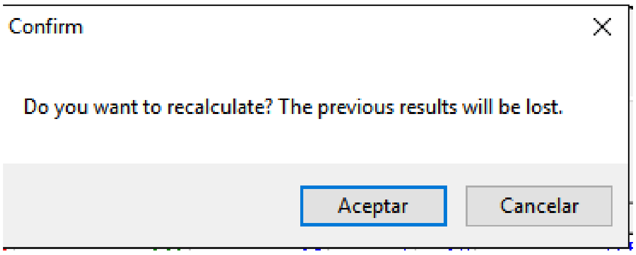
After you save the Excel file, if you open the file with Microsoft Excel, it reports a message asking about opening the file, then you click on "Yes" as answer and the file is correctly opened by Microsoft Excel:

Project: 1

No.	NPV(M€)	Em.CO2(kt/yr)	Unmet(GWh/yr)	Unmet(%)	IRR(%)	Investment(M€)	LCOE (€/kWh)	No. PV. gen.	Pot. PV. gen.(MWp)	P total. PV(MWp)	Slope#1(º)
0	68.614	2.267	0	0	13.3	90	0.0791	7	10	70	35
1	68.61	1.943	0	0	14.2	77.5	0.0743	6	10	60	35
2	67.879	2.267	0	0	13.2	90.625	0.0797	7	10	70	35
3	67.354	1.943	0	0	14.08	78.125	0.0749	6	10	60	35
4	67.712	2.291	0	0	13.11	91.875	0.0804	7	10	70	35
5	67.619	1.964	0	0	13.96	79.375	0.0757	6	10	60	35
6	67.029	2.291	0	0	13.02	92.5	0.081	7	10	70	35
7	66.905	1.964	0	0	13.85	80	0.0763	6	10	60	35
8	66.9	2.314	0	0	12.94	93.75	0.0816	7	10	70	35
9	66.464	1.981	0	0	13.72	81.25	0.0771	6	10	60	35
10	66.273	2.267	0	0	12.99	91.875	0.081	7	10	70	35

If, once the table is opened in Microsoft Excel, we select "Save As" (in Microsoft Excel) and choose the most modern Excel format (xlsx), the next time we open the file, you will not asked for anything.

If we want to calculate again, we must keep in mind that the results will be lost. It is for this reason that, by pressing the "CALCULATE" button, if previously calculated, MHOGA asks if we are sure, since the previous results will be lost.

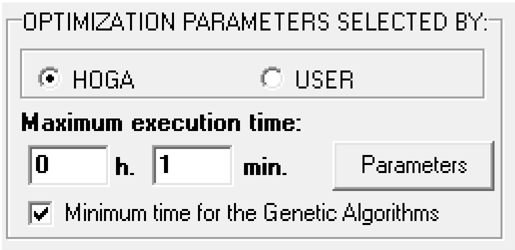


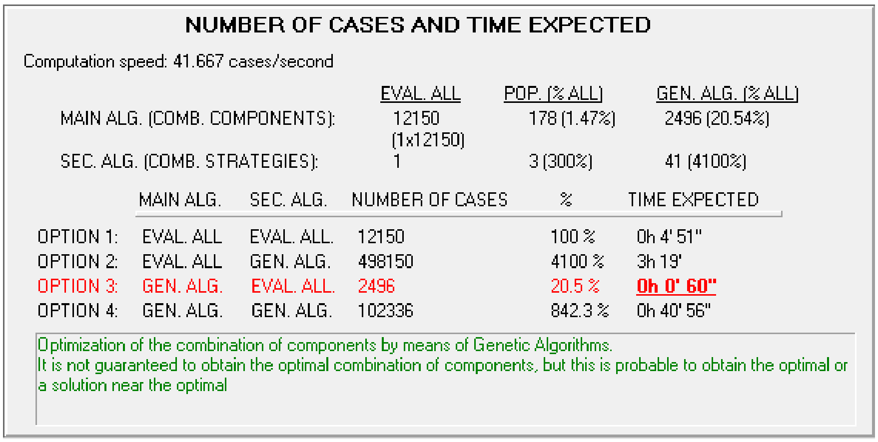
If we want to recalculate, we accept. If we want to save the previous results, press Cancel, save the project, save it as with another name and in the new project we can calculate without losing the results of the original project.

4.2 Mono-objective optimization by genetic algorithms.

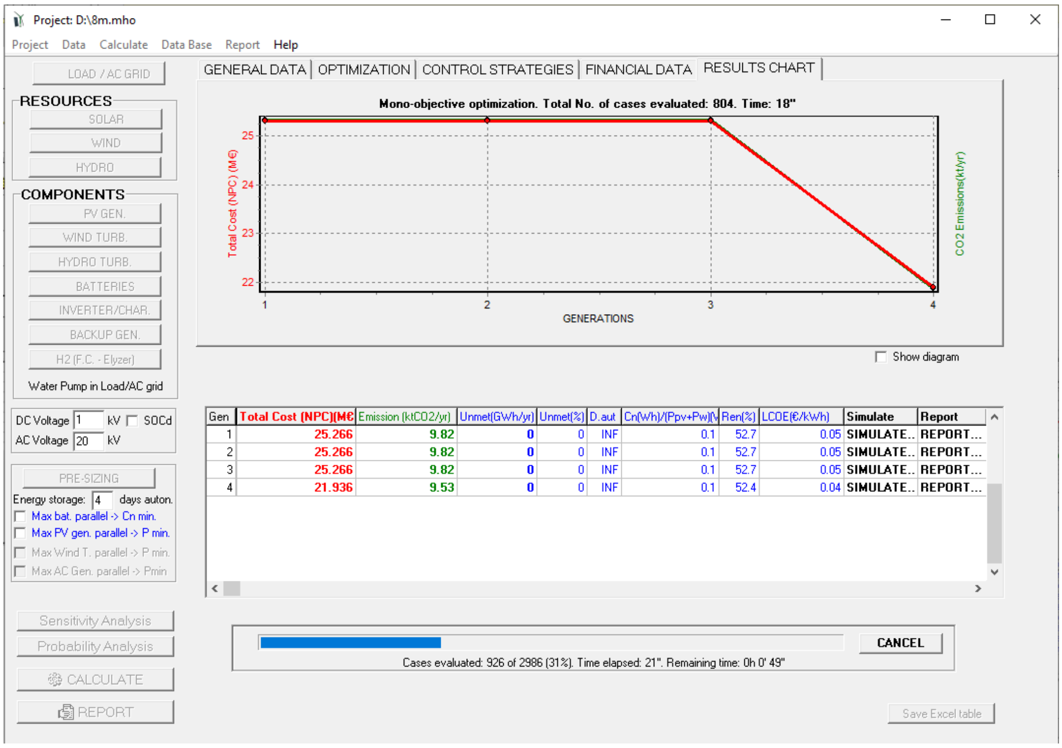
In the case that there are many possible combinations, the enumerative method can take a lot of time. If that time is higher than the maximum allowed, the software will use the genetic algorithms to perform the optimization.

In the following example, just 1 minute is allowed, however there are 12150 possible combinations and the enumerative method would take 4'51''. The genetic algorithms will run the optimization.

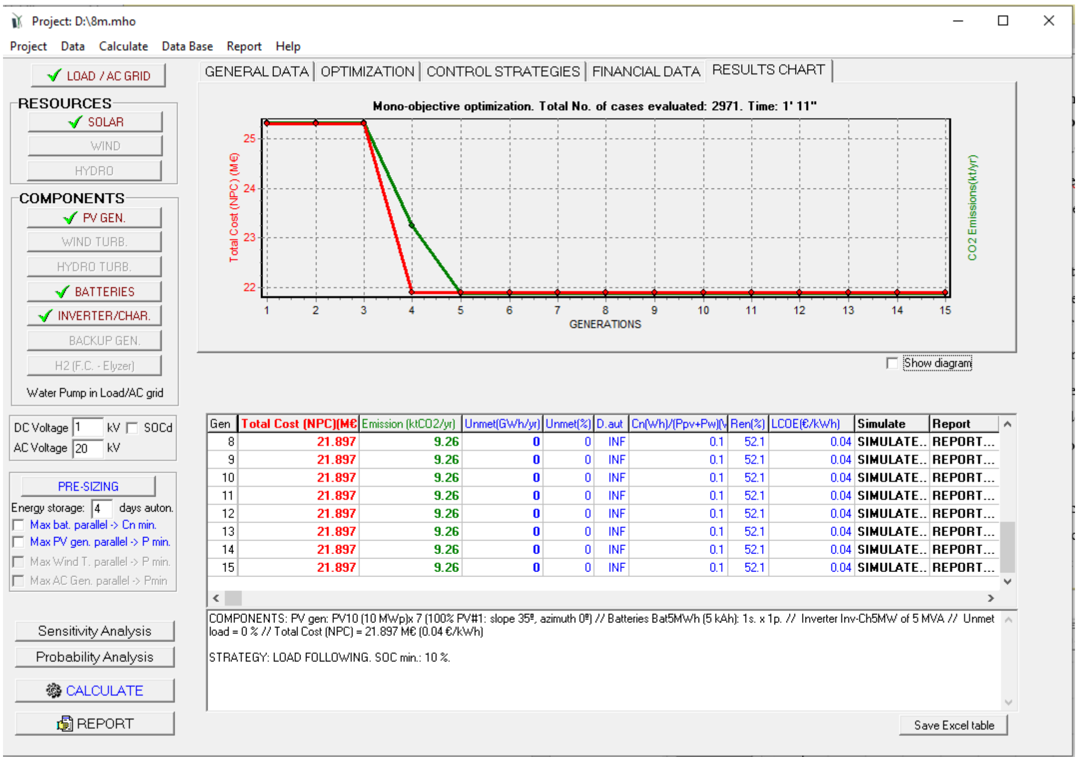




After clicking in "CALCULATE", the generations of the genetic algorithms are being evaluated, and graphically it can be shown that the best solution is being improved with the generations.



When the optimization process finishes, the best solution found is the one of the last generation (the last row of the table), in this case in the 4th generation it was already found.



4.2 Multi-objective optimization.

In the case of multi-objective optimization, it is intended to minimize (or maximize) different objectives (only valid for projects of type minimization of NPC).

In this case, if we have selected "Display only non-domin." (main screen, “OPTIMIZATION” tab), in the table and in the graph we will see only the Pareto of the non-dominated solutions (those that satisfy that there is no other solution that is better in all the objectives).

If we do not select it, we will see all the evaluated solutions of the main algorithm, sorted by the number of solutions that domine them.

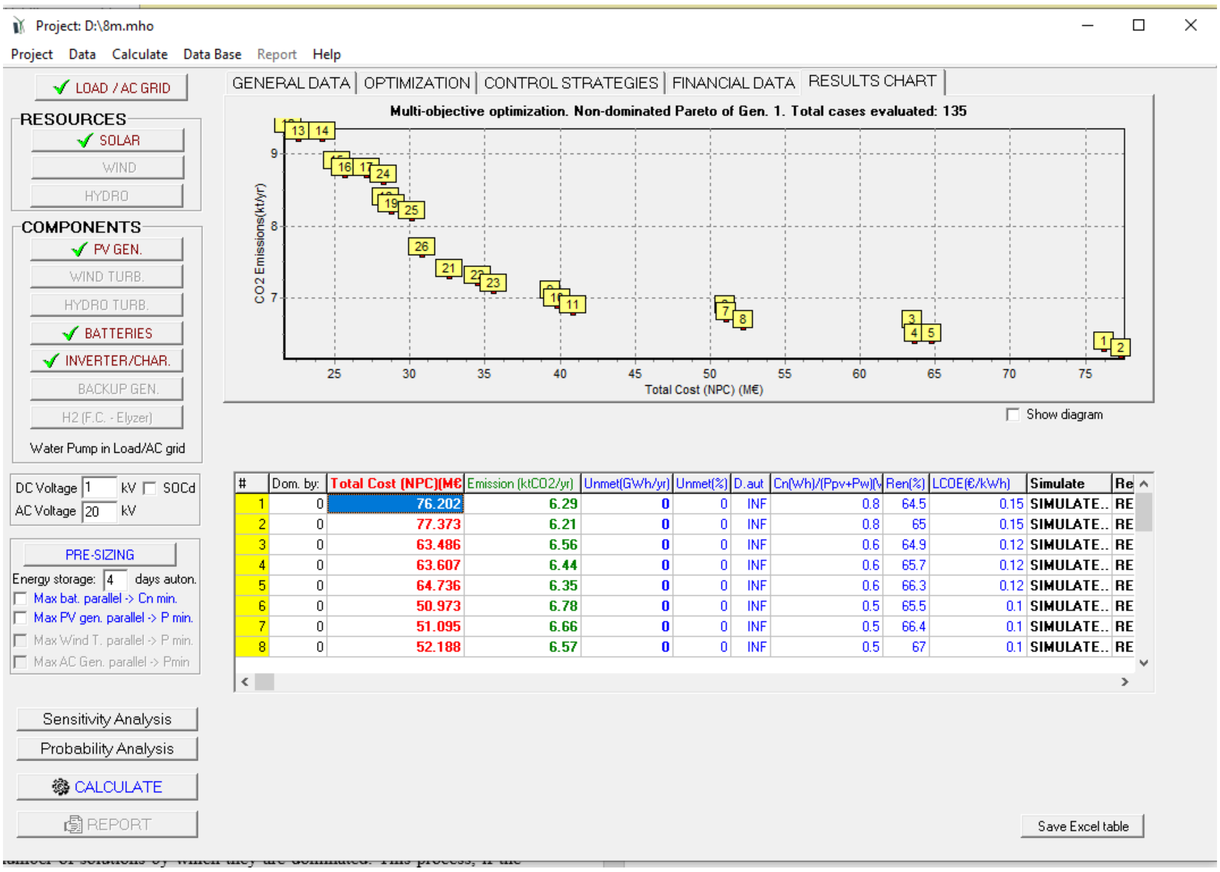
You can select multi-objective Total Cost (NPC) versus CO_2 or Total Cost (NPC) versus Unmet Load or triple multi-objective (cost – emissions – unmet load).

It is necessary to indicate the maximum number allowed for the non-dominated solutions (Max. non-dom.), as well as the maximum allowed percentage of NPC over the minimum NPC of them (% over min. NPC). The number of "Save Pareto every" indicates the interval in the generations we want to save, in addition to the first and last paretos. Once the optimization are completed, the "Export Paretos" button is enabled and we can export the saved paretos to an ASCII file.

By pressing the "CALCULATE" button, each time a generation of the main algorithm is completed, the solutions (all or only the non-dominated ones) are shown, numbered (in yellow, to be identified in the graph) and represented by number of solutions by which they are dominated ("Dom. By"). The graph shows the pareto of each generation.

It should be noted that each time a new generation is obtained, the program must sort the individuals to see the number of solutions by which they are dominated. This process, if the population is large, can take a time, in the order of minutes, so during that time the program screen is stopped.

The following figure shows the last generation of a multi-objective NPC-emissions example. At the bottom it is not specified the data of the best solution, since there is no better solution, it cannot be said that one non-dominated is better than another not dominated.



number of solutions by which they are dominated. This process, if the

4.4 Results table.

In the case of having used the genetic algorithms, the table shows all the characteristics and parameters of the best solution of each generation, sorted from the 1st to the last generation (the best result is the one of the last generation, which is in the last row of the table).

In case of using the enumerative method (all possible combinations have been evaluated), the table shows all the characteristics and parameters of the N best solutions, ordered from best to worst (the best one is the first one in the table).

We can move through the table from right to left with the bar at the bottom.

Each row of the table shows the results of a combination of components.

If multiperiod optimization was selected (Project-> Options), the cells of energies and hours of operation are the average values of all the years of the simulation. For example, if the lifetime of the system is 25 years, in each cell of annual costs, annual energies, etc. it shows the average of the 25 years. The NPC or NPV cells show in that case the NPC or NPV obtained as the sum of the present costs and incomes of each year, therefore the real NPC or NPV. However, the annual costs and incomes are different for each year, and in the table just 1 value can be shown for each filed, the value shown in the table is obtained supposing that all the years the cost was the same and applying the fixed inflation and interest rate. To see the real annual costs and incomes in cash flow of each year: in the simulation screen, MULTIPERIOD tab, Save Multiperiod Data and see the real cash flow values in that file.

In the results table, first column corresponds to the generation number (Gen.) in the case of using genetic algorithms for the optimization of the components or the number of order (No.) if all the combinations have been evaluated or if the optimization is multi-objective. The following columns are the total cost (NPC) or NPV (depending on the type of project), in red, and annual equivalent CO_2 emissions, in green. The rest of the first columns are different depending on the type of optimization:

- Minimization of NPC: in blue there are 6 columns, unmet load (GWh/year and % of load), days of autonomy, the value of the division between the nominal capacity of the battery bank and the peak power of the PV generator + the maximum power of the wind turbine group, Cn (Wh) / (Ppv + Pw) (W), the renewable fraction and the updated LCOE (the 5 magnitudes must comply with the constraints set).

No.	Total Cost (NPC)(M€	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(W	Ren(%)	LCOE(€/kWh)	Simulate	Report
0	21.897	9.26	0	0	INF	0.1	52.1	0.04	SIMULATE..	REPORT...
1	22.576	9.24	0	0	INF	0.1	52.2	0.04	SIMULATE..	REPORT...
2	24.14	9.22	0	0	INF	0.1	52.3	0.05	SIMULATE..	REPORT...
3	25.155	8.77	0	0	INF	0.1	55.7	0.05	SIMULATE..	REPORT...
4	25.676	8.72	0	0	INF	0.1	56	0.05	SIMULATE..	REPORT...
5	27.127	8.69	0	0	INF	0.1	56.2	0.05	SIMULATE..	REPORT...
6	27.199	9	0	0	INF	0.1	51.7	0.05	SIMULATE..	REPORT...
7	27.877	8.97	0	0	INF	0.1	51.9	0.05	SIMULATE..	REPORT...

- Maximization of NPV: in blue there is the unmet load (GWh/year) just for information (it is not a constraint in this kind of projects), and in red we can see the internal rate of return (IRR, %), the investment (M€, which must comply with the constraint) and the LCOE (€/kWh).

No.	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Investment(M€)	LCOE(€/kWh)	Simulate	Report	Costs
0	46.22	2.26	0	11.36	90	0.0958	SIMULATE..	REPORT...	COSTS...
1	46.05	1.94	0	11.98	77.5	0.0925	SIMULATE..	REPORT...	COSTS...
2	45.401	2.26	0	11.26	90.625	0.0965	SIMULATE..	REPORT...	COSTS...
3	45.232	1.94	0	11.86	78.125	0.0932	SIMULATE..	REPORT...	COSTS...
4	43.785	2.28	0	11.07	91.875	0.0977	SIMULATE..	REPORT...	COSTS...
5	43.764	2.26	0	11.07	91.875	0.0978	SIMULATE..	REPORT...	COSTS...
6	43.615	1.96	0	11.63	79.375	0.0946	SIMULATE..	REPORT...	COSTS...
7	43.595	1.94	0	11.63	79.375	0.0947	SIMULATE..	REPORT...	COSTS...

Next on the right are the "SIMULATE", "REPORT" and "COSTS" cells that, when clicked, the simulation, report or cost screens are accessed. Then there are the characteristics of the components of each solution (number of PV generators x power of each PV gen. in MW; slope of the PV generators; number of batteries in series x parallel x capacity of each battery in kAh, number of AC backup generators in parallel x power of each generator in MW, etc).

Simulate	Report	Costs	P. PV (MWp)	Slope#1(º)	Cn Bat. (kAh)	P. Gen (MW)	P. Inv (MW)	P. Wind T. (MW)	F. Turb (m3/s)
SIMULATE..	REPORT...	COSTS...	7x10	35	1x1x5	1x0	5	1x0	0
SIMULATE..	REPORT...	COSTS...	6x10	35	1x1x5	1x0	5	1x0	0
SIMULATE..	REPORT...	COSTS...	7x10	35	1x1x5	1x0	10	1x0	0
SIMULATE..	REPORT...	COSTS...	6x10	35	1x1x5	1x0	10	1x0	0
SIMULATE..	REPORT...	COSTS...	7x10	35	1x2x5	1x0	5	1x0	0
SIMULATE..	REPORT...	COSTS...	7x10	35	1x1x5	1x0	20	1x0	0
SIMULATE..	REPORT...	COSTS...	6x10	35	1x2x5	1x0	5	1x0	0
SIMULATE..	REPORT...	COSTS...	6x10	35	1x1x5	1x0	20	1x0	0

The columns in red are cost.

- Minimization of NPC projects: In the case of optimization of the components and also optimization of the control strategy, in addition to the second column indicating the total cost of the system "Total Cost (NPC) (M€) ", there is the column "C. Sec. (M€)", which gives an idea of the variable costs that depend on the control strategy (costs of replacement of batteries, AC generator, etc., costs of operation and maintenance, fuel ...), that is, costs that are not fixed but depend on the control strategy.

- Maximization of NPV projects: In these cases, that column is "NPV sec.(M€)", it is the total sum of the incomes of the selling electricity and H2 minus the variable costs.

NPV.sec(M€)	STRATEGY	Plim_charge(I	P2(MW)	P1gen(MW)	P1FC(MW)	Pmin_gen(MW	Pmin_FC(MW)	Disch-FC-first	Pcri_c
146.59	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	
132.498	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	
146.59	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	
132.498	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	
146.244	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	
146.59	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	
132.151	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	
132.498	LOAD FOLLOWING	INF	1	INF	INF	1	0	1	

To its right there is is a series of columns in **bold** that indicate the values of the **control variables**. To its right there is is a series of columns in **bold** that indicate the values of the **control variables**. *They are no sense if there is no load (in generating systems), except for the last ones in the cases of grid-connected batteries management.*

To its right there are the columns of annual energy (GWh/year), in blue: Total energy consumed by the load (Etotal), energy generated by renewable sources (Eren), Energy generated by photovoltaic modules (Epv), Energy generated by wind turbines (Ew), Energy generated by the hydraulic turbine (Et), Energy that can be exported to the grid (produced by the renewable sources but that could not be used in the load nor in the battery, electrolyzer…, that is, excess energy that could be exported) (E export), Energy sold to the AC grid (in the case of net metering, this column "E sell (kWh / year)" shows the energy involved in the net metering scheme, i.e. not the total energy that has been injected into the AC grid but the energy that has been injected and later obtained from the grid through the net metering), Energy purchased from the AC network (Ebuy), Battery charging (E ch. Bat., energy that enters into the battery bank) and discharging energy (E disch. Bat., energy that goes out of the battery bank), Electric energy consumed by the electrolyser (E elyzer.), Energy Electric generated by the AC generator (E gen) and Electric power generated by the fuel cell (E FC). All energy values are annual. If the multiperiod optimization was selected, these values are the average of the system lifetime.

Etotal(GWh)	Eren(GWh)	Epv(GWh)	Ew(GWh)	Et(GWh)	E export(GWh)	E Sell(GWh)	E Buy(GWh)	E ch. bat(GWh)
0	99.482	99.482	0	0	97.492	87.785	0	0.0
0	85.27	85.27	0	0	83.564	80.329	0	
0	99.482	99.482	0	0	97.492	87.785	0	0.0
0	85.27	85.27	0	0	83.564	80.329	0	
0	99.482	99.482	0	0	97.491	87.785	0	0.0
0	99.482	99.482	0	0	97.492	87.785	0	0.0
0	85.27	85.27	0	0	83.564	80.328	0	0.0
0	85.27	85.27	0	0	83.564	80.329	0	

It should be noted that sometimes not all excess (export) power can be sold to the AC grid, as the maximum power that can be injected in the grid in some cases is limited (it is set in the LOAD/AC GRID window, in the sell electricity options).

Clarifications:

- E ch. Bat. is the value of the energy that enters into the battery bank. The stored energy will be that value mutiplied by the charging efficiency.

- E disch. Bat. is the value of the energy that goes out of the battery bank (stored energy multiplied by the discharging efficiency).

- E fuel cell is the value of the energy that supplies the fuel cell in DC. If fuel cell is connected to the AC bus, the energy that is injected in the AC bus by the fuel cell will be that value multiplied by the inverter efficiency.

- E electrol. is the value of the DC energy that is consumed by the electrolyzer. If the electrolyzer is connected to the AC bus, the energy that comes from the AC bus is that value divided by the electrolyzer rectifier efficiency.

You must take into account that:

For each time step, the energy produced in the AC bus can be consumed:

- in the AC bus (by the AC load and/or by the AC pump in pumping systems and/or by the electrolyzer connected to the AC bus in hydrogen systems)

- in the DC bus (by the DC load and/or and/or by the DC pump in pumping systems and/or by the electrolyzer connected to the DC bus and/or by the batteries). The energy produced by the AC bus is converted to the DC bus by multiplying by the rectifier (charger) efficiency.

For each time step, the energy produced in the DC bus can be consumed:

- in the DC bus (by the DC load and/or and/or by the DC pump in pumping systems and/or by the electrolyzer connected to the DC bus and/or by the batteries).

- in the AC bus (by the AC load and/or by the AC pump in pumping systems and/or by the electrolyzer connected to the AC bus in hydrogen systems). The energy produced by the DC bus is converted to the AC bus by multiplying by the inverter efficiency.

Then there are columns in black that indicate the AC generator's annual operating hours (including the extra equivalent minutes due to the starts and the extra ageing due to running out of its optimal range), the estimated lifetime for the batteries (in years), the annual hours of charging and discharging of the batteries, and the operating hours of the fuel cell and the electrolyzer. If the multiperiod optimization was selected, these values (except for the battery lifetime) are the average values of the system lifetime.

Hours eq. Gen	Bat. life (yr)	Hours Ch. Bat.	Hours Disch. Bat.	Hours FC	Hours Elyzer.	C. Fuel Gen.(M€/yr)	C. Fuel FC(M€/yr)	E Buy (M€/yr)	E Se
0	15	1780	0	0	0	0	0	-1.2	
0	15	2049	0	0	0	0	0	-1.2	
0	15	1780	0	0	0	0	0	-1.2	
0	15	2049	0	0	0	0	0	-1.2	
0	15	1782	0	0	0	0	0	-1.2	
0	15	1780	0	0	0	0	0	-1.2	
0	15	2051	0	0	0	0	0	-1.2	
0	15	2049	0	0	0	0	0	-1.2	

Next are red columns with annual costs of the year 0 (when the lifetime of the system starts, next years will be updated by inflation) (M€/year): cost of the fuel of the AC generator (C. Fuel Gen.), cost of the external fuel used by the fuel cell (C. Fuel FC) (if any), cost of the power purchased from the AC grid, including the cost due to availability of the power (E Buy, positive value if minimizing NPC as it is a cost, negative value if maximizing NPV), incomes of the power sold to the AC grid (E. Sell, negative value if minimizing NPC as it is income and not cost, positive value if maximizing NPV) and incomes of H2 sold (Sell H2, positive or negative depending on the type of project).

C. Fuel Gen.(M€/yr)	C. Fuel FC(M€/yr)	E Buy (M€/yr)	E Sell (M€/yr)	Sell H2 (M€/yr)	NPV PV (M€)	NPV Bat. (M€)	NPV Aux. (M€)	NPV I
0	0	-1.2	10.49	0	-79.963	-2.059	0	
0	0	-1.2	9.599	0	-68.54	-2.059	0	
0	0	-1.2	10.49	0	-79.963	-2.059	0	
0	0	-1.2	9.599	0	-68.54	-2.059	0	
0	0	-1.2	10.49	0	-79.963	-4.119	0	
0	0	-1.2	10.49	0	-79.963	-2.059	0	
0	0	-1.2	9.599	0	-68.54	-4.119	0	
0	0	-1.2	9.599	0	-68.54	-2.059	0	

Next are the columns also in red that indicate the the total present cost or total present value associated to each of the elements of the system, transferred to the initial moment of the investment (NPC or NPV). If minimization of NPC, all these columns are called "C" (of cost) + the element + (NPC)(M€), if maximization of NPV all these columns are called "NPV"+ the element + (M€). In the first case positive values imply costs and negative values imply incomes, and vice versa in the second case.

For example, in the case of minimization of NPC, "C PV (NPC) (M€)" is the total cost (NPC) of the PV generator, C Bat. (NPC) (M€) is the total cost (NPC) of the Battery bank, etc. The cost per purchase of energy to the AC grid is indicated by "E buy (NPC) (M€)" and it includes the cost per access charge of all the energy consumed from the AC grid; in the case of net metering it also includes the cost of the net metering service (attributable to the energy involved in the net balance, that is to say, the one consumed with charge of the accumulated rights) and by the back-up charge of the self-consumed energy, if appropriate. The revenues from the sale of surplus AC power to the grid (including the transfer charge, if any) and the sale of excess H2 are negative values in the minimization of NPC projects because they are revenues and not costs.

In the next table it is shown the case of a maximization of NPV project.

NPV PV (M€)	NPV Bat. (M€)	NPV Aux. (M€)	NPV Inv. (M€)	NPV Gen. (M€)	NPV WindT (M€	C. Hydro (NPC) (M	NPV FC (M€)	NPV Elyz. (M€)	N
-79.963	-2.059	0	-0.694	0	0	0	0	0	
-68.54	-2.059	0	-0.694	0	0	0	0	0	
-79.963	-2.059	0	-1.387	0	0	0	0	0	
-68.54	-2.059	0	-1.387	0	0	0	0	0	
-79.963	-4.119	0	-0.694	0	0	0	0	0	
-79.963	-2.059	0	-2.774	0	0	0	0	0	
-68.54	-4.119	0	-0.694	0	0	0	0	0	
-68.54	-2.059	0	-2.774	0	0	0	0	0	

4.4.1. Simulation screen.

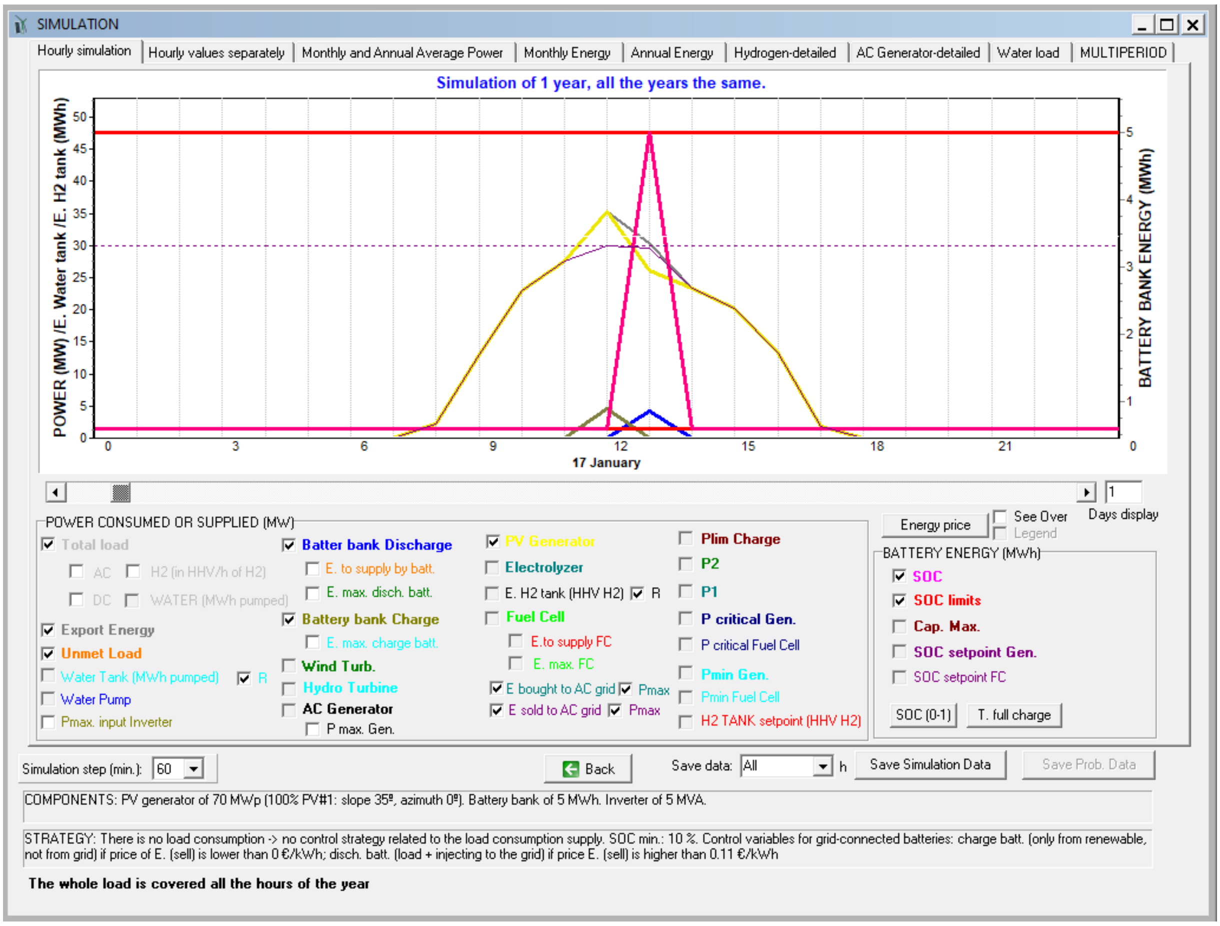
We can visualize the simulation of each solution found by MHOGA, by clicking, in the row corresponding to the solution that interests, in the box "**SIMULATE...**".

Simulate	Report	Costs	HDI	Jobs	P. PV pan. (Wp)
SIMULATE..	REPORT...	COSTS...	0.6212	0.0098	4x8x100
SIMULATE..	REPORT...	COSTS...	0.6212	0.0098	4x8x100
SIMULATE..	REPORT...	COSTS...	0.6212	0.0098	4x8x100
SIMULATE..	REPORT...	COSTS...	0.6212	0.0086	4x7x100

It shows a screen where the results of the system time simulation appear in 8 tabs (and the 9^{th} tab if multiperiod optimization was selected).

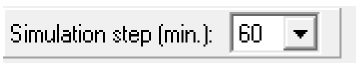
In the default tab (Hourly Simulation) the system is simulated throughout all hours of the year. You can change the way the results are displayed by clicking the tabs at the top.

"Hourly simulation" tab.

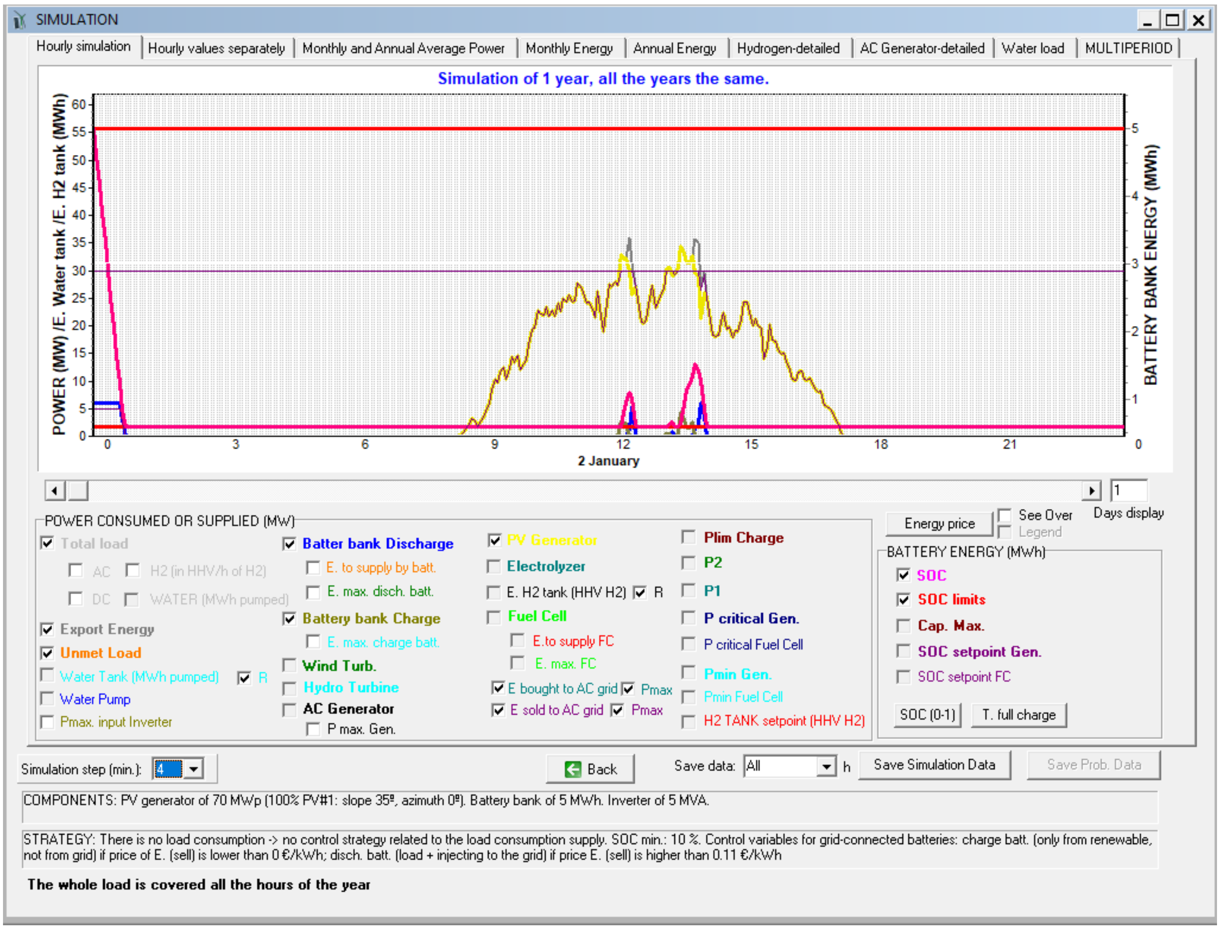


The simulation is seen during 1 year in the time steps that have been used in the optimization (except if the lead-acid battery model is Schiffer, then, the simulation is seen during the life of the batteries).

You can change the simulation time step (under the legend, left):



For example, changing to 4 minutes time step, after several seconds it is updated:



By default, the 1-day display appears. We can move throughout the year with the scroll bar below the graph. You can also see more than one day at a time, putting the desired number in the box on the right (Days display). Below the graph are the names of the represented variables, with their own colors. They can be activated or deactivated with their box. Some variables are disabled, that is because there are variables that the system has not used (for example, if there are no wind turbines, the energy produced by them, which would be represented by the "Wind turbines" curve is disabled).

The power consumed or supplied of all elements of the system refer to the left axis of the graph (power, MW). The state of charge (SOC) of the batteries refers to the right axis (energy in the battery bank, MWh).

In the case of consumption of H2, the energy of the H2 tank in each moment (MWh) is displayed (referred to the left axis), converted to energy by multiplying by the available H2 ton at each moment by 39.4 MWh/t, this value being the H2 HHV. In this case the value of the variable H2TANKstp, also converted to MWh, is also shown, in the left or right axis depending on the check box "R" close to the E. H2 tank (HHV H2) check box.

In the case of water consumption, it is shown the necessary power of pre-pumping (from the well or river to the reservoir or tank) of the consumed water at any moment.

The value of each variable is represented for each time step. For example, if the time step is 1 h and for example on January 1st at 0 h the AC generator supplies 0 MW and at 1 h supplies 20 MW (ie 20 MW for 1 h), this is represented by a ramp, which leaves from 0 MW to 0 h and reaches 20 W at 1 h. It must be clear that in the example what actually happens is that from 0 to 1h the generator supplies 0 W and from 1 to 2h the generator supplies 20 MW.

Total consumption is the sum of the electric consumption AC + DC + consumption of H2 (converted to HHV of H2) + water (converter to power previously pumped). You can view each type of consumption separately by selecting their respective boxes.

With respect to "E H2 tank (HHV H2)", for each hour the energy value of the H2 tank (MWh) is displayed at the beginning of the hour (if the adjacent "R" checkbox is not selected, it will be shown in the left axis, if "R" is selected, it will be shown in the right axis). It can be observed that if in one hour the electrolyser has worked generating H2, the energy of the tank increases in the next hour. If in an hour there is H2 consumption of the tank, used by the fuel cell or by external consumption of H2, in the next hour the H2 tank energy will fall. In one hour there may be H2 consumption and at the same time H2 generation in the electrolyzer, so the tank energy in the next hour will vary depending on which one is greater.

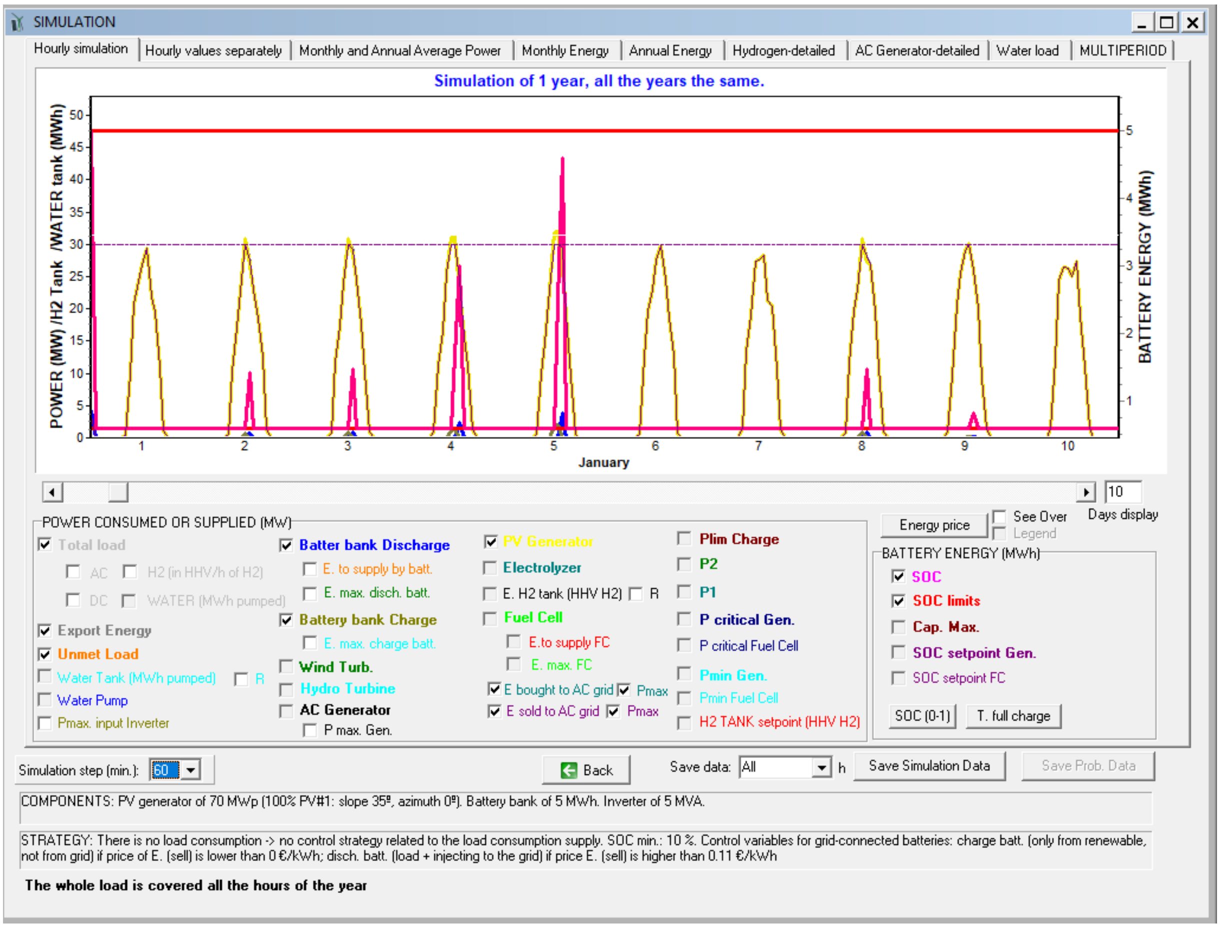
The value represented in the water reservoir or tank is that of the energy that has been needed to pre-pump the water that is stored at the beginning of that hour in the reservoir or tank (if the adjacent "R" checkbox is not selected, it will be shown in the left axis, if "R" is selected, it will be shown in the right axis). If there is water consumption, at the end of the hour (the beginning of the next hour) it is observed that the energy of the water tank decreases. If there is pumping for one hour, at the end of this (beginning of the next hour) it increases.

The value represented in "E sold to AC grid" is the energy injected into the AC grid (energy that cannot be used in the system). "Pmax" adjacent checkbox shows the maximum power that can be sold to the AC grid. If you have chosen a Net Metering option, only the energy injected into the network is represented until the accumulated sum (annual or monthly) is the maximum that can be used so that the net balance (energy or economic, depending on the case) is zero.

Regarding the SOC of the batteries, if during one time step there is net charge of the batteries, in the next time step the SOC grows, whereas if there is net discharge, in the next hour the SOC decreases. Note that if there is no load or discharge the SOC decreases slightly due to the self-discharge coefficient of the batteries.

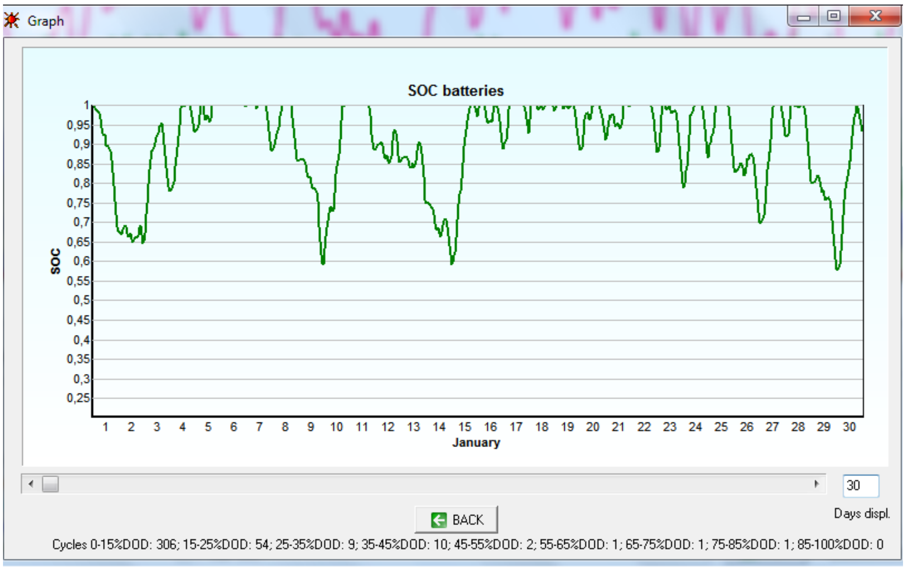
In the case that some value of the represented variables has its maximum very high, the rest of the values may be too small (this can happen mainly with E H2 tank, Water Tank and H2 TANK setpoint values). In that case, deselect the box corresponding to that variable to better observe the other variables.

The following figure shows the 10-day display.

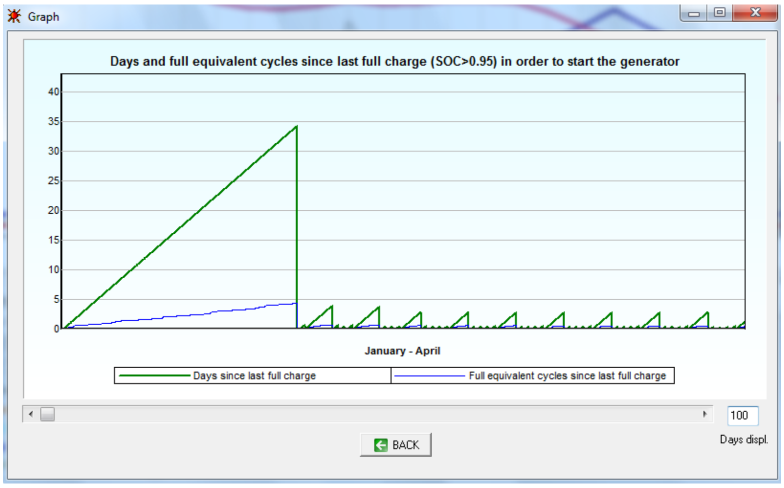


The two buttons on the right side show the battery SOC and the time since the last full charge of the batteries.

By clicking on the "SOC (0-1)" button it displays the following screen (after changing the display days to 30), which displays the state of charge of the batteries for 30 days. At the bottom the number of cycles for each depth of discharge interval (DOD) over the entire year is shown. Next figures correspond to a project different from the previous figures.



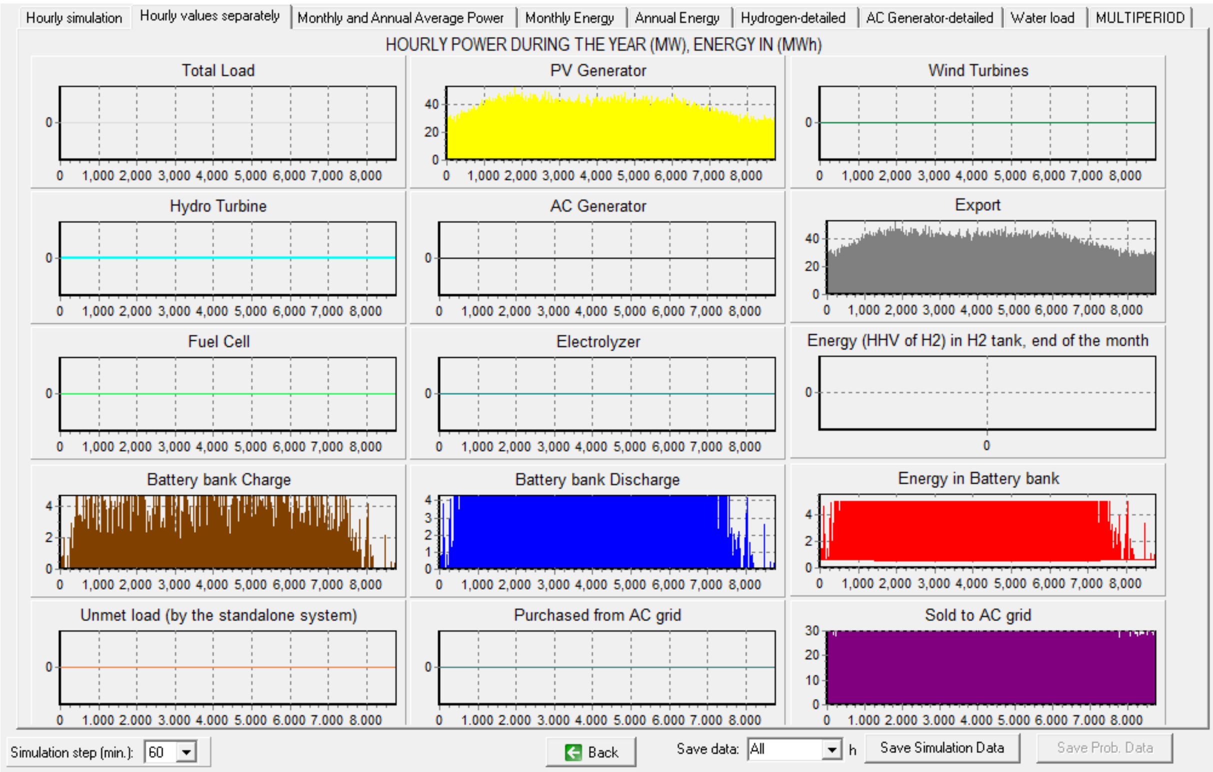
By clicking the "T. full charge" button the following screen appears, in which 100 days are displayed. The number of days since the last complete charge (SOC> 0.95 by default but can be changed on the battery screen) of the batteries (green curve) and the number of complete cycles (blue curve) are displayed.



Below the simulation chart, it informs about the components and the control strategy. It also informs of the months and specific days in which the demand load could not be covered in full.

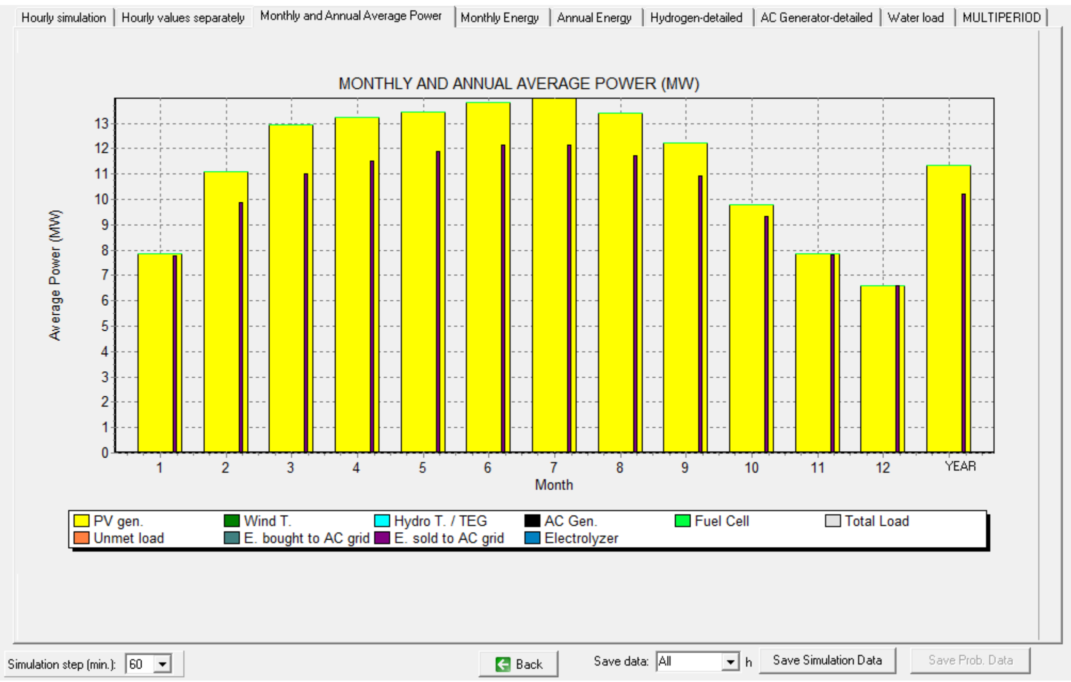
<u>"Hourly values separately" tab:</u>

This tab shows the hourly values for the different energies of the system, each in a different graph.



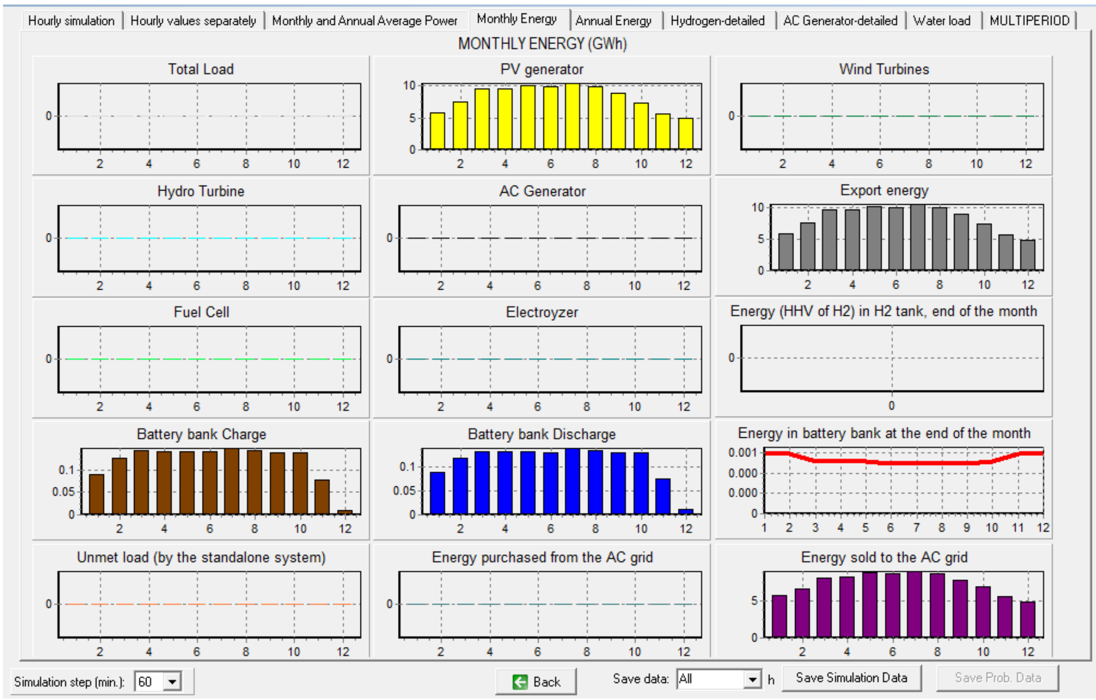
"Monthly and Annual Average Power" tab:

This tab shows, for each month (1 to 12) and for the total of the year, the average values of power (MW) supplied by the different technologies (stacked bars) and average values of load power, unmet load and energy purchased and sold to the AC grid (in fine columns, without stacking).



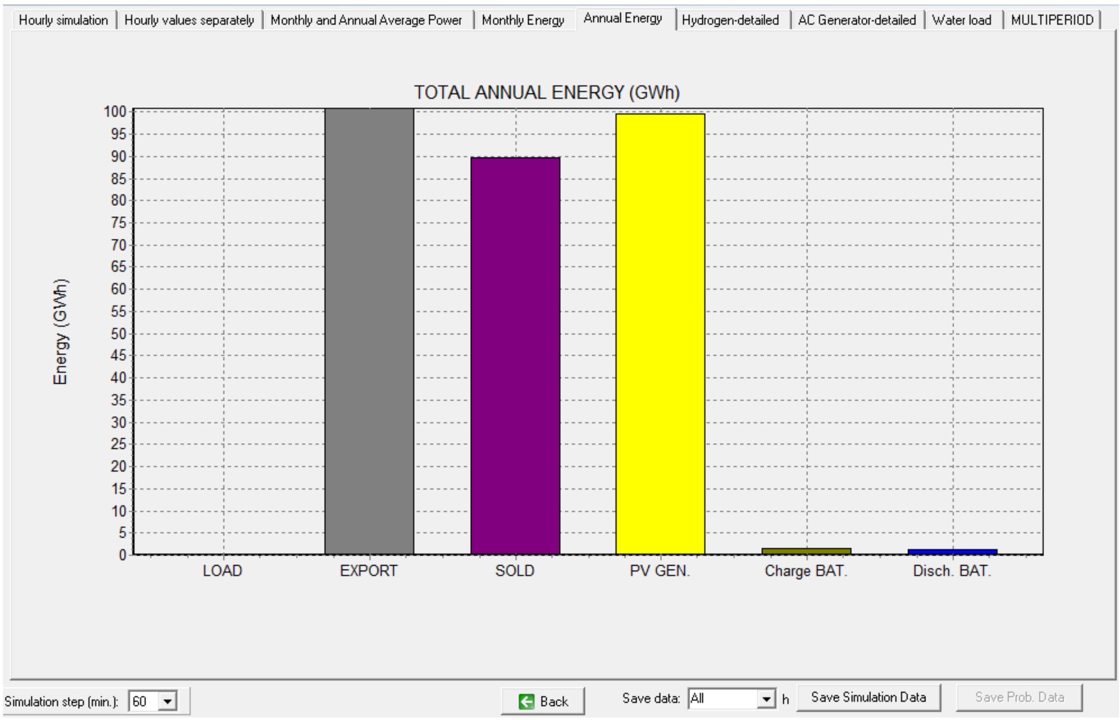
"Monthly Energy" tab:

This tab displays for each month (1-12), monthly energy values (GWh).



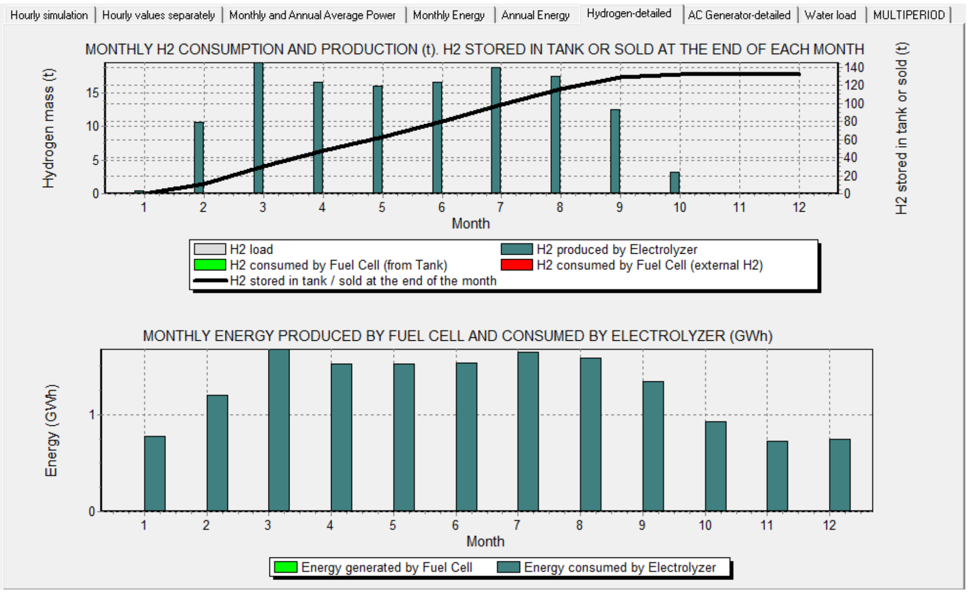
"Annual Energy" tab:

This tab displays total annual energy (GWh) for each component



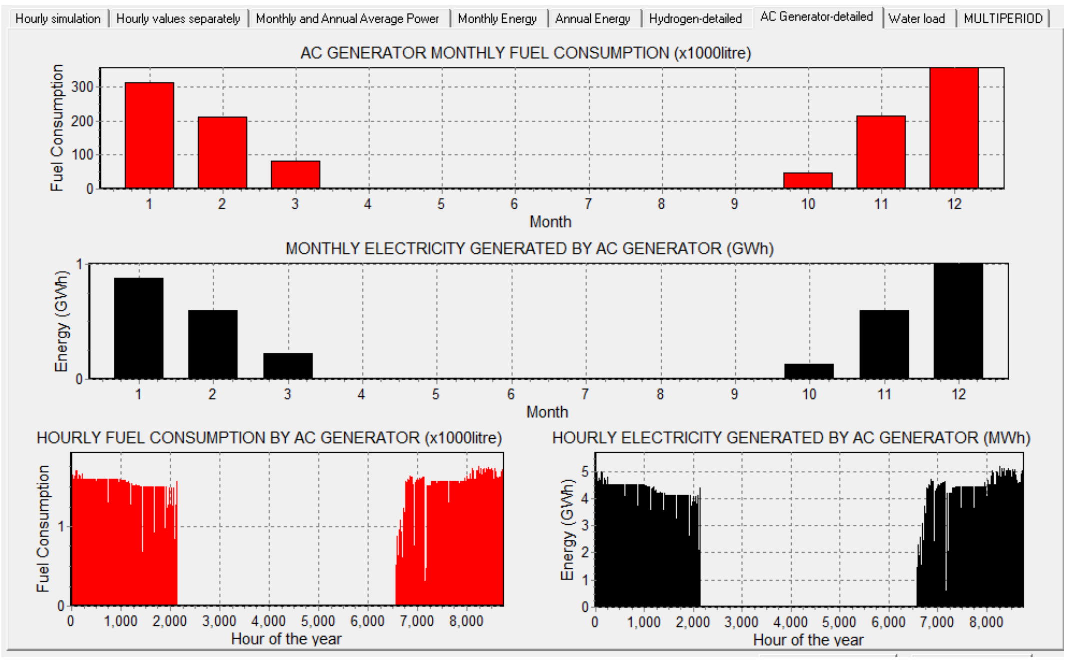
Hydrogen - detailed tab:

Values of hydrogen consumed and generated for each month, in t and GWh energy, are displayed. Also, hydrogen values accumulated in the tank or sold at the end of each month. (*The example figure of this simulation corresponds to a system different from the simulation seen before*).



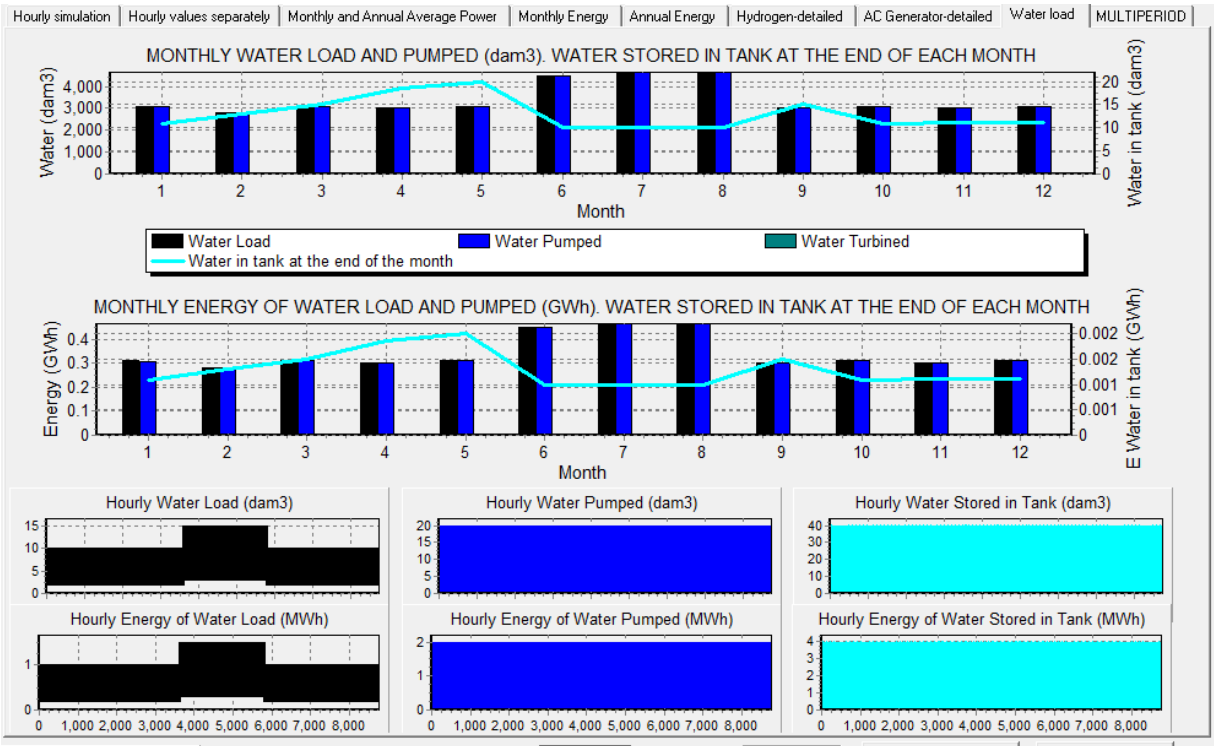
AC generator - detailed tab:

Showing details on consumption and AC generator power. (*The example figure of this simulation corresponds to a system different from the simulation seen before*).



Water load tab:

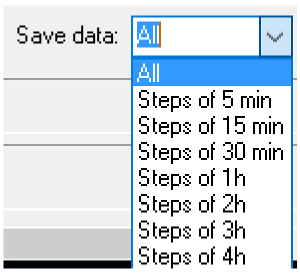
In the case that there is water consumption which has previously been pumped to water tank from river or from waterhole, it shows the values of consumed and pumped water for each month, in m3 and GWh of energy as well as water accumulated in the tank at the end of each month. Also shown are the hourly values throughout the year separated. (*The example figure of this simulation corresponds to a system different from the simulation seen before*).



Save simulation data:

The time data represented can be exported to a file by pressing the "**Save Simulation Data**" button. If a multiperiod project is shown, the data to be saved will be the data of the year shown in this moment (you can change the year with the box of the simulation screen

).

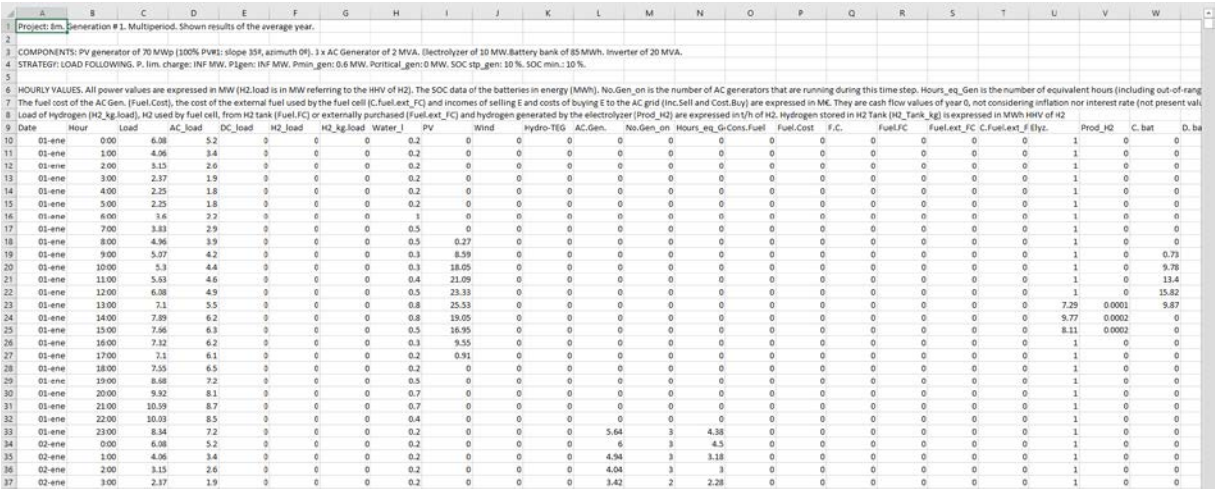


You can save all data used in the simulation or in higher temporal intervals (if the interval is greater than the one used in the simulation, the average of the values of that interval is performed). They are stored in rows (one row for each time interval), in each column the different results of the simulation. You can choose to save as an Excel file (.xls) or as a text file (.txt). In case of saving as an

Excel file, once saved, if we open the file with Microsoft Excel, it reports a message, you must answer "Yes" and it opens correctly.

In Microsoft Excel, you should save the Excel file as xlsx format (in Excel, use "Save As" and choose file format "xlsx"), then the next time you open the xlsx file Excel will not ask you any question.

After the simulation (one time step in each row), the Excel file displays the monthly and annual total values of different energies, and the total values of purchase and sale energy to the AC grid (energy, costs and incomes). Total values also appear for the different time periods defined in the PURCHASE/SELL tab in the LOAD / AC GRID screen.



Project: 8m. Generation # 1. Multiperiod. Shown results of the average year.

COMPONENTS: PV generator of 70 MWp (100% PV#1: slope 35º, azimuth 0º). 1 x AC Generator of 2 MVA. Electrolyzer of 10 MW.Battery bank of 85 MWh. Inverter of 20 MVA.

STRATEGY: LOAD FOLLOWING. P. lim. charge: INF MW. P1gen: INF MW. Pmin_gen: 0.6 MW. Pcritical_gen: 0 MW. SOC stp_gen: 10 %. SOC min.: 10 %.

HOURLY VALUES. All power values are expressed in MW (H2.load is in MW referring to the HHV of H2). The SOC data of the batteries in energy (MWh). No.Gen_on is the number of AC generators that are running during this time step. Hours_eq_Gen is the number of equivalent hours (including out-of-rang

The fuel cost of the AC Gen. (Fuel.Cost), the cost of the external fuel used by the fuel cell (C.fuel.ext_FC) and incomes of selling E and costs of buying E to the AC grid (Inc.Sell and Cost.Buy) are expressed in M€. They are cash flow values of year 0, not considering inflation nor interest rate (not present valu

Load of Hydrogen (H2_kg.load), H2 used by fuel cell, from H2 tank (Fuel.FC) or externally purchased (Fuel.ext_FC) and hydrogen generated by the electrolyzer (Prod_H2) are expressed in t/h of H2. Hydrogen stored in H2 Tank (H2_Tank_kg) is expressed in MWh HHV of H2

Date	Hour	Load	AC_load	DC_load	H2_load	H2_kg.load	Water_l	PV	Wind	Hydro-TEG	AC.Gen.	No.Gen_on	Hours_eq_G	Cons.Fuel	Fuel.Cost	F.C.	Fuel.FC	Fuel.ext_FC	C.Fuel.ext_F	Elyz.	Prod_H2	C. bat	D. ba
01-ene	0:00	6.08	5.2	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	1:00	4.06	3.4	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	2:00	3.15	2.6	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	3:00	2.37	1.9	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	4:00	2.25	1.8	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	5:00	2.25	1.8	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	6:00	3.6	2.2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	7:00	3.83	2.9	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	8:00	4.96	3.9	0	0	0	0.5	0.27	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	9:00	5.07	4.2	0	0	0	0.3	8.59	0	0	0	0	0	0	0	0	0	0	0	1	0	0.73	
01-ene	10:00	5.3	4.4	0	0	0	0.3	18.05	0	0	0	0	0	0	0	0	0	0	0	1	0	9.78	
01-ene	11:00	5.63	4.6	0	0	0	0.4	21.09	0	0	0	0	0	0	0	0	0	0	0	1	0	13.4	
01-ene	12:00	6.08	4.9	0	0	0	0.5	23.33	0	0	0	0	0	0	0	0	0	0	0	1	0	15.82	
01-ene	13:00	7.1	5.5	0	0	0	0.8	25.53	0	0	0	0	0	0	0	0	0	0	0	7.29	0.0001	9.87	
01-ene	14:00	7.89	6.2	0	0	0	0.8	19.05	0	0	0	0	0	0	0	0	0	0	0	9.77	0.0002	0	
01-ene	15:00	7.66	6.3	0	0	0	0.5	16.95	0	0	0	0	0	0	0	0	0	0	0	8.11	0.0002	0	
01-ene	16:00	7.32	6.2	0	0	0	0.3	9.55	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	17:00	7.1	6.1	0	0	0	0.2	0.91	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	18:00	7.55	6.5	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	19:00	8.68	7.2	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	20:00	9.92	8.1	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	21:00	10.59	8.7	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	22:00	10.03	8.5	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
01-ene	23:00	8.34	7.2	0	0	0	0.2	0	0	0	5.64	3	4.38	0	0	0	0	0	0	1	0	0	
02-ene	0:00	6.08	5.2	0	0	0	0.2	0	0	0	6	3	4.5	0	0	0	0	0	0	1	0	0	
02-ene	1:00	4.06	3.4	0	0	0	0.2	0	0	0	4.94	3	3.18	0	0	0	0	0	0	1	0	0	
02-ene	2:00	3.15	2.6	0	0	0	0.2	0	0	0	4.04	3	3	0	0	0	0	0	0	1	0	0	
02-ene	3:00	2.37	1.9	0	0	0	0.2	0	0	0	3.42	2	2.28	0	0	0	0	0	0	1	0	0	

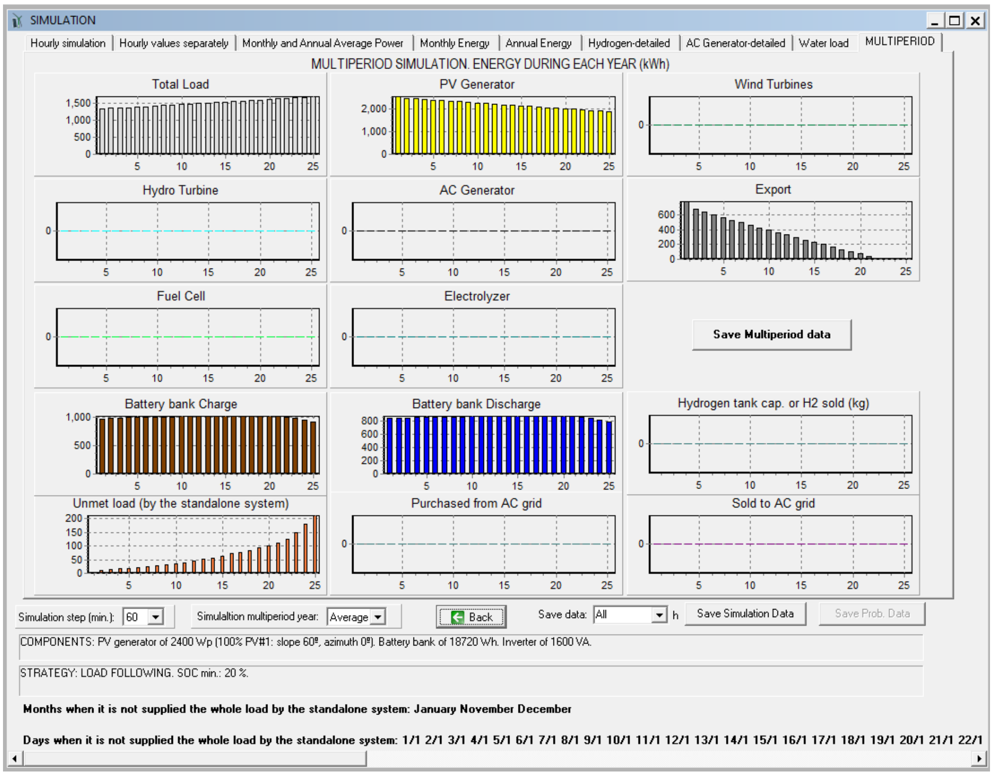
Below is displayed the number of cycles for each case depth of discharge (DOD) conducted by the batteries, using the method "Rainflow" or cycle counting.

If there are days when the whole load is not covered by the standalone system (there is energy not served by the standalone system, which will be purchased from the AC grid if there is AC grid and the purchasing is allowed), the days when not all the energy is covered by the standalone system are shown later.

3813										
3814	CYCLES OF CHARGE-DISCHARGE OF BATTERIES DURING 1 YEAR:									
3815	Range:	0-15%DOD	15-25%DOD	25-35%DOD	35-45%DOD	45-55%DOD	55-65%DOD	65-75%DOD	75-85%DOD	85-100%DOD
3816	Cycles:	326	39	0	0	0	0	0	1	0
3817										
3818										
3819	MONTHS WITH UNMET LOAD (NOT ALL THE LOAD CAN BE COVERED BY THE STAND-ALONE SYSTEM):									
3820	December									
3821										
3822	MONTHS WITH UNMET LOAD (NOT ALL THE LOAD CAN BE COVERED BY THE STAND-ALONE SYSTEM):									
3823	December, day 27									
3824	December, day 28									
3825	December, day 29									
3826	December, day 30									
3827	December, day 31									
3828										
3829										

4.4.2. Simulation in the case of multiperiod optimization.

If multiperiod optimization was selected (main screen, menu Project-> OPTIONS), an extra tab (MULTIPERIOD, last tab) is shown in the simulation screen. This tab will show the results of the energy of the different years of the simulation:



By clicking in the button "**Save Multiperiod data**" (middle right zone of this tab) you can save the Excel file with the annual data of the different variables involved in the multiperiod simulation.

In the saved file you can see the annual values of energies, costs (cash flows, not present values), emissions, etc.

Project: 1. Solution # 1. Multiperiod

Costs and incomes are cash flow of each year (not present value)

Year	Cum. Inf. Purch. E(%)	Cum. Inf. Sell E(%)	Cum. Inf. Sell H2(%)	AC load(%)	DC load(%)	H2 load(%)	Water load(%)	Irrad.(%)	Wind(%)	PV(%)	Wind T(%)
1	104.09	103	103	100	100	100	100	100	100	100	100
2	108	106.09	106.09	101	101	101	101	100	100	97	99
3	112.82	109.27	109.27	102.01	102.01	102.01	102.01	100	100	96	98
4	114.74	112.55	112.55	103.03	103.03	103.03	103.03	100	100	95	97
5	120.17	115.93	115.93	104.06	104.06	104.06	104.06	100	100	94	96
6	123.94	119.41	119.41	105.1	105.1	105.1	105.1	100	100	93	95
7	127.45	122.99	122.99	106.15	106.15	106.15	106.15	100	100	92	94
8	129.05	126.68	126.68	107.21	107.21	107.21	107.21	100	100	91	93
9	132.64	130.48	130.48	108.29	108.29	108.29	108.29	100	100	90	92
10	135.64	134.39	134.39	109.37	109.37	109.37	109.37	100	100	89	91
11	139.79	138.42	138.42	110.46	110.46	110.46	110.46	100	100	88	90
12	144.42	142.58	142.58	111.57	111.57	111.57	111.57	100	100	87	89
13	149.83	146.85	146.85	112.68	112.68	112.68	112.68	100	100	86	88
14	152.83	151.26	151.26	113.81	113.81	113.81	113.81	100	100	85	87
15	158.1	155.8	155.8	114.95	114.95	114.95	114.95	100	100	84	86
16	163.02	160.47	160.47	116.1	116.1	116.1	116.1	100	100	83	85
17	167.97	165.28	165.28	117.26	117.26	117.26	117.26	100	100	82	84
18	170.51	170.24	170.24	118.43	118.43	118.43	118.43	100	100	81	83
19	179.07	175.35	175.35	119.61	119.61	119.61	119.61	100	100	80	82
20	183.9	180.61	180.61	120.81	120.81	120.81	120.81	100	100	79	81
21	188.02	186.03	186.03	122.02	122.02	122.02	122.02	100	100	78	100
22	191.82	191.61	191.61	123.24	123.24	123.24	123.24	100	100	77	99
23	199.07	197.36	197.36	124.47	124.47	124.47	124.47	100	100	76	98
24	206.46	203.28	203.28	125.72	125.72	125.72	125.72	100	100	75	97
25	212.65	209.38	209.38	126.97	126.97	126.97	126.97	100	100	74	96

The rest of the tabs, when simulating a multiperiod projects, show the year selected in the box under the graphs: 

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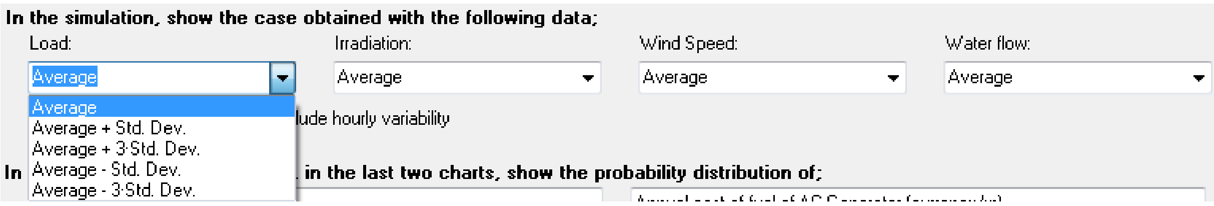
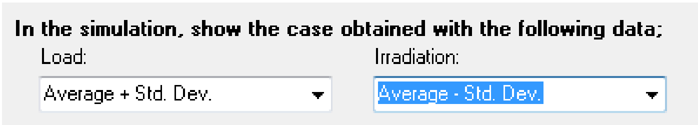
4.4.3. Simulation in case of probability analysis.

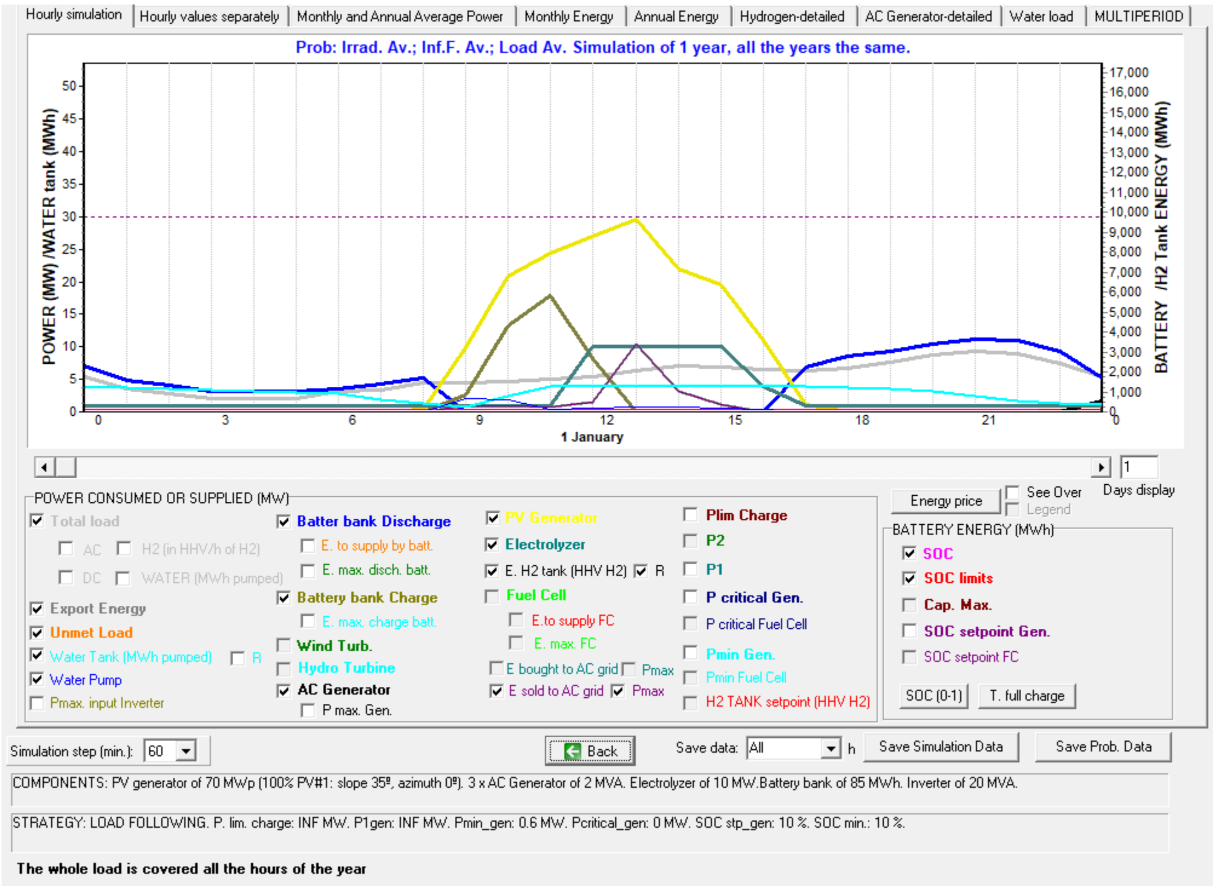
If we performed the optimization with the option of probability analysis, in the simulation screen is will be displayed the case that we have chosen on the screen of probability analysis (see next figure and end of section of probability analysis).



By clicking on "**SIMULATE**", the N series are calculated and also other $5^{number\_of\_probability\_variables}$ additional series (characteristic cases, combinations of *average*, *average + Std. Dev.*, *average + 3Std. Dev.*, *average - Std. Dev*, *average - 3Std. Dev.* of different variables taken into account in the probability anaylsis), where *number of probability variables* is the number of variables included in the probability analysis (this is a number between 1 and 4, the variables can be load, solar irradiation, wind speed and water flow or fuel price inflation). For example, if the number of series for the probability analysis is set in N=500 and the variables to analyze are load and irradiation (2 variables, 5^2 = 25 additional series), the total number of series analyzed when clicking SIMULATE button are 500 (or less if the stopping criterion of the Monte Carlo simulation was reached before the 500 combinations were performed) +25 characteristic cases.

You can cancel by clicking "Cancel" button. If it is not cancelled, the results of the row are updated with the average of the 500 series. In the simulation screen the case corresponding to the options chosen in the probability analysis screen is shown. For example, if we have chosen for the Load the Average + Std. Dev. data and for the Irradiation the Average – Std. Dev. data (next figure), the simulation screen is shown below.





If you click the button "**Save Prob. Data**", the results of the N+5$^{\text{number probability variables}}$ series are saved in Excel format.

If you open the file with Microsoft Excel, it reports a message, you must answer "Yes" and it opens correctly. In Microsoft Excel, you should save the Excel file as xlsx format (in Excel, use "Save As" and choose file format xlsx"), then the next time you open the xlsx file Excel will not ask you any question.

The Excel shows the results for each of the N series (or less if the stopping rule is reached before) (cases prob. numbers 0 to N-1, in the example cases 0 to 499) and for each of the cases $5^{\text{number of probability variables}}$ (combinations of *average*, *average + Std. Dev.*, *average + 3Std. Dev.*, *average - Std. Dev*, *average - 3Std. Dev.* of different variables taken into account in the probability anaylsis, cases numbers N to N+$5^{\text{number of probability variables}}$ -1, in the example cases 500 to 524). It also shows the minimum, maximum, average and standard deviation of each result variable.

1 Project: 8m. Generation # 1
2 COMPONENTS: PV generator of 70 MWp (100% PV#1: slope 35º, azimuth 0º). 3 x AC Generator of 2 MVA. Electrolyzer of 10 MW.Battery bank of 85 MWh. Inverter of 20 MVA.
3 STRATEGY: LOAD FOLLOWING. P. lim. charge: INF MW. P1gen: INF MW. Pmin_gen: 0.6 MW. Pcritical_gen: 0 MW. SOC stp_gen: 10 %. SOC min.: 10 %.
4
5 RESULTS FOR THE DIFFERENT COMBINATIONS OF THE PROBABILITY ANALYSIS:
6 First 500 rows are the results corresponding to random data series. Next 125 rows correspond to characteristical cases. Next row correspond to the case shown in simulation. Finally MINIMUM, MAXIMUM, AVERAGE and STD.DEV. of the results of the 500 random series are shown:
7
8 Results corresponding to random data series:

9	Case prob. No.	Rad.(kWh/m2/day)	Tamb(ºC)	TambV(ºC)	Wind(m/s)	W.Flow(m3/s) or inf. fuel	Load(GWh/day)	Total NPC (M€)	LCOE(M€/kWh)	Emission(ktCO2/year)	Unmet(%)	Renew.(%)
10	0	4.85	13.3	25.95	6.43	5000	0.11	191.7	0.268	7.2	0	93.1
11	1	4.59	13.17	25.95	6.43	4999.67	0.11	198	0.289	6.4	0	94.2
12	2	4.96	15.22	25.95	6.43	5000.59	0.12	209.8	0.275	8.4	0	91.5
13	3	5.11	12.36	25.95	6.43	5000.07	0.11	188.3	0.261	7.3	0	93.1
14	4	5.13	14.49	25.95	6.43	4998.76	0.11	188.7	0.263	7.2	0	93.2
15	5	4.79	14.47	25.95	6.43	5000.27	0.11	204.4	0.282	7.5	0	92.7
16	6	4.78	12.13	25.95	6.43	4998.9	0.1	182.7	0.273	5.8	0	95
17	7	4.45	12.71	25.95	6.43	4999.87	0.07	151.7	0.302	2.9	0	99.9
18	8	5.03	13.85	25.95	6.43	4999	0.14	243.1	0.278	11.9	0	87.2
19	9	4.86	13.37	25.95	6.43	4999.48	0.1	175	0.27	5.3	0	95.7
20	10	4.36	14.2	25.95	6.43	5000.65	0.12	237.1	0.306	9	0	90.6
21	11	5.02	12.7	25.95	6.43	5000.19	0.13	225.3	0.274	10.3	0	89.2
22	12	4.92	12.62	25.95	6.43	4999.66	0.1	180.8	0.268	6	0	94.8
23	13	4.63	12.73	25.95	6.43	4999.32	0.09	166.7	0.281	4.1	0	97.7
24	14	4.68	13.16	25.95	6.43	4999.73	0.13	240.9	0.291	10.6	0	88.9
25	15	5.13	12.89	25.95	6.43	5000.11	0.09	153.5	0.251	4.4	0	97.1
26	16	5.25	11.97	25.95	6.43	5000.42	0.11	180.4	0.253	7	0	93.4
27	17	5.23	13.12	25.95	6.43	5000.68	0.12	199.5	0.26	8.5	0	91.4
28	18	4.89	13.05	25.95	6.43	5000.68	0.11	198.9	0.274	7.5	0	92.8
29	19	4.9	10.63	25.95	6.43	5000.73	0.12	211.2	0.273	8.8	0	91
30	20	5	11.79	25.95	6.43	5000.53	0.1	173.8	0.26	5.8	0	95.1
31	21	4.66	13.29	25.95	6.43	4999.69	0.11	207.1	0.287	7.4	0	92.8
32	22	5.01	15.15	25.95	6.43	4999.71	0.1	175.3	0.265	5.6	0	95.3
33	23	4.7	13.56	25.95	6.43	5000.19	0.13	234.8	0.29	10	0	89.6
34	24	5.28	13.85	25.95	6.43	4999.96	0.1	164	0.248	5.6	0	95.4
35	25	4.81	13.64	25.95	6.43	5000.74	0.11	188.1	0.275	6.3	0	94.4
36	26	5.14	13.45	25.95	6.43	4999.28	0.12	202	0.264	8.5	0	91.5
37	27	4.96	14.83	25.95	6.43	4999.76	0.16	281	0.293	15.3	1	83.2
38	28	4.79	13.22	25.95	6.43	4999.57	0.11	205	0.28	7.6	0	92.5

511	599	4.65	12.3	25.95	6.43	4998.5	0.05	126.5	0.313	2.8	0	100
512	600	4.25	10.3	25.95	6.43	5000	0.11	219.1	0.306	7.4	0	92.9
513	601	4.25	10.3	25.95	6.43	5000	0.13	253	0.31	10.5	0	88.7
514	602	4.25	10.3	25.95	6.43	5000	0.17	325.1	0.327	17.9	3	79.5
515	603	4.25	10.3	25.95	6.43	5000	0.09	185	0.302	4.6	0	96.8
516	604	4.25	10.3	25.95	6.43	5000	0.05	139.1	0.344	2.8	0	100
517	605	4.25	10.3	25.95	6.43	5000.5	0.11	219.1	0.306	7.4	0	92.9
518	606	4.25	10.3	25.95	6.43	5000.5	0.13	253	0.31	10.5	0	88.7
519	607	4.25	10.3	25.95	6.43	5000.5	0.17	325.1	0.327	17.9	3	79.5
520	608	4.25	10.3	25.95	6.43	5000.5	0.09	185	0.302	4.6	0	96.8
521	609	4.25	10.3	25.95	6.43	5000.5	0.05	139.1	0.344	2.8	0	100
522	610	4.25	10.3	25.95	6.43	5001.5	0.11	219.1	0.306	7.4	0	92.9
523	611	4.25	10.3	25.95	6.43	5001.5	0.13	253	0.31	10.5	0	88.7
524	612	4.25	10.3	25.95	6.43	5001.5	0.17	325.1	0.327	17.9	3	79.5
525	613	4.25	10.3	25.95	6.43	5001.5	0.09	185	0.302	4.6	0	96.8
526	614	4.25	10.3	25.95	6.43	5001.5	0.05	139.1	0.344	2.8	0	100
527	615	4.25	10.3	25.95	6.43	4999.5	0.11	219.1	0.306	7.4	0	92.9
528	616	4.25	10.3	25.95	6.43	4999.5	0.13	253	0.31	10.5	0	88.7
529	617	4.25	10.3	25.95	6.43	4999.5	0.17	325.1	0.327	17.9	3	79.5
530	618	4.25	10.3	25.95	6.43	4999.5	0.09	185	0.302	4.6	0	96.8
531	619	4.25	10.3	25.95	6.43	4999.5	0.05	139.1	0.344	2.8	0	100
532	620	4.25	10.3	25.95	6.43	4998.5	0.11	219	0.306	7.4	0	92.9
533	621	4.25	10.3	25.95	6.43	4998.5	0.13	253	0.31	10.5	0	88.7
534	622	4.25	10.3	25.95	6.43	4998.5	0.17	325.1	0.327	17.9	3	79.5
535	623	4.25	10.3	25.95	6.43	4998.5	0.09	185	0.302	4.6	0	96.8
536	624	4.25	10.3	25.95	6.43	4998.5	0.05	139.1	0.344	2.8	0	100

537 Results corresponding to case shown in simulation:

538	Case prob. No.	Rad.(kWh/m2/day)	Tamb(ºC)	TambV(ºC)	Wind(m/s)	W.Flow(m3/s) or inf. fuel	Load(GWh/day)	Total NPC (M€)	LCOE(M€/kWh)	Emission(ktCO2/year)	Unmet(%)	Renew.(%)
539	625	4.85	13.3	25.95	6.43	5000	0.11	194.8	0.272	7.2	0	93.2

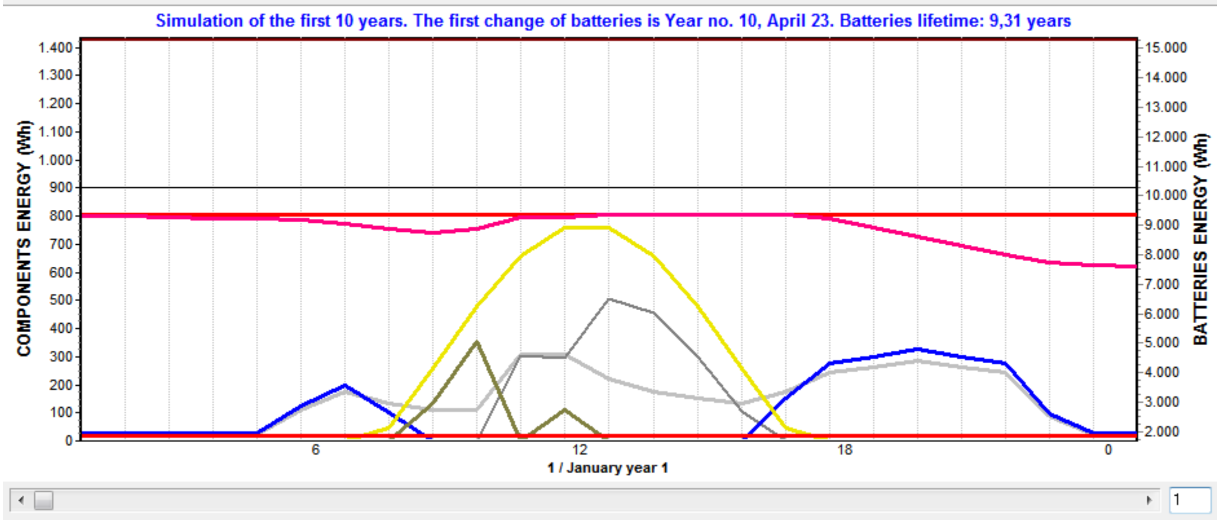
540
541 Values MINIMUM, MAXIMUM, AVERAGE and STD. DEV. of each result obtained in the 500 series:

542	Case prob. No.	Rad.(kWh/m2/day)	Tamb(ºC)	TambV(ºC)	Wind(m/s)	W.Flow(m3/s) or inf. fuel	Load(GWh/day)	Total NPC(M€)	LCOE(M€/kWh)	Emission(ktCO2/year)	Unmet(%)	Renew.(%)
543	MINIMUM:	4.33	10.15	25.95	6.43	4997.84	0.046	113.385	0.241	2.822	0	80.88
544	MAXIMUM:	5.47	16.3	25.95	6.43	5001.35	0.169	307.071	0.334	16.99	2	100
545	MEAN:	4.86	13.2	25.95	6.43	4999.99	0.11	195.86	0.276	7.24	0.02	93.29
546	STD.DEV.:	0.19	1.03	0	0	0.5	0.02	33.9	0.013	2.78	0.19	3.8

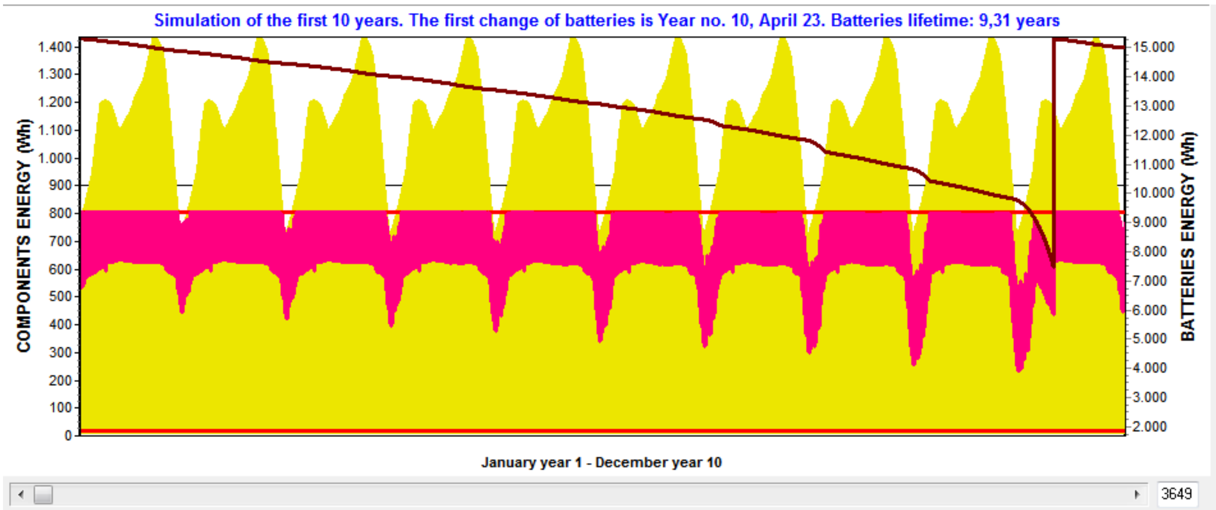
547

4.4.4. Simulation in the case of "Schiffer" lead-acid battery model

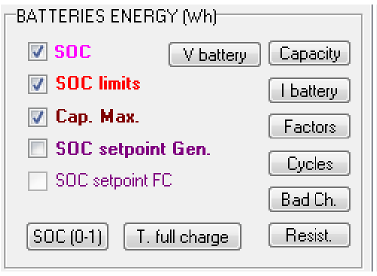
In the case of using the battery model "Schiffer" (for lead-acid batteries), the simulation is performed until the end of the lifespam of the batteries. For example, in the case of the figure below, the batteries lifespam is 9.31 years.



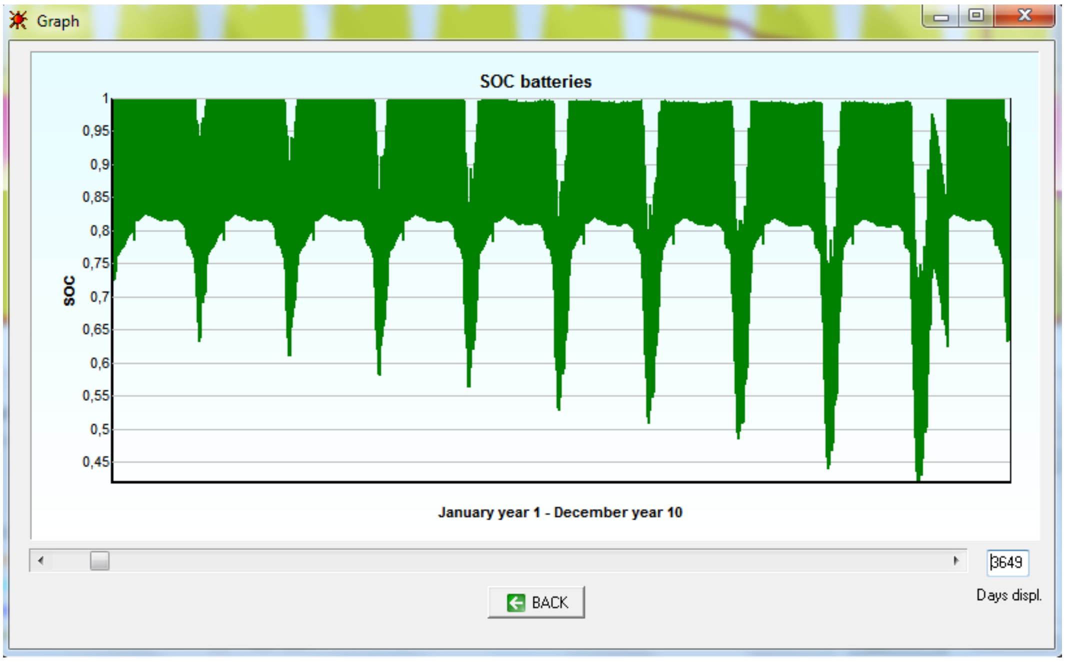
The following figure shows the simulation of the first 10 years (3649 days display). You can see how in the year 10, on April 23, the maximum capacity of the battery (brown curve) has dropped to 80% of its nominal value (9360Wh * 80/100 = 7494 Wh), indicating that battery has exhausted its useful life and must be replaced. This day the batteries are replaced.



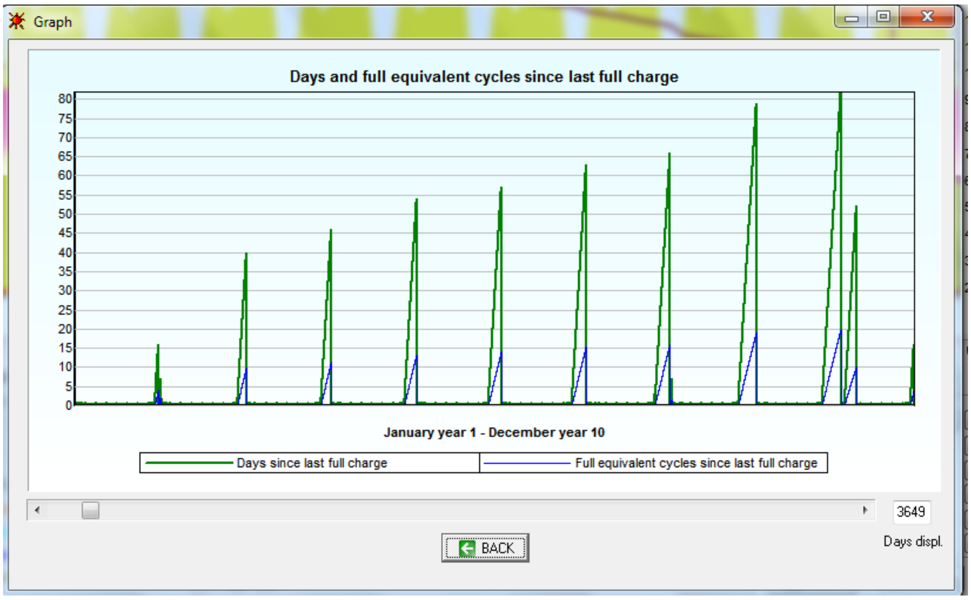
By clicking on the buttons on the right of the screen simulation, different variables appears in a new simulation screen:



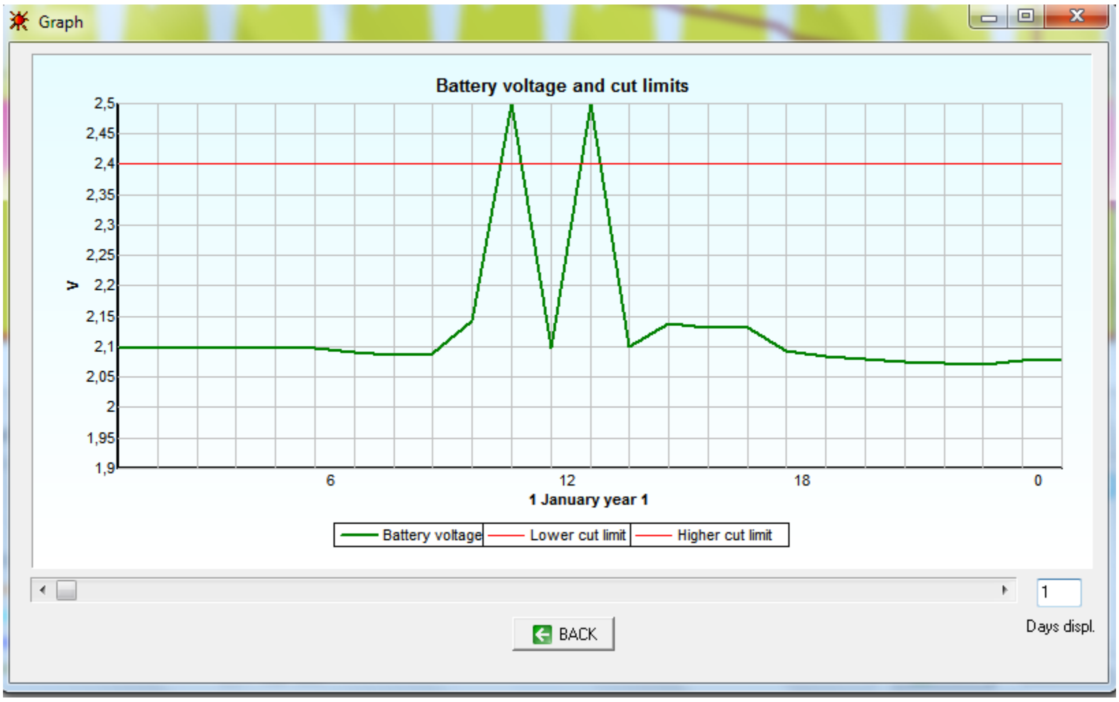
- SOC(0-1): SOC of the battery bank, in per unit (in Figure 10 years displyed, 3649 days):



- T. full charge: Time and equivalent cycles since the last full charge



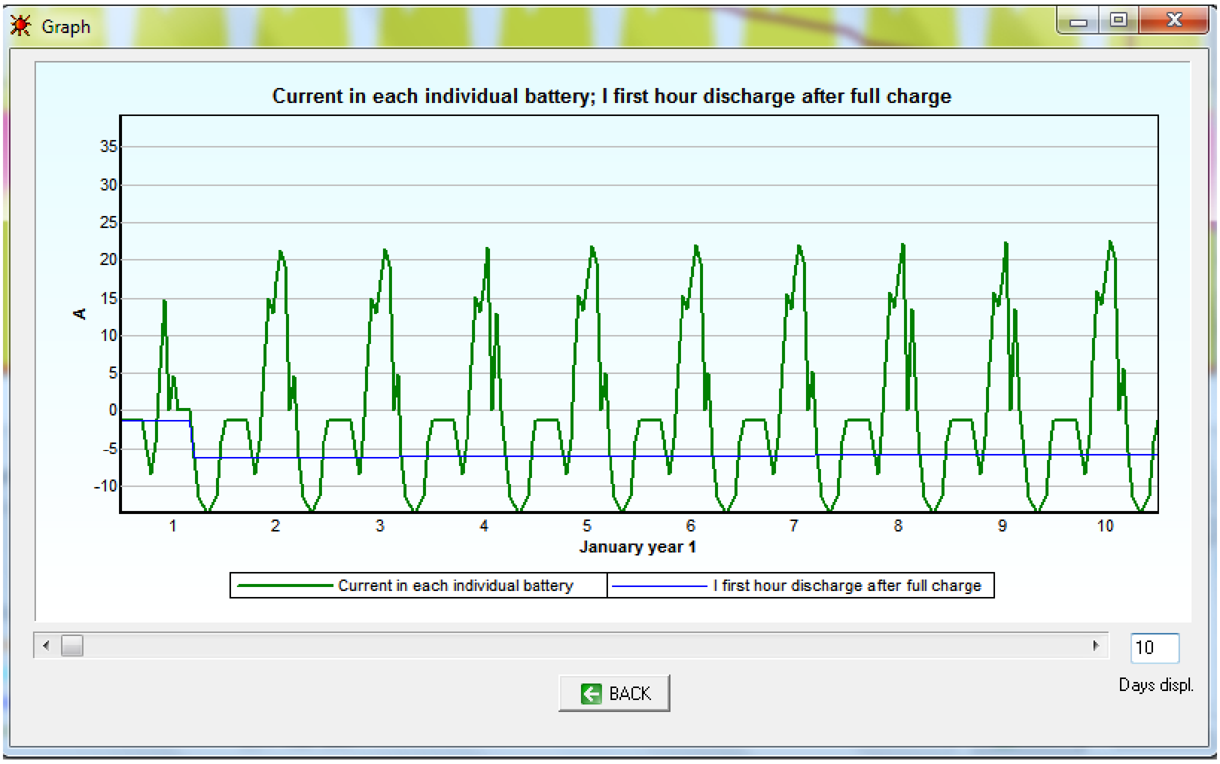
- V Battery: Battery voltage and cutting limits (in Figure 1 days display):



- Capacity. Is displayed (in Figure 10 years displayed, 3649 days):

It is shown the maximum capacity in brown, with the end of lifespan when it reaches 80%, the loss of capacity for degradation (green curve) and the loss of capacity due to corrosion (blue curve). It is noted that, in this case, the capacity loss due to corrosion is far greater than by degradation. This is only taken into account by the Schiffer model and not by another model of batteries, making it much more accurate than the other models.

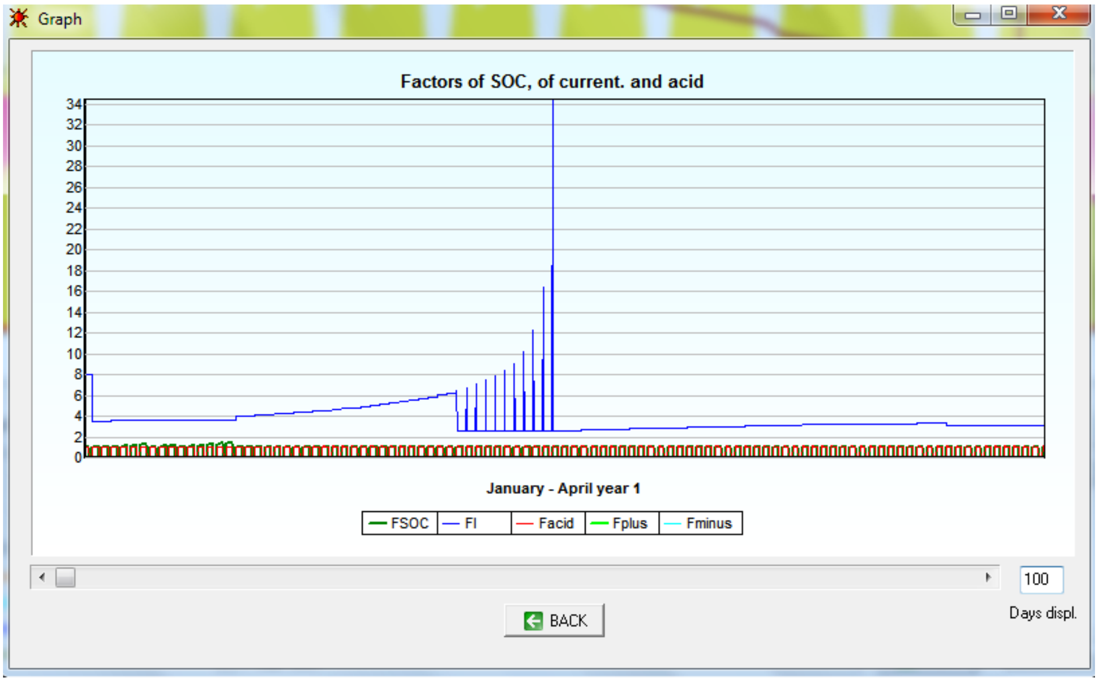
- I battery: current (A) in each individual battery is displayed (in the figure, 10 days displayed):



It is shown the current for each individual battery (green curve) and the discharge current for the first hour after full charge (blue curve), very important parameter for calculating the current factor and quantify the effect of sulfation and its degradation effect.

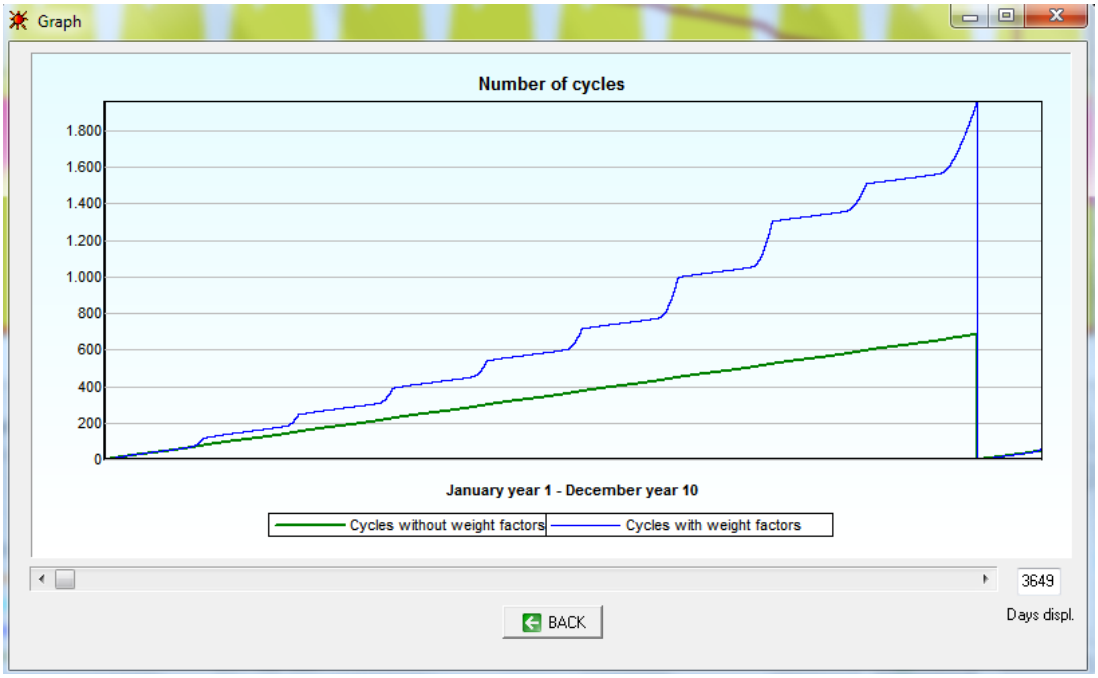
- Factors: factors used in the Schiffer model (in figure display 100 days):

FSOC, FI, Facid, Fplus, Fminus

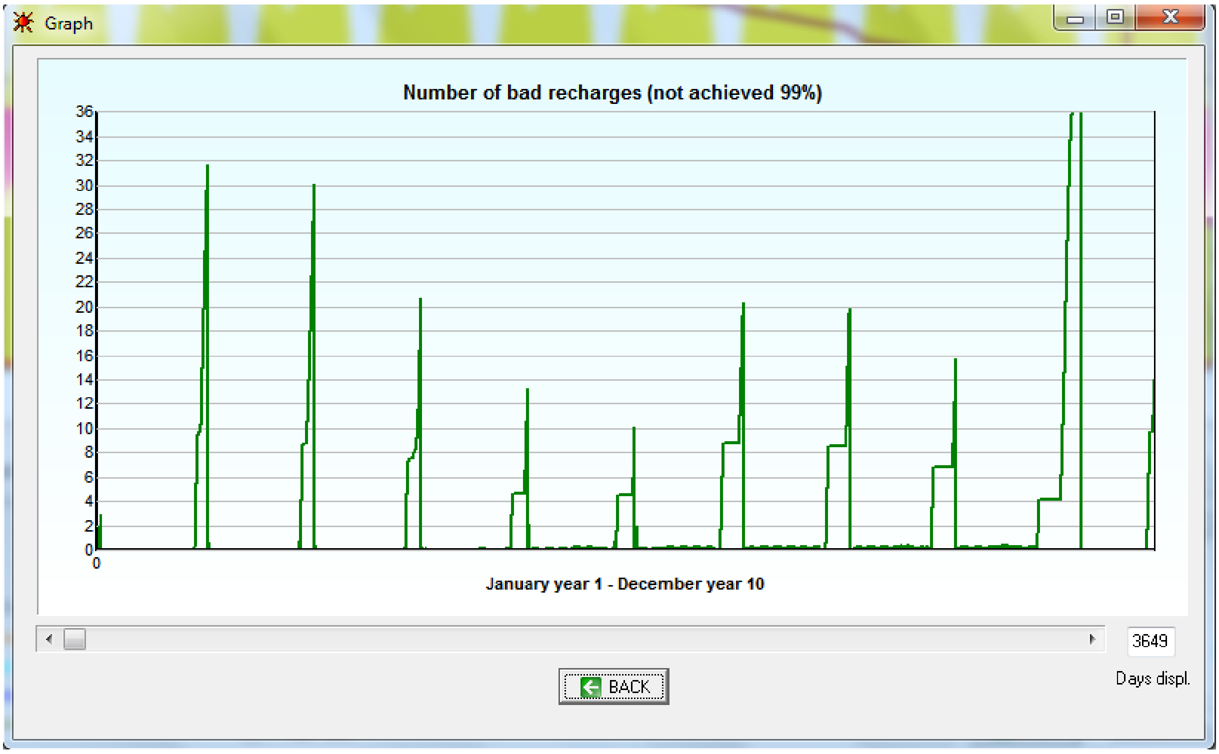


- Cycles: full cycles performed by the batteries (in the figure, displayed 10 years):

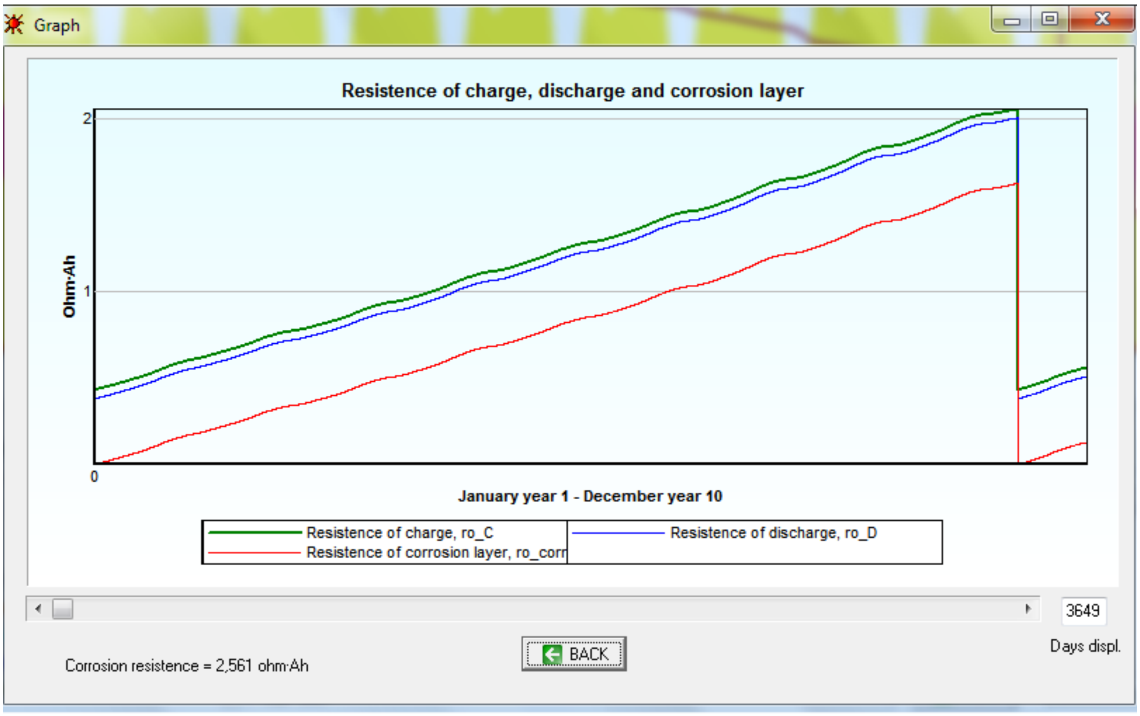
It is shown the cycles without weight factors (curve green) and the weight cycles (blue curve).



- Bad ch.: Number of bad recharges (not achieved 99% of SOC) (in the figure, displayed 10 years):



- Resist.: Resistances (charge, discharge and and corrosion layer) (in the figure, 10 years of viewing):



The simulation results shown in the other tabs of the simulation screen (separate hourly values, etc.) refer to last year of the simulation.

4.4.5. Changing Values in the Results Table.

Some values of the control variables in the result table can be changed. Although this modifies the results obtained, it can be useful to see how a parameter affects the simulation of the system and the different energy and economic results. For example, we can modify the resources or the characteristics of the elements on their screens, and then if clicking on any cell if the results table MHOGA will take into account the changes in that row.

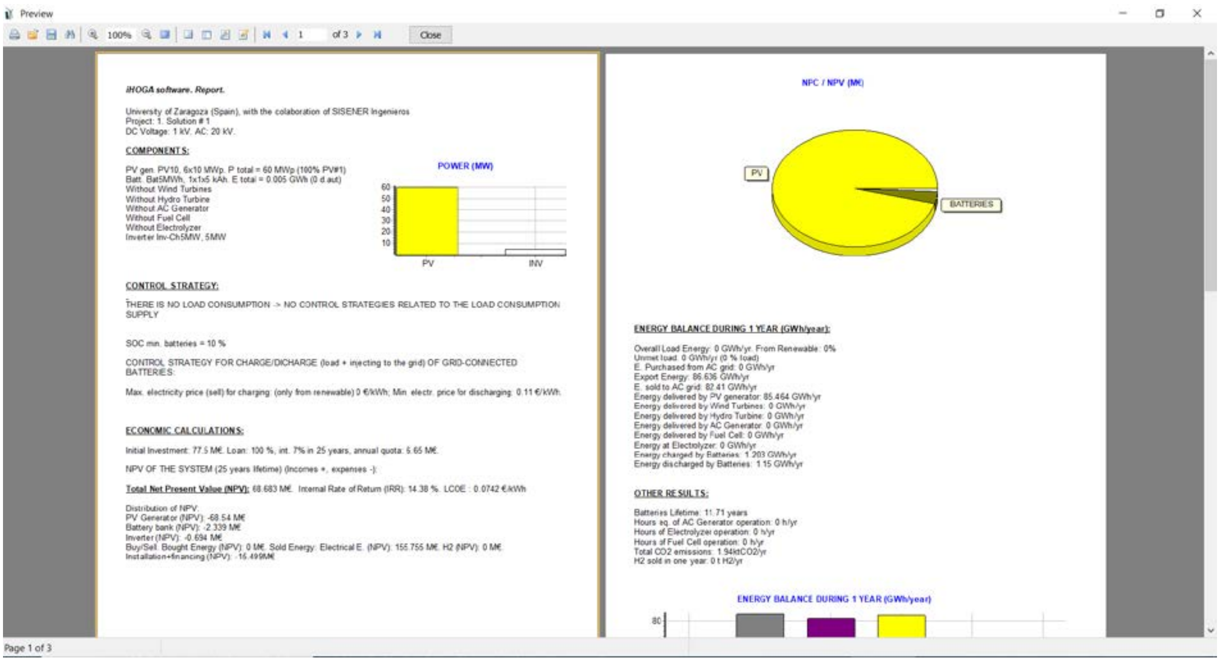
4.4.6. Report.

Click on the “**REPORT...**” column in the results table to display a report for each solution.

Details are provided in the report on System Components (with a power chart), Control Strategy, Annual Energy Balance, and NPC or NPV values (with charts).

If multiperiod optimization was selected (Project-> Options), annual values of energies shown in the annual energy balance are the average values of all the years of the simulation. For example, if the lifetime of the system is 25 years, in each cell of annual energies it shows the average of the 25 years. The NPC or NPV cells show in that case the NPC or NPV obtained considering the present costs and incomes of each year. At the end of the report, it shows the energy of the different components during the years.

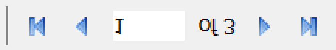
The menu at the top provides the following options: Print, Open, Save, Find, Zoom, and others. Reports may be saved in pdf format using Adobe Acrobat and the Print option. If you have installed in your computer Adobe Acrobat or a PDF virtual printer (for example, free software doPDF, http://www.dopdf.com/es/), by clicking in the printer  button there appears a window where you can choose as printer name the PDF virtual printer, then clicking in OK it generates the report as a pdf file, which can be saved.



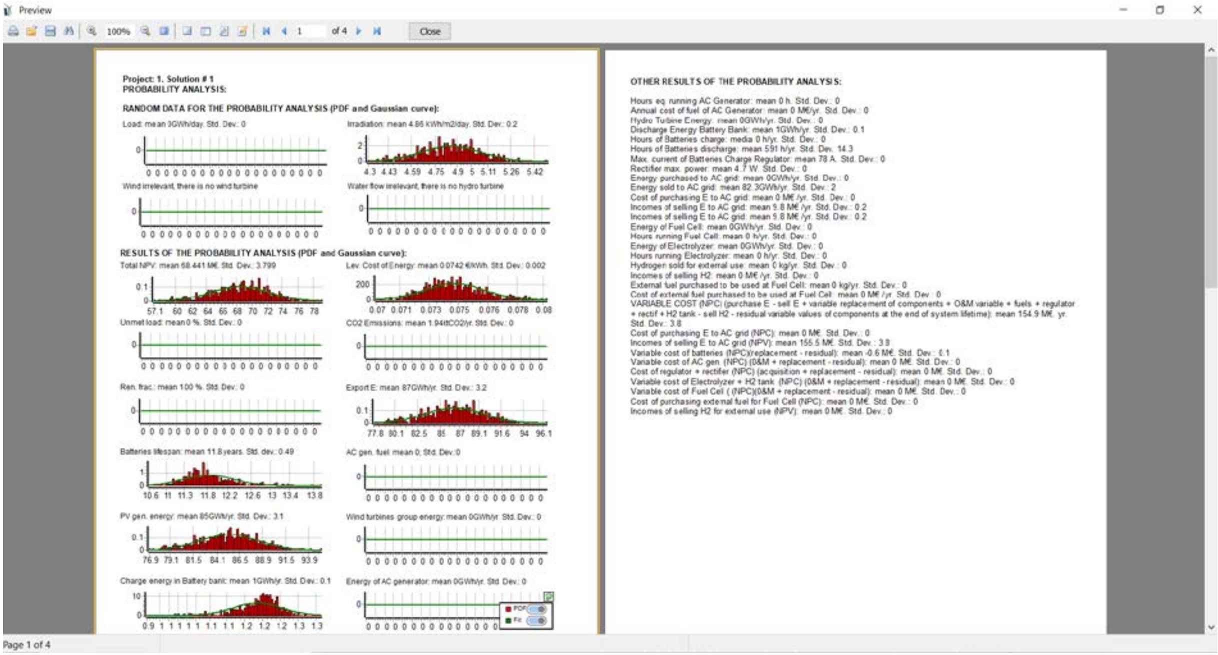
When closing the report, a message appears asking us if we want to save the report in a .rtf file (which can be open by Microsoft Word or other text processors).

Extra Report in the case of probability analysis: Only in PRO+ version

If we performed the optimization with the option of probability analysis, the results of the general report are the average values of the results (average values of the results corresponding to the N series of simulations performed in the probability analysis). When closing the general report, the probability analysis report is automatically opened. Data and results more relevant appear in graphical probability distributions.

This report has multiple pages (bottom left of the page informs where we are). Clicking on the top , we move through the different pages of the report. On the first page there are the most important results with their probability distribution graphs. On page 2 it is reported the mean and standard deviation of the other results, and the report of the most important results of the characteristic cases combinations ($5^{\text{number of probability variables}}$, combinations of *average*, *average + Std. Dev.*, *average + 3Std. Dev.*, *average - Std. Dev*, *average - 3Std. Dev.* of different variables taken into account in the probability analysis: load, solar irradiation, wind speed and water flow or fuel price inflation, if applicable).

This report can be printed (a printer or PDF) in the same way as explained for the general report.



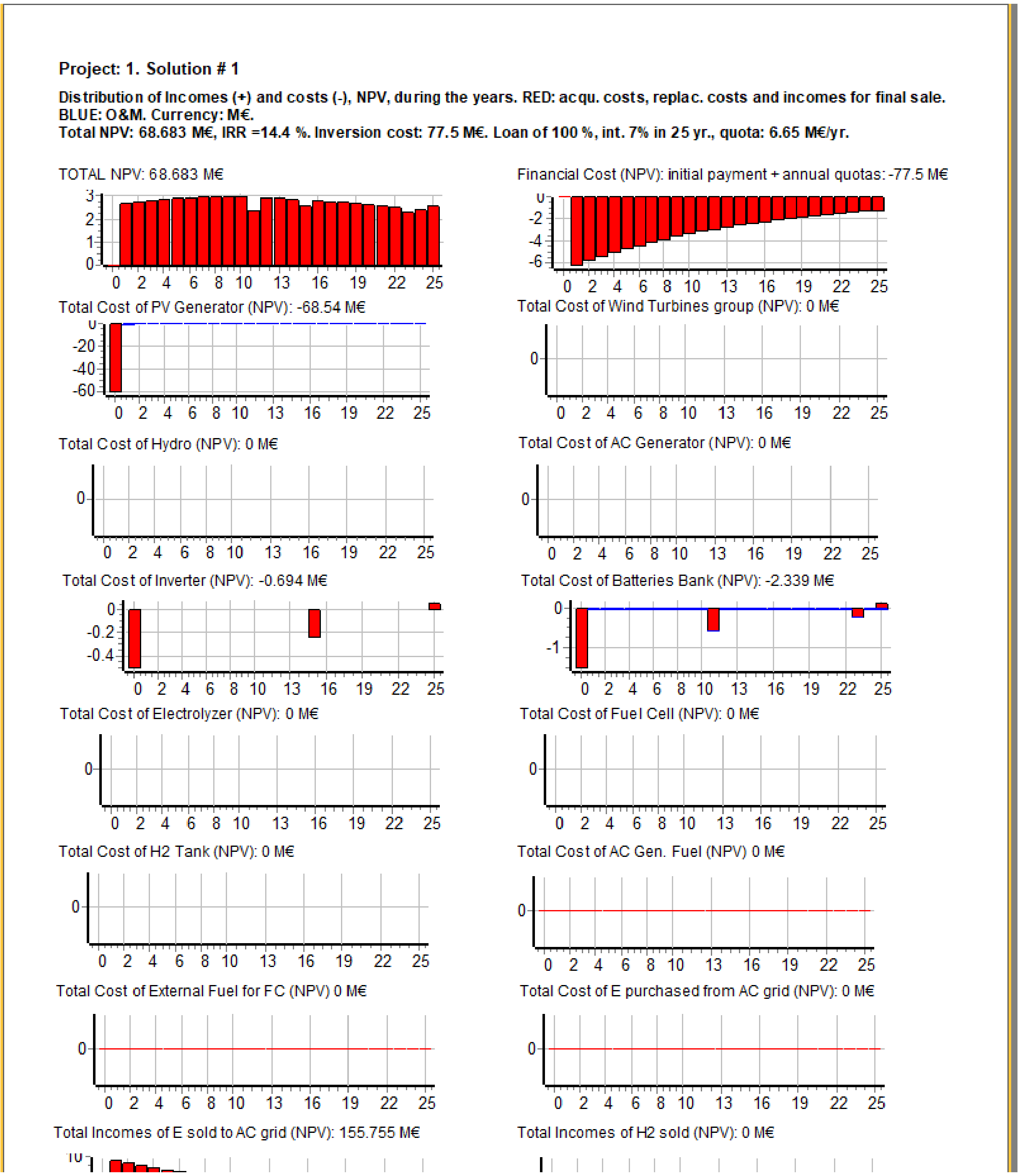
When we close the probability report, a screen appears asking if we want to save the results of the analysis of probability as Microsoft Excel file (same Excel file as the one which is saved when clicking the button "**Save Prob. Data**" in the simulation window shown in section 4.4.2).

4.4.7. System Costs.

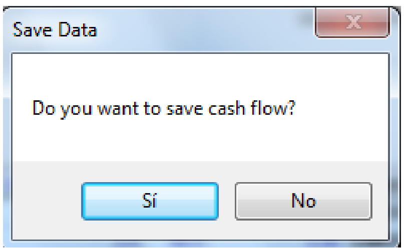
Clicking on the “**COSTS...**” cell of the result table corresponding to the row of the solution you want to study, a report shows the cash flows of the different components of the system throughout the years of the life of the system. In minimization of NPC projects, costs are considered positive values (+) and incomes are considered as negative values (-); in maximization of NPV projects, the contrary, incomes + and costs -. You can see how some components have an income cash flow at the end of the lifetime of the system (income is obtained by the sale of the component at the end of the lifetime of the system, with value proportional to the remaining life of the component).

Please, note that the cost of the electricity bought to the electrical grid includes the cost of the availability of the power.

This report can be printed (in a printer or in PDF format) in the same way as explained in the previous section.



When you close the report a screen appears asking if you want to save the results of the cash flows in the form of Microsoft Excel.



If you click "Yes", you save the file and, when you open it, the cash flow of costs (+ or -, depending on the project type) and incomes (- or +) of the years of the system lifetime are shown for each component, and also for purchasing or selling energy from the AC grid, etc. For each cost or income, for each year it is shown the cash of the year and the actualized cash (NPC or NPV). Also, total values for each component and for each year are shown.

Project: 8m. Generation # 1

Inversion cost: 190 M€(included installation and initial variable costs of 38 M€). Loan: 100 %, int. 7% in 25 years.
CASH FLOW THROUGHOUT SYSTEM LIFETIME.
CASH FLOW OF COSTS (+) AND INCOMES (-):
All values in M€. Costs +, Incomes -. For each component, cash flows correspond to acquisition cost (year 0), replacement costs (years in which the component is replaced), and return revenue at the end of the system's life, if it has a useful life (negative value), the three sums are represented in the same

YEAR	Costs PV Gen.		O&M PV Gen.		Costs Wind T.		O&M Wind T.		Costs Hydro T.		O&M Hydro T.		Costs AC Gen.		O&M AC Gen.		Costs Inverter		Costs Batteries		O&M Batteries		Costs
	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash year	NPC	cash
0	70	70	0	0	0	0	0	0	0	0	0	0	5	5	0	0	1	1	36	36	0	0	
1	0	0	0.714	0.667	0	0	0	0	0	0	0	0	0	0	0.056	0.052	0	0	0	0	0.367	0.343	
2	0	0	0.728	0.636	0	0	0	0	0	0	0	0	0	0	0.057	0.05	0	0	0	0	0.375	0.327	
3	0	0	0.743	0.606	0	0	0	0	0	0	0	0	0	0	0.058	0.048	0	0	0	0	0.382	0.312	
4	0	0	0.758	0.578	0	0	0	0	0	0	0	0	0	0	0.06	0.045	0	0	0	0	0.39	0.297	
5	0	0	0.773	0.551	0	0	0	0	0	0	0	0	0	0	0.061	0.043	0	0	0	0	0.397	0.283	
6	0	0	0.788	0.525	0	0	0	0	0	0	0	0	0	0	0.062	0.041	0	0	0	0	0.405	0.27	
7	0	0	0.804	0.501	0	0	0	0	0	0	0	0	0	0	0.063	0.039	0	0	0	0	0.414	0.258	
8	0	0	0.82	0.477	0	0	0	0	0	0	0	0	0	0	0.064	0.037	0	0	0	0	0.422	0.245	
9	0	0	0.837	0.455	0	0	0	0	0	0	0	0	0	0	0.066	0.036	0	0	0	0	0.43	0.234	
10	0	0	0.853	0.434	0	0	0	0	0	0	0	0	0	0	0.067	0.034	0	0	29.415	14.953	0.439	0.223	
11	0	0	0.87	0.414	0	0	0	0	0	0	0	0	0	0	0.068	0.032	0	0	0	0	0.448	0.213	
12	0	0	0.888	0.394	0	0	0	0	0	0	0	0	0	0	0.07	0.031	0	0	0	0	0.457	0.203	
13	0	0	0.906	0.376	0	0	0	0	0	0	0	0	0	0	0.071	0.03	0	0	0	0	0.466	0.193	
14	0	0	0.924	0.358	0	0	0	0	0	0	0	0	0	0	0.073	0.028	0	0	0	0	0.475	0.184	
15	0	0	0.942	0.341	0	0	0	0	0	0	0	0	0	0	0.074	0.027	1.346	0.488	0	0	0.485	0.176	
16	0	0	0.961	0.326	0	0	0	0	0	0	0	0	0	0	0.075	0.026	0	0	0	0	0.494	0.167	
17	0	0	0.98	0.31	0	0	0	0	0	0	0	0	0	0	0.077	0.024	0	0	0	0	0.504	0.16	
18	0	0	1	0.296	0	0	0	0	0	0	0	0	0	0	0.079	0.023	0	0	0	0	0.514	0.152	
19	0	0	1.02	0.282	0	0	0	0	0	0	0	0	0	0	0.08	0.022	0	0	0	0	0.524	0.145	
20	0	0	1.04	0.269	0	0	0	0	0	0	0	0	0	0	0.082	0.021	0	0	0	0	0.535	0.138	
21	0	0	1.061	0.256	0	0	0	0	0	0	0	0	0	0	0.083	0.02	0	0	23.553	5.688	0.546	0.132	
22	0	0	1.082	0.244	0	0	0	0	0	0	0	0	0	0	0.085	0.019	0	0	0	0	0.557	0.126	
23	0	0	1.104	0.233	0	0	0	0	0	0	0	0	0	0	0.087	0.018	0	0	0	0	0.568	0.12	
24	0	0	1.126	0.222	0	0	0	0	0	0	0	0	0	0	0.088	0.017	0	0	0	0	0.579	0.114	
25	0	0	1.148	0.212	0	0	0	0	0	0	0	0	0	0	0.09	0.017	-0.547	-0.101	-15.139	-2.789	0.591	0.109	
TOTAL	Costs PV Gen.		O&M PV Gen.		Costs Wind T.		O&M Wind T.		Costs Hydro T.-TEG		O&M Hydro T.-TEG		Costs AC Gen.		O&M AC Gen.		Costs Inverter		Costs Batteries		O&M Batteries		Costs
NPC		70		9.963		0		0		0		0		5		0.783		1.387		53.852		5.124	

TOTAL COST (NPC) = 58.405 M€
LEVELIZED COST OF ENERGY = 0.08 €/kWh

In Microsoft Excel, you should save the Excel file as xlsx format (in Excel, use "Save As" and choose file format ".xlsx"), then the next time you open the .xlsx file Excel will not ask you any question.

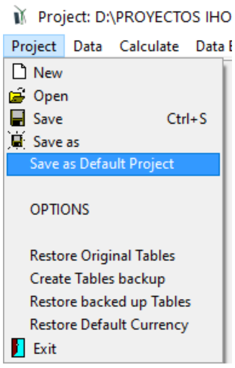
4.5 Zooming on Charts.

The "zooming" option is available for the graphical data on algorithm evolution, Pareto representation, simulation, load, and resources (irradiation, wind and hydro). Draw a window with your mouse over the area to be enlarged (click from top left to bottom right).

To undo the zoom window, click and drag from bottom right to top left.

4.6 Save project as the default project.

Once we have calculated a project, we can save it as a default project, so that from then on when a new project is created, it will be created based on this project.

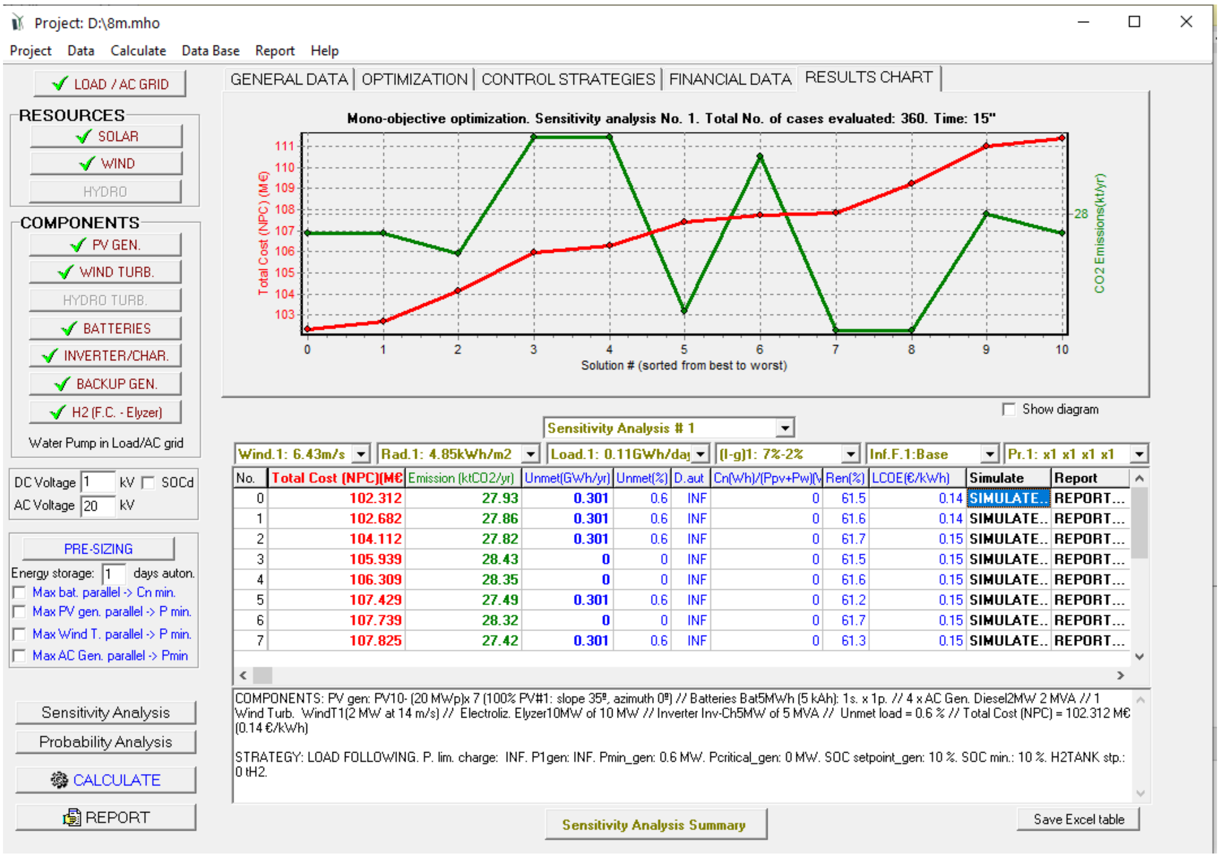


You can save another project as a default project later.

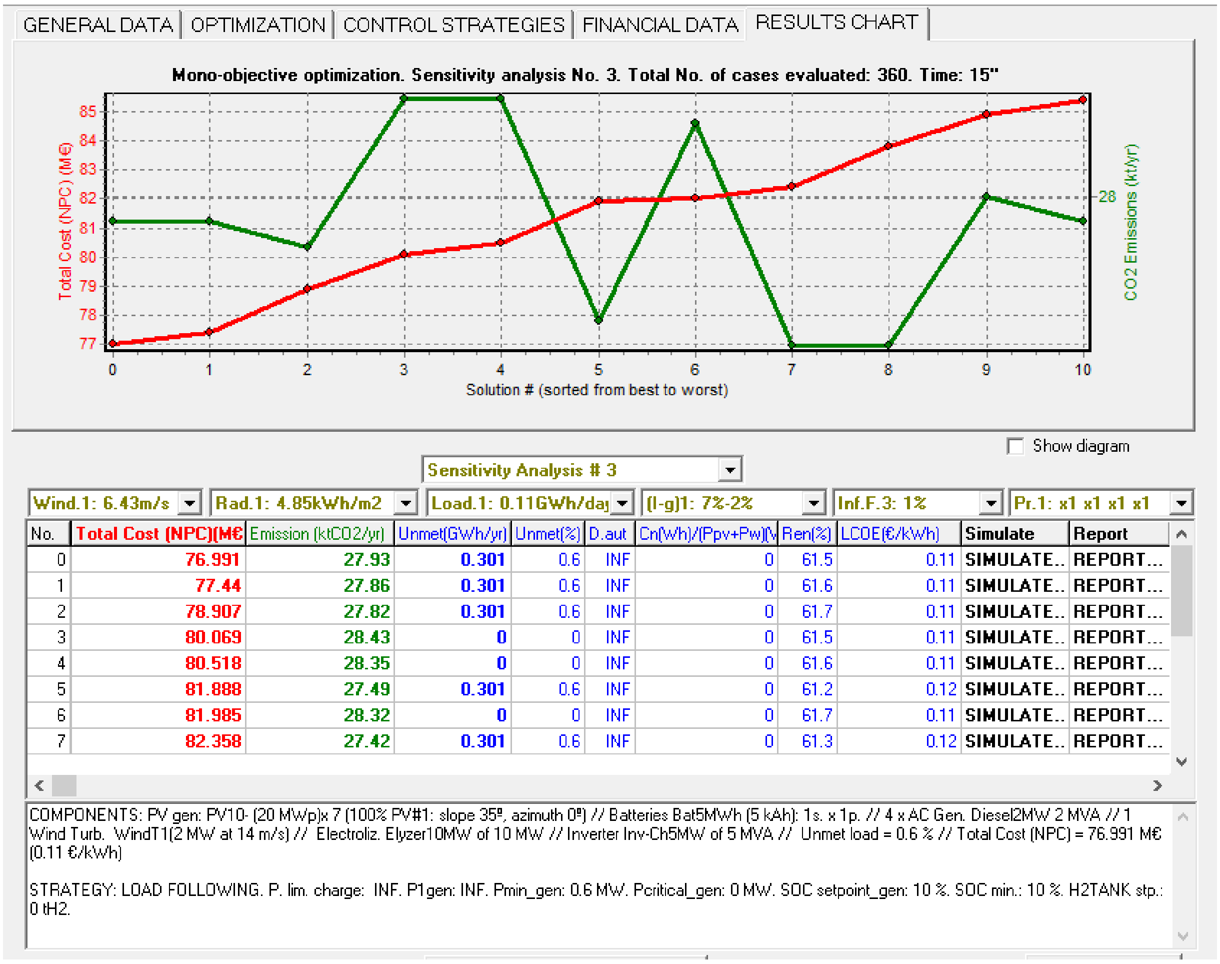
4.7 Sensitivity Analysis.

If the sensitivity analysis is performed, i.e. if cases have been entered on the sensitivity analysis screen, MHOGA calculates each sensitivity analysis project, i.e. each combination of sensitivity analysis cases. For example, if we have fixed 3 cases of wind, 2 of irradiation, 3 of load, 2 of interest and inflation, 2 of fuel price inflation of generator AC and 3 of prices of components, the number of sensitivity analyzes (the number of optimizations) that MHOGA will perform is 3x2x3x2x2x3 = 216 projects.

The figure below shows the results of the optimization in which the number of optimizations (sensitivity analysis number) is 6. Upon completion all the sensitivity analysis, it is shown in the table of results the results of the analysis No. 1 (the basis of all cases), next figure.



We can see the results of any other analysis by selecting the number of analysis down or selecting each individual case analysis variables. For example, in the following screen it is selected Sensitivity Analysis # 3 (corresponding to Wind.1, Rad.1, Load.1, (I-g) 1, Inf.F.3, Pr.1, and results are shown in the table (next figure).



No.	Total Cost (NPC)(M€	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(\	Ren(%)	LCOE(€/kWh)	Simulate	Report
0	76.991	27.93	0.301	0.6	INF	0	61.5	0.11	SIMULATE..	REPORT...
1	77.44	27.86	0.301	0.6	INF	0	61.6	0.11	SIMULATE..	REPORT...
2	78.907	27.82	0.301	0.6	INF	0	61.7	0.11	SIMULATE..	REPORT...
3	80.069	28.43	0	0	INF	0	61.5	0.11	SIMULATE..	REPORT...
4	80.518	28.35	0	0	INF	0	61.6	0.11	SIMULATE..	REPORT...
5	81.888	27.49	0.301	0.6	INF	0	61.2	0.12	SIMULATE..	REPORT...
6	81.985	28.32	0	0	INF	0	61.7	0.11	SIMULATE..	REPORT...
7	82.358	27.42	0.301	0.6	INF	0	61.3	0.12	SIMULATE..	REPORT...

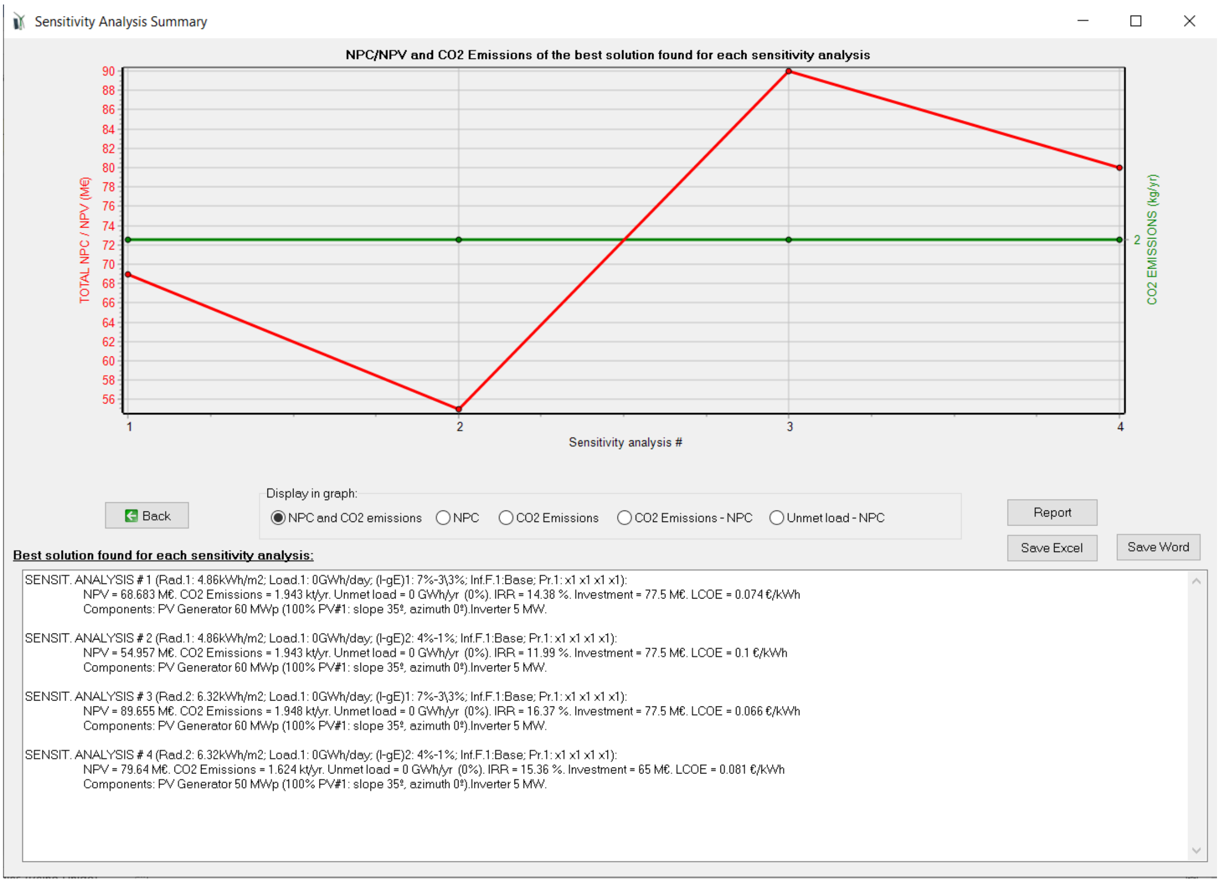
COMPONENTS: PV gen: PV10- (20 MWp)x 7 (100% PV#1: slope 35º, azimuth 0º) // Batteries Bat5MWh (5 kAh): 1s. x 1p. // 4 x AC Gen. Diesel2MW 2 MVA // 1 Wind Turb. WindT1(2 MW at 14 m/s) // Electroliz. Elyzer10MW of 10 MW // Inverter Inv-Ch5MW of 5 MVA // Unmet load = 0.6 % // Total Cost (NPC) = 76.991 M€ (0.11 €/kWh)

STRATEGY: LOAD FOLLOWING. P. lim. charge: INF. P1gen: INF. Pmin_gen: 0.6 MW. Pcritical_gen: 0 MW. SOC setpoint_gen: 10 %. SOC min.: 10 %. H2TANK stp.: 0 tH2.

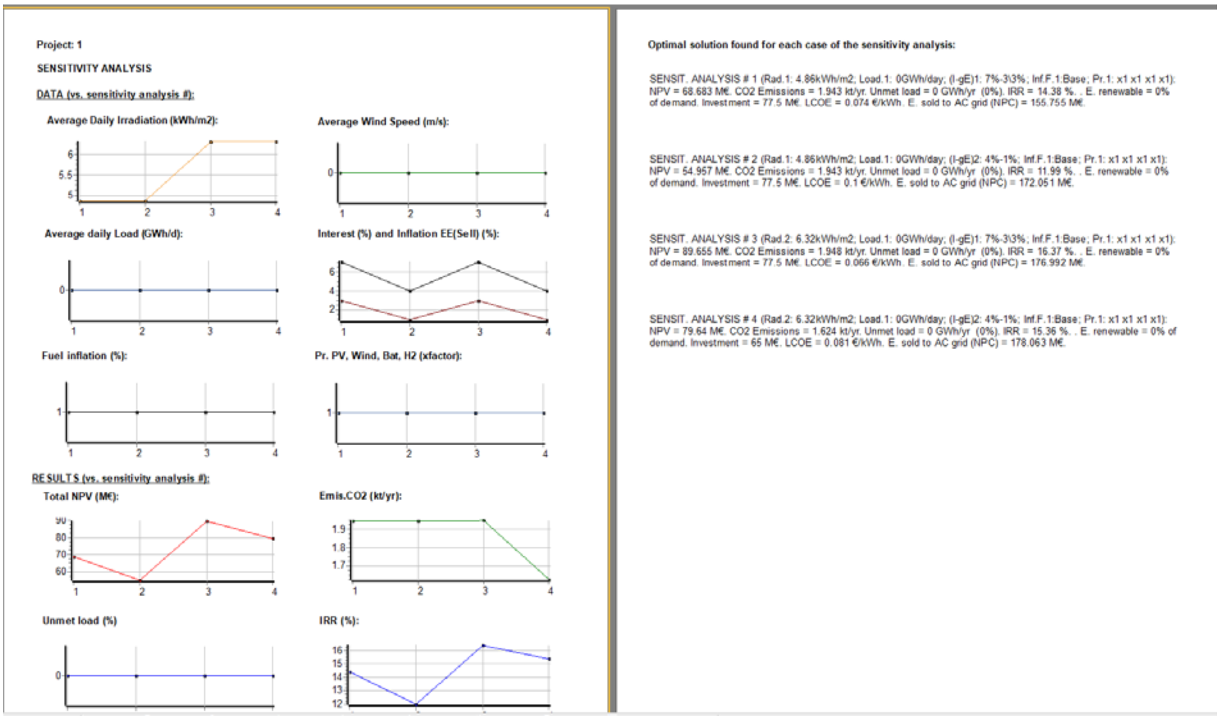
4.8 Summary of the sensitivity analysis.

Once the sensitivity analysis is done (once all optimizations have been performed, one for each combination of sensitivity analysis cases), by clicking on the "**Sensitivity Analysis Summary**" button on the main screen (bottom), it is shown, for each sensitivity analysis, the optimal system found.

For example, the following figure shows the summary of the sensitivity analysis of a project in which the number of sensitivity analysis cases is 6. A graph that represents the NPC (red, based on the left vertical axis) and CO2 emission (green, based on the right vertical axis) for each number of sensitivity analysis is shown. Below the chart there is a box where you can choose other representation. Below there is the summary text of the best solution found for each sensitivity analysis.



By clicking on the "**Report**" button on the screen of sensitivity analysis summary, it displays a report that can be printed or saved as pdf (if we have a virtual pdf printer installed on the computer). In this case, the report occupies 1 page.



Clicking on the button "**Save Excel**" on the screen of the summary of the sensitivity analysis, a detailed table with the results of the sensitivity analysis (best combination found for each sensitivity analysis) can be saved in format .xls or format .txt. If we keep it as. .xls, when opening the file with Microsoft Excel it shows a message, then you must answer "Yes" and it opens correctly. In Microsoft Excel, you should save the Excel file as .xlsx format (in Excel, use "Save As" and choose file format ".xlsx"), then the next time you open the .xlsx file Excel will not ask you any question.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Project: 8m.	Best system found for each case of the sensitivity analysis												
2	Sens.#		Wind (m/s)		Rad(kWh/m2/d)		Load(GWh/d)		Interest(%)		Inflation(%)		Infla.Fuel(%)	
3	1		6.43		4.85		0.11		7		2		Base	
4	2		6.43		4.85		0.11		7		2		4	
5	3		6.43		4.85		0.11		7		2		1	
6	4		6.43		4.85		0.14		7		2		Base	
7	5		6.43		4.85		0.14		7		2		4	
8	6		6.43		4.85		0.14		7		2		1	
9														

By clicking in "**Save word**" button we can save the report in .rtf format, which can be open by Microsoft Word, for example:

Project: 8m. Optimal solution found for each sensitivity analysis:

SENSIT. ANALYSIS # 1 (Wind.1: 6.43m/s; Rad.1: 4.85kWh/m2; Load.1: 0.11GWh/day; (I-g)1: 7%-2%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPC = 102.312 M€. CO2 Emissions = 27.928 kt/yr. Unmet load = 0.301 GWh/yr (0.6%). Days auton. = INF. E. renewable = 61.5% of demand. Levelized cost of energy = 0.144 €/kWh
Components: PV Generator 140 MWp (100% PV#1: slope 35°, azimuth 0°).Wind Turbines group AC of 2 MW. 4 x AC Generator of 2 MW. Electrol. 10 MW. H2 Tank of 731 t. Inverter 5 MW.

SENSIT. ANALYSIS # 2 (Wind.1: 6.43m/s; Rad.1: 4.85kWh/m2; Load.1: 0.11GWh/day; (I-g)1: 7%-2%; Inf.F.2: 4%; Pr.1: x1 x1 x1 x1):
NPC = 117.903 M€. CO2 Emissions = 27.928 kt/yr. Unmet load = 0.301 GWh/yr (0.6%). Days auton. = INF. E. renewable = 61.5% of demand. Levelized cost of energy = 0.166 €/kWh
Components: PV Generator 140 MWp (100% PV#1: slope 35°, azimuth 0°).Wind Turbines group AC of 2 MW. 4 x AC Generator of 2 MW. Electrol. 10 MW. H2 Tank of 731 t. Inverter 5 MW.

SENSIT. ANALYSIS # 3 (Wind.1: 6.43m/s; Rad.1: 4.85kWh/m2; Load.1: 0.11GWh/day; (I-g)1: 7%-2%; Inf.F.3: 1%; Pr.1: x1 x1 x1 x1):
NPC = 76.991 M€. CO2 Emissions = 27.928 kt/yr. Unmet load = 0.301 GWh/yr (0.6%). Days auton. = INF. E. renewable = 61.5% of demand. Levelized cost of energy = 0.108 €/kWh

5. FREQUENTLY ASKED QUESTIONS

1. What components should be selected and how to select its maximum number in parallel?

This choice will depend on: load consumption, design, available renewable resources, and the commercial models to be used of each component. If there is load consumption, PRE-SIZING button helps you to choose the maximum number of components in parallel. If there is no load consumption (generating systems), the designer must decide the maximum number of components in parallel.

2. After I select a certain component, how can I enable the option to include/exclude the component in/from the system?

You can import from the database the "Zero" component. It inserts an additional row into the component table, assigning zero value to power, cost, and operating and maintenance costs. This allows the hybrid system to use (or not) the component, since this has 0 power and 0 cost.

3. When saving or opening a project, the following error message is displayed: "File name is too long for a Paradox version 5.0 table".

The Paradox tables used by MHOGA accept a maximum number of 70 for the characters to be used on the access path defined by the user. Note that around 10 characters are already used by several tables (table folder + table name), so the maximum number of characters for any project directory and folder should be limited to 60. As an example, for a project saved with the name "Test" in "My Documents" under Windows XP, the access path would be C:\Documents and Settings\Rodolfo\My Documents\Test, with 55 characters. Any longer names for the project would result in problems. It is recommended that all projects be saved to a folder in the root directory, rather than to the "My Documents" folder.

4. What values should be assigned in the genetic algorithms for the following parameters: number of generations, population, mutation rate, crossing rate?

In many cases you will not have to use genetic algorithms. If you allow enough computation time for the optimizations (default 15'), in most of the cases the total number of combinations of components and control strategies will be evaluated in less than that time. However, if you allow less time or the number of combinations is high, MHOGA will use genetic algorithms.

MHOGA can select the parameters of the genetic algorithms, this is recommended. If you want to select them yourself, you must know that this basically depends upon the time available and on the accuracy required for calculation of results. Better solutions will be obtained for larger population sizes and number of generations, at the expense of longer calculation times. In general terms, the best choice is a large population rather than a large number of generations. For populations of a small size, it will be difficult to find an optimum system, regardless of the number of generations used.

For the main algorithm, these values must depend on the component variability: number of components considered for each component type and maximum number of components in parallel allowed (PV generators, batteries, wind turbines and AC generators). For larger component variability, large populations are necessary.

For the secondary algorithm, this depends on the control variables to be optimized and on the degree of accuracy required for the optimization process. For a large number of variables, a larger population will be required. For higher accuracy, a larger population will also be required, since many values will be available for each variable (as an example, for a value of 50 in accuracy, variables will take 50 discrete values in 2 % steps).

Number of generations should be around 15. Population must be greater than 0.003% of all the combinations (Bernal-Agustín & Dufo-López, 2009a).

Mutation rates are usually within 0,5-1 %. Crossing rate is usually 70-90% (Bernal-Agustín & Dufo-López, 2009a).

5. NCP is displayed with a value of infinite (INF), and a screen is shown at the end saying "No solution fulfills system requirements"

In this case (minimization of NPC project), the system cannot find any solution which meet all constraints.

If the unmet load constraint is not achieved, there are several likely reasons for this:

- The diesel generator cannot work at certain hours (for example during the night, if you have specified that option) and therefore cannot supply the load during those hours.

- The system includes H_2 load, but no electrolyzer is accounted for. Include this component in the system.
- If you want to consider the possibility to buy the unmet load to the AC grid, don't forget to select this (LOAD / AC GRID -> PURCHASE / SELL E tab).
- The electrolyzer power consumption when it is not running (in standby) must be covered as the defined load. Maybe grid-connection should be defined.
- Either the size or the maximum number of components (PV gen., batteries, wind turbines or AC backup generator) allowed is too small. In this case, the system cannot deliver enough energy to meet the energy demand. Increase the power or the maximum number of system components allowed.
- The search space may be too small for some of the algorithms (small population and/or few generations), so no system can be found that meets the criterion for Maximum Allowed Unmet Energy Allowed. Increase population size and number of generations.

6. I have a system that includes an electrolyzer, and in the simulation screen I see that in some hours there is excess energy but this energy is not used in the electrolyzer, why?

The electrolyzer has a minimum operating power, defined in its characteristics, but its income electrical power must be higher than the minimum energy required to start generating hydrogen (B·Pn) (see section of hydrogen components). If the excess energy is not sufficient to start generating the hydrogen, electrolyzer is not used, i.e. it does not operate.

If the hydrogen tank is full (in the simulation it has reached the limit set on its size), the electrolyzer will not work (hydrogen will not be generated as it cannot be stored).

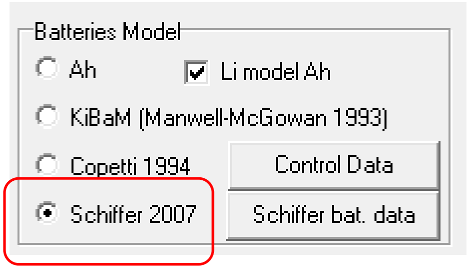
7. I have a system that includes fuel cell and in the simulation screen I see that in a certain time the fuel cell should be used but it is not used, why?

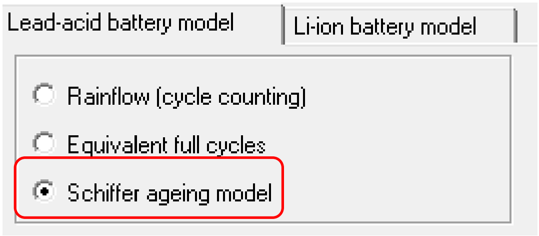
The fuel cell needs a minimum hydrogen mass flow to start generating electrical power output. If the amount of hydrogen available in the tank is not enough to cause the minimum mass flow during that time, the fuel cell is not used, i.e. it does not work.

8. Which battery model should I select?

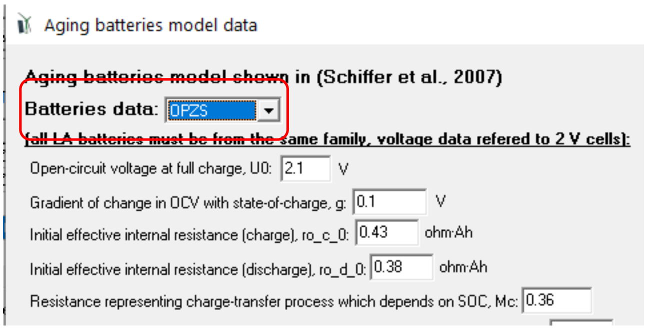
<u>LEAD-ACID BATTERIES:</u>

For lead-acid batteries, you should use Schieffer 2007 for the battery model and Schieffer ageing model for the ageing model. This way, MHOGA will use the Schieffer et al., 2007 model, which is the best model to estimate the lead-acid batteries.



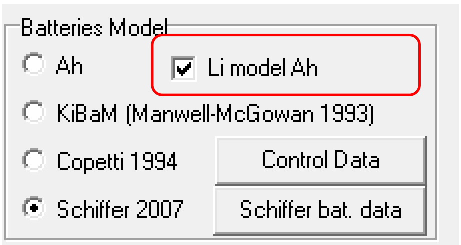


You must ensure that all the lead-acid batteries of the battery screen table are of the same type (all OPZS or all OGI), then you click on the button "Schiffer bat. data" and select OPZS or OGI in the top left of the window that appears:



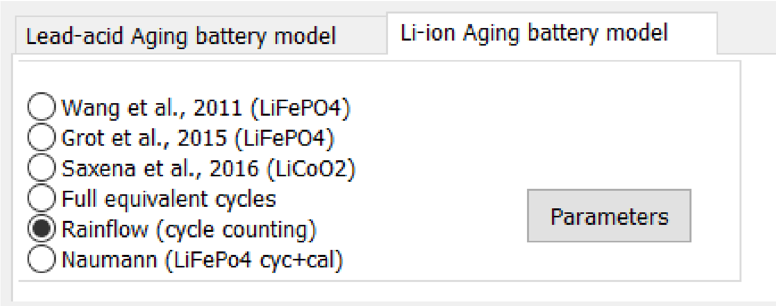
LITHIUM-ION BATTERIES:

For lithium-ion batteries, for the battery model you should select "Li model Ah" because it is the most simple and adapts correctly to lithium-ion batteries.



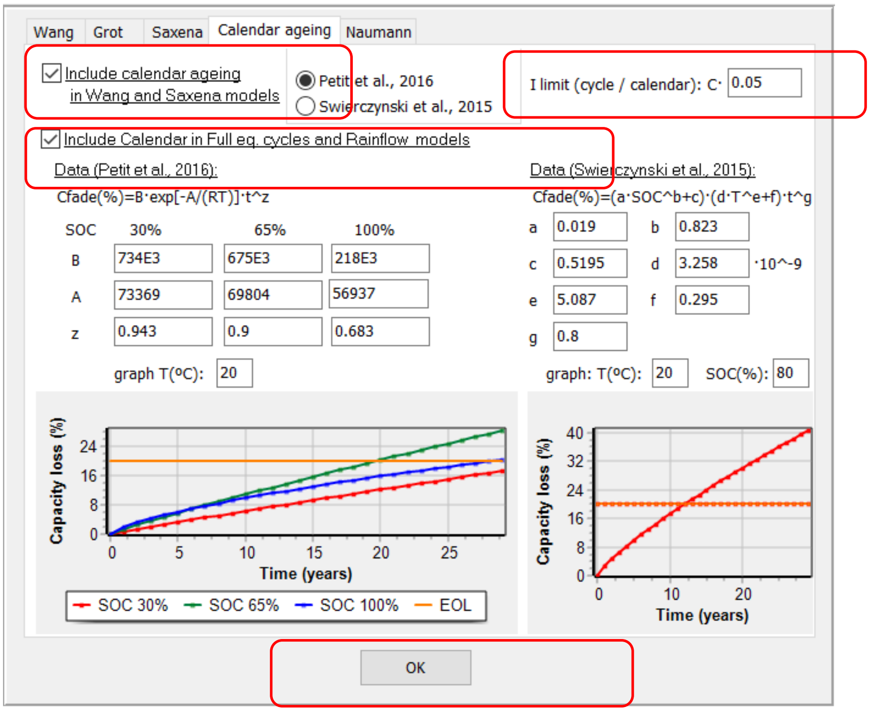
For the ageing model, you can select several models: Wang, Grot or Naumann for LiFePO4, Saxena for LiCoO2 or generic models (Full equivalent cycles or Rainflow).

It is important to say that Wang, Grot, Naumann and Saxena models were obtained by researchers by testing specific commercial batteries, so these models are only adequate for those commercial batteries tested and for the conditions they were tested. If you are not sure about if your battery is similar to the ones tested by these models, it would be better to select a generic model (Full equivalent cycles or Rainflow).



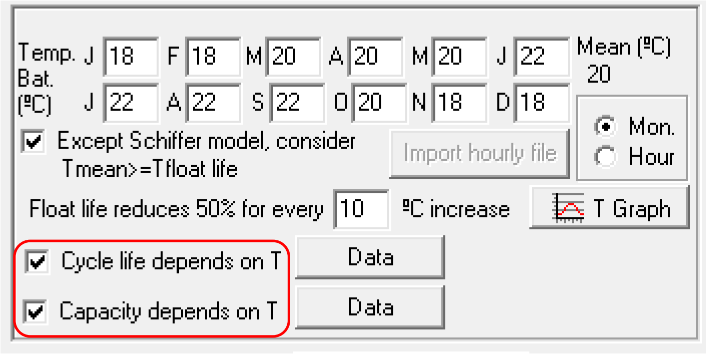
Full equivalent cycles or Rainflow models are generic models, and they consider the number of cycles to failure of the battery data.

After you select the model, click in "Parameters" button and **you should be sure that the calendar ageing model is includ**ed, then calendar and cycle degradation will be considered. In some cases (specially in stand-alone systems where cycling degradation is low), if you do not include calendar ageing you can obtain very high battery lifetime, which would be not real.



You should set a threshold limit to consider cycle or calendar ageing, by default a C-rate of 0.05 is the limit. In the time steps when the C-rate is lower than this value calendar ageing will be considered and when it is higher cycle ageing will be considered. Then click OK to save the changes.

It is also important to select the checkboxes "Cycle life depends on T" and "Capacity depends on T", to consider the cycle life dependence on temperature and also the capacity dependence on temperature during each time step. With the button "Data" you can change that dependence.



14. How can I update MHOGA?

https://ihoga.unizar.es/en

https://personal.unizar.es/rdufo/

ANNEX 1. Genetic Algorithms.

Genetic algorithms are used in computers to carry out simulations for breeding, mutation, and selection that are present in nature. All possible solutions provided by genetic algorithms to any given problem are thus presented as "individuals" within a certain species. Each individual is actually a combination of the variables ("genes") to be optimized (in our case, the variables or "genes" correspond to the hybrid system components and to the variables utilized for the system control strategy). Our variables or genes are integers (number of PV modules, codes for panel types, ...). The structure of the variables or genes is called "genotype", whereas any concrete combination of variables or genes in the genotype is called individual or "phenotype".

The first "generation" includes a random set of individuals, which we call "population". These individuals are "crossed" (that is, they mix with each other, with a higher probability of reproduction for the best individuals, those with the lowest NPC or the highest NPV, depending on the type of project, i.e. the best fitness). New individuals are generated by reproduction ("children"), thus replacing the worst "parents", and creating a new generation. Some individuals "mutate" (values for variables or genes are randomly altered). The process repeats itself, with more and more new generations, and better solutions provided as the algorithm progresses.

MHOGA makes use of two genetic algorithms, the main algorithm and the secondary algorithm.

The main algorithm provides an optimum configuration for the PV modules, the wind turbines, the hydraulic turbine, the batteries, the AC generator, the fuel cell, the electrolyzer, and the inverter, in order to minimize total system costs. These are calculated for the total system lifespan, and updated with respect to the initial time, i.e. to the Net Present Cost (NPC) or Net Present Value (NPV) for the system, in mono-objective optimization (for multi-objective optimization MHOGA will seek solutions with low NPCs as well as low CO_2 emissions or unmet load or it can consider other objectives).

The genotype for the **main algorithm** includes 11 genes, all of them integers:

- Number of PV generators in parallel
- Type of PV generators
- Number of Wind Turbines in parallel
- Type of Wind Turbines
- Type of Hydraulic Turbine.
- Type of Fuel Cell

- Type of Electrolyzer
- Number of Batteries in parallel
- Type of Batteries
- Type of Inverter
- Type of AC Generator

Code types for all different elements are integers (e.g. solar panel 0, solar panel 1, solar panel 2, ...).

It is not possible to optimize the number of PV modules and batteries connected in serial. These variables are fixed, and depend on the DC bus voltage, and on the nominal voltage of the panel and the battery.

The user decides whether the inverter may be optimized or it has a fixed value (with its rated power higher than the maximum AC load power). All remaining elements (battery charge regulator, rectifier, hydrogen tank) are optimized by MHOGA with respect to each other and to the control variables in use.

The **secondary algorithm** obtains the most appropriate control strategy (combination of control variables) for minimum costs, and for any given component setup provided by the main algorithm.

The secondary algorithm genotype includes 12 genes, all of them being system control variables and integers.

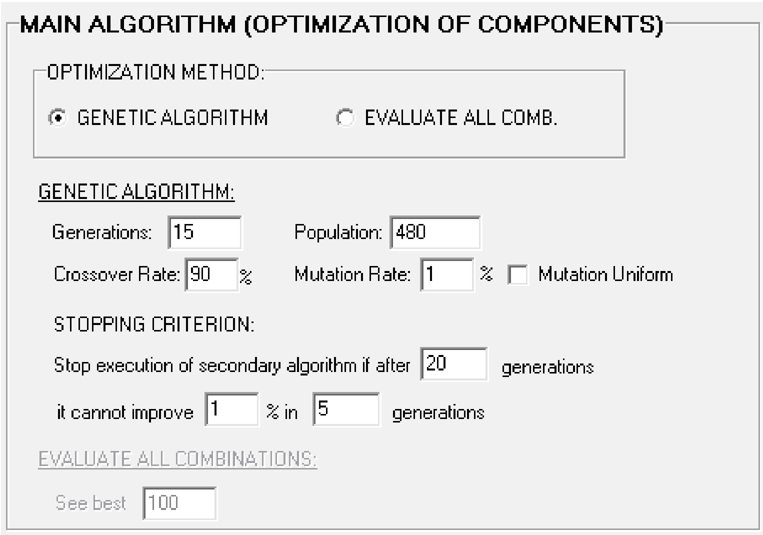
P_{lim_charge}, $P1_{gen}$, $P1_{FC}$, $P2$, P_{min_gen}, P_{min_FC}, SOC_{min}, $P_{critical\_gen}$, $P_{critical\_FC}$, SOC_{stp_gen}, SOC_{stp_FC}, H_2TANK_{stp}

The total cost may thus be calculated referred to the initial installation time (NPC) for each possible solution obtained from both algorithms.

Main algorithm (optimization of components)

On the MAIN ALGORITHM (OPTIMIZATION OF COMPONENTS) box, the user must decide if the optimization method is GENETIC ALGORITHM or EVALUATE ALL COMB. In the first case numeric values must be provided for a number of system parameters. For each given genetic algorithm to be used for optimizing the physical system components, the numeric values to be provided include: the number of generations, the population, mutation and crossover (breeding) rates and uniformity in mutation.

For uniform mutation, the value for each mutated gen or variable is selected at random. For non-uniform mutation, the value is also selected at random, but there is a higher degree of probability that this mutated value is close to the original one.



The solutions obtained will be more representative for larger populations and larger numbers of generations, where the genetic algorithm will provide an optimum solution more easily. However, when both values are high, a longer time will be necessary for the simulation (this time is proportional to the population and the number of generations included, for both the principal and the secondary algorithm). A balance must be reached between the required accuracy and the time available for execution.

For large differences in maximum and minimum values for batteries, PV modules, and wind turbines in parallel, many combinations will be available for the "sizes" of solar and wind turbines, as well as batteries. For very low maximum values, problems may arise when catering for energy demand (unless additional sources are available, such as a diesel generator, a fuel cell, etc).

The number of cases to evaluate in order to optimize component combinations using genetic algorithms will be given by:

Combinations_main_alg =

*[Population_main+(Generations_main- 1)*Population_main*(Crossover_Rate_main/100+Mutation_Rate_main*long/100)]**

**Combinations_secondary_alg*

For all possible component combinations, select "EVALUATE ALL COMB.". This will apply forced optimization (evaluating all the combinations), with no genetic algorithms. For a large number of combinations, execution times may increase enormously.

The number of possible combinations (when all components are selected) will then be:

Combinations_main_alg=

= No._Pv_Gen _Types(1+No._max_Pv_Gen_parallel- No._min_Gen_parallel)**

No._Wind_T_types*(1+No.max_Wind_T_parallel – No.min_ Wind_T_parallel)

**No._battery_tpes*(1+No.max_batteries _parallel – No.min_batteries_parallel)* No._AC_gen_types*No. Hyd_T_types*No._electroliz_types*No._Fuel_Cell_types*Combinations_secondary_alg*

A criterion may be specified to halt the genetic algorithm. Once a certain number of generations has been produced (e.g., 20), the algorithm will stop if no improvements are made on the objectives.

In the example shown above, the algorithm continues provided system costs for generation 25 are less than 99% of those for generation 20 (mono-objective optimization), as this implies that results may be further refined. If the value is over 99% the algorithm will stop (an optimum state has been reached, or near it)

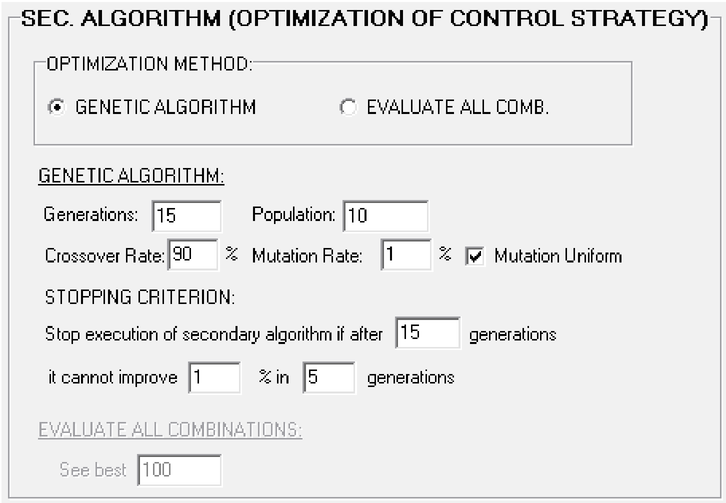
Check boxes related to the genetic algorithm are disabled when "EVALUATE ALL COMB." is selected. In this case, a check box is enabled to select the number of best possible solutions to be shown. If a very large number of solutions is possible, the application may use a large proportion of memory, or it may even block. Solutions to be shown are the best ones available, including the optimum fit, so the number of solutions selected should not be too large, unless many combinations are required**.**

In the message box shown below information will be provided here on the number of cases to be evaluated. This number depends on the user selection: GENETIC ALGORITHM or "EVAL. ALL" for both algorithms. (this message box is also displayed towards the central part of the main screen whenever the cursor is moved over the optimization parameters or maximum and minimum components or the control variables areas).

There are 4 possible combinations (option 1 through option 4, with the option selected highlighted in red). Figures are displayed for the number of cases to evaluate, and the time estimated for the simulation, provided the speed test has been carried out beforehand (press CALCULATE and CANCEL after a few seconds):

Secondary algorithm (optimization of control strategy)

On the SECONDARY ALGORITHM (OPTIMIZATION OF CONTROL STRATEGY) box, numeric values must be provided for a number of system parameters. For the genetic algorithm to be used for optimizing the system control variables, the numeric values to be provided include: number of generations, population, mutation and crossover (breeding) rates, and uniformity of integers mutation.



For optimization of the control strategy using genetic algorithms, the number of combinations will be given by:

$$Combinations\_secondary\_alg = Population\_sec + (Generations\_sec - 1) * Population\_sec * (CrosoOver\_rate\_sec/100 + Mutation\_rate\_sec * long/100)$$

As explained above for the main algorithm, for all possible component combinations, "EVALUATE ALL COMB." must be selected. This will apply forced optimization, with no genetic algorithms.

In this case, the number of possible combinations is given by:

$$Combinations\_secondary\_alg = (Variable\_accuracy + 1)^{No\_variables\_to\_optimize}$$

For large numbers of variables to optimize, an extremely high value may result. This will render the optimization process unfeasible.

ANNEX 2. Control Strategies for systems with load consumption.

Global strategy and its variables ONLY HAVE SENSE IN SYSTEMS WITH LOAD CONSUMPTION. These strategies are not used for systems without load consumption (grid-connected generating systems).

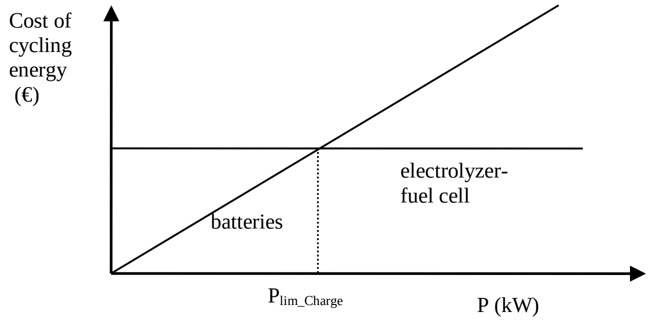
Control strategies utilized by MHOGA are based of the strategies described by Barley and Winn (Barley & Winn, 1996) in 1996, and of those developed by the HOMER application. The current version of the programme uses a more complex and accurate global strategy (Rodolfo Dufo-López, Bernal-Agustín, & Contreras, 2007), developed by the authors, and optimized by means of genetic algorithms. There are 12 control variables.

Once the values have been estimated for all variables for each hour, the system control is subject to certain conditions in order to minimize total system cost (for the case of mono-objective optimization), or to minimize both costs and levels of CO_2 or unmet load (for multi-objective optimization).

As a fundamental premise for control, the energy produced from renewable sources (photovoltaic, wind-based and/or hydraulic) will be used to feed the loads, as this energy is free (once the components have been purchased). Besides, preference will be given for every energy source, renewable or otherwise, to feed the loads on their voltage bus (DC or AC). External consumption of H_2 will be covered by the H_2 tank. Should this not be enough, additional energy may be generated with the electrolyzer.

Should more energy be produced from the renewable sources than that which is needed for consumption, the remaining energy will be used to pump water to the water tank as much as possible (if water consumption from water tank, previously pumped, is modelled in the project). Once the remaining energy has been used in pumping water, if there is remaining energy, this energy (which we will call P_{charge}), would be used to charge the batteries or to generate H_2 in the electrolyzer. This process will be called **CHARGE**. The choice will depend on the "cycling" costs of the energy in the batteries and on the electrolyzer.

The cycling cost for an energy accumulator (batteries or electrolyzers) is the total cost of storing energy within the component, for later supply to the system, as needed. This cost includes operation and maintenance, proportional tear and wear, and replacement costs. Cycling costs are approximately proportional to the power in the case of batteries, and approximately constant for electrolyzers, as shown in the figure below. The point of intersection of both straight lines (P_{lim_charge}) will be then used as a reference to determine surplus energy in the system at any given time. If the surplus energy is below this point, it will be cheaper to use this to charge the batteries, whereas if the surplus energy is above it, it will be more convenient to use it for generation of H_2 in the electrolyzer.



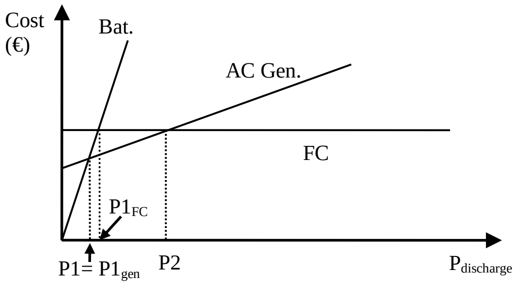
Cost of cycling energy

The Charge Strategy will thus be:

- *For $P_{charge} \leq P_{lim\_charge}$ the batteries will be charged to their maximum, and any surplus energy will be used to generate H_2 in the electrolyzer.*
- *For $P_{charge} > P_{lim\_charge}$ as much hydrogen as possible will be generated in the electrolyzer, and any surplus energy will be used to charge the batteries.*

In case the renewable sources alone do not have the capacity to generate all of the energy required for consumption, the rest of the required energy (which we will call $P_{discharge}$) will be supplied by the batteries, the AC generator, or the fuel cell. This process will be called **DISCHARGE**.

MHOGA will determine the cost of energy supply for each element (the batteries, the AC generator, or the fuel cell). This cost depends on replacements, useful lifespans, fuel prices (as for the AC generator), etc. The figure below shows an example of costs associated to energy supply for different elements, as a function of power.



Costs of supplying energy (DISCHARGE process)

In the example provided by the figure above, the optimum discharge strategy will be as follows:

For $P_{discharge}$ < P1 it will be best to supply energy with the batteries. Should these not have enough capacity for all of $P_{discharge}$, the rest, $P_{lack} = P_{discharge} - P_{batt}$ will be supplied by the AC generator provided P_{lack} < P2. Otherwise, energy will be supplied by the fuel cell.

For P2 > $P_{discharge}$ > P1, energy should be supplied from the generator. Should this not have enough capacity for all of $P_{discharge}$, the rest, $P_{lack} = P_{discharge} - P_{gen}$ will be supplied by the batteries provided $P_{lack} < P1_{cell}$. Otherwise, energy will be supplied by the fuel cell.

For $P_{discharge}$ > P2 it will be best to supply energy from the fuel cell. Should the cell not have enough capacity for all of $P_{discharge}$, the rest, $P_{lack} = P_{discharge} - P_{cell}$ will be provided by the AC batteries, provided $P_{lack} < P1_{gen}$. Otherwise, energy will be provided by the AC generator.

From a general standpoint, the Discharge Strategy will be provided as follows:

- *For $P_{discharge}$ < P1, energy will be supplied by the batteries*
- *For $P1 \leq P_{discharge} \leq P2$, energy will be supplied by the element with lowest P1(AC generator or fuel cell)*
- *For $P_{discharge}$ > P2, energy will be supplied by the element with highest P1(AC generator or fuel cell)*
- *In case the system element selected can not supply all of the required $P_{discharge}$, an additional element must be chosen to provide the rest (P_{lack}) at the lowest possible cost*
- *When the 2^{nd} element cannot supply the rest of the power, a 3^{rd} element must be selected*

Calculation may not be carried out accurately for P_{Lim_charge}, $P1_{gen}$, $P1_{FC,}$ P2, as no data is available beforehand (such as battery lifespan, etc). Therefore, "optimum" values for the variables do not necessarily match those values provided by the calculation. The final optimum values for all the variables in order to minimize the system's NPC will be found through the secondary genetic algorithm, which optimizes correction factors for those variables.

Details are provided below about the remaining system variables used for the system's control strategy.

P_{min_gen} and P_{min_FC} represent the minimum operating power for the AC generator and the fuel cell, as provided by manufacturers. However, AC generators usually show a high specific consumption for low powers. Higher power values may contribute to lower the system's NPC. Fuel cells have a more constant consumption, though this may increase for low powers.

SOC_{min} represents the minimum state of charge allowed for the batteries. Though this is provided by the manufacturer, higher values may be better.

$P_{critical\_gen}$, $P_{critical\_FC}$, SOC_{stp_gen}, SOC_{stp_FC} , and H_2TANK_{stp} are control variables for the AC generator and the fuel cell.

Since AC generators have a higher specific consumption for low powers, under the critical value ($P_{critical\_gen}$), it may be interesting to make them deliver higher power values. The rest may then be used to charge batteries until a certain state of charge (SOC) is reached, called SOC generator setpoint, and represented by SOC_{stp_gen} . H_2 could also be produced in the electrolyzer until a certain level of charge is reached within the H_2 tank, called H_2TANK_{stp} (in kg of H_2). The order in which the excess energy is used (charging batteries to reach SOC_{stp_gen} or generating H_2 to reach H_2TANK_{stp}) will depend on the amount of excess energy itself. If this is less than P_{Lim_charge}, batteries will be charged first, and any remaining energy would be used to generate H_2. If the excess energy is more than P_{lim_charge}, the process order will be inverted.

The same holds for the fuel cell, so the paragraph above applies here, replacing $P_{critical\_gen}$ with $P_{critical\_FC}$ and SOC_{stp_gen} with SOC_{stp_FC}. However, H_2TANK_{stp} would not be applicable if the fuel cell uses up H_2 from the H_2 tank (previously produced by the electrolyzer).

When the power required by the loads from the AC generator is less than $P_{critical\_gen}$, the operating power for the AC generator will equal the minimum power to supply the power still not delivered to the loads, plus the power required to bring the batteries up to SOC_{stp_gen} , and the power needed by the electrolyzer to produce H_2 until H_2TANK_{stp} is reached, with no energy lost. In some cases the minimum power from the AC generator will be over $P_{critical\_gen}$, so energy will be lost.

The same is true for the fuel cell.

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