iHOGA

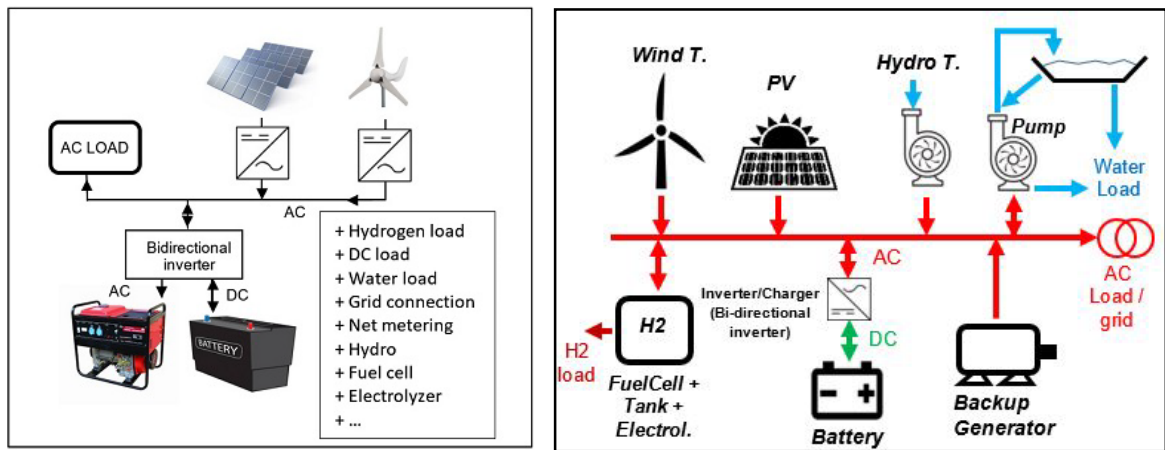## Version 4.0

User's manual

February 26, 2025

Main researcher:

Dr. Rodolfo Dufo López

(rdufo@unizar.es)

https://ihoga.unizar.es/en/

Electrical Engineering Department

Universidad de Zaragoza

Zaragoza, Spain

CONTENTS.

1. <u>INTRODUCTION AND OVERVIEW</u>

iHOGA (improved Hybrid Optimization by Genetic Algorithms) is a software developed in C++ for simulation and optimization of Hybrid Renewable Systems. There may be load consumption of electrical energy (DC and /or AC) and/or Hydrogen load (for external consumption), as well as load of water form a reservoir, previously pumped. The program can simulate and optimize systems of any size up to 5 MW (for higher power you will need MHOGA software). **It can also simulate and optimize systems connected to the AC grid**, and **generation systems**.

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.

1.1 Modifications in this version (4.0).

February 26th, 2025:

> - NASA changed the format of the irradiation / wind speed / temperature download file. NASA data acquisition has been updated.

January 29th, 2025:

> - For the comparison with AC ONLY systems (which would supply all the load only with AC conventional grid), included the possibilty to add the power cost (previously it was included in the O&M cost of the AC ONLY system).

> - Fixed minor bugs.

January 16th, 2025:

- Fixed bug of error in unmet load in some cases with priority to supply energy not covered by renewables using AC grid.

- Fixed minor bugs.

December 21th, 2024:

- Improved probability analysis, adding more results variables.

- Fixed bugs in probability analysis in NPV minimizing systems.

- Added more options for PHS to supply reserve capacity.

- Improved calculation speed.

- Fixed minor bugs.

EDU VERSION:

- Now DC load, H2 load, water load and AC grid tabs of LOAD / AC GRID window not available in EDU version.

- Now hourly download of irradiation, wind speed and temperature not available in EDU version.

- Now hydro not available in EDU version.

- Now forcing AC gen. to run all the time and AC gen. injecting power to AC grid in NPV systems not available in EDU version.

1.2 Modifications in previous version.

November 7th, 2024:

- Now minimum number of diesel generators in parallel can be 0.

- Total tax for electricity sold now is used to reduce electricity incomes due to selling electricity to the grid (before it was considered to increase incomes). Projects created with previous versions, when opened, will have the sign of this data changed, so that the results are not modified.

- In the report, added percentage of total load energy self-consumed.

- LCOE now has 4 decimal positions.

- Added LCOH and LCOS results in the Excel file of the costs.

- In NPC optimization systems, added calculations of annual savings and IRR of the savings (comparing our system with the system to supply all the load only with AC grid) in the Excel file of the costs.

- In NPV optimization systems, added calculations of IRR in the Excel file of the costs.

- In NPC optimization systems, added the possibility to optimize by maximizing the IRR of the savings (comparing our system with the system to supply all the load only with AC grid).

- Added the possibility of considering the loan in payback calcualtions (before it was not considered).

- Added the possibility of considering the loan in IRR calcualtions (before it was not considered).

- Improved calculation of the pump efficiency (if variable pump efficiency)

- Fixed bug when in particular cases when using variable losses in hydraulic pipelines using Haaland equation for Colebrook approximation.

- Fixed bug when in particular cases

- Fixed bug when considering minimum time of running the backup generator.

- Fixed bugs in the calculation of payback period in the case of multiperiod.

- Fixed bug when calculating E back-up charge (self-consumed energy) in grid-connected sytems with batteries.

- Fixed minor bugs

October 3rd, 2024:

- Fixed bug when calculating Export (excess) energy in some cases when charging batteries due to the grid limitation.

- Added losses in wire and transformer in Energy purchased to the grid (if the user selects this option).

- Subtracted losses in wire and transformer in Export energy and in Bach-up charge energy (if the user selects these options).

September 12th, 2024:

- Added variable head for turbine and pump in PHS (considering variable height of the reservoirs).

- Added variable losses in penstock (turbine and/or pump)

- Added optimization of minimum power (%) of the turbine to be used primarily to supply the load.

- Added the possibility to consider the water tank or reservoir CAPEX (capacity x specific cost), in PHS systems.

- Added optimization of the water tank or upper reservoir in PHS.

- Added cost due to the starts of hydro turbine and of pump.

- Added variable O&M for turbine and for pump.

- Added the possibility to calculate the water tank or reservoir capacity as the maximum obtained in the simulation, with specific limits (in PHS systems).

June 11th, 2024:

- Fixed bug related to extra cash flow. If you open a previous project where you added "Extra cash flow", check the value of the last year.

- Fixed bug of the cash flow Excel file generated in build 20240526.

- Fixed minor bugs.

June 3rd, 2024:

- Fixed minor bugs.

May 26th, 2024:

- Added the possibility to import a file with the hourly values of the whole year for the grid power limit.

- Added another optimization option: minimization of payback period.

- The user can choose to calculate simple payback period or discounted payback period.

- In NPC minimization projects, the payback period is calculated comparing our system with to the only AC grid system, taking into account the difference in investment costs and the savings.

- In NPV minimization projects, the payback period is calculated considering the initial investment of the system and the net incomes.

- In the report and in the cash flow Excel file, the payback period is shown.

- In the report, added levelized cost of storage (LCOS) of the batteries.

- Added the possibility to generate or import PV maintenance shutdown and wind turbines maintenance shutdown hourly files.

- Added the option not update or not the component when we click in the components' table, if there is a component with the same name in the database (before it was done always, now it is an option in Project->Options, not done by default).

- Improved speed when opening a project.

- Fixed bug when using option of electrolyzer at full load.

- Fixed minor bugs.

April 30th, 2024:

- In NPC minimization projects, PHS AC hydro turbine (different machine from pump) creates operational reserve, added to diesel, grid and fuel cell.

- In NPC minimization projects, during each time step, if there is AC capacity shortage, added the option to run the PHS AC hydro turbine (different machine from pump) and, if not enough, the backup generator(s) to increase operating reserve and reduce capacity shortage.

- Added minimum backup generator running time.

- In the Excel of the simulation results, shown required operational reserve DC and AC and real reserve DC and AC.

- Fixed bug when calculating IRR in systems with fixed initial CAPEX.

- Fixed minor bugs.

April 24th, 2024:

- In NPC minimization projects, added the constraint of the maximum capacity shortage.

- Added Power Purchase Agreement (PPA) specific price for the PV energy injected to the grid. Also PPA for the Wind turbines generation injected to the grid.

- Fixed bug when using PHS storage to supply electrical load.

- Fixed bug when using backup generator to create grid reference.

- Fixed minor bugs.

March 27th, 2024:

- Reduced height of some screens in order to improve visualization in laptops.

- Added checked legend to some graphs.

- Improved PDF graphs of the PDF tab of the simulation screen.

- Fixed minor bugs.

March 20th, 2024:

- In NPV maximization projects, added constraint of maximum unexported energy (%). Unexported energy (%) defined as: (Exported_energy-Sold_energy)/Exported_energy*100.

- In systems without load consumption, added the option to evaluate the performance of a new power generating system to be added to a previous existing PV system (LOAD/AC GRID->PURCHASE/SELL E->"-Ppv" checkbox). For example, if you have a grid-connected PV generator and you want to consider to add some wind turbines.

- In systems without load consumption, added the option to evaluate the performance of a new power generating system to be added to a previous existing Wind turbines system (LOAD/AC GRID->PURCHASE/SELL E->"-Pwt" checkbox). For example, if you have a grid-connected wind farm and you want to consider to add a PV generator.

- Added the option to compare with the system without generation, that is, a system where all the load is consumed from the AC grid (LOAD/AC GRID->PURCHASE/SELL E->"-Load cost" checkbox). The cost of supplying all the load by the AC grid (buy price + access price) will be subtracted from the NPC.

- Added graphs for the visualization of the daily difference between maximum and minimum hourly prices (purchase / sell electricity prices).

- Added Probability Density Function (PDF) graphs for the hourly purchase / sell electricity prices.

- Added Probability Density Function (PDF) graphs for the main results of the simulation.

- Improved calculation of lifecycle CO2 emissions in multiperiod simulation.

- Now all the simulation graphs can be copied to clipboard (right button click).

- Improved vertical axis visualization in some graphs.

- Fixed minor bugs.

March 13th, 2024:

- Added a button to import load consumption tables (a button for each table consumption type: AC, DC, H2)

- Improved visialization of the simulation and the graphs of renewable sources and load: added grid, scroll options...

- Added an option to check for updates at the start without asking.

- Improved speed when calculating projects with water pumping and in multiperiod projects.

- In multiperiod optimization, if load increase is fixed, the first year load is not increased (it is the defined in the LOAD screen).

- Changed the checkbox named "(sell price)" to "(comapre with sell price)".

- In the simulation graph added visualization of the battery auxiliary load.

- Fixed bug for maximizing NPV projects, when CAPEX is 0 there was an infinite loop for calculating IRR.

- Fixed bug when saving a project as the default project.

- Fixed bug in some cases when using battery Schiffer model with backup generator.

- Fixed bug in some cases in cycle charging strategy with SOC setpoint.

- Fixed bug to run the fuel cell if electrolyzer standby power is higher than 0.

- Fixed bug in optimization of temporary installations.

- Fixed minor bugs.

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.
- Added the possibility to consider the cost of the CO_2 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 problem to visualize worst month method results (in iHOGA low power projects) when opening.

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

- Corrected error in iHOGA some cases when opening a project after another one is open.

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 (Pmax=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 when showing unmet load in multi-objective optimization.

- - Corrected bugs related to systems with hydrogen load consumption.

- - Fixed minor bugs.

1.3 Software versions.

PRO+ version (full profesional version):

The PRO + version can be used without any limitation, in any field.

The PRO + version includes all the features of the program.

EDU version (educational, free):

EDU version can only be used in training or educational fields. The use of EDU version is not allowed in engineering works, simulation or optimization of installations, etc., and, in general, in any case in which there are derived economic transactions. Nor is it allowed to be used in research projects such as the development of doctoral theses, etc.

In EDU version the average total load consumption is limited to 7 kWh/day.

EDU version includes all program features except the following:

- High power projects

- Multiperiod simulation and optimization

- Maximization of net present value (NPV)

- In load consuming systems, different options from minimization of net present cost (NPC)

- DC load

- Hydrogen load

- Water load

- Buy/sell electricity to the AC grid.

- Hydro turbine

- TEG generator

- Download hourly irradiation, wind speed and temperature

- Pumped Hydro Storage (PMH)

- Options for the contracted power in grid-connected systems

- PV generator divided in two zones at different slope and azimuth

- Bifacial PV

- Concentrating PV (CPV)

- Sensitivity analysis

- Probability analysis

- Copetti and Schiffer lead-acid battery models

- Lithium-ion battery models

• Battery maximum capacity dependence on temperature

• Battery cycle number dependence on temperature

• Net metering or net billing in buying / selling power to the AC grid

• Hydrogen

• Hourly price of electricity to buy / sell to the AC grid

• Simulation steps lower than 1 h

• MPPT Photovoltaic

• PV generator connected to AC bus

• PV solar tracking (1 or 2 axes)

• Battery charge / discharge control on systems connected to the AC grid

• Periodic charging of the batteries through the AC generator

• Multiple AC generators in parallel

• Variable efficiency for water pump

• Choose power limit for priority to use surplus energy in pump or in batteries

• Wake effect in wind turbines

• Minimization of the weight to be transported or of the cost of operation in temporary transportable installations

• Control strategy "Cycle charging" and optimization of control variables

• Get latitude, longitude and altitude of the locality in web map

• Import wind data from Windfreedom

• Obtain optimal PV modules slope / optimize panel slope together with all other variables to be optimized

• Export the results of the simulation

• Possibility to choose priority for supplying the energy not covered by renewables through the AC grid.

• AC grid time availability.

• DC voltage dependence on batteries SOC.

1.4 Conditions for using iHOGA.

Conditions for all versions:

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 commercial components of the databases have been obtained on the manufacturers websites and costs have been obtained from online shops at a certain date. Current costs 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.

Additional conditions (only for EDU version):

6. The publication of results obtained by iHOGA must include a reference to iHOGA.

7. You agree to use this software only in the field of education or training. You agree not to use this software in any other area, including business, research or commercial areas (for these areas must purchase the license PRO+).
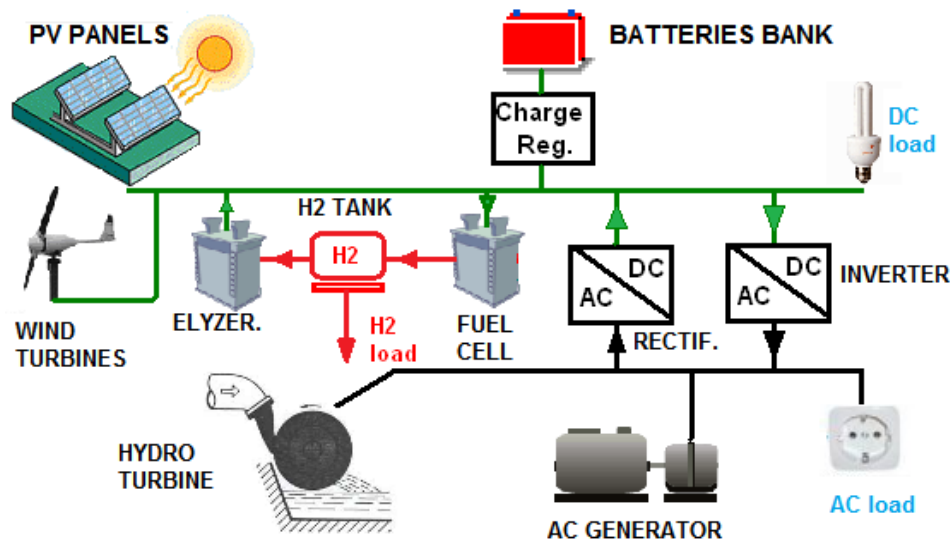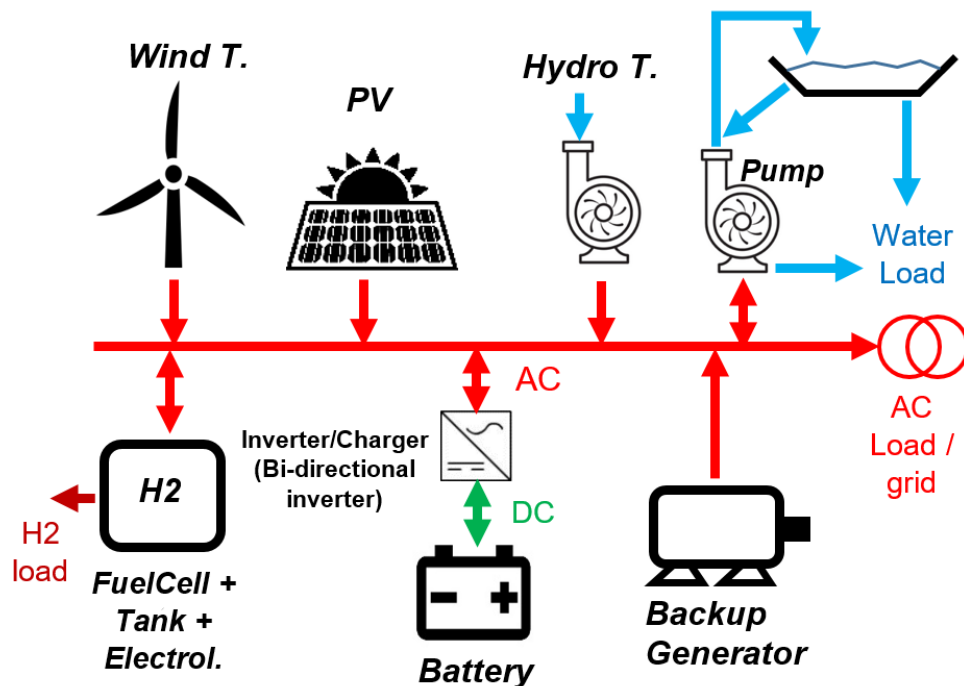
1.5 Software overview.

iHOGA is a simulation and optimization software of electric systems based on renewable energies, off-grid (stand-alone systems) or grid-connected systems.

1.5.1 Types of systems.

Two different kinds of projects can be simulated and optimized: low power or high power systems.

Low power system

High power system. Only in PRO + version

Low power systems:

The default values for low power systems are typical for households or other off-grid or grid-connected systems, where the load is not too high and we want to cover the electrical demand at the minimum cost. The system can be DC or AC coupled. Power is measured in W, monthly or annual energy in kWh and costs in the monetary unit (Euro, Dollar or any other).

High power systems: Only in PRO + version

The default values for high power systems are for grid-connected systems, where a high load must be covered (for example a big farm or a village), where we want to cover the demand at the minimum cost, or generator systems (without any load) where we want to maximize the benefits of selling electricity to the grid. The system is AC coupled. Power is measured in kW, monthly or annual energy in MWh and costs in kilo monetary units (k€, k$ or any other).

1.5.2 Optimization.

In the systems where we want to cover the load demand, optimization is achieved by minimizing total system costs throughout the whole of the useful lifespan of the system, where those costs are referred to or updated for the initial investment (Net Present Cost, NPC), this is the default optimization in low power projects.

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 in high power projects. Only in PRO + version.

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.

In low power projects, we can also include in the multi-objective optimization Human Development Index (HDI) and job creation (these two objectives are maximization).

There is also the possibility of optimizing temporary installations (which are used only for a period of time, with the need to transport, assemble and dismantle them), minimizing the

associated cost (transport + operation and maintenance + degradation) or the weight to be transported.

The program can **optimize the combination of elements and also the control stratetgy** (which determines when batteries or diesel genset must supply the load, to what level the batteries should be charged, ...).

1.5.3 Possible components of the system.

The hybrid system can include the following components:

> • Photovoltaic modules (including bifacial and concentrating PV, CPV)
>
> • Wind Turbines
>
> • Hydro turbine (PHS can be considered)
>
> • Fuel cell
>
> • H2 tank
>
> • Electrolyzer
>
> • Batteries (lead-acid or lithium-ion)
>
> • Battery Charge Controller
>
> • Inverter (DC/AC converter), rectifier (AC/DC converter) or bi-directional converter (inverter/charger, which includes inverter, rectifier and controller)
>
> • AC backup generators (gasoline, diesel ...)
>
> • Thermoelectric generator (TEG)

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 devices using AC electric energy.
- Electric DC loads: electric devices using DC electric energy.
- Hydrogen loads (production of H_2 for external consumption, e.g., electricity-powered fuel-cell vehicles). Only in PRO+ version
- Water pumping load.

The photovoltaic (PV) generator can be connected to the DC bus (by default, DC coupling) or to the AC bus (with its own inverter, AC coupling). Wind turbines can also be defined in AC or DC. The hydrogen components (fuel cell and electrolyzer) can also be connected to the DC bus (by default) or to the AC bus (with their respective inverter and rectifier). For example, the following is an scheme where all the components are on the AC bus:
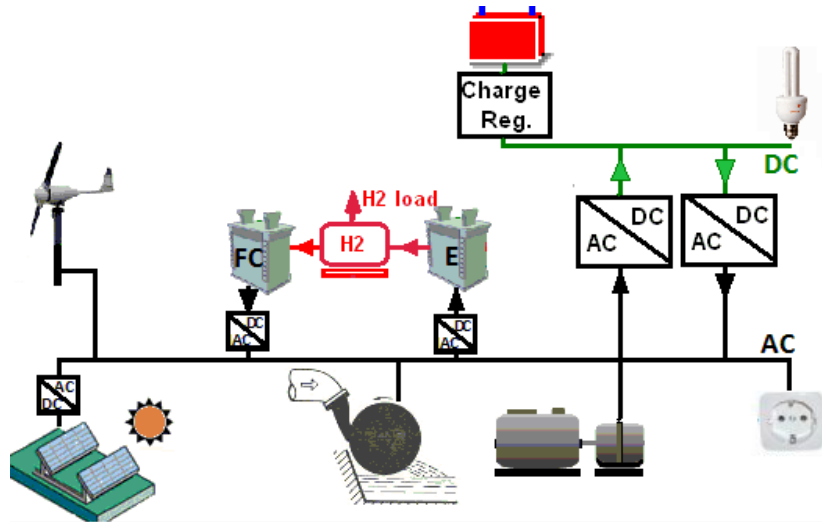
In high power systems all the components are AC coupled.

1.5.4 Grid connection.

The software allows for **selling AC electric energy to the grid** (surplus unused energy), **purchasing AC electric energy to the grid** (unmet load) or **selling surplus hydrogen**, produced in the electrolyzer and stored in the tank. Simulation and optimization is also possible for feasibility studies of zero or low consumption renewable energy generators connected to the grid. 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). The sale to the AC grid can be of any excess energy or not exceeding the energy purchased annually or monthly (**Net Metering** of energy, annual or monthly, with or without hourly periods). You can also define the Net Billing, i.e. to take into account, instead of the energy balance, the economic balance. Net Mettering only in PRO + version

It can also be considered the **case of systems with batteries connected to the AC grid**, optimizing the periods of charging (purchase of network energy) and discharge (supply the consumption load by means of the battery, which can even inject energy into the AC grid to sell

it). The strategy of storing energy in **Pumped hydro storage (PHS)** can also be optimized, and also the strategy for generating **hydrogen** in the electrolzyer.

1.5.5 Energy storage.

Energy storage is usually carried out using batteries, usually lead-acid batteries in off-grid systems, but in the last years li-ion batteries are being also installed. The most suitable lead-acid batteries in off-grid systems are tubular batteries optimized for solar systems: OPZS (flooded electrolyte) and OPZV (gel, maintenance free). Lead-acid classical OGi batteries (flat-plate with a flooded electrolyte, electrodes are thicker than for automotive batteries) are also usually used, their lifespan is lower but they are also cheaper.

Lithium-ion batteries (the most common LiFePO4) can be an economical alternative (they support many more cycles than lead-acid) depending on their cost of acquisition.

Pumped hydro storage (PHS) can also be defined. Moreover, storage in hydrogen can also be considered in iHOGA.

1.5.6 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 or gasoline). It is the system most widely used as an auxiliary system for periods of low irradiation or to cover certain high power consumption. However, AC generators have the environmental disadvantage of generating toxic and greenhouse gases.

1.5.7 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. However, the low energy efficiency of electricity-hydrogen-electricity conversion (around 30%), as well as the high prices of these equipments, mean that at the moment they are not competitive with battery storage. (with much lower prices and much higher efficiencies, of the order of 80% or higher).

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.

1.5.8 Thermoelectric generator.

Thermoelectric generator (TEG) can be a good option in places with very low irradiation in winter, where heating is needed (Champier, 2017) (Dufo-lópez, Champier, Gibout, Lujano-rojas, & Domínguez-navarro, 2019). Also in off-grid systems where a stove is used, for heating or cooking (see figure), TEG can use the residual heat of the stove to produce electricity (with a low efficiency, around 5%). The TEG is usually composed by several thermoelectric modules (TEM) in serial or parallel. The hot side of the TEM is connected to the combustion exhaust hot gasses of the stove and the cold side is connected to the ambient temperature or to a cooling circuit.
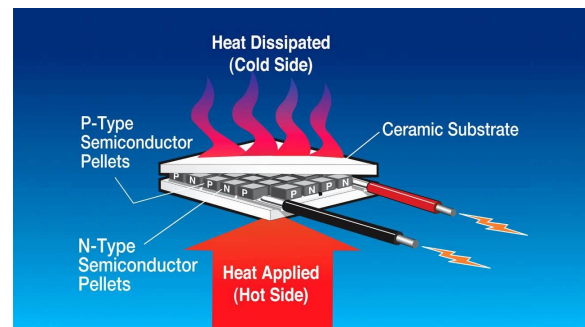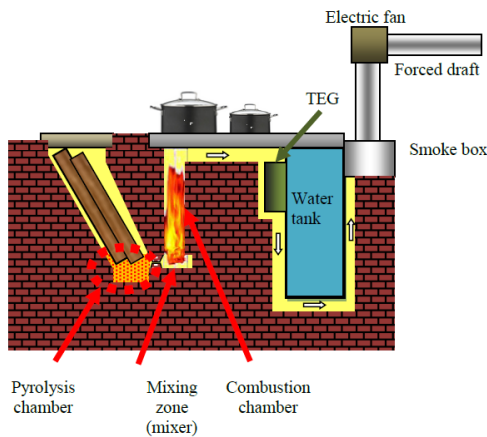
A DC voltage appears in the TEM that is proportional to the difference of temperatures. If the TEM is connected to the electrical load (or to the battery bank to store the electricity produced) by means of a MPPT system (so that the load connected to the TEG is always the same as the internal resistance, that is, matched load), the output power of the TEG will be the maximum. In places with very low irradiation in winter, where heating is needed, or in off-grid systems where there is a stove for cooking or heating, TEG can be part of the optimal solution to supply the electricity.

1.5.9 iHOGA exclusive features.

Unlike other commercial hybrid optimization software, iHOGA uses advanced models in the simulations: variable inverter efficiency (dependant on the inverter output power), advanced battery lifetime models, 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, iHOGA 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 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 modules, wind turbines, hydraulic turbine, batteries, AC generator, fuel cell, electrolyser, inverter 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 tools for the simulation and optimization of hybrid systems (Bernal-Agustín & Dufo-López, 2009c)(Rodolfo Dufo-López, 2007)(Rodolfo Dufo-López & Bernal-Agustín, 2011), but none uses advanced optimization algorithms except iHOGA. Other programs (eg HOMER) 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. In addition, the control strategies are too simple, and no in-depth optimization is possible as in iHOGA. Other advantages of iHOGA are in the models used, more precise than in HOMER, in the components as well as in the economic calculations, besides functionalities like the pre-sizing, the optimization of the slope of the photovoltaic modules, the probability analysis, the advanced battery ageing models, multi-objective optimizations, etc.

iHOGA uses Genetic Algorithms (GA), see Annex 1 for more info, and references (Bernal-Agustín & Dufo-López, 2009a)(Rodolfo Dufo-López, 2007)(Rodolfo Dufo-López & Bernal-Agustín, 2011)(Rodolfo Dufo-López & Bernal-Agustín, 2005)(Rodolfo Dufo-López, Bernal-Agustín, & Contreras, 2007)]). GA are used to perform the optimization, for the combination of the components (main GA) and also for the control strategy (secondary GA). Genetic

algorithms allow to obtain satisfactory solutions when applied to problems with a great level of complexity, and with very low calculation times. If the number of possible combinations is very high, using a population of 0.003% of the possible combinations, with 15 generations, i.e. evaluating approximately 0.04% of the possible combinations, there is a very high probability of obtaining the optimal or a solution very close to the optimal one (Bernal-Agustín & Dufo-López, 2009a). That is, the optimization time can be reduced to less than 0.1% with great probability of obtaining the optimal solution or a very close solution.

iHOGA also has the possibility to evaluate all possible combinations of components and control variables of the strategy, i.e. optimization according to the enumerative method, without genetic algorithms. This possibility is feasible if only the combination of components is optimized, since the number of possible combinations is usually not very high. However, on other occasions (if you want to optimize components and control strategy simultaneously or if the time step is low or if multi-period is selected) this possibility is not feasible, since the number of combinations of components and strategies can be enormous, and calculation times can be made unfeasible, needing many days). Genetic algorithms allow finding very close to optimal solutions with very low calculation times (Bernal-Agustín & Dufo-López, 2009a)(Rodolfo Dufo-López, 2007)(Rodolfo Dufo-López & Bernal-Agustín, 2011).

In summary, iHOGA is a computer tool for the optimum dimensioning of hybrid installations contemplating the possibility of including solar, wind and hydraulic renewable energies, together with support systems based on storage (batteries), back-up generators (AC generators), and fuel cell (combined or not with electrolyzer and hydrogen tank), including the possibility of AC grid connection (purchase and sell electricity to the AC grid) and also the possibility to generate hydrogen to be sold. To do this efficiently, it can use genetic algorithms, which obtains the optimal combination of components and control strategies (see Annex 2 for more information on control strategies for off-grid systems).

1.6 System optimization.

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

iHOGA 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, the inverter and / or the TEG, 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)[1] 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.

---

[1]In off-grid systems where optimization is applied through iHOGA, cash flows are usually expenses only (purchasing, replacement, maintenance, and fuel costs, etc), with no income. The different costs throughout the whole of the study period are referred to the initial time of the investment using the discount rate (approx. interest rate minus inflation rate), thereby producing the NPC. The lower the NPC value, the better the investment .

It is possible to use the option in iHOGA to sell surplus hydrogen or to sell electric energy to the AC grid (it is also possible to purchase energy from the grid to compensate for unmet load by the hybrid system). In those cases, if calculating NPC, sales are accounted for within iHOGA as negative values, since they must be subtracted from component acquisition costs, replacement, and maintenance expenses. We may thus achieve an income from energy sales which is higher than system costs, resulting in a negative value for "NPC". This means that our facility will achieve a net benefit (positive values mean expenses, i.e. costs). A larger negative value for our "NPC" will indicate a more profitable system.

- 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.

The equations for the NPC calculation are detailed in (Rodolfo Dufo-López, Cristóbal-Monreal, & Yusta, 2016a).

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:

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

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

$$- \sum_{y=1}^{Life_{HS}}\left(\frac{Incomes_{sell\_H2\_y}}{(1+I)^y}\right) + Cost_{INST}$$

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:

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

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

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:

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

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 $(1+Inf_{gen})^y/(1+I)^y$ 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 $H2_{\text{load\_y}}(t)$ is the hydrogen consumption load (kg) during each time step of year y supplied by the system.

The levelized cost of storage (LCOS), for batteries, is shown in the report of each solution. It is calculated as the net present cost of the battery bank divided by the discharge energy during the system lifetime:

$$LCOS_{i,k} = \frac{NPC\_bat_{i,k}}{\sum_{y=1}^{Life_{HS}}\left[\sum_{t=0}^{8760h} E_{discharge\_batt\_y}(t)\right]}$$

The user can decide to include in the denominator the ratio $\left(1 + Inf_{gen}\right)^y / (1 + I)^y$ as shown for LCOE and LCOH:

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

The simple payback period (years) in NPC minimization projects is calculated considering the savings when comparing our system with an only AC grid system (*system where all the load is supplied by the AC grid and there is no own generation or storage system, data in LOAD / AC GRID window, PURCHASE / SELL E tab, right bottom corner*): difference in investment cost divided difference in costs of year 1:

$$Payback_{i,k} = \frac{Investment\ difference}{Savings\ year\ 1} = \frac{Investment_{i,k} - Investment_{GRID}}{Cost_{GRID\_year\_1} - Cost_{i,k\_year\_1}}$$

Where $Investment_{i,k}$ is the investment cost of our system (sum of the acquisition cost of all the components plus installation cost; loan is not considered), $Investment_{GRID}$ is the investment cost of the AC grid only system, $Cost_{GRID\_year\_1}$ is the cost of the year 1 of the AC grid only system (O&M cost and cost of purchasing all the load consumption to the grid) and $Cost_{i,k\_year\_1}$ is the cost of the year 1 of our system (O&M cost plus fuel cost plus cost of purchasing electricity to the grid minus incomes due to selling electricity to the grid minus incomes due to selling hydrogen, note that some of these concepts can be 0).

$$Cost_{GRID\_year\_1} = Cost_{O\&M\_GRID\_1} + Cost_{purch\_E\_GRID\_1}$$

$$Cost_{i,k\_year\_1} = Cost_{O\&M\_1} + Cost_{F_1} + Cost_{purch_{E_1}} - Incomes_{sell_{E_1}} - Incomes_{sell_{H2_1}}$$

By default, iHOGA calculates the discounted payback time or period is calculated considering discount cash flows (https://www.wallstreetprep.com/knowledge/discounted-payback-period/)

It is calculated considering the discounted cash flow (savings of our system compared to the only AC grid system) for each year. The cash flow of each year is the saving of each year, compared to the only AC grid system: it is the cash flow cost of the AC only grid system of that year minus the cash flow cost of our system of that year. In the year 0 (the beginning of the system) the cash flow is the opposite to the investment difference (negative value). The first year when the cumulated discounted cash flow is negative and the next is positive is the "Years Until Break-Even". The payback is that value plus the portion of the next year needed to cover the negative value of the cumulated discounted cash flow.

Maximization of NPV:

If the optimization is the maximization of NPV (gird-connected systems with no load or very low load), in its calculation incomes are positive (selling electricity 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).

$$Total\_Present\_Cost =$$

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

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

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

The 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).

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

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

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

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

The LCOS for batteries is calculated as shown for minimization of NPC projects.

The payback time (years) in NPV maximization systems is calculated as the ration between the investment cost and the net incomes of the first year (incomes minus costs):

$$Payback_{i,k} = \frac{Investment_{i,k}}{Net\_incomes\_year\_1}$$

Where $Net\_incomes\_year\_1$ is the amount of the net incomes of the year 1 (incomes of selling electricity plus selling hydrogen minus O&M costs minus fuel cost minus purchasing electricity to the grid cost, all of year 1; note that some of these concepts can be 0):

$$Net_{incomes_{year_1}} = Incomes_{sell_{E_1}} + Incomes_{sell_{H2_1}} - Cost_{O\&M\_1} - Cost_{F_1} - Cost_{purch_{E_1}}$$

By default, iHOGA calculates the discounted payback period is calculated considering discount cash flows (https://www.wallstreetprep.com/knowledge/discounted-payback-period/)

It is calculated considering the discounted cash flow for each year. The cash flow of each year is the incomes of each year minus the costs of each year. In the year 0 (the beginning of the system) the cash flow is the opposite to the investment cost (negative value). The first year when the cumulated discounted cash flow is negative and the next is positive is the "Years Until Break-Even". The payback is that value plus the portion of the next year needed to cover the negative value of the cumulated discounted cash flow.

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, et al., 2016a)(Coello, Veldhuizen, & Lamont, 2002)(Zitzler & Thiele, 1999), iHOGA looks for solutions with low NPC and low CO_2 and/or low unmet load by the stand-alone system. Also there are two other possible objectives to maximize: Human Development Index (HDI) and Job Creation.

iHOGA 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 or gasoline), 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 kg or t 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).

Optimization of temporary installations:

There is the possibility of optimizing the cost or the weight of the system in temporary installations (Cristóbal-Monreal & Dufo-López, 2016) (to be transported, assembled and at the end of their period of use, must be dismantled and transported back to the origin). In such cases, if the cost is optimized, the transport, operation and wear costs of the system are minimized during use (the NPC is not calculated since the costs are not updated since the duration is less than one year). In the case of minimizing the weight, the total weight to be transported is minimized, including going and return.

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 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):

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.

1.7 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, new feature in version 3.0), in time steps from 1 minute to 1 hour.

1.7.1 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 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% or nominal). From that moment, the cycle is repeated.

1.7.2 Multiperiod simulation   `Only in PRO+ version`.

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.

1.7.3 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, iHOGA 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 (both AC and DC)

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 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). Using PRO+ version, we can calculate the irradiation over the back surface of the PV modules, 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, iHOGA 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 of the system. In the first versions of the software it was estimated according to the simplified method of Equivalent Cycles to failure (used by other optimization programs like HOMER). It is possible to choose between this method 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), used by other software programs more accurate (as HYBRID2) (Green & Manwell, 1995). In version 2.2 it was added 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, iHOGA knows the different parameters that will determine the NPC of the system over its useful life: fuel consumption, energy cycled by the batteries, operating hours of the different components, CO_2 emissions, etc. With these data, iHOGA can know the annual cost of the fuels and the cost of operation and maintenance, in addition to the initial cost of acquisition of the elements and, if there is AC grid, costs of purchasing and incomes of selling electricity, and incomes of selling hydrogen, in its case. 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 of the system is obtained.

2. INSTALLING AND RUNNING THE APPLICATION

2.1 Installation

To run the software 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 (however new version adapts to any screen size and DPI).

To install the application double click on the auto-installable file called iHOGA with the version and build number and follow the steps.

iHOGA 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**

If you want to install the irradiation and wind speed local database (in the case NASA online database fails), you must download (https://ihoga.unizar.es/en/descarga/) and execute the "RESOURCES-ENG.exe" self-extracting compressed file and install the database into the iHOGA installation folder (into a subfolder called "RESOURCES").

2.2 Running the Application

The application may be started:

- From the Start button, Select All Programmes, select iHOGA.

- From the Desktop, double click on iHOGA.

3. <u>INTRODUCING DATA</u>

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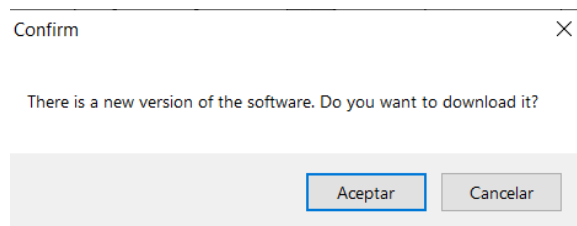
It is strongly recommended that you download and install the new available version. After downloading it, you must close the software and install it.

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** *(do it for both types of projects, low and high power projects):*

        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 (names are TI-date for low power projects and TM-date for high power projects).*

        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).*

    5. **If you changed the components of the databases** *(do it for both types of projects, low and high power projects): 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".
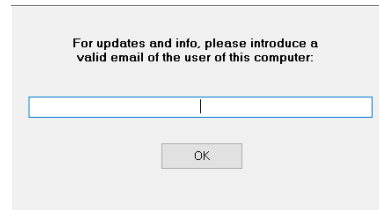
On the Project Menu, there is a choice to create a new project, open an existing one, exit the application or other options (available after a project is created or open).
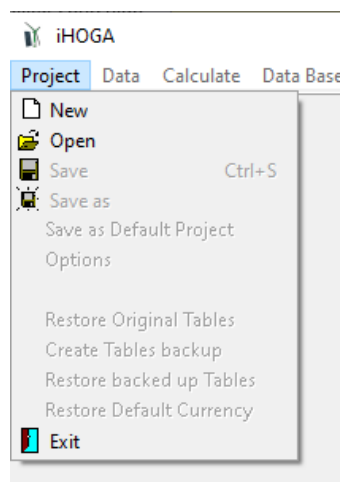
PRO+ version licensing:

The first time we run iHOGA PRO+ version, after accepting several messages showing that the license is not active, you should click in the upper menu "License" -> "Activate License".
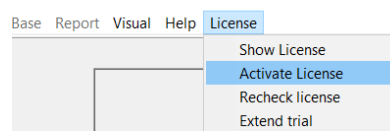
Then a window appears, where you must click "Activate software online now".
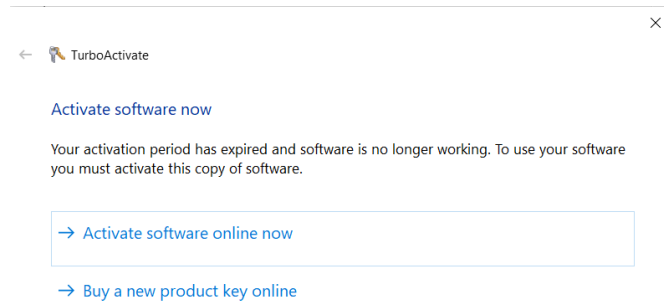
Then it asks for the product key (you should have bought the key previously):

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.
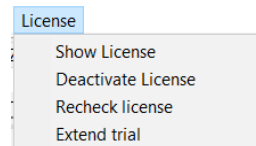
Change the default currency which will be used by iHOGA:

The first time you create a new project (menu Project->New), iHOGA asks if you want to change the default currency, i.e., if you want to use as default a currency different from Euro (€).
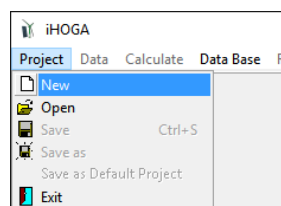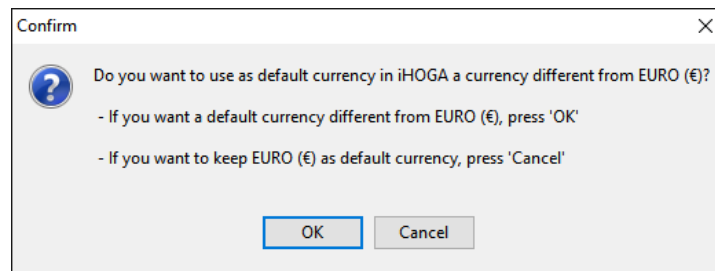
iHOGA will only ask for the default currency this first time we create a project. If it is not changed at this time, the default currency will be the Euro.

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.
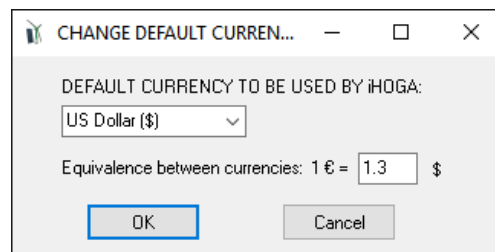
If we choose another currency, a text box appears at the right where we must write its abbreviated name. Below we must indicate the equivalence between the Euro and the new currency.
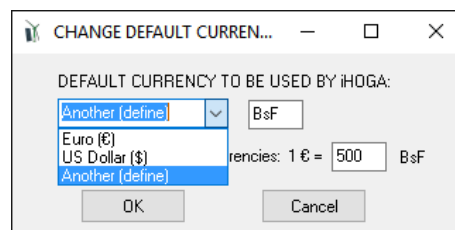
If we click the "**Cancel**" button, the Euro will be kept as the default currency and the default databases and data will not be altered. However, the next time you create a new project or open a project, you will be asked to define the currency.

If we click **"OK"**, the new currency will be the one that will use iHOGA 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.
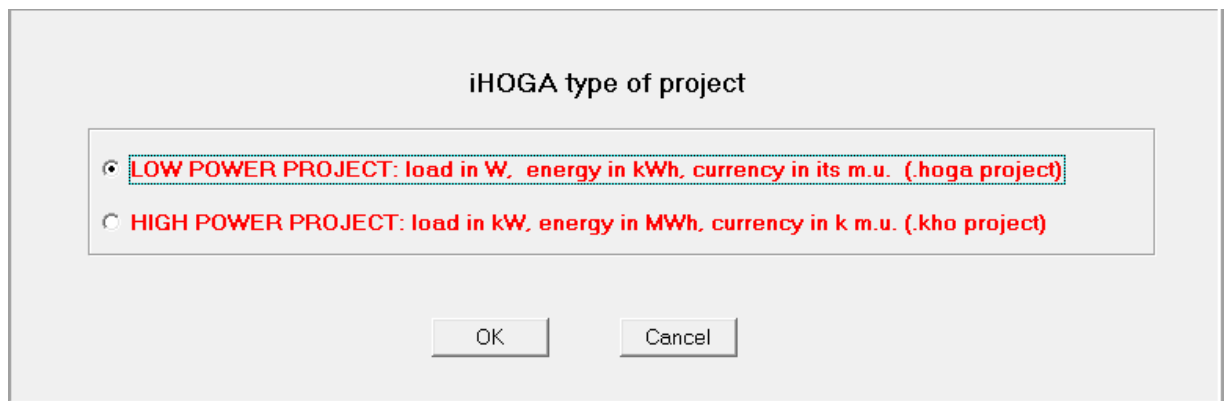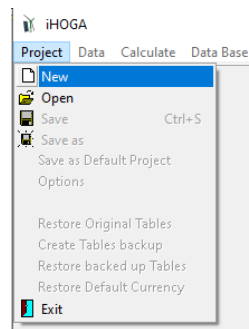
First, we must select the type of project. By default, low power project is selected.

High power projects only in PRO+ version

After selecting the type of project and clicked OK, the Windows save window appears to select the name and folder where the project will be created.
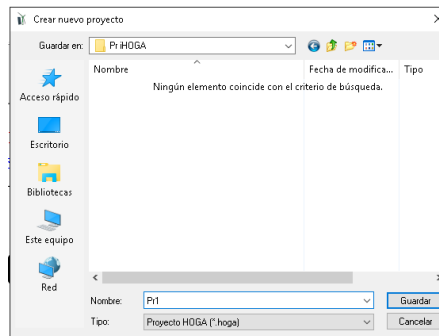
If low power project was selected, the file of the project will have **.hoga** extension. However, if high power project was selected, the extension will be **.kho**.

Once pressed "**Save**" button, the program will create a file with the name that we have given to the project plus ".hoga" or plus ".kho", depending on the type of project, 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 .hoga or .kho 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:

If the **low power project** was selected, the default values are for a PV-diesel-battery off-grid system, with a specific load and irradiation of Zaragoza, Spain. Of course, the user can change any data.
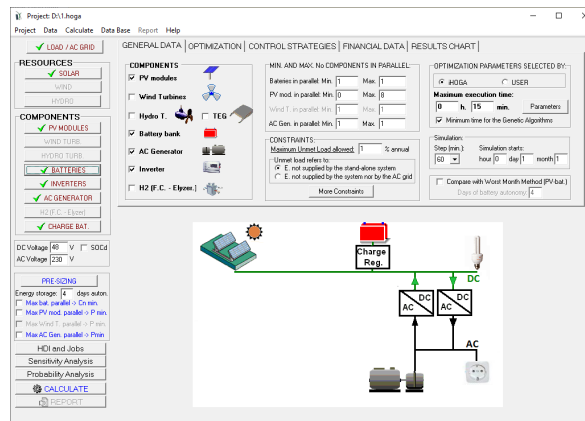
If the **high power project** was selected, the default values are for a PV-battery grid-connected generator, with no load. The user can change any data.
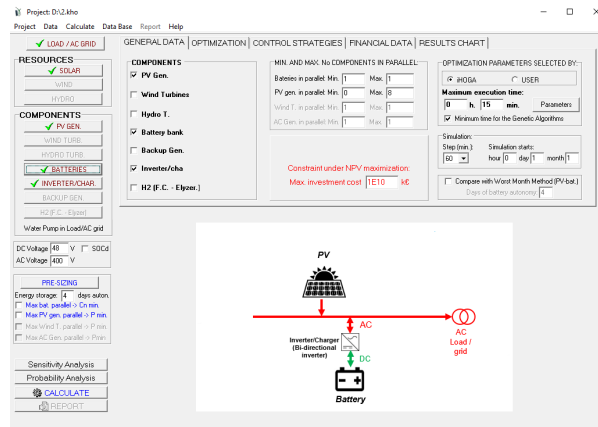
Open an existing project:

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 .hoga or .kho, depending on the type of project).

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, iHOGA creates both the .hoga or .kho file and the folder with the same name) . In the following figure it can be seen that we opened a low power project, the project "pv-diesel", marking the file pv-diesel.hoga, and it is observed that in the same directory there is a folder also called pv-diesel.
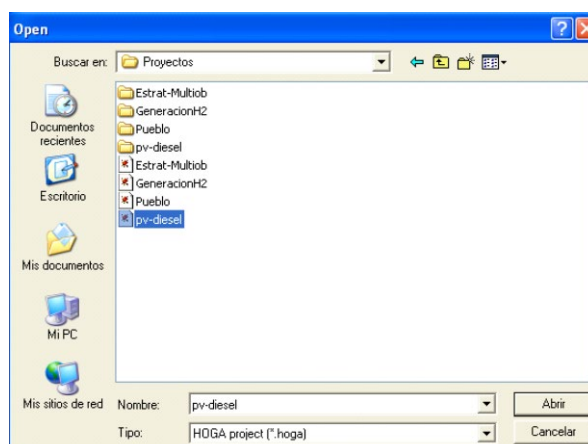
3.1 Main screen and main options of the project

The main screen of the program looks like this:

If we selected **Low power project:**
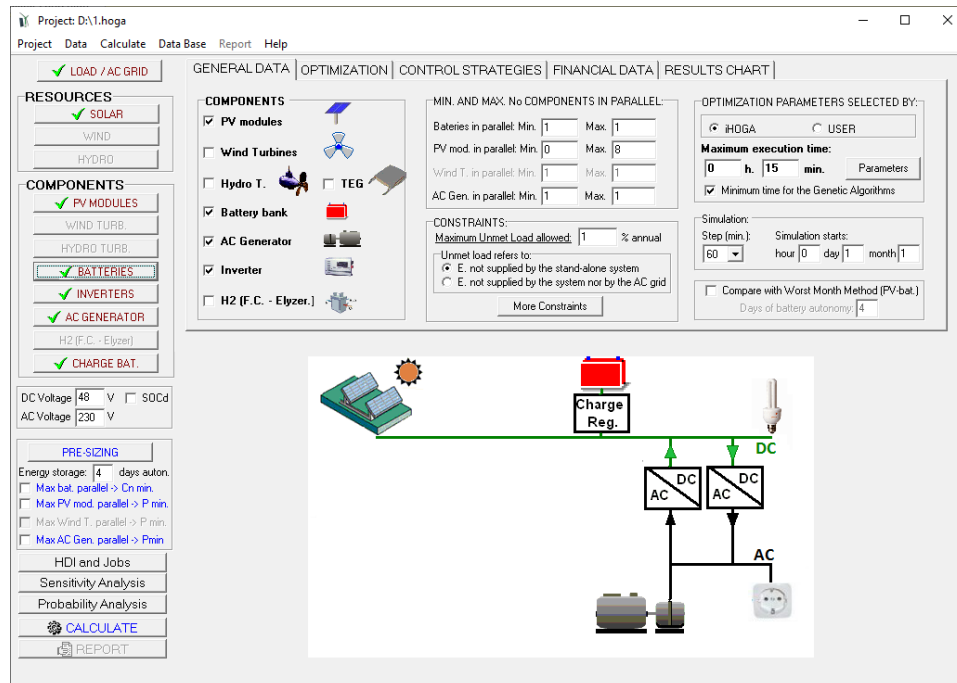
If we selected **High power project:**
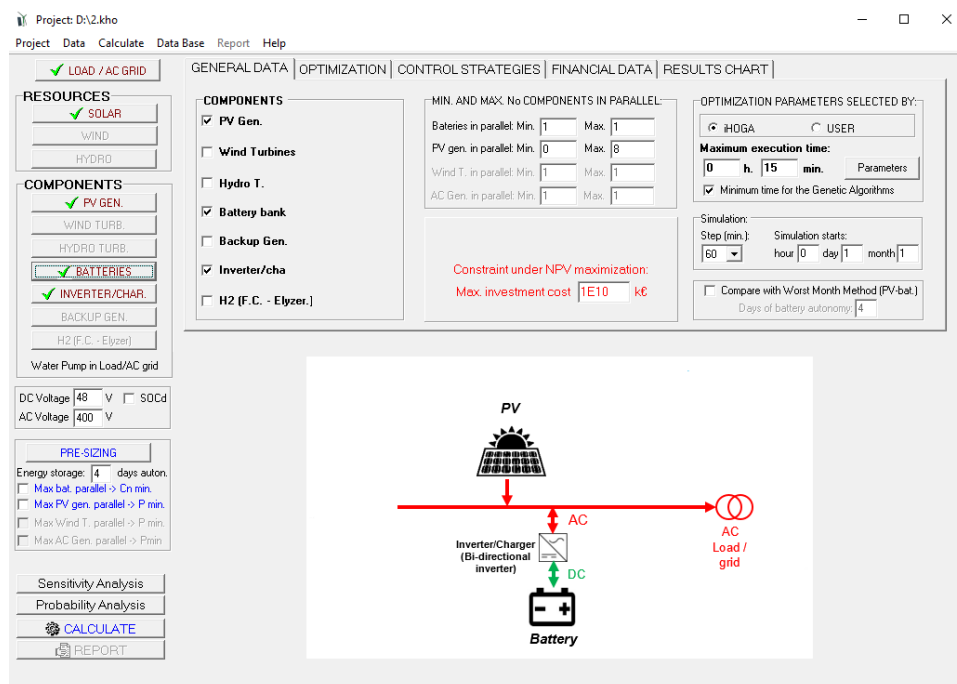
The scheme of the system is different, as the low power project allows to have DC or AC coupled system while the high power system just allows AC coupled. Also, by default, the low power system does not include grid-connection while the high power system includes it.

The main screen shows menus and buttons. All of them 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**:
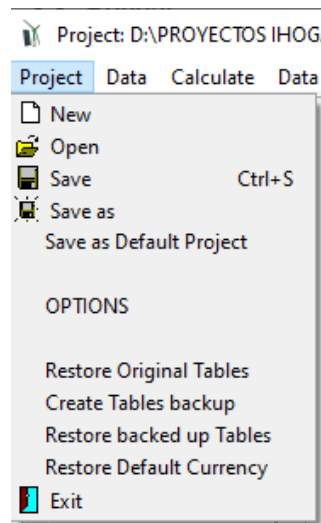
The next window appears, where we can choose the main options of the project.

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,...).

Multiperiod only in PRO+ version

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), default for low power projects. We can select minimization of

NPC, minimization of LCOH (if there is hydrogen load) or minimization of payback period (comparing to the only AC grid system). (*Only in PRO+ version*).

Or

- **Maximization of the net present value (NPV)** *Only in PRO+ version* (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 and the minimization of the payback period.

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.

If we select the box "**In the simulation window, show the probability density function (PDF) of the main results**", in the simulation window the third tab will be visible and it will show the probability density functions of many results. However, in cases of multiperiod simulation and/or small time steps, it can take a high extra time to show the simulation screen, so this option is by default unselected.

If we select the box "**When clicking a component in a table, update the component with the values of the database**", if a component has the name of a component stored in the database, when we click in the component (in the table), it is updated to the values of the database. If it is not selected, the component won't be updated.

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

In the case of high power projects, in this window there is an extra checkbox:

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.

By selecting **Multiperiod** (*Multiperiod only in PRO+ version*) the number of years of the system lifetime must be indicated (by default 25 years) and a button appears to select several options:
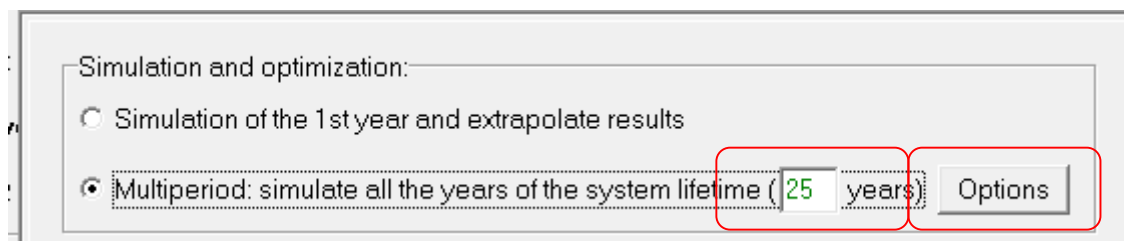
By clicking in **Options** button a new window appears, where we can choose:

- 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"). As all the payments and incomes are supposed to be done at the end of each year, the inflation will also affect the first year: the first year the payments and incomes will be the defined plus the inflation.

- 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 first year of the simulation uses the data introduced, therefore, if "Fixed", the first year the load will not be increased; however, if not fixed, you can define an increase for the first year.

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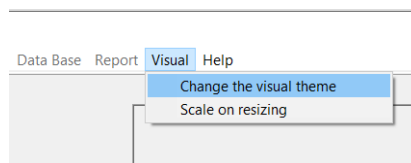
A small window appears, where you can change the visual theme (*if you use a different one from the deault "Windows", the software may slow down*):

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.
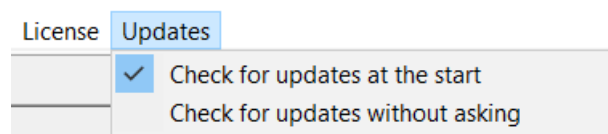
If "Check for updates without asking" is checked, at the start the software will check for updates automatically, without any asking.

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 6 tabs where data must be entered (in the 6th tab we can see the results of the optimization as a graph):

-   GENERAL DATA

-   OPTIMIZATION

-   CONTROL STRATEGIES

-   FINANCIAL DATA

-   Maintenance shutdown

-   RESULTS CHART

In next sections, in general we will show the screens of the low power system project. The high power system project screens are similar, usually with less options. For example, in low power projects the PV generator can include or not MPPT, so there are options to select it, while in high power projects the PV generator always include MPPT so this option is not available to

be changed and therefore these options are not visible.

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 allowed in parallel for some components.

- Constraints that must be met.

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

Also indicated:

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

- The comparison with the worst month method of photovoltaic-battery systems.

COMPONENTS:

The default hybrid system is PV-Diesel, with batteries. To add or remove components, select them on "COMPONENTS.
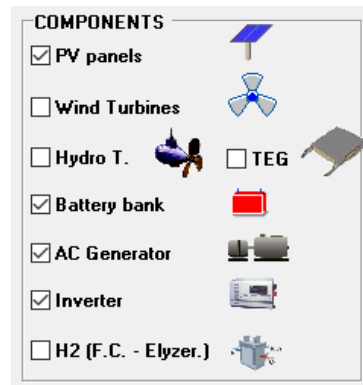
When you add or remove a component, the schematic of the lower part is automatically updated, and the buttons on the left that will introduce us to the screens of the different components are enabled or disabled.

Hydrogen components (Fuel cell – electrolyzer) only in PRO+ version

MINIMUM AND MAXIMUM NUMBER OF COMPONENTS IN PARALLEL:

Minimum and maximum number allowed for batteries, PV modules, wind turbines and AC generators parallel must be provided.

In section 3.16 PRE-SIZING it is shown that iHOGA can help to decide the maximum values.
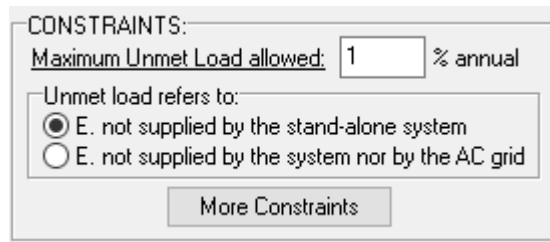
Note: The parallel connection of more than two batteries is in some cases problematic, in those cases the maximum number allowed in parallel battery should be 1 or exceptionally 2 (unless you have multiple controllers for different battery banks).

The availavility of several AC generators in parallel only in PRO+ version

CONSTRAINTS:

In **NPC minimization projects**, 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 referred as:

- E. not supplied by the stand-alone system (default): The energy demanded by the load that is not supplied by the standalone system (energy not served by all the components of the standalone system, including the renewable sources, the batteries, the AC generator and the fuel cell), but not including the AC grid.

> In this case, it will be possible to purchase energy from the AC grid in some cases, to compensate for unmet load by the stand-alone system (this option is shown within the "LOAD / AC GRID" screen, section 3.2). In these cases, we may select a maximum percentage of energy to be purchased from the grid. This value must be introduced in the field defined as "Maximum Unmet Load allowed".

- E. not supplied by the system nor by the AC grid: The energy demanded by the load that is not supplied by the standalone system (energy not served by the standalone 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 0.01%. 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.

- Maximum Capacity Shortage (% of total load) *Only in PRO+ version*. Maximum allowed for the annual total reserve capacity shortage in percentage of the total annual load. (*You must take into account that, in some specific cases, the capacity shortage can be higher than 100% of the load; in these cases, if you set the maximum to 100%, this constraint won't be met*). During each time step, the capacity shortage is calculated for both buses, AC and DC. For each time step and for each bus, it is calculated as the subtraction between the required reserve capacity and the real reserve capacity. The total reserve capacity shortage is the total amount of the capacity shortage of both buses. The required reserve capacity is needed to supply the sudden increase in load and to compensate the sudden decrease in renewable power (PV and wind), avoiding stability and frequency problems. For each time step, the required reserve capacity (of AC or DC bus) is calculated considering a percentage of the load of the time step plus a percentage of the maximum load during the year plus a percentage of the PV power generated during the time step plus a percentage of the wind power generated during the time step. These percentages are defined by the user, for AC and for DC buses, near the maximum capacity shortage defined by the user. The real reserve capacity is supplied by the sources which can instantly supply the sudden fall of renewable generation or increase of load: the AC grid, the batteries, the hydro turbine in PHS (if different than pump), the fuel cell and the AC backup generators which are running during the time step. A backup generator (diesel, gasoline…) can only supply capacity reserve if it is running during the time step; if it is stopped, it does not supply reserve capacity because during a renewable generation sudden decrease or during a load sudden increase, the diesel generator could not supply the load instantly, as it should start and reach the working temperature during several minutes. For each time step, the real reserve capacity (of AC or DC bus) is calculated considering the available power from the batteries (maximum available power from the batteries, considering the discharge from the present SOC in the minutes set by the user, default 15 min, minus battery discharging power during the time step), plus the maximum AC grid power minus the electricity purchased to the grid during this time step, plus the available power from the PHS turbine (if different machine than pump) if it is running, plus the rated power of the backup generators which are running during the time step minus the power they are generating, plus the rated power of the fuel cell minus the power it is generating during the time step. In AC bus the real reserve capacity obtained from the DC

components is limited by the inverter maximum power, while in DC bus the real reserve capacity obtained from the AC components is limited by the charger maximum power.

If you check the box "If cap. shortage, try to obtain real AC operating reserve….", during each time step, if there is AC capacity shortage, the software tries to run the PHS AC hydro turbine (different machine from pump) and, if not enough, the backup generator(s), to increase operating reserve and reduce capacity shortage.

☐ If cap. shortage, try to obtain real AC operating reserve to meet required reserve using PHS and backup generators

Capacity shortage is considered as a constraint in the publication (Dufo-lópez & Lujano-rojas, 2025) (https://www.mdpi.com/2313-0105/11/2/70).

In projects of minimization of NPC, iHOGA 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 <u>maximization of NPV</u>, where there is typically no load (grid-connected generators so sell the electricity to the AC grid) there can be three constraints:

Constraints under NPV maximization:

Max. Investment cost	1E10	M€
Min. Capacity Factor	0	% ☐ Pmax_sell
Min. Renew. Fraction	0	%
Max. Unmet load	100	%
Max. Unexported E.	100	%

- 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 (by default 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 unexported energy (by default 100%, so by default this constraint is not considered %). Unexported energy (%) id defined as: (Exported_energy-Sold_energy)/Exported_energy*100.

iHOGA assigns a -infinite value to every element combination that does not meet the three constraints.

SELECTION OF THE PARAMETERS OF THE OPTIMIZATION.

The parameters of the optimization can be selected by iHOGA (default) or by the USER. If the parameters are selected by iHOGA, 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 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 iHOGA 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 iHOGA.

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 iHOGA select the parameters of the optimization.

However, if the maximum execution time we allow is too small, iHOGA 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 "iHOGA".

If the time allowed by us is lower than the time needed for the enumerative method, iHOGA 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 optimial solution by mans of the genetic algorithms, iHOGA will take the minimum time that it considers correct to run the genetic algorithms (as, by default, the checkbox ☑ Minimum time for the genetic algorithms is selected). If this checkbox is not selected, the time allowed will always be the time used by iHOGA, 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 iHOGA. 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.
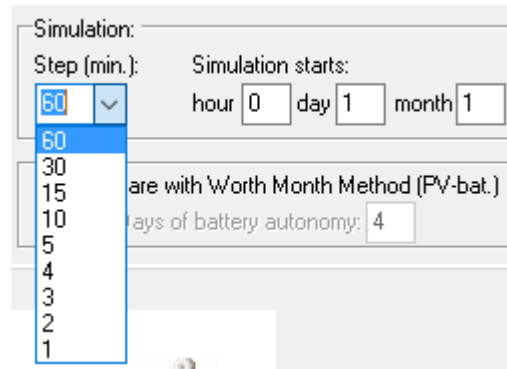
It is common to use the 60 minute time step, since the simulations are much faster and therefore the optimization is also faster. If you want to give more detail to the simulations you can reduce the time step, up to 1 minute, but that involves much longer calculation time.

Simulation time steps of less than 60 minutes only in PRO+ version

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 3.12). 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 3.16) 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.

THE WORST-CASE METHOD (PV-ONLY SYSTEM): SETTING COMPARISONS

An option is available to compare the results obtained in the optimisation of the system and those provided by a pure Photovoltaic system (PV-only) calculated according to the Worst-Case Method.

For this option, a number of days of autonomy must be introduced for the battery to supply the load. Please note that PV modules and batteries must be selected for this option to be available.

3.1.2 OPTIMIZATION tab.

In this tab the TEMPORARY INTERVAL must be chosen first: Fixed installations (the entire useful life of the system is considered, which will be set in the tab "Financial data" tab) or temporary installations that are transported from one place to another (where only considers a certain operating time).

TEMPORARY INTERVAL: ALL USEFUL LIFE OF THE SYSTEM (FIXED INSTALLATIONS).

This is the option marked by default. The entire useful life of the system is considered (the study period marked in the tab "Financial data" tab, default 25 years). 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. Other types of optimization can be defined, including the Human Development Index (HDI) and/or Job Creation (maximizing them).

If "Another" is selected, a panel appears to the right, where you can define double or triple multiobjective optimization.

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 (or highest HDI or highest job creation, depending on the objectives selected to be optimized). 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 or higher HDI or higher job creation, depending on the objectives selected to be optimized). 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 € 100,000. If the percentage specified by the user is 60%, all non-dominated solutions with NPCs above € 160,000 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".

TEMPORARY INTERVAL: LESS THAN ONE YEAR (TRANSPORTABLE FACILITIES, ONLY FOR PV-DIESEL-BATTERIES): *Only in PRO+ version*

In the case of selecting this type of optimization, it would be for transportable systems that are installed temporarily in a certain place, and that we want to minimize the weight to be transported (round trip) or we want to minimize the total cost of operation + maintenance + transport (round trip) + degradation, according to the methodology set out in the reference (Cristóbal-Monreal & Dufo-López, 2016).

This type of optimization can only be done for photovoltaic-diesel-battery systems (or photovoltaic-diesel, or photovoltaic-batteries, or diesel-batteries).

It must be set the following data: time when the temporary installation begins, the number of days that it works, the distance to which the installation is to be transported, the diesel density (kg/m3), if there is a minimum amount of litres of diesel fuel wants to set, the transport cost in the monetary unit per ton and km, as well as the extra ageing (degradation) of the PV modules, batteries, AC generator and inverter in percentage (extra deterioration due to transport, assembly and disassembly of the components).

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).

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):

- o 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.

- o CYCLE CHARGING *Only in PRO+ version*, 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 to 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: <mark>*Only in PRO+ versinon*</mark>

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 *Only in PRO+ version*:

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 *Only in PRO+ version*

Of the variables allowed to be optimized, we can choose all or only some (in this case the variables not chosen 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, iHOGA will need a high time to perform the optimization. Combinations of components are usually more important than control strategies in the Net Present Cost.*

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. Only in PRO+ version

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:

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

- o Optimize the 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, in low power projects, these values are 0 (in high power projects defaults are different, see previous figure), 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). For example, let's suppose that in our case we have three hourly periods for the electricity cost 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 ensure that the "(Compare with Sell price)" checkbox is unchecked (to consider the purchase prices, if it was checked sell prices would be considered).

 Then, 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.

This option is appropriate if we have an electricity price tariff such that the price curve is the same for all days, but with valleys and peaks within the day (for example in Spain the supervalley tariff, see figure below). The methodology is set out in article (Rodolfo Dufo-López & Bernal-Agustín, 2015b).
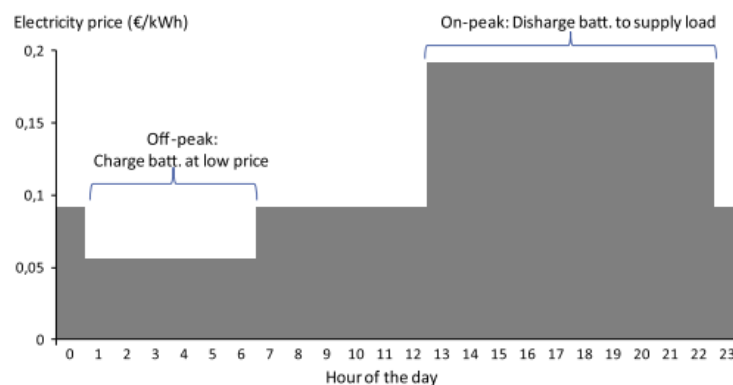
Fig. 2. Hourly price of a TOU tariff used in the example of Section 4.

All the options related to the battery control strategy will be applied the same if we have pumped hydro storage. In the example, the same strategy would be applied if we had pumped

hydro storage: when the sell price is lower than 0.07, water is pumped with the renewable sources to store energy in pumped water; when the sell price is higher than 0.17 €/kWh the hydro turbine works with the stored water, supplying the load.

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.

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

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>Batteries can inject electricity to the AC grid:</u>

If the checkbox "**Batteries can inject electricity to the AC grid**" is selected, the batteries, 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.).

☑ Batteries can inject electricity to the AC grid
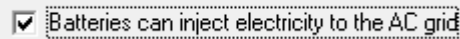
<u>Consider sell electricity prices instead purchase prices, and do not use AC grid to charge the batteries:</u>

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 **"(Compare with Sell price)"**. Also, if **"(Compare with Sell price)"** is checked, <u>the batteries will not be charged by the AC grid,</u> they will just be charged by the renewable sources when the price is lower than the limit (or when the power from the renewable sources is higher than the maximum power that can be injected in 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.

☑ (Compare with Sell price)
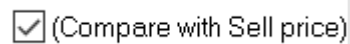
When selecting this option, a message appears telling us that batteries will not be charged from the AC grid.

HOGA   ✕

Batteries will not be charged from the grid, they will be charged from the rewewable sources considering the price of selling electricity to the grid

OK
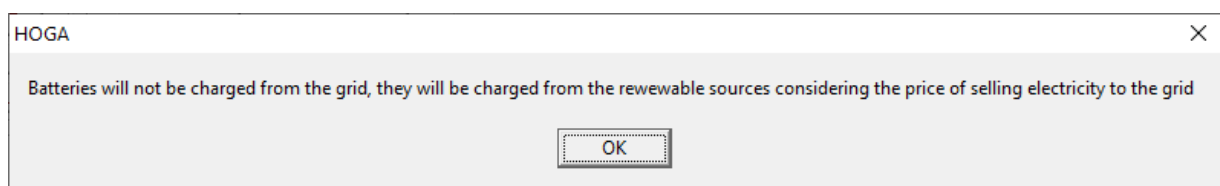
<u>Other options:</u>

If the box ☐ 1 day at low SOC -> charge battery 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 ☐ When batteries are off, compensate autodis 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**".

☑ Optimize strategy of grid-conneted batteries:
   ⦿ 3 variables: X1(dif.), X2(%), X3(%).   X1:min. `0`   max. `0`   €/kWh
   ◯ 2 variables: price E. min. and max.   Min.> `0.135`   ; Max< `0.165`   €/kWh   ☑ PrCh<PrD

This optimization can be useful for grid-connected systems where the hourly price of energy is different every hour (real time pricing, RTP), as in Spain. 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 iHOGA allows (photovoltaic modules, wind turbines ...).
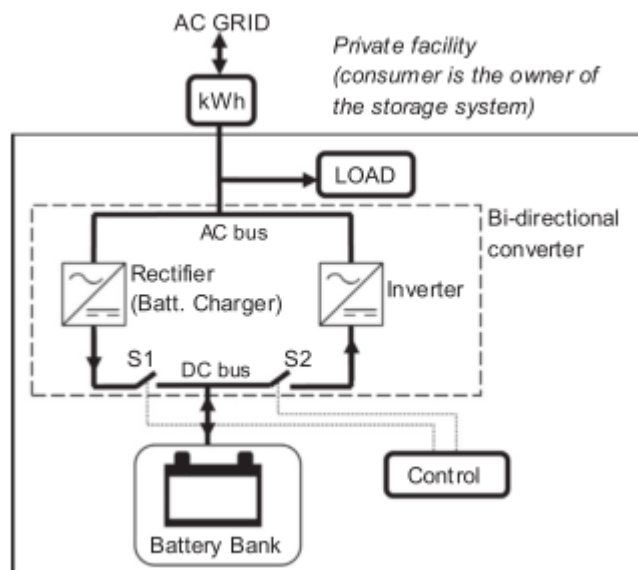
You can choose between optimization with 3 variables: X1, X2 and X3, following the methodology outlined in the article (Rodolfo Dufo-López, 2015), or the optimization by 2 variables (the minimum price for the discharge and the maximum for the charge).

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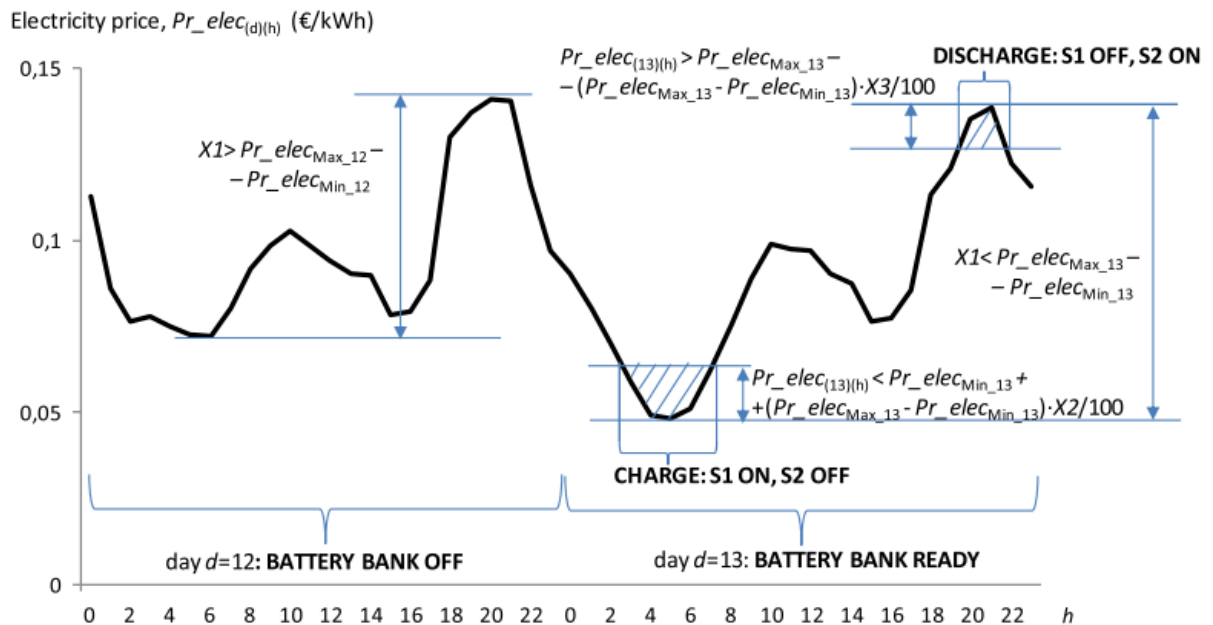
- X3: is the percentage of the difference between the maximum and minimum price of the day that is subtracted from the maximum price so that in the hours whose price falls within that range the batteries are discharged (see previous figure, hours in the DISCHARGE zone).

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 **Batteries availability** [Batteries availability] 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:

BATTERIES AVAILABILITY
FOR THE CHARGE FROM AC GRID / DISCHARGE
DEPENDING ON THE ELECTRICITY PRICE (ARBITRAGE):

CHARGE UNDER ARBITRAGE: DISCHARGE UNDER ARBITRAGE:

C-rate   All 1st

☑ January   ☑ 0 - 1 h   1   ☑ January   ☑ 0 - 1 h   1
☑ 1 - 2 h   1   ☑ 1 - 2 h   1
☑ February   ☑ 2 - 3 h   1   ☑ February   ☑ 2 - 3 h   1
☑ 3 - 4 h   1   ☑ 3 - 4 h   1
☑ March   ☑ 4 - 5 h   1   ☑ March   ☑ 4 - 5 h   1
☑ 5 - 6 h   1   ☑ 5 - 6 h   1
☑ April   ☑ 6 - 7 h   1   ☑ April   ☑ 6 - 7 h   1
☑ 7 - 8 h   1   ☑ 7 - 8 h   1
☑ May   ☑ 8 - 9 h   1   ☑ May   ☑ 8 - 9 h   1
☑ 9 - 10 h   1   ☑ 9 - 10 h   1
☑ June   ☑ 10 - 11 h   1   ☑ June   ☑ 10 - 11 h   1
☑ 11 - 12 h   1   ☑ 11 - 12 h   1
☑ July   ☑ 12 - 13 h   1   ☑ July   ☑ 12 - 13 h   1
☑ 13 - 14 h   1   ☑ 13 - 14 h   1
☑ August   ☑ 14 - 15 h   1   ☑ August   ☑ 14 - 15 h   1
☑ 15 - 16 h   1   ☑ 15 - 16 h   1
☑ September   ☑ 16 - 17 h   1   ☑ September   ☑ 16 - 17 h   1
☑ 17 - 18 h   1   ☑ 17 - 18 h   1
☑ October   ☑ 18 - 19 h   1   ☑ October   ☑ 18 - 19 h   1
☑ 19 - 20 h   1   ☑ 19 - 20 h   1
☑ November   ☑ 20 - 21 h   1   ☑ November   ☑ 20 - 21 h   1
☑ 21 - 22 h   1   ☑ 21 - 22 h   1
☑ December   ☑ 22 - 23 h   1   ☑ December   ☑ 22 - 23 h   1
☑ 23 - 24 h   1   ☑ 23 - 24 h   1

☑ Batt. charge with surplus E. at unchecked hours allowed   ☑ Batt. disch. to supply load at unchecked hours allowed

☐ Charge batteries at the selected hours   ☐ Discharge batteries at the selected hours
only from renewables, not from AC grid ('(Sell price)'),   injecting power to the AC grid, at C-rate,
regardless of the price of electricity   regardless of the price of electricity
(regardless of arbitrage).   (regardless of arbitrage).
  ☐ Rest of the time available for charge (arbitrage)   ☐ Rest of the time bat. available for disch. (arbitrage)

FOR PUMPING HYDRO STORAGE:

☐ Pump at maximum power at the selected   ☐ Turbine at maximum power at the selected hours
only from renewables, not from AC grid ('(Sell price)')   injecting power to the AC grid
(regardless of arbitrage).   (regardless of arbitrage)

OK

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 ☑ In LCOE / LCOH include real disc. rate in Energy is checked, LCOE, LCOH and LCOS will be calculated as shown in section 1.5, the total present cost divided the total supplied energy during system lifetime, including in the energy the real discount rate.

-If minimizing NPC:

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

-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).

If the checkbox ☑ Discounted Payback period is checked, the payback will be calculated as the discounted payback. If "Discounted Payback period" is not checked, the payback calculated will be simple payback.

The calculation of the payback and of the IRR can consider or not the loan (by defatult, not considered):

Consider loan: ☐ for payback   ☐ for IRR

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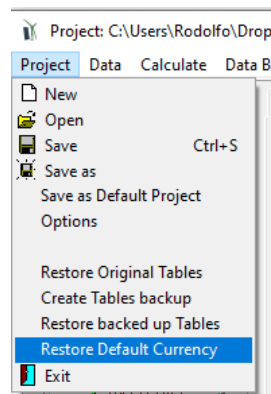
Accept the questions about restoring the currency and restoring the original tables.

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, 80% 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 C_o 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 Maintenance shutdown tab Only in PRO+ version.

The shutdown (parcial or total) of the PV generator and of the wind turbines group, due to maintenance or failures, can be defined in this tab.

GENERAL DATA   OPTIMIZATION   CONTROL STRATEGIES   FINANCIAL DATA   Maintenance shutdown   RESULTS CHART

PV AND WIND TURBINES SHUTDOWN DUE TO MAINTENANCE OR FAILURES:

☑ PV maintenance shutdown: ⦿ Generate randomly   [Generate randomly]   Total shutdown time (% of the year): [10]   Steps 0-1: [2 (0-1)   ∨]
                              ◯ Import hourly file (8760 h)   Duration (hours): Average: [10] Std. dev.: [5]   [≋ Graph]

☑ W.T. maintenance shutdown: ⦿ Generate randomly   [Generate randomly]   Total shutdown time (% of the year): [10]   Steps 0-1: [11 (0-0.1.. ∨]
                              ◯ Import hourly file (8760 h)   Duration (hours): Average: [10] Std. dev.: [5]   [≋ Graph]

If we check the box "PV maintenance shutdown", we can generate randomly or import a hourly file with the data of the shutdown of the PV of a whole year.

Generate randomly: we must define the total time (% of the year) there is shutdown, the average duration (hours) and its standard deviation. Also, in the "Steps 0-1" we must select the number of steps between 0 and 1 for the calculation of the factor which by which the PV generation will be multiplied. For example, if we select "2 (0-1)", the hourly generation of the shutdown will be between 2 possible values: 0 or 1, that is, for each hour, the PV generation will be normal or 0. If, for example, we select "11", the hourly generation will be of 11 values between 0 and 1: 0, 0.1, 0.2, …. 1, that is, for each hour, there will be a partial shutdown (only some strings of the PV) and the PV generation will be a fraction between 0 and 1 of its normal operation. Clicking in the button "Generate randomly", we will obtain the hourly file, which can be shown with the button "Graph":
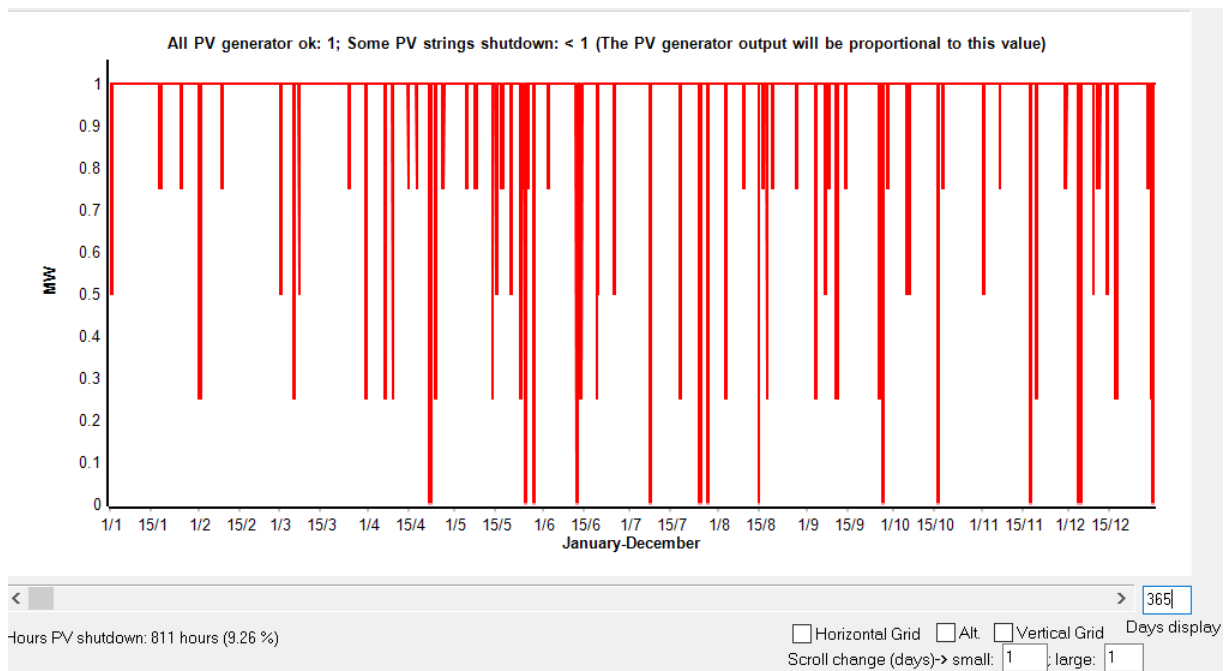
For each hour of the year, in the simulation of each combination of components and control, the PV generation will be multiplied by the value corresponding of that hour.

We can import the hourly file of a whole year (for each hour, 0 for complete shutdown, 1 for normal functioning, a value between 0 and 1 means partial shutdown), selecting "Import hourly file (8760 h)" and clicking in the corresponding button.

We can do the same for the wind turbines shutdown.

3.1.6 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).

3.1.7 System DC and AC Voltage.

System DC and AC voltage must be introduced on the main screen (bottom left). The DC voltage is common to be a multiple of 12 V, choosing 12 V for systems with very little power consumption and increasing the DC voltage as the system consumption increases.

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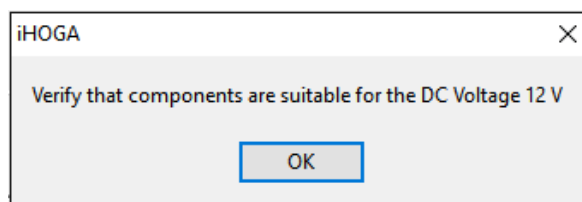
The program will calculate the number of batteries in series as the division of the voltage DC between the nominal voltage of the battery.

With respect to photovoltaic modules, the serial number shall be the division of the DC voltage between the nominal voltage of the panel, unless otherwise defined in the PV panel window (section 3.8). In the event that the photovoltaic generator is connected to the AC bus through its

own inverter (defined in section 3.8), the voltage of the PV generator and the number of modules in series are defined in said section 3.8.

The box ☐SOC d. (Only in PRO+ version) indicates whether we want to consider the dependence of the DC voltage vs. the state of charge (SOC) of the battery bank, 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).

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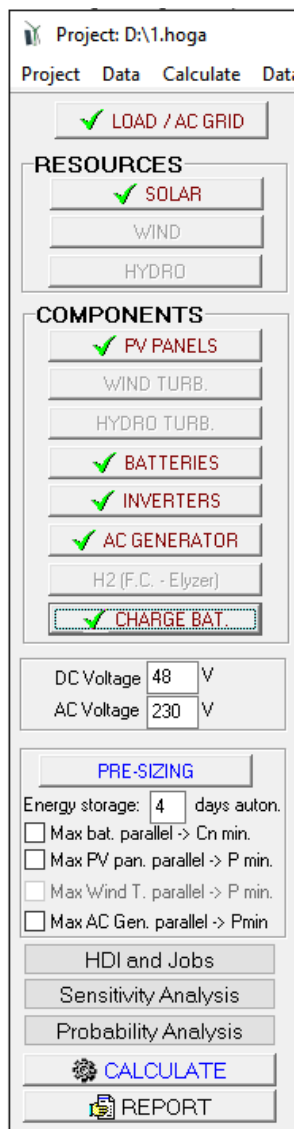
Several menus are available on the main screen (top left): Project, Data, Calculate, Database, Report, Visual, Help and License.

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)
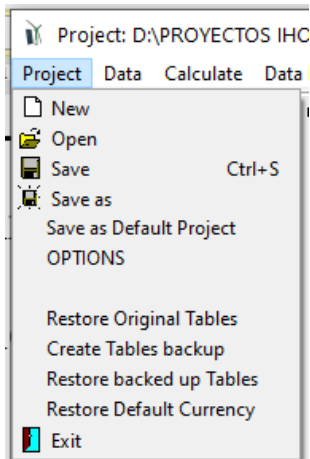
The options available under the "Project" menu are: New (create new project), Open (open an existing project), Save (save the current Project, shortcut Ctrl+S), Save As (save the current project with an alternative name), Save as Default Project (save the current project as the default project, that 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 "<u>Save As</u>" button.

The tables mentioned above are the tables used in the windows where the Load, Wind, PV modules, Wind Turbines, Hydraulic Turbines, Batteries, Inverters, AC Generators,

AC LOAD (W)	DC LOAD (W)	H2 LOAD (kg/h)		WATER (m	
Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h
JANUARY	22	22	22	22	22	22
FEBRUARY	22	22	22	22	22	22
MARCH	22	22	22	22	22	22
APRIL	22	22	22	22	22	22
MAY	22	22	22	22	22	22
JUNE	22	22	22	22	22	22
JULY	22	22	22	22	22	22

H_2 (Fuel Cell and Electrolyzer) are defined, and also the table of results (once the system has been calculated).

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.
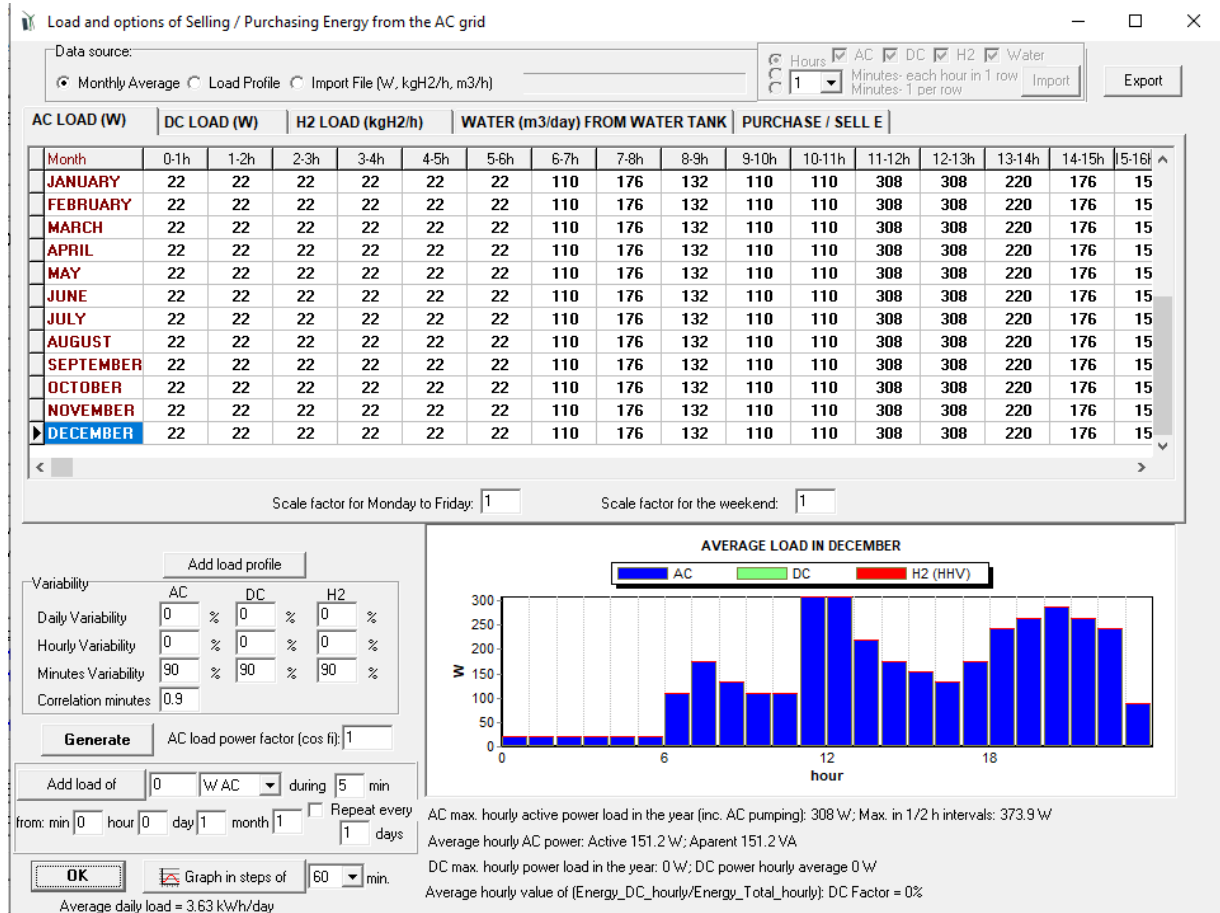

The default load corresponds to a house of low consumption in AC, in average monthly values.

> *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:
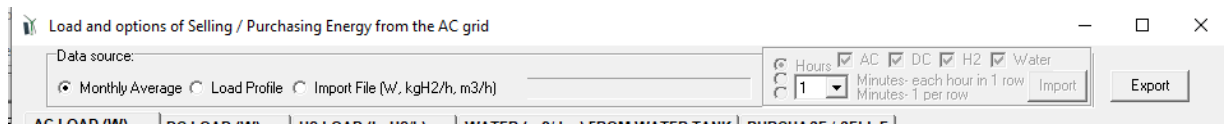
The default option is "Monthly Average". This is adequate in case the expected load is known in monthly average hourly values. Data on load must be introduced on the load tables (in watts and kg H_2 per hour). Three load tables are available, for AC, DC, and H_2 (click on the tabs to display them). Load 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 39400 Wh/kg 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 (W) 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	15-16h
JANUARY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
FEBRUARY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
MARCH	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
APRIL	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
MAY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
JUNE	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
JULY	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
AUGUST	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
SEPTEMBER	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
OCTOBER	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
NOVEMBER	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154
DECEMBER	22	22	22	22	22	22	110	176	132	110	110	308	308	220	176	154

Import AC table   Scale factor for Monday to Friday: 1   Scale factor for the weekend: 1

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 500 W, 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 (500 W).

You can also import the table from a .txt file with 12 rows (one fore each month) and 24 tab separated columns (one for each hour). For example, if you have the AC load profile in an Excel file (next figure).

Select the data of the table, copy it and paste in Notepad (next figure).

Save the file (.txt) and then, in iHOGA, import that .txt file with the button "**Import AC table**":

You will obtain the AC table in iHOGA:

Scale factor must be entered, one for weekdays and another one for weekend.

DC LOAD (W) tab: Only in PRO+ version

In this table you must enter the DC load (W) values for each hour of the day, for each month. You can import the DC table in a similar way as explained for AC. Scale factor must be entered, one for weekdays and another one for weekend.

H2 LOAD (kg/h) tab: Only in PRO+ version

In this table you must enter the H2 load (kg/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 a hydrogen car), not to be sold, it will be used by our company without any charge. You can import the DC table in a similar way as explained for AC. Scale factor must be entered, one for weekdays and another one for weekend.

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 Default profile). Additional preloaded profiles are available by clicking on the dropdown menu, which is displayed under the tables.
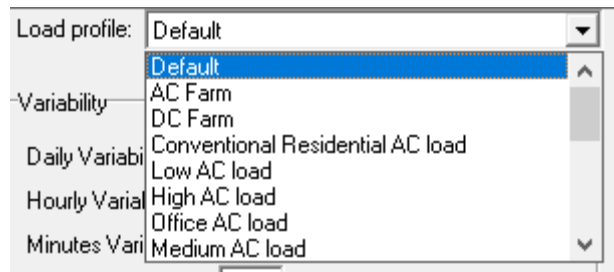
Scale factors:

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.

Another function of the scaling factor is to easily enter large consumption data, e.g. to enter the data in kW, we place in all scaling factors AC and DC factor 1000.

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 (m3/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 (m3/day) FROM WATER TANK (PREVIOUSLY PUMPED): Only in PRO+ version

This tab displays the following:

In which we must define different data:

- The DAILY WATER CONSUMPTION of each month (m3/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 (m3), 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, which could be variable with the button "H var."), friction losses (%, which could be variable if selected the checkbox "Var."), pump rated electric power (W) (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 we want to consider variable head, click in "H var." button, the next window appears (==Only in PRO+ version==)**:**

To consider variable head, you must click in "Consider variation in water hieght in upper reservoir or tank" checkbox. When considering variable head, the variation in upper reserovir heith, pump elevation head and turbine head must be defined for upper tank or reservoir empty and lower tank or reservoir full.

Then, new data must be set:

Data for the variable head:

If selected the variation in upper reservoir height, pump elevation head and turbine head are defined:
-For upper tank or reservoir empty and
-For lower tank or reservoir full

☑ Consider variation in water height in upper reservoir or tank

    ⦿ Fixed value for the area (m2) of the upper reservoir
    ◯ Define height (volume/area) (m) of the upper reservoir when it is full

Upper reservoir or tank area (m2): 40000   -> Reservoir or tank water height (vol./area):

☐ Consider variation in water height in lower reservoir or tank

    Variation in upper reservoir implys inverse variation in lower reservoir in (%): 20

    ☑ Do not consider lower reservoir height variation in the turbine head

OK

We must define the area of the upper reservoir (m^2), by default, or the height (m) when it is full. Also, we can consider the variation in water height in lower reservoir or tank (checking its checkbox), setting the inverse variation in lower reservoir (%) related to the variation in upper reservoir. Also, by default, the lower reservoir height variation in the turbine head is consider (to not consider this, uncheck its checkbox).

If we want to consider variable friction losses in the penstock between pump and water tank or reservoir, we must select the "Var" checkbox close to the Friction Losses data (Only in PRO+ version):

Friction Losses: 10   % ☑ Var.   Losses

Then, click in "Losses" button:

We must set the dynamic viscosity of water (Pa·s), which can be dependant on water temperature by checking the "Dept. on T(ºC)" checkbox. Alos water density must be set.

Losses in the penstock between the pump and the tank or reservoir depend on the pipe diameter, which must be set (mm). If we check the option "This diam. is the max; Min:….", the diameter set is the maximum to be considered, the minimum is set as a percentage of that maximum, and the real diameter for each case will depend on the rated nominal pump flow so that the nominal water speed is the value set (by default 2 m/s).

We must also set the pipe length (m) from pump to tank or reservoir and the absolute roughness of the pipe (mm). The coefficient resistance of the fittings (K) to consider the losses in the fittings must also be set. Finally, we must choose the equation for the approximation to Colebrook equation (Prandtl, von Karman and Nikuradse PKN, by default, Haaland or the use of both equations). For more info the reader is referred to the publication (Rodolfo Dufo-López & Lujano-Rojas, 2024) (https://www.mdpi.com/2076-3417/14/16/7033).

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

PUMP VARIABLE EFFICIENCY (EFFICIENCY % VS MAX. FLOW RATE %):

0 %	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
0	12	25	35	42	52	58	65	68	72	78

If reversible pump/turbine, max. flow rate of the turbine.
If different machines, using pump of 0 W -> Max. flow rate 0 l/s for elevation head + losses of 33 m with 78 % efficiency at max. flow

OK

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). If "Opt" is checked, this variable will be optimised.

Priority to pump if surplus P > [0] % P. pump.   ☐ Opt

The optimization of this variable is considered in the publication (Dufo-lópez & Lujano-rojas, 2025) (https://www.mdpi.com/2313-0105/11/2/70).

Next to the box of the daily flow of each month appears in brackets the daily energy in kWh/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 iHOGA 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 DC or AC loads (depending on the type of pump, DC or AC).

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 iHOGA 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, from 1 to 30) 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 (W in low power project, kW in high power project), DC (W in low power project, kW in high power project), H2 (kg/h in low power project, t/h in high power project) and/or Water load (m3/h in low power project, dam3/h in high power project), 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 W, 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 W, 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 (W), then the 8760 rows of hourly consumption of H2 (kg/h) and finally the 8760 rows of water consumption from tank (m3/h). *The separation decimal point should always be dot (.), not comma.*
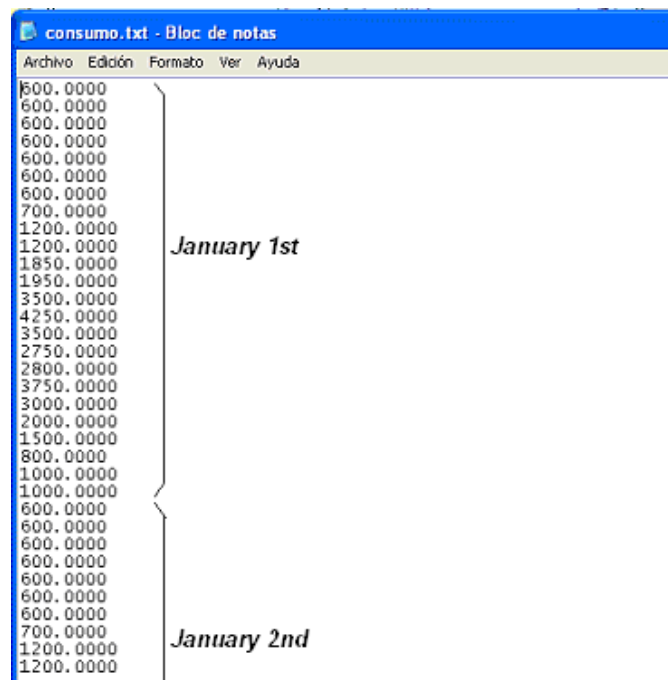
Lower time steps data:

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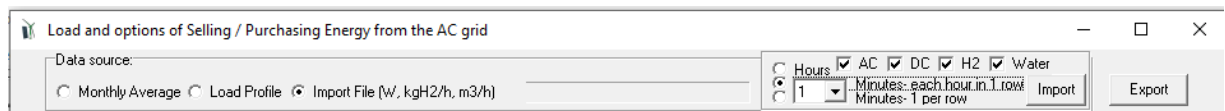
If we click in "Minutes –each hour in 1 row" we must have a file in which we have 8760 x M rows, where M is the number of types of data to import (AC, DC, H2 and/or Water), if all are selected, M =4 and therefore the file must have 35040 rows. Each row corresponds to 1 hour, and in each row there are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

In the example, when you click on "**Add load of**" iHOGA will add 100 W 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: Only in PRO+ version

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).

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 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.

- AC grid availability(Only in PRO+ version)**:**

On the right there is the button **AC GRID AVAILABILITY** .

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.

In EDU version the AC grid availavility is at every time (and it cannot be modified).

- Priority to supply E not covered by renewables (Only in PRO+ version):

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 ☐ Sto./Gen. priority if Pr.E >= [0] 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, when doing the simulation, if the AC grid is available, all the energy load that cannot be supplied (unmet load) by the renewable sources and by the storage, generator and fuel cell will be purchased from the AC grid. However, it must be taken into account that in the case of H2 loads, if the electrolyser nominal power is lower than the power required to supply the H2 load that could not be covered from the H2 tank, the difference cannot be obtained anywhere. In that case the energy not served will be higher than the one purchased to the AC grid. It may also happen that the unmet load during a time step is greater than the maximum power that can be purchased from the grid Pmax (kW), in that case it will not be possible to cover all the unmet load from the AC grid.

When you check the option, if in the main window the unmet load is defined as the energy not covered by the stand-alone system, a window will appear indicating the maximum unmet load

allowed (defined in "Constraints"), which will be the maximum energy that can be purchased from the AC grid.
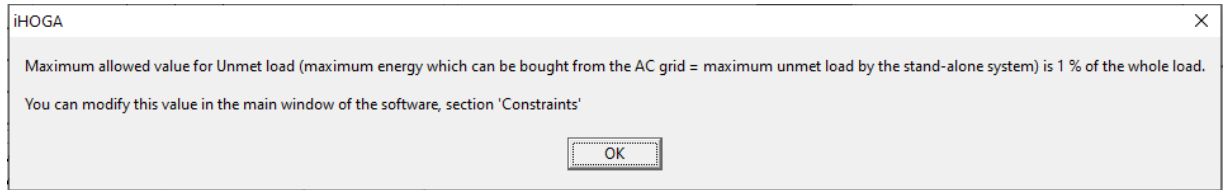
You can choose a fixed price for the cost of the energy purchased from the grid, not including the charges, which are indicated separately (for all hours of the year the same price by ticking the box "Fixed Buy Price (€/kWh)"):

Or set a price for each hour or by hourly periods (***Only in PRO+ version***), if the indicated checkbox is not checked, the button on the right ⬚ Hourly Price 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 ⬚ Hourly Price 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)**.**

HOURLY PRICE OF THE ELECTRICITY PURCHASED FROM THE AC GRID

Hourly Price Data (€/kWh)
- ● Hourly, all days the same
- ○ From file (8760 hourly values)   Import   🔺 Draw
- ○ Hourly Periods

Hourly price, all days the same:

0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h
0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

12-13h	13-14h	14-15h	15-16h	16-17h	17-18h	18-19h	19-20h	20-21h	21-22h	22-23h	23-24h
0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

OK

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 iHOGA 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

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.

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 "**Graph**" button and we can see the hourly price of the electricity.
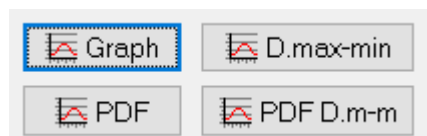
In the next figure we can see the hourly price for two weeks (14 days shown), during the weekend (two first days of the year) the period is P3 (valley) and during the weekdays several hours it is P1, other P2 and other P3.
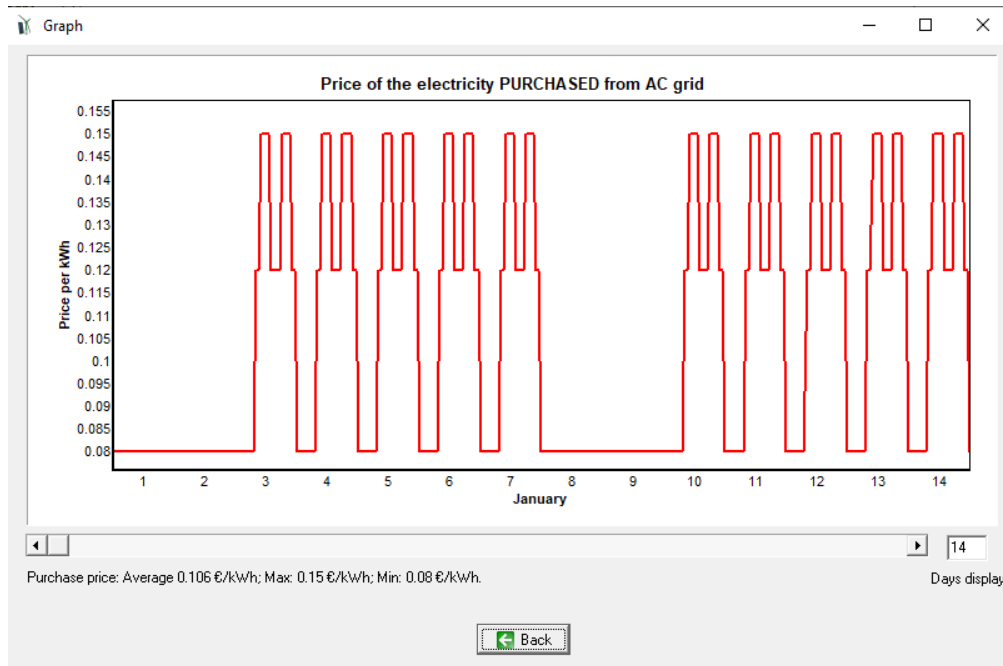
If the option "**From file (8760 hourly values)**" is selected, you must import the hourly price file (8760 columns, in monetary unit / kWh) by clicking the button "**Import hourly price**":

Once imported, the file name is shown.

With the button "**Graph**" it shows the hourly price during the year.
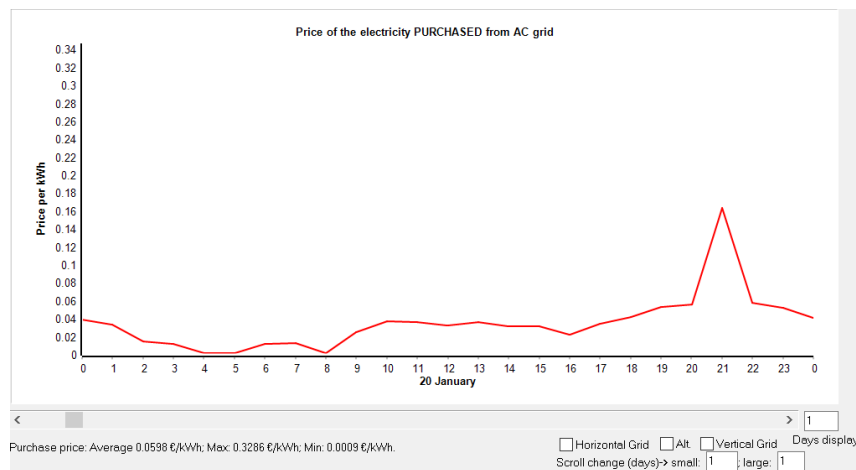
With the button "**PDF**" it shows the probability density function (PDF) of the price, showing also (below the graph) the mean and standard deviation (and, with these values, it shows in green the Gaussian curve). Next figure shows an example, where most of the time price is near

0, and also there is a lot of hours with price around 0.06 €/kWh; the Gaussian curve does not fit well in this case (that is, the original data does not follow a Gaussian normal PDF).
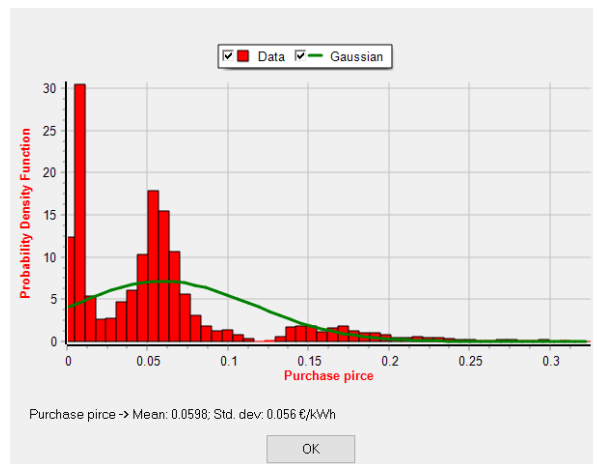
With the button "**D.max-min**" it shows, for each day, the difference between the maximum price and the minimum price of that day. This graph is interesting to see the daily price difference (max.-min.), important for arbitrage energy cases (for example, charging batteries at low price hours and discharging during hours at high price hours). Showing 365 days display, se can see many days, in this example of prices, the difference is higher than 0.2 €/kWh, which could make profitable (in some cases) the energy arbitrage:
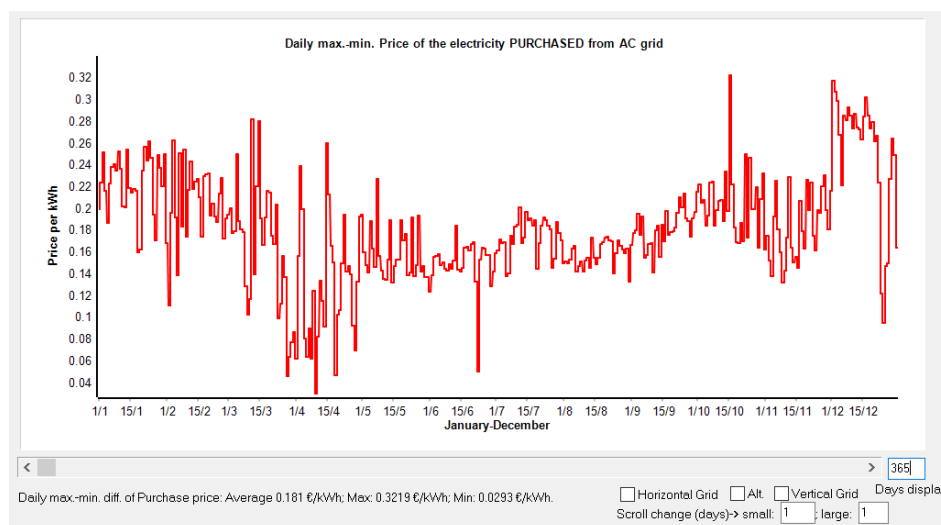
With the button "**PDF Dm-m**" it shows the probability density function (PDF) of the previous graph (values of difference between the maximum price and the minimum price of that day), showing also the mean and standard deviation (and, with these values, it shows in green the Gaussian curve). In next figure we can see that, in this case, the most of the values (difference between max. and min. price for each day) is around 0.18 €/kWh, and the PDF curve is not very different from a Gaussian PDF curve.

Purchase pirce: Daily max.-min. difference -> Mean: 0.181; Std. dev: 0.0485 €/kWh
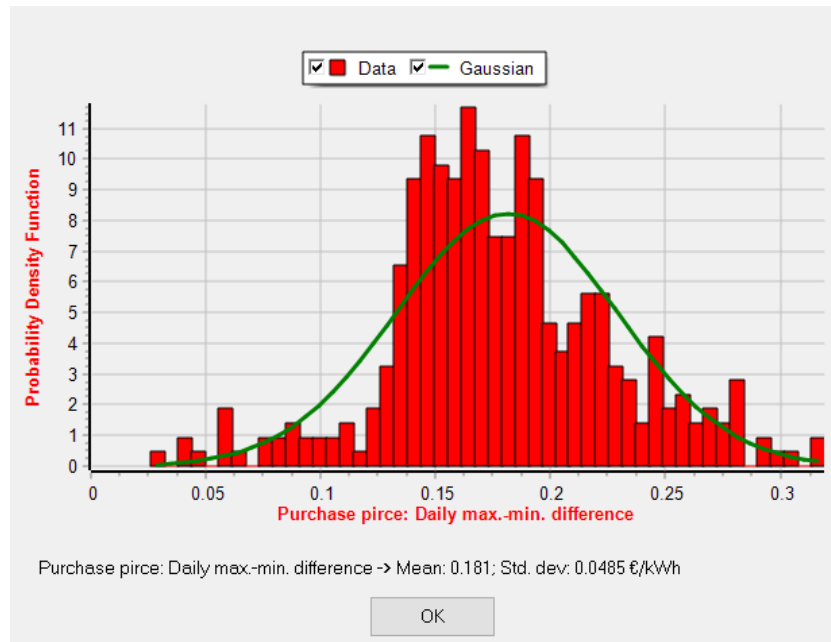
Finally, it is necessary to click on "OK" to save the changes of the hourly price.

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

Also it must be set the maximum contracted power Pmax (kW) 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 maximum grid power by periods or hourly for all the year.

- By periods: 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.

- Hourly: importing the hourly file (8760 rows) with the grid power limit (kW) for each hour of the year. We must also define the annual cost of power (€/yr for low power systems and k€/yr for high project systems).

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 before) 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.
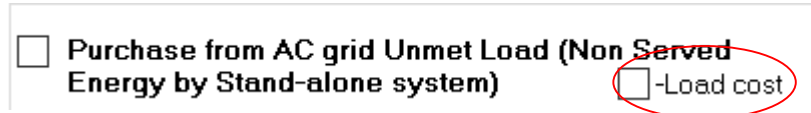
Back-up charge:

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 will be an income, and this income will be added (in negative value) to the back-up charge.

Substract the cost of supplying the load consumption by the AC grid (to compare with the system without generation):
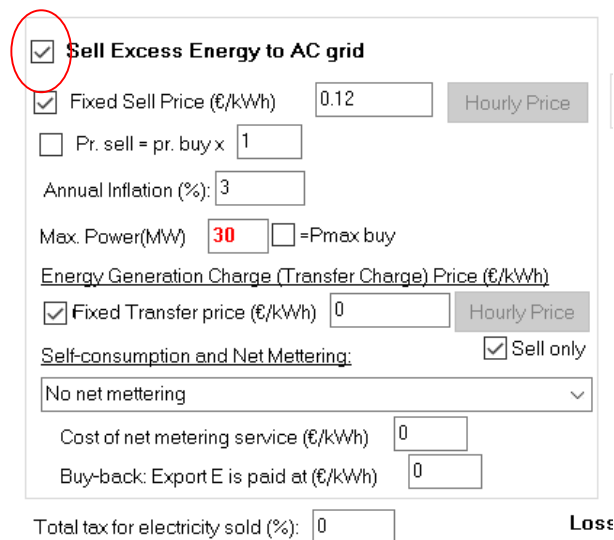
If you check the box "**-Load cost**" (upper right area of the purchase; be aware with this option!!!), the cost of supplying all the load consumption by the AC grid (buy price + access price) will be subtracted from the NPC. This way, you can see the extra cost of your system compared to the system without power generation. In this case, the cost of the availability of the AC grid power should be set to 0.

This option can be set even if the option of purchasing from AC grid is not selected.

- 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, the electrical energy that can not be used by the standalone system will be attempted to evacuate to the AC grid.

The excess energy (called "export energy") in DC is converted to the AC bus by means of the inverter, which introduces losses. Therefore if there is excess energy in the DC bus the energy that is sold to the grid will be less than the export energy. It must be taken into account that if the excess power in the DC bus is higher than the maximum power of the inverter, the difference cannot be converted to the AC bus and cannot be sold. In that case the energy sold may be much lower than the excess energy.

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".

> ☑ Fixed Sell Price (€/kWh)   0.12   Hourly Price
> ☐ Pr. sell = pr. buy x 1

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

Power Purchase Agreement (PPA) specific price can be considered for the PV generation injected to the grid (checking the box "PPA PV"). Also PPA for the Wind turbines generation injected to the grid (checking the box "PPA WT").

> ☐ PPA PV:
> ☐ PPA WT:

Use the first option if you want to consider a special PPA price for the PV generation injected to the grid. In this case, it will be supposed that the electricity injected to the grid minus the PV generation will be valued at the normal sell price, and the PV generation will be valued at the PPA price. It is not valid for net metering or net billing. It will be considered in the economical results (NPC / NPV, LCOE, etc.), but IT WON'T BE SHOWN IN THE EXCEL OF THE SIMULATION RESULTS (there you will see all the injected energy at the same sell price).

Use the second option if you want to consider a special PPA price for the wind generation injected to the grid.

If both PPA for PV and for Wind are selected, during the time steps when total generation is higher than maximum grid power allowed, priority for energy injection will be for PV.

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 (kW)", by default the same as the maximum Power limited for the purchase (checked the "=Pmax buy" checkbox).

> Max. Power(kW)   100 ☑ =Pmax buy   ☐ -Ppv ☐ -Pwt

In grid connected systems, there is the option to evaluate the performance of a new power generating system to be added to a previous existing one. For example, if you have a grid-connected PV generator and want to consider to add some wind turbines, you can select "-Ppv": during each time step, the maximum power limit that can be injected to the grid will be reduced by the existing PV generation, this way we can evaluate the energy that will be injected to the grid by the new power generating system; the existing PV generating won't be considered (its power won't be used by the system neither injected to the grid).

In the same way, if you have an existing grid-connected wind farm and you want to consider adding another generating sources, you should select "-Pwt".

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. Only in PRO+ version

As default, No Net Metering is selected. However, you can choose up to 4 cases of Net Metering (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 metering: 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 metering: 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.*
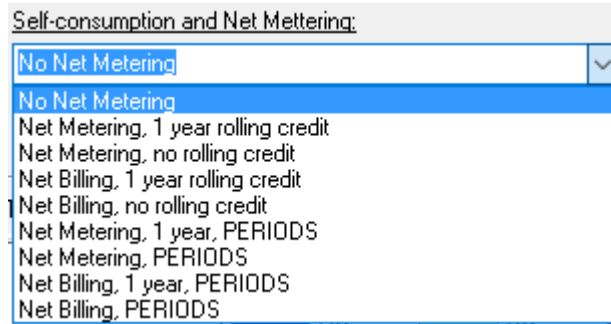
The "**Cost of net metering service**", is the price of the energy involved in the net metering (€/kWh) and must be placed in the following box:

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:
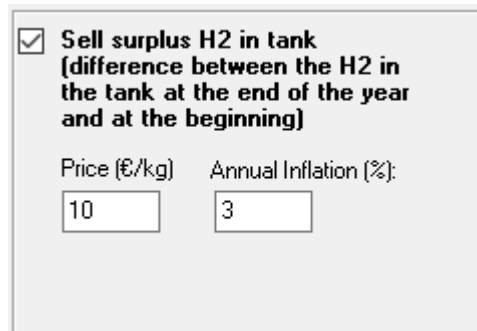
Taxes:

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.
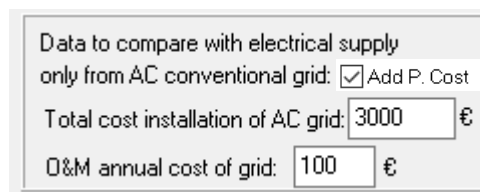
- **Data to Compare with AC grid supply only (NPC minimization projects)**:

These data are taken into account to compare with the hypothetical case in all the energy was purchased from the AC grid (i.e., the installation has only load, no generation and no storage, AC only system). The hypothetical initial total cost of the AC mains installation, as well as the annual maintenance cost, must be indicated. It should be borne in mind that these costs have nothing to do with the studied system itself, only serve to compare with a case in which a generation system was not acquired, but the only thing that was done was to connect to the AC grid and consume all the load from the AC grid. The cost of the purchase of the electricity to the AC grid will be the energy load multiplied by the electricity purchase cost, including the access charge. If the checkbox "**Add P. Cost**" is checked (as by default), the cost of the power contracted will also be added to the cost of the AC only system. With this data, iHOGA calculates the total cost (NPC) and the levelized cost of energy for that hypothetical case, and shows it in the REPORT to compare with our cases. It also calculates the payback period of our system and the IRR compared to the system of supply only from AC grid, and it is shown in the

REPORT and in the cash flow Excel file. In the cash flow Excel file you can also see its broken down costs.

- Losses in wire and transformer:

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

Losses in wire and transf. (%): 0 ☐ Buy ☐ Export ☐ Back-up

If the option "Buy" is selected, the energy bought to the grid will be incremented in the same percentage. If the option "Export" is selected, the export energy (excess energy that cannot be used by the system) will be reduced in the same percentage. If the option "Back-up" is selected, the back-up energy (self-consumed energy to which is applied the "back-up charge") will be reduced in the same percentage.

Button "Graph in steps of":

In the LOAD / AC GRID window, at the bottom left there is the button
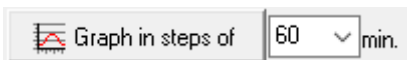
Graph in steps of 60 ∨ min. , with which, once the loads of the year are generated (or imported), a screen with the annual load chart appears in Watts, dark blue AC, green DC, H2 red and light blue WATER . It can be displayed in steps of between 1 and 60 minutes. With respect to the consumption of H2 (kg/h) although the data entered are in kg of H2, to be able to represent it together with the electrical consumptions, it is converted to energy (Wh) by multiplying by the Higher Heating Value of H2 (HHV), roughly 39,000 Wh/kg and then divided by the time step in hours it its converted to power in W. In water consumption (m3/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), default 1 day. You can see the horizontal grid by clicking on the "Horizontal grid" checkbox. Horizontal axis labels can be seen in alternate positions by clicking on "Alt" checkbox (if you have select less than 60 min. for the graph, you will see the hours and the half hours). Vertical grid is shown by clicking on "Vertical grid" checkbox. Scroll change in days can be set for small changes (changes in the screen when you click in the arrow of the scroll) and for large changes (changes in the screen when you move the scroll cursor or when you click in the scroll bar).
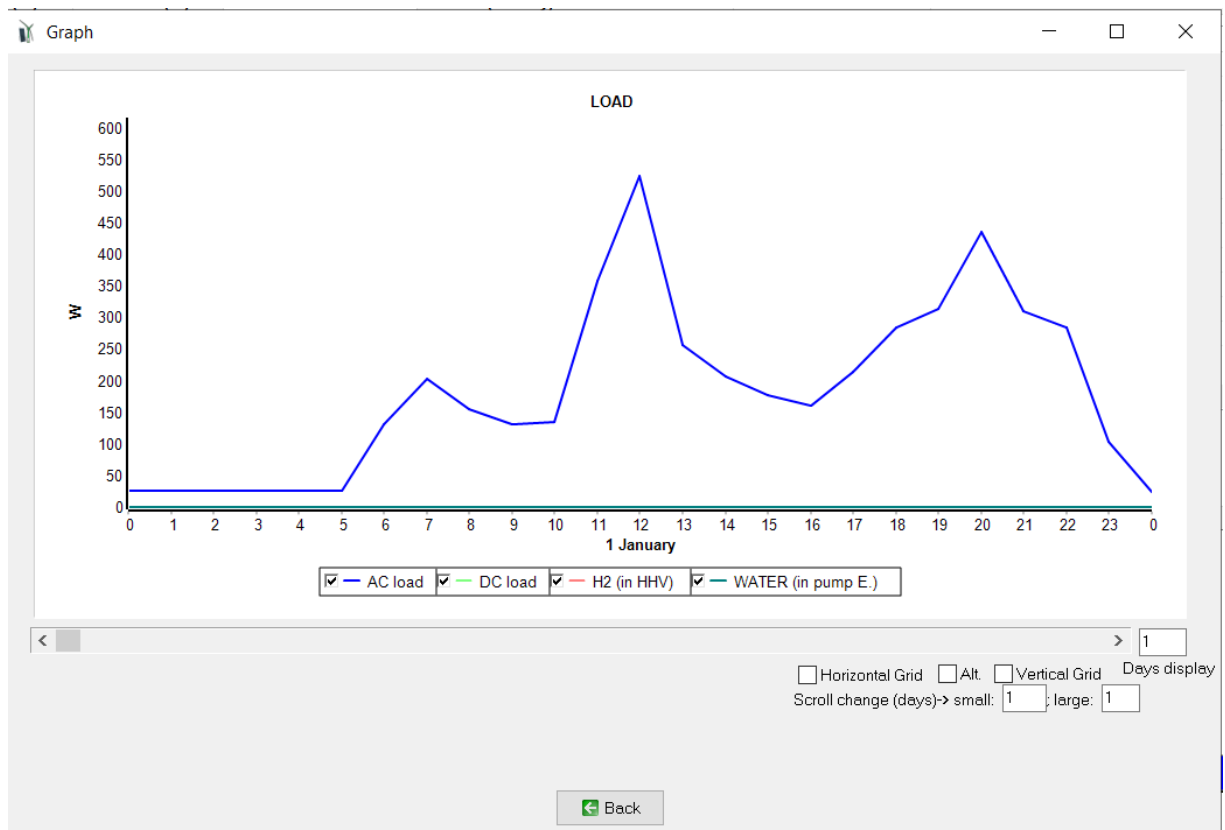
You can zoom in the graph (draw a window with your mouse over the area to be enlarged: click from top left to bottom right).
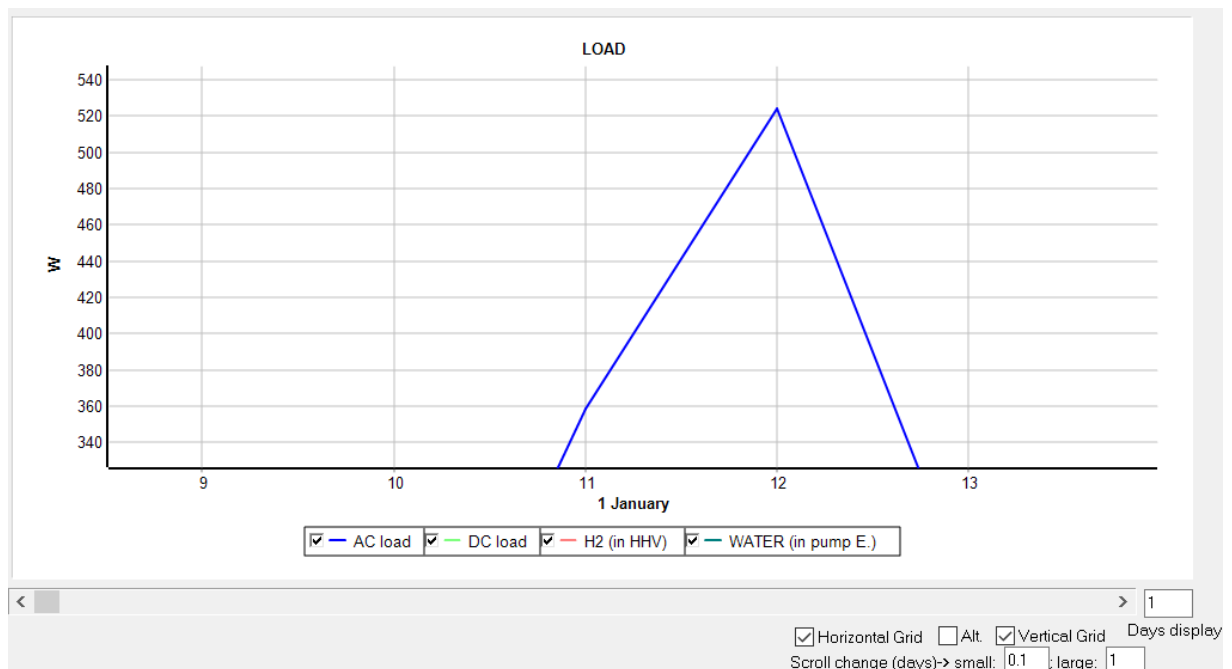
To undo the zoom window, click and drag from bottom right to top left.

By clicking the right button on the graph shows a menu where you can select "Copy" (to the clipboard) or "Save Picture".

You can also export the time values generated (or imported) by pressing the "Export" button (up right).
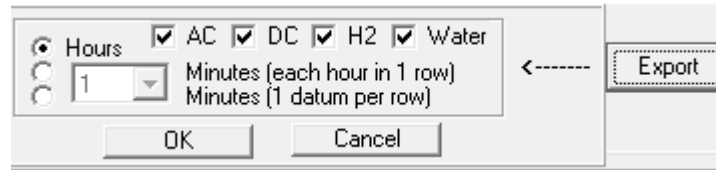
A small window appears where you have to indicate the format of the data to be exported:

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".

AC LOAD (W)		DC LOAD (W)		H2 LOAD (kg/h)		WATER (m3/day) FROM WATER TANK (PREVIOUSLY PUMPED)							PURCHASE / SELL E			
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	2			176	132	110	110	308	308	220	176	15
OCTOBER	22	22	22	22	2	Save Table		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.
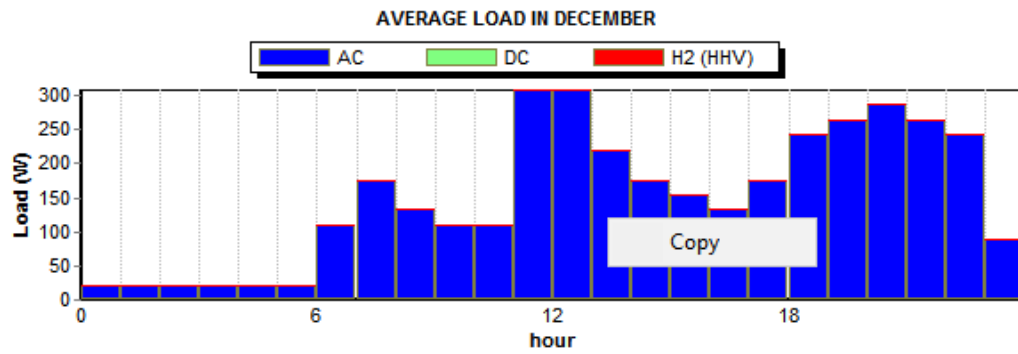
Once we have defined the consumptions, click on the "OK" button and we return to the main screen.

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 PV modules / generators (also bifacial PV or CPV can be defined).

In the upper left zone, you must define **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.

PRO+ version 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 iHOGA.

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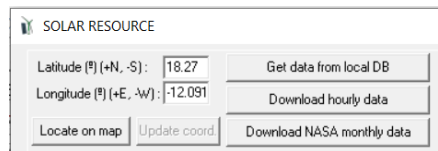
The next time you try to locate on a map, you will be prompted to enter the credential.

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 iHOGA 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.

iHOGA 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 Only in PRO+ version:
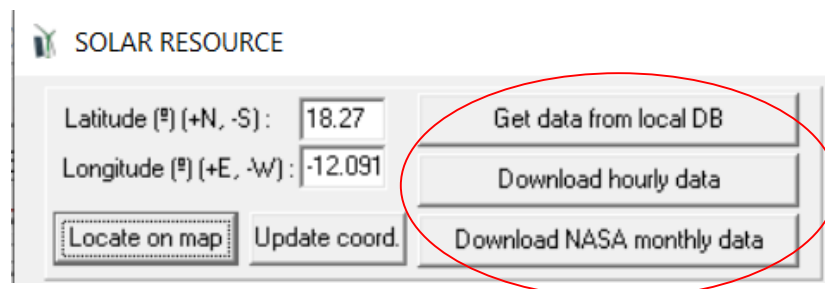
-PVGIS (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html)

-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** Only in PRO+ version

-    **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 photovoltaic modules 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 iHOGA 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 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 iHOGA (you must have previously installed the database by downloading from iHOGA web and executing the self-extracting .rar file "RESOURCES-ENG.exe", installing into the iHOGA installation folder, subfolder "RESOURCES". Available in:

https://www.dropbox.com/s/p3sd0t3ru19lros/RESOURCES-EDU-eng.exe?e=1&dl=0.

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 <mark>Only in PRO+ version</mark>

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 modules 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 ($G_{\text{hours}(t)}$ and $D_{\text{hours}(t)}$) 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:

$$\gamma_{(t)} = \phi_{1G}\,\gamma_{(t-\Delta t)} + N\left(0, \sigma_G\sqrt{1 - \phi_{1G}{}^2}\right) \tag{1}$$
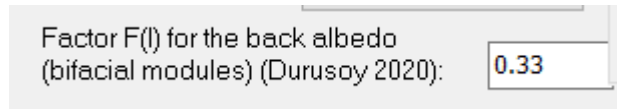
$$G_{(t)} = \max\left(D_{\text{hours}(t)},\, G_{\text{hours}(t)}\left(1 + \gamma_{(t)}\right)\right) \tag{2}$$

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.

The

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

iHOGA 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.

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**". *Only in PRO+ version*

Note that it can only work if you have the following data:

- Monthly average data
- Montly data downloaded from NASA
- 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). 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**".
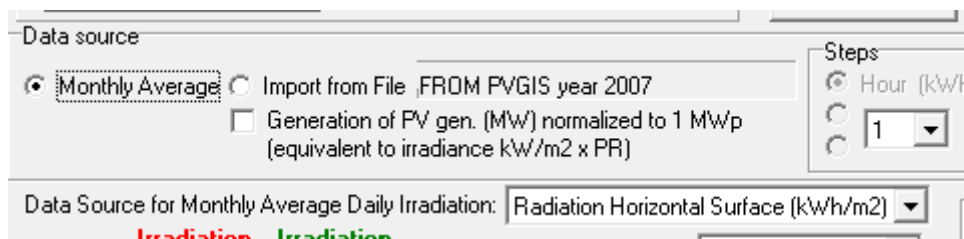
- Data imported from file, only if #1 PV panels slope is 0º and 100% Same procedure as with the web downloaded data shown above.

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

Optimal slope for PV panels   — ☐ ✕

Average daily irradiation for each month and for the whole year. Slope: 0, 15, 30, 45, 60, 75, 90º and optimal

Azimuth (0º) is optimal for northern latitudes

	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

Month of lowest irradiation over horizontal surface is DECEMBER

Optimal slope to maximize the irradiation in DECEMBER (fixed PV modules) is 56 º

Optimal slope taking into account the ratio 'load/irradiation' over tilted surface (fixed PV modules) is 50 º

Month of worst ratio 'load/irradiation' for that optimal slope of 50º is DECEMBER with equivalent DC load of 4.39 kWh/day and irradiation over tilted surface 50º is 5.51 kWh/m2/day

⬅ Back

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 iHOGA 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.

iHOGA 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 modules will be a variable to be optimized, like the number of modules, panel type, etc. *Only in PRO+ version*

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).

☐ Optimize PV#1 panels slope during the optimization of the system

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.

Variability minutes: correlation factor: 0 ; std. dev.: 0

Also, do not use the Graham method for the calculation of hourly irradiation (because this method introduces random variability).
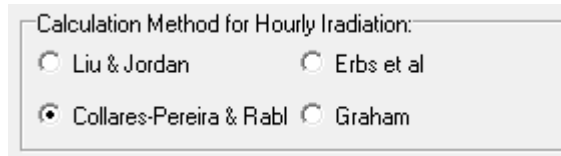
This way, when you open a project where the PV slope optimization has done, the results will not change, as the irradiation obtained for the different slopes (which will be calculated again when the project opens will be the same.

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). You mustn't click **"Calculate"** button after that.

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

iHOGA 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, iHOGA 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 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/m²). In that case, modify the hours of advance of the official time with respect to the solar until coherent results appear.
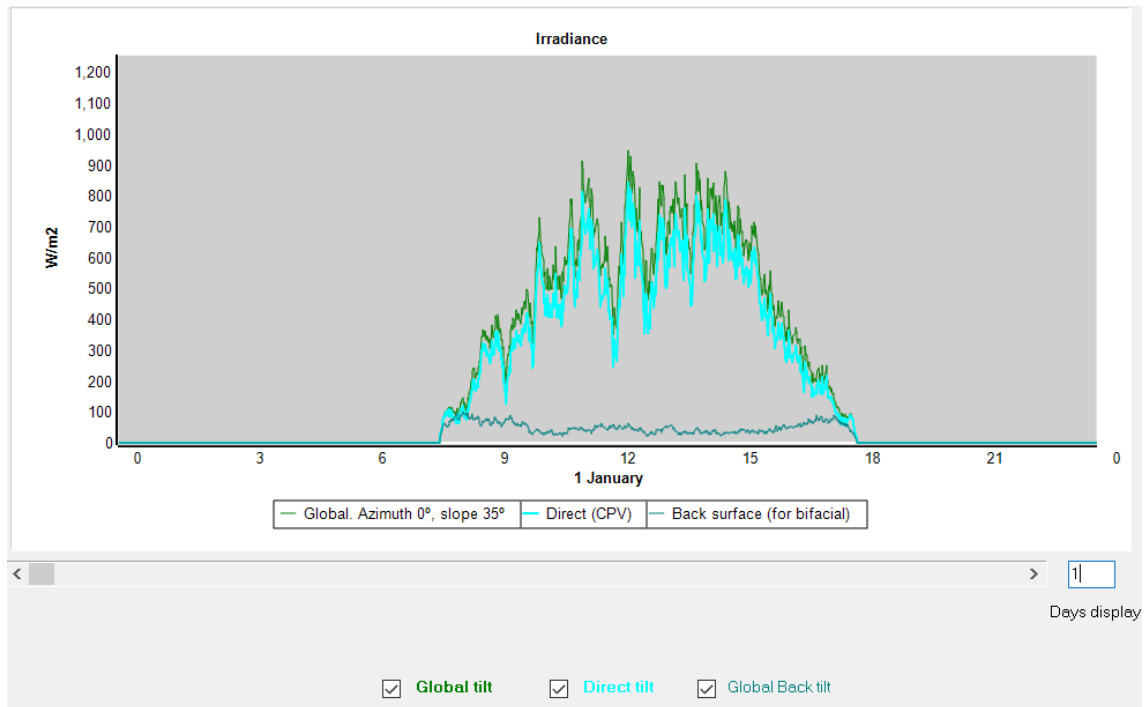
3.3.14. Import hourly irradiation over the back surface or direct irradiation (tilt surface)

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 iHOGA calculated, using the buttons "**Export G. tilted**" or "**Export G. horiz**".
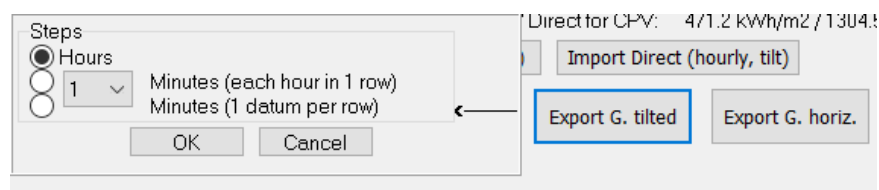
The first one exports the global irradiation on the tilted surface of the modules, in the form of hourly values or in different time steps values (default 1 minute time step), in the number columns of time steps of 1 hour in each row or 1 datum per row. The second exports the hourly values of irradiation 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 iHOGA to calculate the generation of the PV modules.

Scale factor (x by) 1

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 Weibul form parameter) using the button "**Download NASA monthy 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:
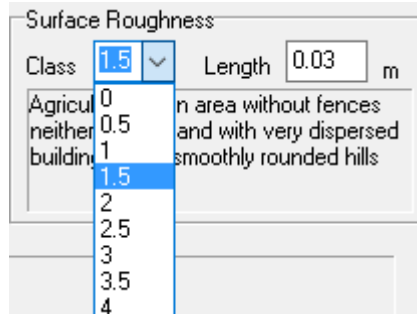
When downloading from the NASA (button "**Download NASA Monthly data**"), you can select only wind speed or other parameters, as shown in the irradiation section before. Wind speed Weibull shape factor is necessary to the accurate calculation of hourly wind speed (only available from local database), 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.
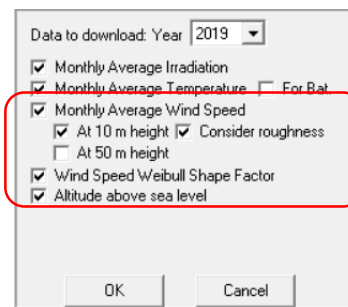
Monthly average wind speed can be downloaded at 10 m height (considering or not roughness for the download data) or at 50 m height. After downloading NASA average wind speed, the value of the anemometer height is updated to 10 or 50 m, depending on the downloaded data.
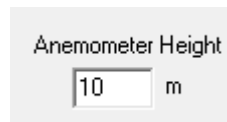
You can also download hourly data from Renewable Ninja (at any height) of from PVGIS (data only for 10 m height) or from NASA (only at 10 or 50 m height), clicking in the button "**Download hourly data**". *Before downloading the data from Renewables Ninja, you must indicate the anemometer height*.

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:
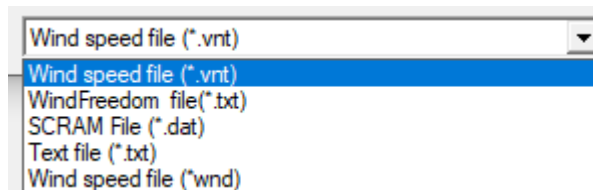
- Files * .vnt: These files are text files generated by the software, the height of the measurement is stored in the first row and in the rest is the sequence of wind speed hour values.

- Files obtained through Windfreedom software, * .txt files *Only in PRO+ version*: 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 iHOGA.

- *.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.

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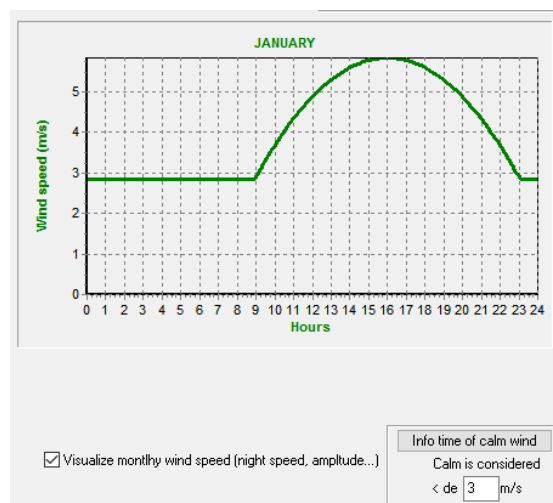
A description is provided below for the parameters mentioned above (Rivas-Ascaso, 2004).

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.
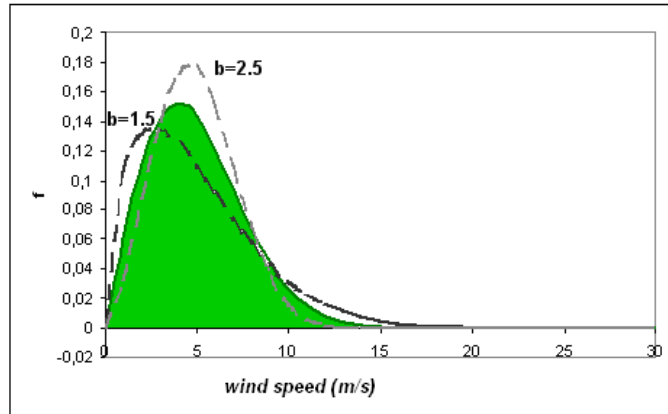
Autocorrelation Factor

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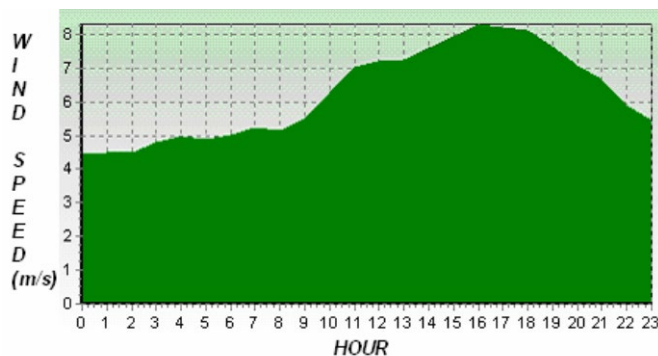
The curve may be modelled according to the time at which maximum speed is recorded, so that wind speeds may be higher at night or in the morning.

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.
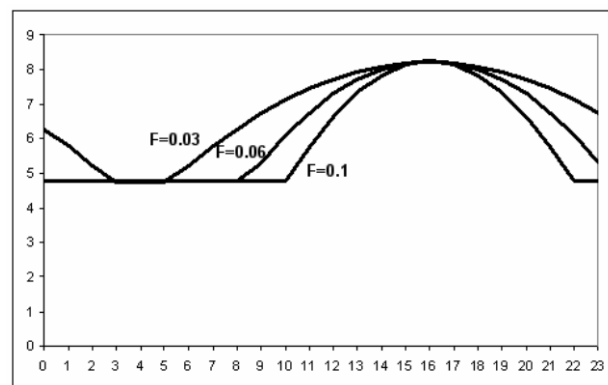
"Export" button:

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.
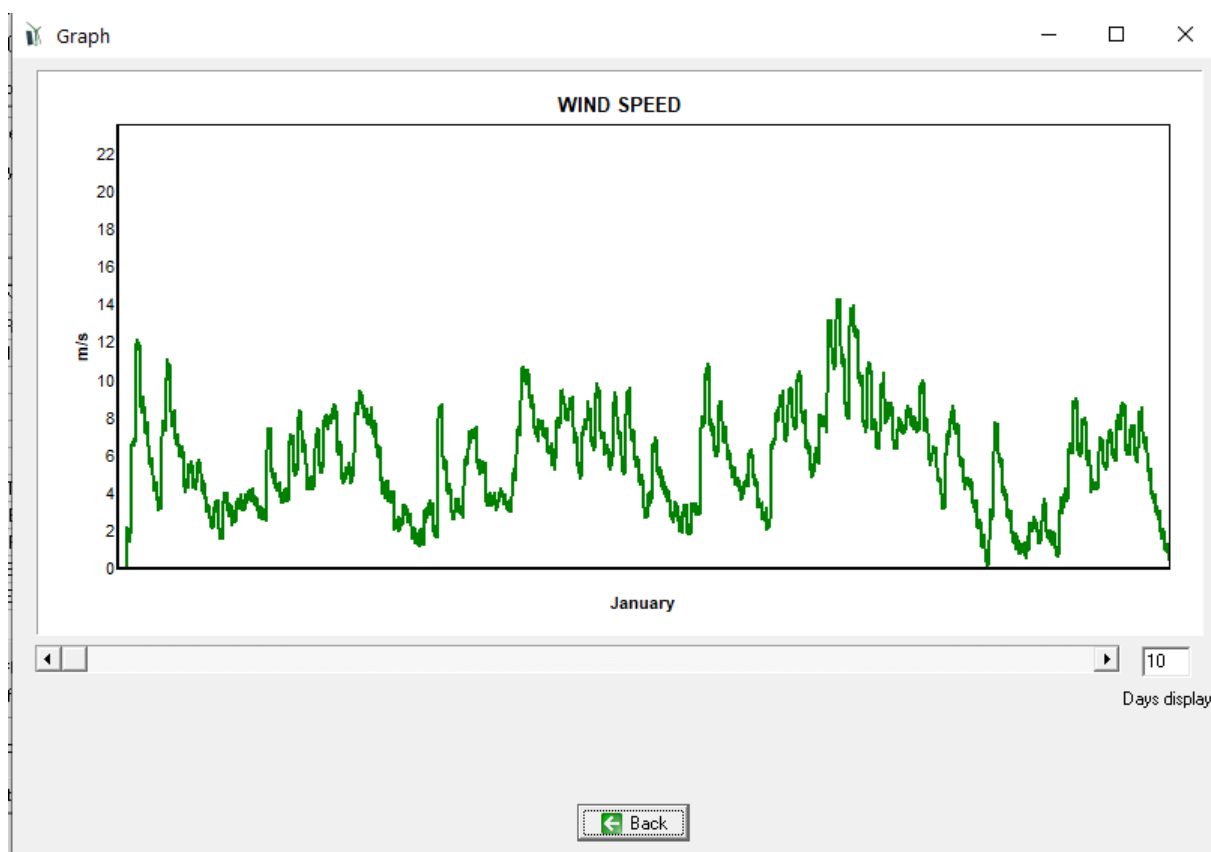
Info time of calm wind:

Click "**Info time of calm wind**" to see the information about calmness (low wind speed periods) for each month.
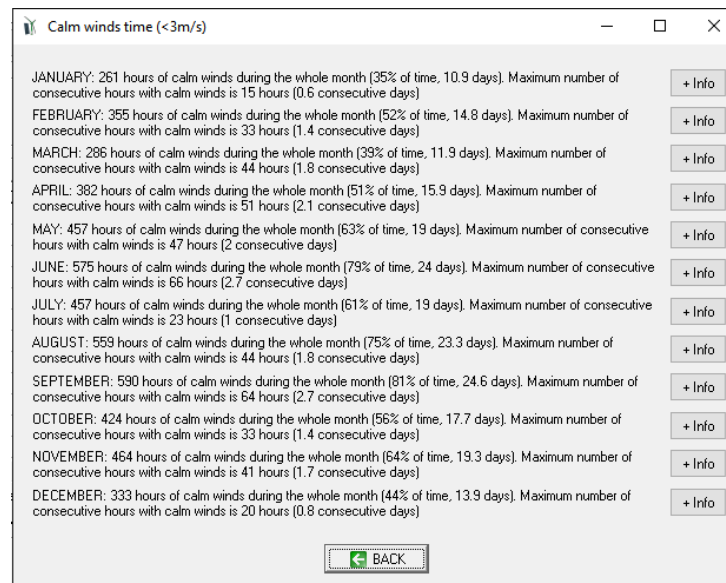
More info can be seen clicking the button "+Info" for each month.

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

3.5 Hydraulic resource <mark>*Only in PRO+ version*</mark>

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.

iHOGA 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 l/s in low power projects, in m^3/s in high power projects), 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} (kW) = 9.81 · H'' (m) · Q_{max} (l/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 iHOGA.

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

3.6 TEG temperatures <mark>*Only in PRO+ version*</mark>

If the system includes thermoelectric generator (TEG), the temperatures of the hot source (from the combustion exhaust gas) and of the cold source (where the cold side of the TEG is connected) are needed.

We suppose that the energy supply for the TEG (that is, the hot source temperature) is free of charge (no cost related to the hot source), as it is the residual exhaust gas of the combustion that was used for heating or cooking (example in next figure, where TEG is included in a multi-function heating+cooking stove)
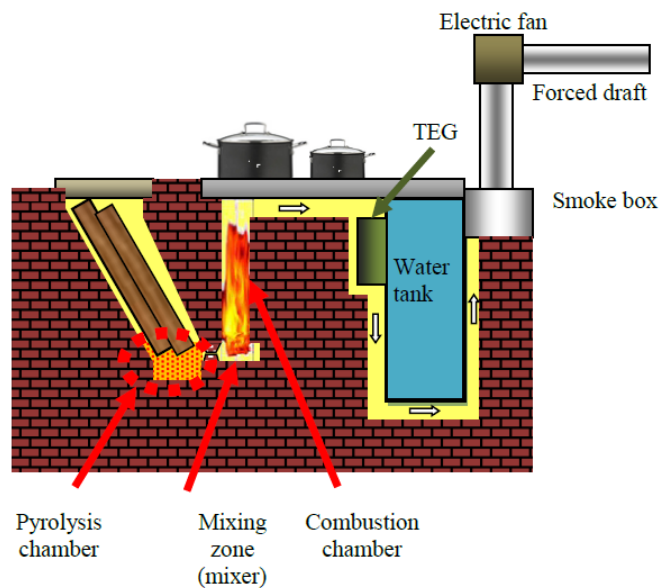
The TEG is composed by several thermoelectric modules (TEM) that can be connected electrically in serial or parallel.

For each time step (1 hour or less) of the year, it must be known the data of the temperature of the two sources: hot source $T_{cold\_s(t)}$ and cold source $T_{cold\_s(t)}$.
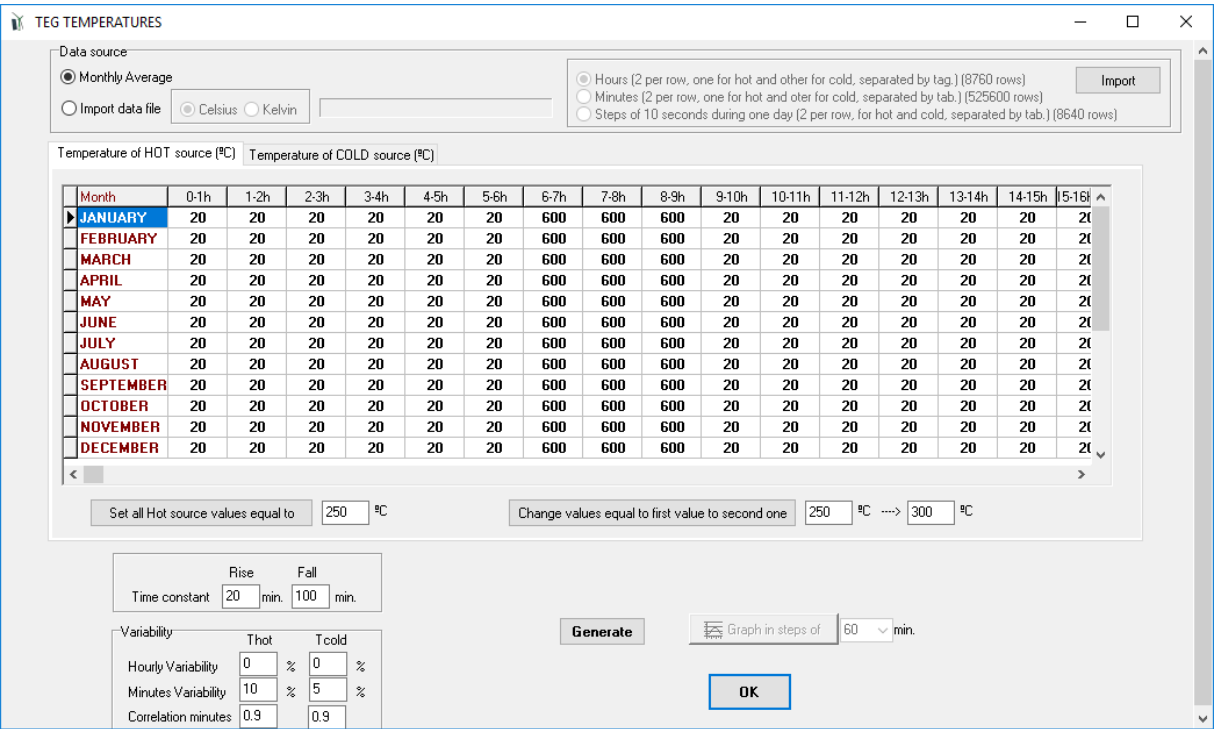
Data source of the temperature can be from Monthly Average values (hourly values for each day, all the days of the months the same, in ºC) or it can be imported (in different formats, in ºC or in K).
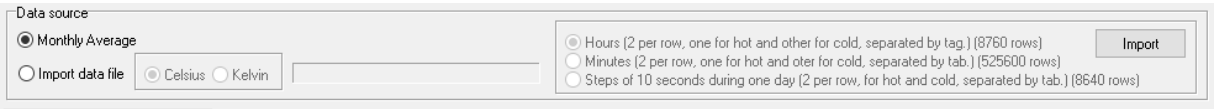
If we use the monthly average values, the table must be filled (there is a tab for HOT and another one for COLD temperature). After changing the value of january for a specific hour, if you click in an adyacent row (righ or left), all the column is changed.

You can set all values of the hot temperature to a specific value:
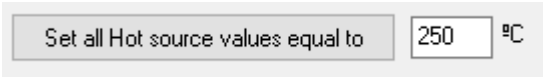
You can also change all the fields equal to a specific value by another value:
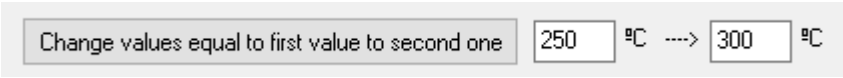
Time constant for the rise of the temperature and for the fall (in minutes) must be set, so that when the temperature in steps of 1 minute is generated they are considered.
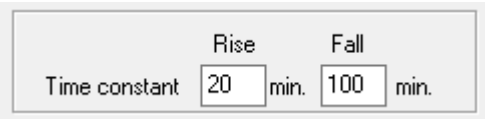
Variability for hours and minutes must be set. Also the correlation for the calculation of the values in steps of one minute.

Variability	Thot		Tcold	
Hourly Variability	0	%	0	%
Minutes Variability	10	%	5	%
Correlation minutes	0.9		0.9	

Then we can click the button "**Generate**" to obtain the hot and cold source temeprature values of the whole year.

By clicking in the button "**Graphs in step of**"… we obtain the plot of the temperatures (in the example in steps of 1 minute), in Kelvin (K).
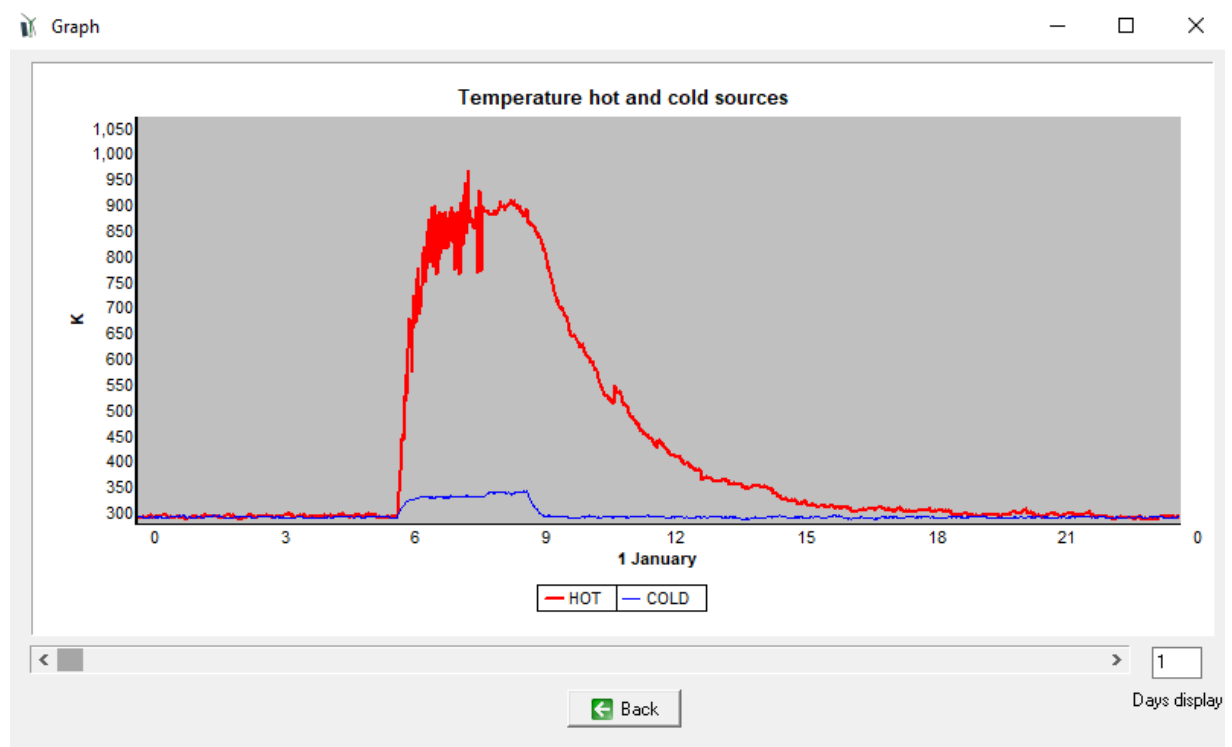
3.7 Data bases

iHOGA 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.

Access to databases:

At the top of the main screen you can access the menu "**Data Base**".
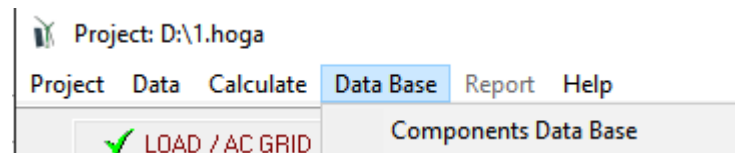
Then, clicking on "**Components Data Base**" iHOGA shows the database of the components. The commercial components are in tables, each type in a tab.
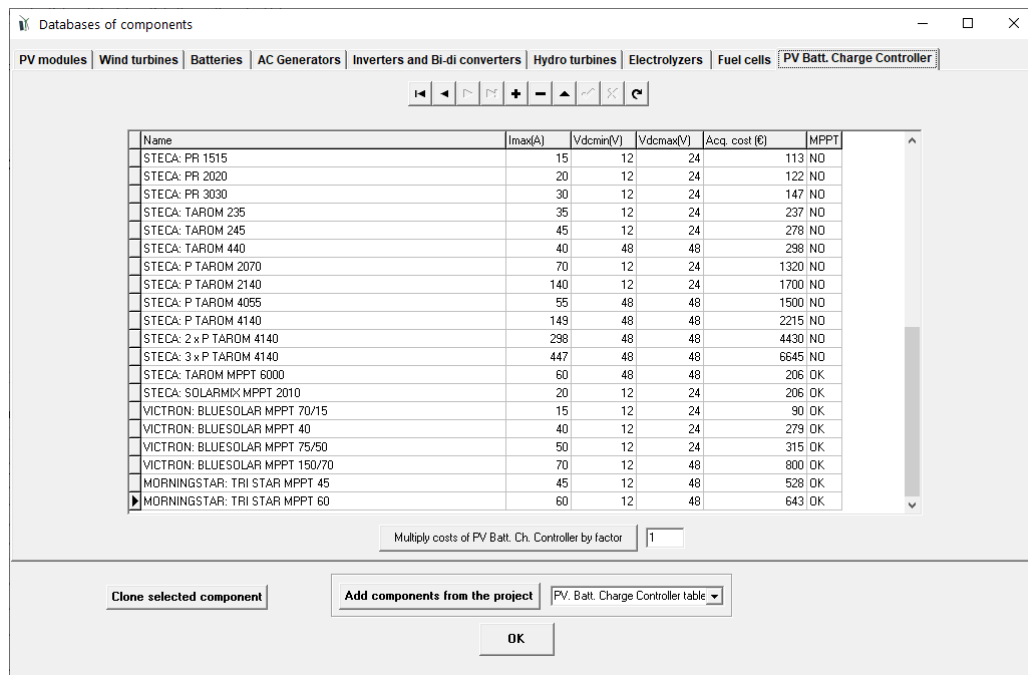
Component "Zero":

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 modules", "Wind Turbines" and "Batteries" should be arranged by families, because, in this way, then you can import entire families when you define the components used in the optimization. For iHOGA 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. For example, the modules "SiM12-Atersa: A10J" and "SiM12-Atersa: A20J" are two modules of the same family "SiM12-Atersa ".

SiM12-Atersa: A10J	12	0,68	10	64
SiM12-Atersa: A20J	12	1,32	20	109
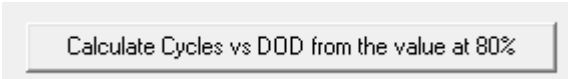
Multiply the costs:

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"

Multiply costs of PV Panels and O&M by factor	1

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".

3.8 Photovoltaic modules

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

The software allows the user to modify, eliminate, or add PV modules to be considered in the optimization.

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

PV modules data:

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

- Name

- The nominal voltage, Vn (V). Typically, the modules used in stand-alone systems are composed of 36 photovoltaic cells in series, giving an open circuit voltage of about 21 or 22 V and a maximum power voltage of the order of 17 V. These modules have a nominal voltage of 12 V.

Although many manufacturers supply the value of the nominal DC voltage, it can be calculated as the nearest 12 V multiple below the maximum power voltage, leaving a certain margin. For example, if the maximum power voltage is 34 V, the nominal voltage will be 24 V, the nearest multiple of 12 below. However, if the maximum power voltage is 36.5 V, the nominal voltage will not be 36 V, but 24 V, as there must be some voltage difference for the modules to charge the batteries without problems.

The nominal voltage can also be obtained as a function of the open circuit voltage:

- o Open circuit voltage is between 20 and 40 V -> Vnominal = 12 V

- o Open circuit voltage is between 40 and 60 V -> Vnominal = 24 V

- The short-circuit current, Isc (A)

- Peak nominal power under standard test conditions (STC) Pn (Wp)

- The acquisition cost (€), where the proportional cost of the mounting structure where they are mounted must be included.

- The unit cost of operation and maintenance (O&M) (cost per module of the photovoltaic generator, apart from the fixed cost for the whole set of modules of the generator, in €/year)

- Expected life (usually 25 years)

- NOCT (normal operating temperature of the cell, in °C). It is only necessary if we want to consider the effect of temperature.

- Coefficient of variation of the power with the temperature, Ct (%/°C). Necessary if we want to consider the effect of temperature in the power.

- BIFACIALITY (0-1) *Only in PRO+ version*: 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 short-circuit current Isc (A) and the peak nominal power under STC Pn (Wp) set in the table must be the values for the front surface.

- CPV *Only in PRO+ version*: if the PV 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 module 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.

- Weight (kg).

The nominal voltage must be chosen from a drop-down menu that appears when clicking on the box. Any value can also be written directly.

Navigation toolbar:

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.
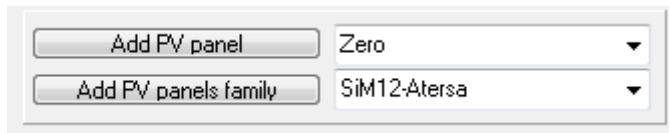
When the user edits a cell, the components shown in the image below are enabled:
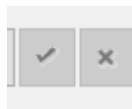
Clicking on the first symbol validates all changes to the cell, whereas clicking on the second one cancels all changes. When nothing is selected, any changes to the cell will be automatically validated.
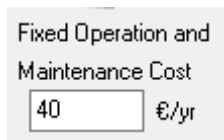
Add PV modules from database:

Modules can be added from the database: individually or a whole family of modules, by selecting the panel from the drop-down menu and clicking the button "Add PV panel" or by selecting the family and adding it by clicking 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 modules used for the photovoltaic generator. Fixed operator cost and costs for maintenance material are included, regardless of the size of the generator.
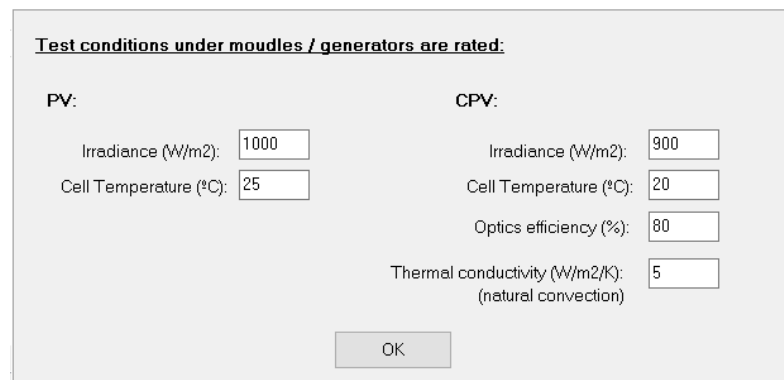
The total cost for operation and maintenance of the PV generator will be the fixed costs plus the individual cost of PV modules multiplied by the number of modules in the PV generator.

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 irradiance and short-circuit current (if there is no maximum MPPT tracking) or peak power (if MPPT exists). 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.

Efficiency due to degradation of the modules, losses in wires, dirt in panels, etc. `0.8`

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. Therefore this factor should be much higher than 0.8 in that case.

Maximum Power Point Tracking (MPPT): *Only in PRO+ version*

The user must define whether the inverter or the battery charge controller will include MPPT or not.

☐ PV inverter or battery charge regulator includes Maximum Power Point Tracking (MPPT)

Output power:

If the MPPT box is not selected:

If the box corresponding to MPPT is not selected, the voltage set by the batteries (DC bus voltage) is considered, so that the voltage on the photovoltaic generator will be the nominal of the system (V_{busDC}), that is, that of a module multiplied by the number of modules in series. Therefore the number of serial modules required is:

$$Nmodules\_serial= V_{busDC}/Vn\_panel$$

Where *Vn_panel* is the nominal voltage of the PV module (typically 12 or 24 V).

In this case the current that a photovoltaic panel generates is calculated as follows (see figure below, left graph, obtained from (Rodolfo Dufo-López et al., 2014)):

$$I_{PV}(t) = I_{SC} \cdot \frac{G(t)}{1 \text{ kW/m}^2}$$

Where *G(t)* is the irradiance over the tilted Surface of the PV modules, in kW/m^2 and *Isc* (A) is the shortcut current of the PV module.

The power produced by the PV generator (composed by *Nmodules_serial* *Nmodules_parallel*) during time *t* is, taking into account the reduction introduced by the efficiency defined previously (*Eff*):

*P(t)=Isc*G(t)*Vn_panel* Nmodules_serial* Nmodules_parallel*Eff*
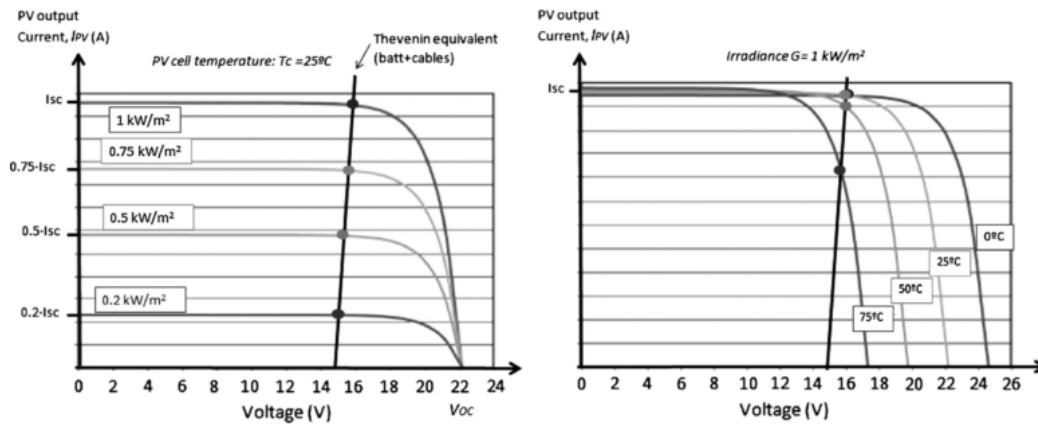
Fig. 2. Intersection of the *I* = *f*(*V*) curve of the PV generator and Thévenin equivalent that it sees when the battery is fully charged. *Left:* Curves for a constant PV cell temperature (*T_c* = 25 °C) and irradiance *G* variable. *Right:* Curves for a constant *G* = 1 kW/m^2 and *T_c* variable.

In this case the power depends little on the ambient temperature (except for extreme temperature values, see figure above, right graph, obtained from (Rodolfo Dufo-López et al., 2014):).

If the MPPT box is selected: <mark>*MPPT only in PRO+ version*</mark>

In this case the inverter or the charge controller of the batteries has MPPT, so at each instant the PV modules 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*Nmodules_serial*Nmodules_parallel*Eff*

Where Pn is the nominal power (peak power, Wp) of the PV panel and *Gref* (kW/m^2) is the global irradiance under 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*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).

In the case of concentrating PV (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.

A small screen appears to be able to consider the effect of the temperature, since in this case the PV generation is modified according to the ambient temperature.

Calculation of number of modules in series taking into account the maximum power voltage instead of the nominal voltage of the PV modules:

In small PV systems with storage (batteries), the number of modules required is calculated according *VbusDC/Vn_panel*, where *VbusDC* is the rated voltage DC (fixed by batteries) and *Vn_panel* is the PV module rated voltage (typically 12 or 24 V).

In systems with high power which include DC/DC conversion and MPPT (grid-connected systems...) normally the number of PV modules in series is calculated as *VbusDC/Vmax_p_panel*, where *Vmax_p_panel* is the voltage of maximum power of the PV panel. In this case, you must check the "Calculate the number of modules in serial as:..." shown in the figure below, and indicate the value of *Vmax_p_panel / Vn_panel* so that iHOGA will know the value of *Vmax_p_panel* from *Vn_panel*. Normally, for PV modules rated voltage 12 V, the voltage of maximum power is about 17 or 18 V. For example, if it is 17.7 V, the ratio will be 17.7 / 12 = 1.475, this would be the value that must be introduced.

Efect of ambient temperature:

The effect of ambient temperature Tamb (°C) can be taken into account by checking the box "Consider effect of Temperature" and entering monthly average data or by importing data from file (8760 values), including files generated with Windfreedom software. Data can be downloaded 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).
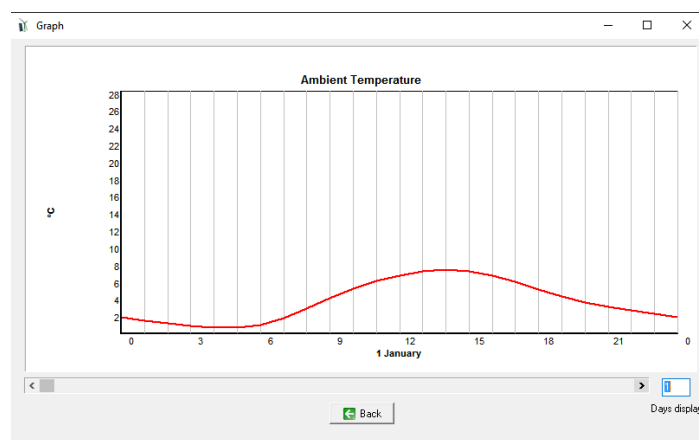
By clicking the button "Wind for CPV" a small window appears where we can set the wind speed at the height of the CPV which will be used to calculate the CPV cell temperature. Monthly average values or hourly values from file can be used:

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 (%/°C) 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:

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

<u>CPV generator:</u>

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 (%/°C) and *Tc_ref* the cell temperature of the conditions the CPV were tested.

PV generator connected to AC bus: *Only in PRO+ version*

You can define that the PV generator is connected to the AC bus (by means of its own grid inverter) by checking the chekbox:

☑ PV generator is connected to AC bus (it has its own inverter) --> Number of PV panels in serial: 4 | PV inverter data

The number of serial modules in this case must be defined here, it does not have to be the same as if the PV generator was connected to the DC bus.

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 instead of defining a photovoltaic generator we define individual modules, the proportional cost of the inverter must be included in the cost of the panel.

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.

<u>PV modules price inflation:</u>

Prices for PV modules 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 modules, including an upper limit for those. iHOGA will then use this data to calculate the number of years required to reach the price limit. Once this value has been reached, PV modules will be assumed to see their prices increased in line with general inflation. This calculation is used to estimate the price of the PV modules 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 PV modules will be replaced, the replacement cost will be calculated using the explained procedure.

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

Cases of very high load:

When very high loads are present (for supply to a town or a city for example), it may be best to introduce data for "photovoltaic generators" on each row, i.e. sets of PV modules in series and in parallel, instead of data for discrete modules. In this case, each table row corresponds to one photovoltaic generator. An example could include one 1 kWp generator, one 2 kWp generator, etc.

3.9 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 3.8.

Wind turbines data:

General data are: Name, Voltage Type (DC or AC, in a pop-up menu), Acquisition Cost, including the tower (€), 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 for each generator (currency/yr), Useful Lifespan (yrs), Height of the Hub (m) and CO_2 emissions in manufacturing, recycling etc. (kg).

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 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
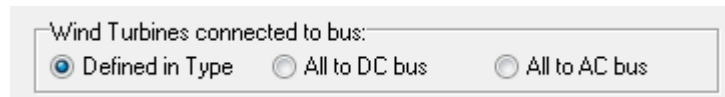
another density, that is, if the curve was measured in different conditions than standard, we can define the air density when it was measured (shown at the left of the curve

Power curve measured at air density (kg/m3): 1.225). This curve is represented in the graph at the bottom, in red color. For DC wind turbines (including the ones which generator is AC but it is non-regulated and it converts to DC regulated voltage in the controller), the losses in the controller must be included in the output power. If the DC output voltage is different from the voltage for the system's DC bus, losses must also be accounted for at the DC/DC converter, which connects the wind turbine to the DC bus.

DC turbines will be connected to the DC bus, and AC wind turbines will be connected to the AC bus. In the diagram of the main screen the wind turbine appears always represented in the DC bus, although this is only a representation, i.e. if the chosen wind turbine is AC it will of course on the AC bus.

Wind turbines connected to bus:

We can define for each turbine which bus is connected to (default option), or we can force all turbines considered in the system to be at DC bus or at AC bus:

Wind Turbines connected to bus:
● Defined in Type   ○ All to DC bus   ○ All to AC bus
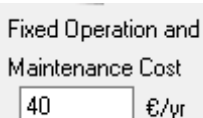
If all of them are connected to the AC bus, in the scheme of the system the wind turbine will be seen connected to the AC bus.

Add or remove wind turbines:

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

Fixed Operation and Maintenance (O&M) cost:

Fixed Operation and Maintenance Cost
40   €/yr

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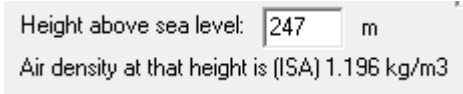
The total cost for operation and maintenance of the group of wind turbines will be the fixed costs plus the individual cost of wind turbine multiplied by the number of wind turbines in parallel.

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). iHOGA 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.

Height above sea level: 247　m
Air density at that height is (ISA) 1.196 kg/m3

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 above sea level 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:

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

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.

Effect of Ambient temperature:

During the simulations, if we want to consider the effect of ambient temperature on air density, the ckeckbox ☐ Consider the effect of temperature must be checked. 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 modules, 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 Renewable 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:

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

<u>Options to adjust the power curve during the simulation:</u>

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/m^3). In any case, with the **Graph** button, we will see the air density during the year that will be used in the simulations.

<u>Do not consider reduction in power after a specific wind speed limit:</u>

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" 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.
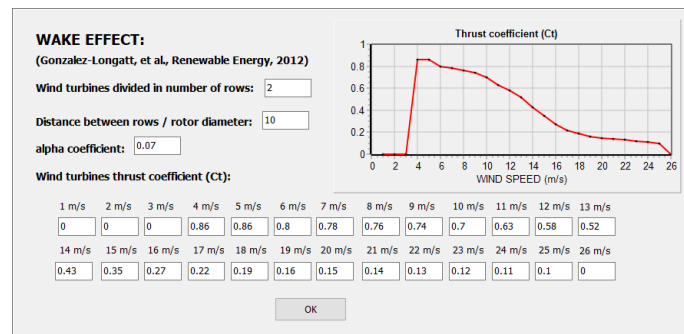
Wind turbines price inflation:

As explained in the screen of the PV modules, 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.

Cases of very high load:

As mentioned above, when very high loads are present for the hybrid system (for a town or a city, for example), it may be best to introduce data for "wind turbine sets" on each row, i.e. sets of wind turbines in parallel. Thus, each table row would correspond to one wind turbine set, e.g., one group of 100-kW, another group of 200-kW, etc. In this case, the following values would be introduced on the main screen: Wind Turb. in parallel, Min 1, Max 1.

Press "OK" to return to the main screen.

3.10 Hydro turbines Only in PRO+ version

The Hydraulic 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.

Hydro turbines data:

The general data for each turbine include: Name, Voltage Type (DC or AC, in the pop-up menu), Maximum Flow (l/s), Minimum pressure height (m), Maximum pressure height (m), Acquisition Cost (€), Useful Lifespan (years) and Operation and Maintenance Costs (€/yr) for each 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.

If the turbine voltage is DC, it will be placed on the DC bus (with or without DC / DC converter), whereas if it is AC it will obviously go on the AC bus. In the diagram of the main screen, the turbine is always represented on the AC bus, although this is only a representation, i.e. if the

turbine chosen in a certain combination of components is DC it will of course be connected to the DC bus.

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

> 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

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.

Pumped hydro storage (PHS):

Under the table, we can read the red text:

> If you want to consider Pumped Hydro Storage, check one of the check box below (reversible pump-turbine or pump and turbine different machines).
>
> In that case, data from HYDRO resource will not be considered. Water tank and pumping data (elevation head, friction losses, pumping efficiency and pump minimum load) considered will be the ones shown in the LOAD/AC GRID window (Water tab).
>
> Water will be pumped from reservoir when there is renewable energy or when settled by the control strategy; turbine will generate electricity when water consumption or when settled by control strategy
>
> ☐ PHS: Reversible Pump-Turbine, data here. Same height and friction losses (data in LOAD/AC grid, water)
> ☐ PHS: Pump machine and pumping data in LOAD/AC grid window. Turbine data here:

We can select one of the two options below the text for pumped hydro storage. Anyway, 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. 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. The data of the tank, height and friction losses will be the ones of the LOAD/AC GRID window, tab "Water…".

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

  > ☐ PHS: Reversible Pump-Turbine, data here. Same height and friction losses (data in LOAD/AC grid, water)

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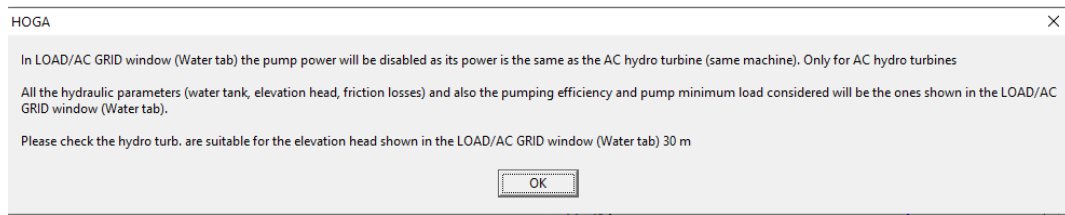
The data of this machine will be the data shown in the table of this window. As it is a unique machine, which can be operated as pump or turbine, it has same height and friction losses, and these data (height and friction losses) will be the ones shown in the LOAD/AC GRID window, tab "Water…".

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

When checking that checkbox, available head and penstock losses for the turbine appears under the checkbox (if we want to consider variable friction losses in the penstock between the turbine and the water tank or reservoir, check the "Variable friction losses" and set the data with the button "Losses" which appears). Also, this message appears:
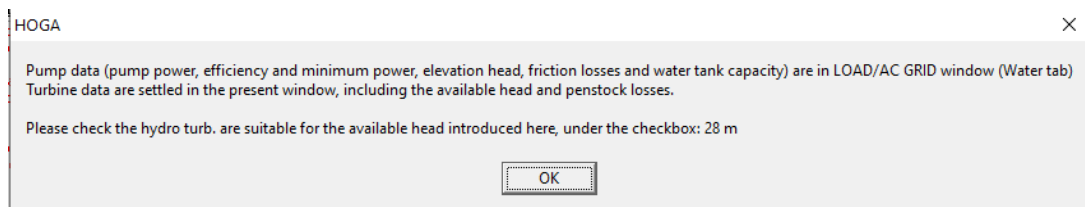
The data of the turbine will be the data shown in the table of this window, however the data of the pump is the data shown in LOAD/AC GRID window. As turbine and pump are different machines, there can be different values for height and friction losses: for example, the pump can obtain water from a reservoir 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 also applied for the turbine when it is in the "discharge" mode of the PHS in energy arbitrage. If "**Optimize**" is checked, this variable will be optimized when running the optimization. The optimization of this variable is considered in the publication (Dufo-lópez & Lujano-rojas, 2025) (https://www.mdpi.com/2313-0105/11/2/70).

If the checkbox "**Consider this % as min. turbine…**" is checked, that percentage will be considered 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, see the publication (Rodolfo Dufo-López & Lujano-Rojas, 2024). 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 "**Water Tank capacity is the maximum capacity…**", after the simulation of each combination of components and control strategy, the water tankc capacity will be set as the maximum obtained, with the limit selected (limit to the value defined in the LOAD/AC GRID or limit of a specific duration in h).

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).

If we check the box "**Optimize Water T. capacity, with a max. duration…**", the water tank capacity will not be a fixed value, it will be optimized, considering a maximum duration, and the optimization steps.

The cost of the water tank or reservoir in €/m^3 and its residual value in % must also be set (by default 0 if we consider water tank cost is included in the turbine cost).

More data:

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

Also, varaible O&M costs and start-up costs, for turbine and for pump, must be set (Only in PRO+ version).

If the turbine is DC voltage, and its voltage is different from that of the DC bus of the system, the performance of the electric generator must include losses in the DC/DC converter that will connect the turbine to the DC bus.

Above the graph, the nominal power and its maximum power, calculated in kW [9.81*Available_head(m)*Flow_max(l/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.

3.11 TEG Only in PRO+ version

The Thermoelectric generator screen may be accessed by clicking on "**TEG**" button.

The TEG is composed by several modules (TEM) that are connected to the hot source and to the cold source by means of heat exchangers:
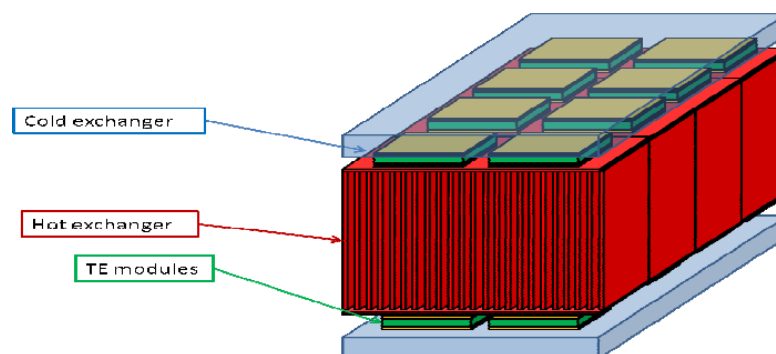
The thermal circuit for each TEM is shown in next figure, where the thermal resistance (measured in K/W) of the TEM is $R_{\text{th\_TEM(t)}}$, while the thermal resistance of the hot and cold exchangers are, respectively $R_{\text{th\_hot(t)}}$ and $R_{\text{th\_cold(t)}}$. They depend on the time step as they depend on temperature (they are not fixed values).

We will always suppose that the TEM modules are connected to MPPT DC/DC converters so that the resistance conntected to them is always the same as their internal resistance (matched load), therefore the maximum power is extracted from the TEM (matched output power).

During the simulation of a specific combination of components, for each time step (t) the hot source and cold source temperatures are known (data) ($T_{\text{hot\_s(t)}}$, $T_{\text{cold\_s(t)}}$), the problem is to find the hot and cold temperatures of the TEM ($T_{\text{hot(t)}}$, $T_{\text{cold(t)}}$). After calculating them, it can be calculated the open circuit voltage of the TEM and its output power.

$T_{\text{cold\_s (t)}}$ Cold source

$R_{\text{th\_cold(t)}}$ Cold exchanger

$T_{\text{cold (t)}}$

$R_{\text{th\_TEM (t)}}$ TEM

$P_{\text{elec (t)}}$ $T_{\text{hot (t)}}$

$R_{\text{th\_hot(t)}}$ Hot exchanger

$T_{\text{hot\_s (t)}}$ Hot source
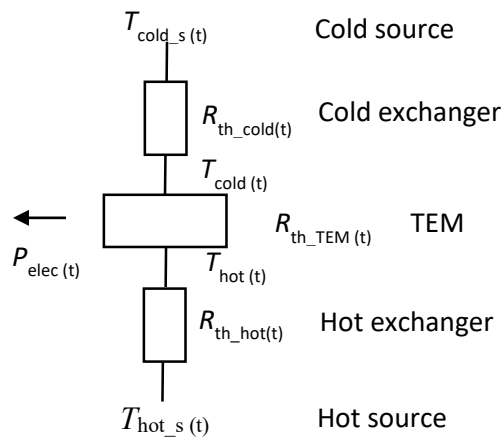
The screen of the TEG window is the following:

THERMOELECTRIC GENERATORS

Matched load, output power of 1 module   Seebeck coefficient, thermal and electrical conductivities

☑ Use this power curve ->
  ☑ Interpol. Seeb.
  ☐ I from M
☐ Thot, Tcold using circ.
Z at 300 K (x1E-3 K-1): 3.7
Z at 500 K (x1E-3 K-1): 0.75
☐ Consider Z in M

T cold (ºC): 30 -> , 50 -> , 80 -> , 120 ->

Output power curve — Output power (W) vs Temperature of hot side (ºC); legend: Tcold= 30°C, Tcold= 50°C, Tcold= 80°C, Tcold= 120°C

Output power at matched load, 1 module (W):

T hot	50ºC	100ºC	150ºC	200ºC	250ºC	300ºC	350ºC	400ºC	450ºC	500ºC	550ºC	600ºC	650ºC
30 ->	0	1.8	4.9	9.1	14.2	20	20	20	20	20	20	20	20
50 ->	0	1	3.7	7.4	12.1	17	17	17	17	17	17	17	17
80 ->	0	0	1.8	4.9	9	13	13	13	13	13	13	13	13
120 ->	0	0	1	3	7	8	8	8	8	8	8	8	8

Increase of thermal conductivity of hot heat exchanger with temperature (%/K): 0.08
Increase of thermal conductivity of cold heat exchanger with temperature (%/K): 0.08   Factor Voc: 1
Thermal resistance of ceramics and contacts of the module (% of total Rth): 0
Inertial Time Constant (min): 3
Losses due to Thomson effect and others (%): 10   Parameters of 1 module

Name	Power(W)	Cost(€)	Nmodules	N couples	Re(ohm)	Rth(KW-1)	Thot (C)	Tcold (C)	Rth-exch.Hot(KW-1)	Rth-exch.Cold(KW-1)	Lifetime(yr)
TEG1X6	48	850	6	63	0.8	0.675	300	30	0.8	0.2	15
TEG0	0	0	0	1	0.1	0.1	300	30	0.1	0.01	15
TEG1	8	150	1	63	0.8	0.675	300	30	0.8	0.2	15

MPPT eff.

Calculation of Thot, Tcold of the module:
Max. difference (%): 1
Max. Iterations: 10

Annual Inflation Rate for TEG Cost : -10 %
Max. Variation of TEG Cost (e.g., for an expected 70% reduction on current TEG cost, introduce "-70%"): -70 %
Limit is reached in 11.4 years

OK

During the simulation of each combination of components, for each time step the software will use the TEG standard simplified model (including the temperature dependance of the Seebeck coefficient and the thermal and electrical conductivity) to calculate the temperatures of the hot and cold side of the TEM: $T_{hot(t)}$, $T_{cold(t)}$.

Then, after knowing the temperatures of the hot and cold side of the TEM:

- We can use the matched load output power curves of the TEM modules datasheet (by default) to obtain the output power (if the uper left "Use this power curve->" checkbox is selected ☑ Use this power curve ->). This option was used in the paper (Dufo-lópez et al., 2019).

- Or we can use the matrix equations of the simplified model (Favarel, Bédécarrats, Kousksou, & Champier, 2016) to calculate the open circuit voltage and the ouptut power calculation. The matched load output power (W) of the TEM is $P_{(t)}=V_{oc(t)}^{2}/(4R_{e(t)})$, where $V_{oc(t)}$ is the open circuit voltage (V) and $R_{e(t)}$ (Ω) is the internal electrical resistance of the TEM. (If the uper left "Use this power curve->" checkbox is unselected).

$V_{oc(t)}=N\cdot\alpha_{(t)}\cdot(T_{hot(t)} - T_{cold(t)})$ where N is the number of thermocouples of the TEM and $\alpha_{(t)}$ is the Seebeck coefficient of the thermocouple, which depends on the average temperature of the thermocouple.
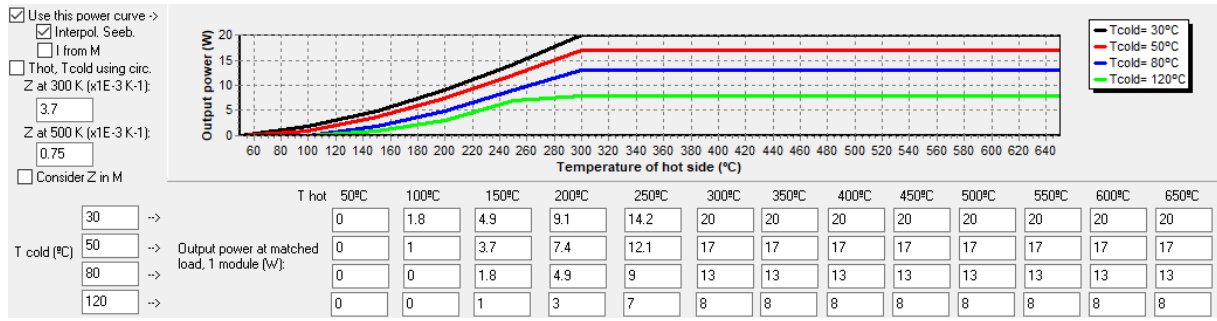
In order to interpolate and extrapolate output values from the curves, we can consider that output power is proportional to $[\alpha_{(t)} \cdot (T_{hot(t)} - T_{cold(t)})]^2 / R_{e(t)}$ (default, checkbox ☑ Interpol. Seeb. checked) or we can neglect the dependance on $\alpha_{(t)}$ and $R_{e(t)}$ (checkbox unchecked).

The output current of the TEM can be calculated using the output power (default, checkbox ☐ I from M unchecked) or considering the current calculated from the matrix equations of the simplified model (checkbox checked).

If the checkbox ☐ Thot, Tcold using circ. is unchecked, $T_{hot(t)}$, $T_{cold(t)}$ are calculated by using the matrix equations of the standard simplified model.

If that checkbox is checked, $T_{hot(t)}$, $T_{cold(t)}$ are calculated by using the thermal resistances of the thermal circuit shown before, including the dependence of the TEM conductivity on current and on ZT (Goupil, Ouerdane, & Apertet, 2013):

$$K_C(I) = K_{I=0}\left(1 + \frac{I}{I_{cc}} Z\bar{T}\right)$$

If the checkbox ☐ Consider Z in M is checked, the previous relation will also be considered in the matrix equations of the standard simplified model.

The increase of thermal conductivity of the hot and cold exchangers (%/K from 30ºC) must be set. Also, if we don't use the matched load output curves of the TEM, we can specify a value for the thermal resistance of ceramics and contacts of the TEM (%). A intertial time constant can be set (min, default 0) and additional losses due to Thomson effect can be set (default 0).

A factor for the correction of the open circuit voltage can be set (default 1): Factor Voc 1

Several TEG can be considered. For each one, the total nominal (peak) power of the TEG must be set (Power (W)), the total cost (€) (including installation, thermal exchangers and MPPT), the number of modules (Nmodules). And also the parameters of each TEM (for 1 module): number of thermocouples (N couples), internal electrical resistnace (Re (ohm)) and thermal resistance (Rht(KW^{-1})) for the values of Thot(C) and Tcold(C); also the thermal resistance of the hot and cold exchangers (KW^{-1}) at 30ºC for each TEM module (for example, if 2 TEM are connected to one exchanger, the thermal resistance of the exchanger set in the table must be 2 times the total resistance of the exchanger). Finally the expected lifetime (years) of the TEG must be set.

Losses due to Thomson effect and others (%) 0 | Parameters of 1 module

Name	Power(W)	Cost(€)	Nmodules	N couples	Re(ohm)	Rth(KW-1)	Thot (C)	Tcold (C)	Rth-exch.Hot(KW-1)	Rth-exch.Cold(KW-1)	Lifetime(yr)
TEG1X6	48	850	6	63	0.8	0.675	300	30	0.8	0.2	15
TEG0	0	0	0	1	0.1	0.1	300	30	0.1	0.01	15
TEG1	8	150	1	63	0.8	0.675	300	30	0.8	0.2	15

By clicking on the "**MPPT eff.**" Button the efficiency of the MPPT DC/DC conversor must be set:
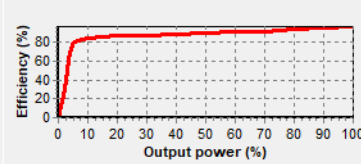
$T_{hot(t)}$, $T_{cold(t)}$ are calculated by using the matrix equations of the standard simplified model, which imply iterative calculations until a maximum difference between two iterations in $T_{hot(t)}$, $T_{cold(t)}$ and current is lower than a specified maximum difference (%) or until the maximum number of iterations is reached:

There is a tab "**Seebeck coefficient, thermal and electrical conductivities**" where the dependende on that values vs. temperature must be set. By default the values of Bi_2Te_3-based ingots used in the thermocouples of a specific manufacturer are shown.
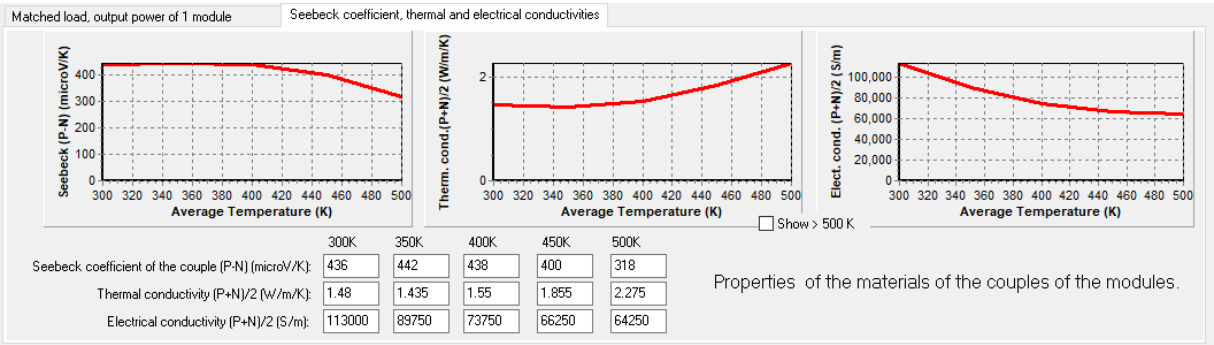
All the values are for the average temperature of the thermocouple (Tav=(Thot+Tcold)/2), in K.

For Seebeck coefficient, the total value of the thermocouple must be set ($\alpha=\alpha_P - \alpha_N$) in $\mu V/K$. For thermal and electrical conductivity, the average value of the thermocouple (value of P + value of N divided 2) must be set.

3.12 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.

3.12.1. General data

General data for batteries includes:

- Name

- Nominal Capacity (Cn) in A·h (in high power projects, Cn unit is kAh) 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 (Vn)

- Energy rated (nameplate) capacity, in Wh, will be: $Cn(Wh) = Cn(A·h)·Vn(V)$. In high power projects, $Cn(kWh) = Cn(kA·h)·Vn(V)$

- Acquisition Cost (€)

- Operation and Maintenance Costs (€/yr) 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. The maximum power (for charge and for discharge) will be $Pmax = Imax·Vn$.

- 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.
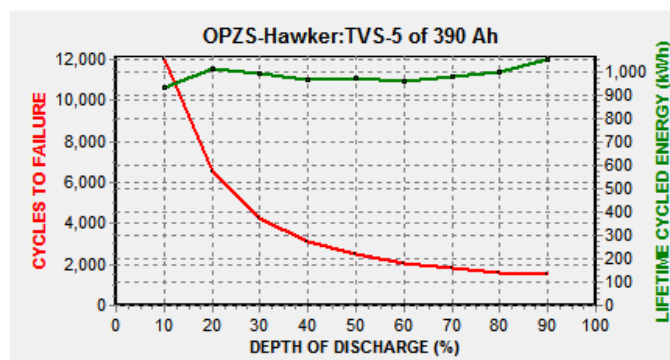
Some manufacturers of batteries usually indicate the curve cycles to failure vs. depth of discharge. If it is not known, and we know the cycles that the battery can perform at a certain

discharge depth, for example we know $Cicles_k = 2000$ for $DOD_k = 80\%$ ($k = 8$), the rest of the data of $Cicles_i$ ($i = 1 \ldots 9$) 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 3.7.

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

E_{cycled_i} (kWh) $= Cn$ (Ah) $\cdot Vn$ (V) $\cdot DOD_i$ (%) $/ 100 \cdot Cycles_i \ / 1000$

This value is displayed in green.

The number of equivalent cycles is calculated as:

$N_{eq\_cycles} = E_{cycled\_average}$ (kWh) $\cdot 1000 / (Cn$ (Ah) $\cdot Vn$ (V))

Where:

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

This value is displayed under the chart.

Number of full equivalent cycles 1254.3

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 hybrid 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 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.
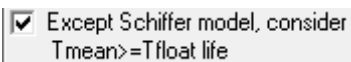
Cycle life dependence on temperature:

If the checkbox is selected (as default in PRO+ version), 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**": Only in PRO+ version
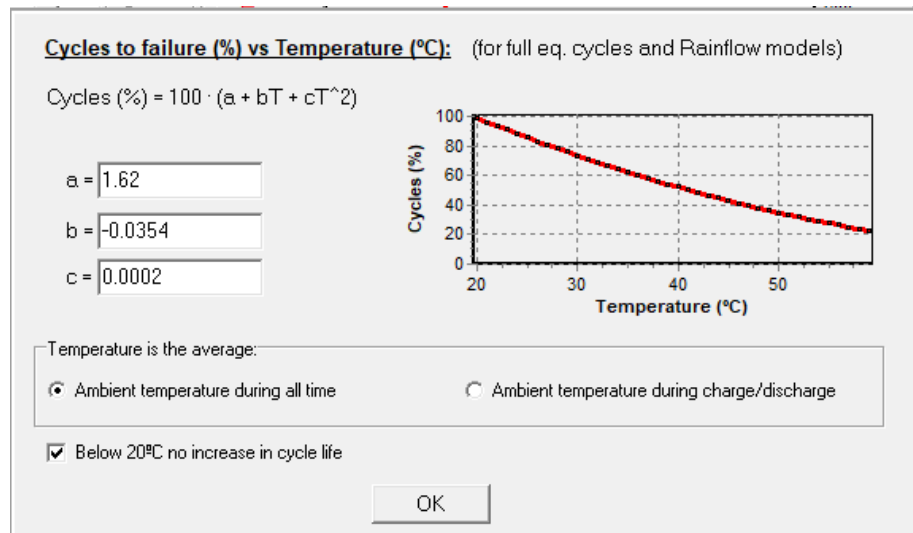
If you are using PRO+ version, it is very important that you select this option when using li-ion batteries or for lead-acid if you do not use Schiffer model, as temperature is very important in the degradation.

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

Capacity dependence on temperature:

If the checkbox is selected (as default in PRO+ version), the available battery capacity for each hour will be obtained considering the data shown by clicking button "**Data**": Only in PRO+ version
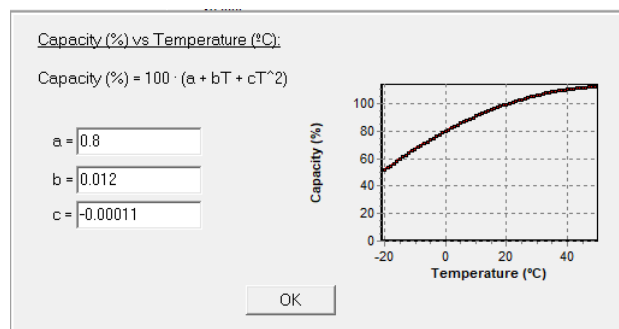
As explained in the previous sections, if you want to know the overall life cycle emissions, you must introduce (above the graph) equivalent CO2 emissions due to the manufacture of the batteries, in kg of CO_2 equivalent per kWh of capacity.

Equivalent CO2 emissions (manufacturing...): 55   kg CO2 equiv / kWh 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).

Annual Inflation Rate expected for Batteries Costs: -2 %   Max. Variation of Wind Batteries expected (e.g., for an expected 60% reduction on current Batteries cost, introduce "-60%"): -60 %

Limit is reached in 45.4 years

Above the cycles to failure graph, you must enter the percentage of the SOC at the beginning of the simulation.

SOC at the begining of simulation: 100   % of SOCmax

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%):

Li-ion batteries maximum SOC: 100   %

At the top bottom of this screen, we must indicate the remaining capacity at battery end of life, by default 80%.

Remaining capacity at battery end of life (%) : 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:

☐ If there is an AC Gen., every 14 days or 8 equivalent full cycles
charge battery bank at least up to 95 %

In the same way that we have commented on photovoltaic modules and wind turbines, if the hybrid system must supply very high loads, it may be better, instead of entering the discrete battery data, to enter in each row the data of "banks of batteries", that is to say, data of sets of batteries in series and parallel. Thus, each row of the table would indicate a bank of batteries. For example, in a row a group of 120 V 500 Ah, in another row a group of 120 V 1000 Ah, etc

(in this example the system DC voltage would be 120 V). In this case in the main screen of the program we would place: Batteries in parallel: Minimum 1, Maximum 1.

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.

3.12.2. 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: <mark>Only in PRO+ version</mark>

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. <u>If we use li-ion batteries, these data will not be used.</u>

By pressing the **"Control Data"** button (<mark>Only in PRO+ version</mark>), 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: <mark>*Only in PRO+ version*</mark>

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):

3.12.3. 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 iHOGA 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 Ah). 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. iHOGA calculates discharge intensities (in A) 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.
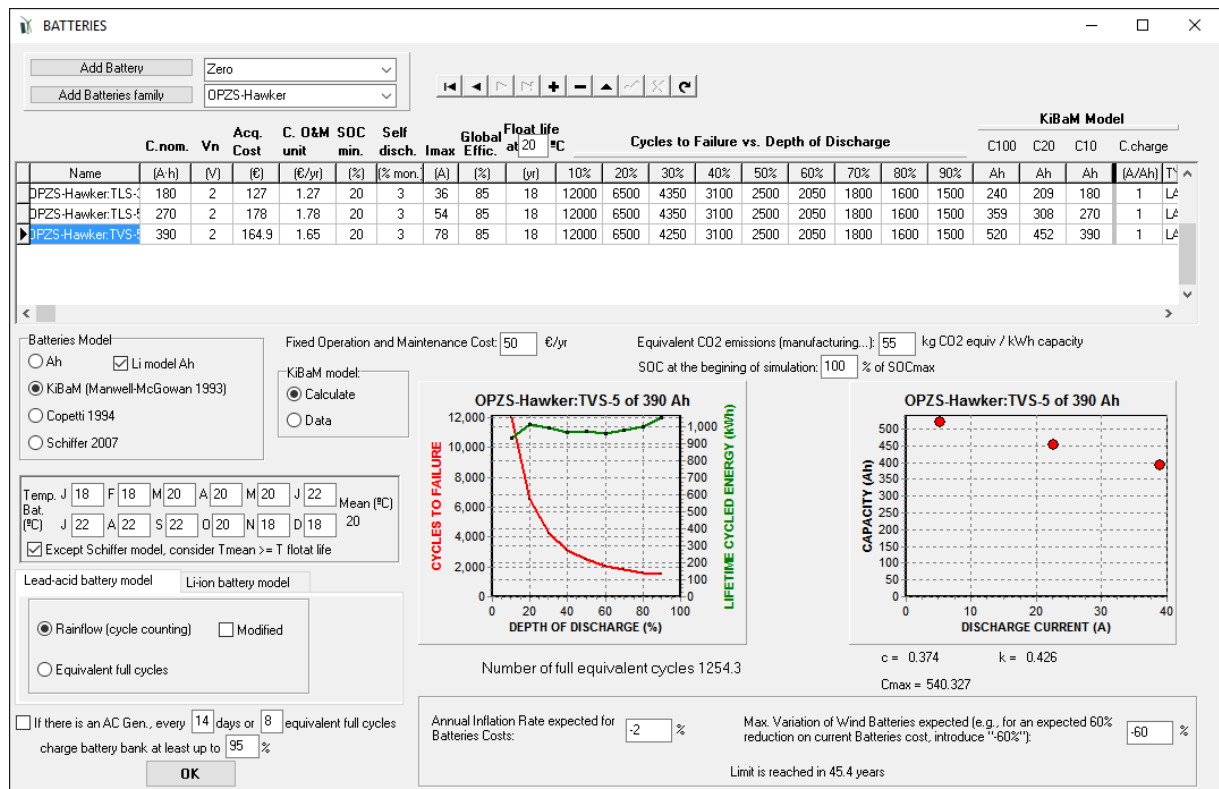
There is a last column in the table, which is also new (C. charge), in A / Ah, which represents the Maximum Battery Charge Rate or Maximum Battery Charge Current Coefficient, which is an additional limitation of Maximum charge current using the KiBaM model.

If in the KiBaM model we choose "Data" instead of "Calculate", the new graph disappears and instead of the columns C100, C20 and C10, we will have k (1/h), c and Cmax (Ah), besides the fourth column, which is maintained. In this case, the battery manufacturer should have provided these values.

3.12.4. Schiffer model. <mark>Only in PRO+ version</mark>

Using PRO+ version, we encourage you to use Schiffer model for lead-acid batteries, 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:

3.12.5. 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. In the first versions of the program it was estimated according to the simplified method of Equivalent Full Cycles. It is possible to choose between this method 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), used by other software programs with more precise simulation (HYBRID2) (Green & Manwell, 1995). In version 2.2. we added the Schiffer model (Schiffer et al., 2007), 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).

Lead-acid battery model   Li-ion battery model

○ Rainflow (cycle counting)
○ Equivalent full cycles
◉ Schiffer ageing model

In the case of Rainflow, if you check the box "Modified", a box appears where "Factor rainflow (0-1)" should be indicated.

◉ Rainflow (cycle counting)   ☑ Modified   Factor rainflow 0.5 (0-1)
○ Equivalent full cycles

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.
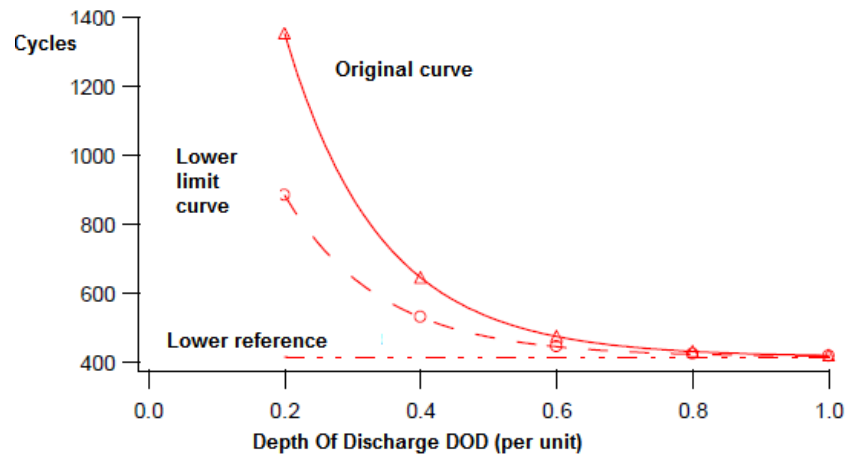
For each cycle, this method takes into account the average SOC of the batteries during the cycle, and obtains the number of life cycles from the curve for that SOC, which will be between the original and the lower limit.

3.12.6. Lithium-ion batteries lifetime models. <mark>Only in PRO+ version</mark>

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 small window appears where you can see (in different tabs) and edit the parameters of the different models (Wang, Grot, Naumann or Saxena).

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):
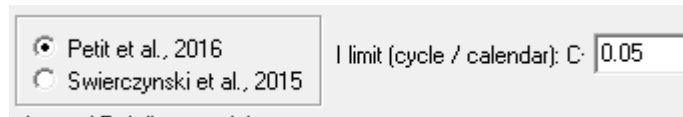
There are two models for calendar ageing:

- 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 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.

3.13 Auxiliary equipment for the charge/discharge of the batteries

In the case of low power projects, the screen of the auxiliary equipment for charging/discharging the batteries may be accessed by clicking on "CHARGE BAT." in the components area, or selecting "Charge Bat." in the Data menu. Auxiliary equipment includes the PV Battery Charge Controller and the Rectifier (also called "Battery charger", it is an AC/DC converter, usually used by the diesel or gasoline generators to charge the batteries).

In high power projects, we assume the battery controller and the rectifier are included in the inverter/charger (next section).

<u>PV Battery Charge Controller:</u>

The photovoltaic charge controllers to be considered must be indicated in the table (it is assumed that the wind turbines are fitted with their own controller). In the case of bi-directional controllers (inverter-chargers) that include charge controller, it will be indicated in the "Inverters" screen (see section 3.14) and, if an inverter-charger of this type is used in a certain combination of components, the charge controllers of this table will not be considered, as the charge controller is included in the inverter.

Once simulated each combination of components and strategy, for each case iHOGA chooses the minimum controller such that its maximum nominal current is higher than the maximum that is expected obtained in the simulation.

If there is no controller in the table that comply it, it will be considered a generic one with the cost obtained with the data on the right side of the table:

Acquisition cost (€):

30 + 7 * Ireg,max (A)

If the checkbox ☐ **Consider only first one of the table** is selected, then iHOGA will only consider the first charge controller of the table, so its current will be the limit current for the charge of the battery bank (except if the battery bank is being charged by the AC generator, in that case the limit will be the one of the inverter-charger, if that device includes charger).

You can add database controllers, individually (button "Add from database"). You can also, using the button "Include only VDC suitable and selected MPP from family", force the controllers of the table to be only those of a particular family, which comply with the nominal DC voltage of the system and whether or not they include MPPT (depending on what has been marked below the table).

The characteristics of the control of the charge and discharge of the batteries are displayed by clicking on "Control Data" (Only in PRO+ version): if the control used by the charge controller and by the rectifier is PWM or ON/OFF (the two components, charge controller and rectifier 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 set (those of the manufacturer of the controllers or rectifiers to be used, which must be suitable for the batteries to be used).

In the case of PWM regulation, the data for the charge in several stages (typically 3 stages: bulk, boost or absorption, float) and also the data of the equalization or compensation load 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)

Rectifier (battery charger, AC/DC converter):

AC / DC converters (rectifiers or battery chargers, usually auxiliary elements of AC generators) are selected, for each combination of components and strategy, after simulating the system, so that the power required in the rectifier is the one chosen (if there is AC generator, the minimum power of the rectifier is the nominal power of the AC generator). Their costs are modeled as

linearly dependent on power (within limits), fixed at the bottom of the screen. The efficiency is usually high, of the order of 90%, and little dependent on the power of the converter.

If the rectifier is included in the cost of the AC generator, here we must set the costs to 0. If the rectifier is included in the bi-directional inverter, its cost will automatically be set to 0.

3.14 Inverters and inverter-chargers (bi-directional converters).

The "Inverters and inverter-chargers" screen may be accessed by clicking on "INVERTERS" (Components area), or selecting "Inverters" in the Data menu.

The inverter is a are a very important component, with a considerable influence on the operation and total cost of the system. Inverter performance is heavily dependent upon power at any time (apparent power).

Some commercial components include inverter (DC/AC converter) and battery charger (AC/DC converter), called inverter-charger or bidirectional converter

<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 (VA)

- Lifetime (years)

- Acquisition cost (€)

- If it includes a battery charger (bi-directional inverter or inverter-charger), select in the drop-down menu in the "Batt.. Charger" column "OK" option. In this case, the value of the maximum charge current that can be supplied to the batteries must be set in the following column "Imax_ch.DC (A)" and the efficiency of the charger in the next column.

- Minimum and maximum operating DC voltage. The nominal DC voltage of the system set in the main screen must be between these two values.

- If it includes PV battery charge controller: inverter-chargers or bi-directional inverters can include the controller for the charge of the battery bank from renewable PV and/or wind power sources, in which case you must select OK in the drop-down column "PV batt. controller". The controller can include MPPT, then select MPPT instead of OK. In that case, in the next column you must set "Pmax_ren (W)" the maximum input power from the photovoltaic generator and wind turbines.
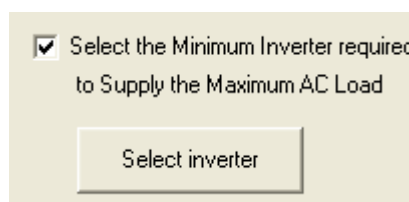
In addition, for each type, the efficiency (%) vs. the output power (in % of rated power, from 0 to 100%) must be defined. This is reflected in the graph. The last column shows the weight (kg).

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, and that also comply with the table on the right: without rectifier (charger) or rectifier without PV batt. controller or rectifier with batt. controller (MPPT or not, depending on what is indicated in the Checkbox "MPPT" below the table).

<u>Select the Minimum Inverter required to Supply the Maximum AC Load:</u>

If the checkbox "Select the Minimum Inverter required to Supply the Maximum AC Load" is checked, iHOGA will select the inverter with lowest power that can supply the maximum AC load, and it will use only this type in the optimization.

In this case, you must click on "Select Inverter" before clicking on "OK". Under the efficiency graph it is shown the AC power required by the loads, as well as the power of the inverters selected. A warning message will be displayed when no inverters meet the power requirements.

In addition, under the graph also we are informed of the average hourly power consumption AC, what percentage has respect to the nominal power of the selected inverter, and therefore what average efficiency will give the inverter. This value is used by the program in the calculation of some parameters of the control strategy. However, for the calculation of the energy balances of the system during each time step of the simulation, the program uses the actual efficiency of the inverter, depending on the output power according to the efficiency curve.

If, on the other hand, we have not activated the "Select the Minimum Inverter required to Supply the Maximum AC Load " box, the program in the optimization of the hybrid system will test combinations with the different inverters, i.e. in principle it will consider them all equally. Low power inverters will likely in some cases give solutions that are not useful, as they will probably imply unmet load due to the limitation of the inverter.

Maximum output power in the simulation:

Permissible overloads can be defined in the case of simulations with time steps of less than 60 minutes.
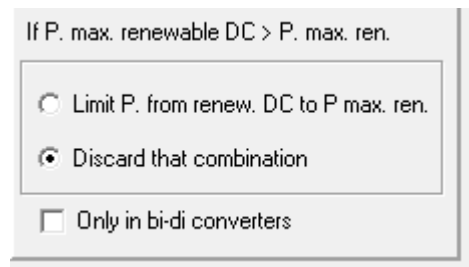
The maximum output power of the inverter must be settled, depending on the time step of the simulation:

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 (W)" 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.

By default this applies to any kind of inverter. If you want to apply this condition just to inverters / chargers (bidirectional converters), check the option "Only in bi-di converters".

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 VAfinan will be the battery capacity in Wh 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.

3.15 AC backup generators (diesel, gasoline…)

By clicking on "AC GENERATOR" (Components area), or selecting "AC Generator" in the Data menu the screen of the AC backup generators appears.

AC 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 (kVA), Acquisition Cost (€), 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:

$$\textit{Consumption (fuel unit/h)} = P_n(kW) \cdot B + P(kW) \cdot A,$$

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):

S_rated (VA) / P_rated (W) =   1

Data for the calculation of life cycle emissions must be set: equivalent CO2 emissions in the manufacturing of the generator, recycling, etc. (kg CO2 per kVA of rated power).

Equivalent CO2 emissions (geneartor manufacturing...): 215   kg CO2 equiv. / kVA rated power

Force the generator to run all the time: Only in PRO+ version

We can force the generator to run all the time to create the AC grid, in this case you should select the checkbox:

☐ **Generator runs all the time (AC grid reference)**

If you check the box ☐ Spinning reserve (+1 gen.), during each time step an extra generator will be on (to increment spinning reserve). If the checkbox ☐ Only if partial load > Pmin 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: <mark>Only in PRO+ version</mark>

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 ☑ Only during hours when control strategy is to inject to the grid 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 ☑ Only if P needed >Pmin gen 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:

Maximum output powr in sumulations of:
30 minutes:	20	% higher than nominal
15 minutes:	30	% higher than nominal
10 minutes:	30	% higher than nominal
<=5 minutes:	30	% higher than nominal

We can also count a penalty on the consumption during each start, default equivalent to 5 minutes running at full load. Also, a minimum running hours (Only in PRO+ version) can be set (the backup generator, when it starts running, it will be running at least the number of hours set).

☑ Each start is considered that consumes
5 minutes of lifespan
Minimum running hours 0

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:

Extra aeging and O&M when running out of optimal conditions (50-80%):
- Factor for 30%: 1.25
- Factor for 100%: 1.5

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.
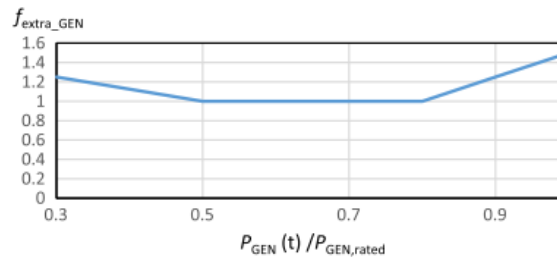
3.16 Fuel Cells and Electrolyzers. Only in PRO+ version

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, i.e. there are three screens in one.

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.
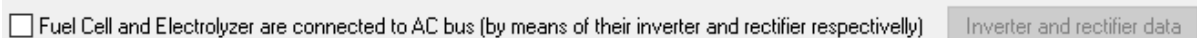
Note that when we have selected that we want fuel cell and in addition the origin of the fuel is H2 produced in the electrolyzer, there must be an electrolyzer and H2 tank where the H2 is stored, so the electrolyzer and tank are mandatory (they cannot be deselected).

If there is any element that we do not want, deselecting its checkbox will disappear the corresponding tab.

As explained in the PV panel 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.

In low power projects, by default fuel cell and electrolyzers are connected to the DC bus. At the top bottom of the screen there is a box where we can indicate that the fuel cell and the electrolyzer are connected to the AC bus of the system. In this case a button is enabled which indicates the efficiencies of the electrolyzer rectifier and the fuel cell inverter.

3.16.1 Fuel Cell

By clicking on the tab "Fuel Cells" the fuel cells window appears, where we can add, delete or change data.

Data of the fuel cells:

In the table of the fuel cells we must introduce the following data for each fuel cell to be considered: Name, Nominal Power P_{N_FC} (kW), 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 $P/P_{N\_FC} > P_{max\_ef}(\%)$:

$$Cons_{FC} = B_{FC} \cdot P_{N\_FC} + A_{FC} \cdot P \cdot \left(1 + F_{ef}\left(\frac{P}{P_{N\_FC}} - \frac{P_{max\_ef}(\%)}{100}\right)\right)$$

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.
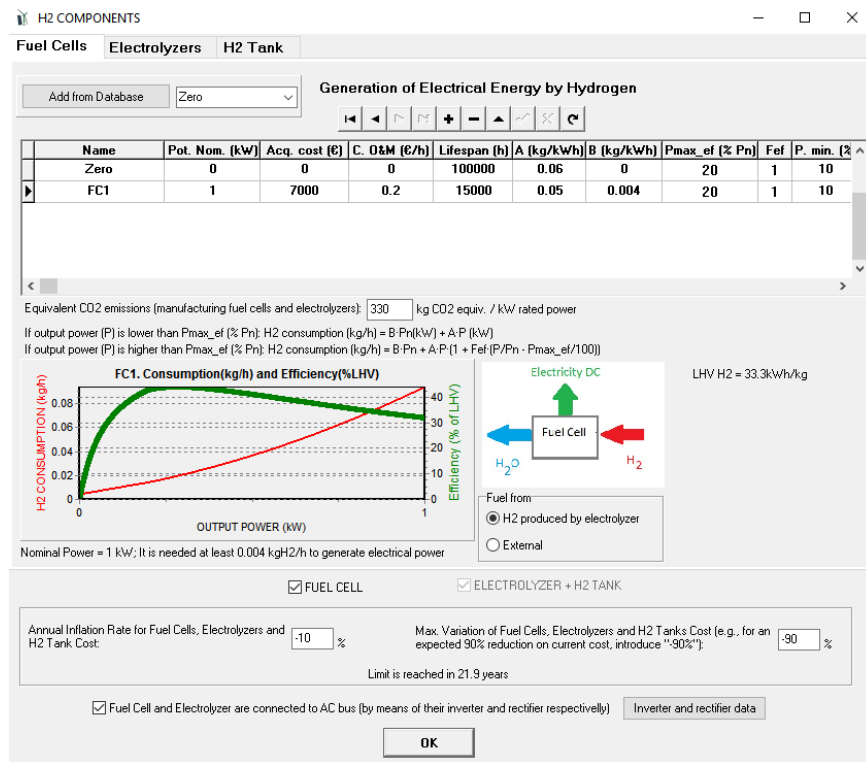
The graph of consumption and efficiency of the fuel cell that is selected in the table is represented. Below the graph it shows the nominal power of the fuel cell (kW) and the minimum amount of H2 required to start generating electricity. In the case of the figure, the fuel cell needs at least a hydrogen mass flow rate of 0.004 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 0.004 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).

Nominal Power = 1 kW: It is needed at least 0.004 kgH2/h to generate electrical power
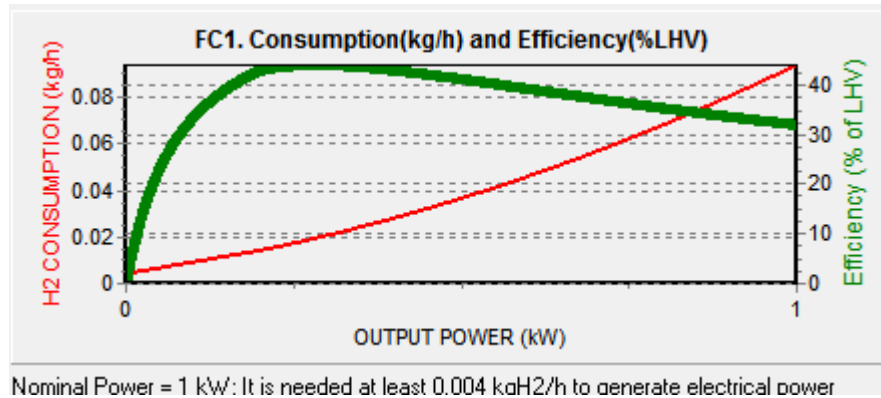
As explained in the previous sections, if we are interested in the calculation of the life cycle emissions, we must enter (below the table) the equivalent CO_2 emissions due to the manufacture of the fuel cell and of the electrolyser, in g of equivalent CO_2 per kW of nominal power. It depends on the technology.

You can define the months and hours of the day when the fuel cell is available with the button

.

<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 (externally produced) price:
10   €/kg
Fuel price inflation:
2   %
Fuel CO2 emissions:
0   kgCO2/kgFuel

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).

<u>Systems which include Electrolyzer but do not include Fuel Cell:</u>

Uncheck the "Fuel Cell" check box when no fuel cell is required (e.g., when an electrolyzer is present, but only H$_2$ is used for external use).

☑ FUEL CELL

3.16.2 Electrolyzer

By clicking on the tab "Electrolyzers" the electrolyzer window appears.

Data that must be introduced: Name, Nominal Power (kW), Acquisition Cost (€), Operation and Maintenance Cost, 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, $\dot{H2}_{prod\_rated}$ is the rated hydrogen mass flow of the electrolyzer (kg/h), $\dot{H2}_{prod\_limit}$ (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).

$$P_E(t) = \frac{H2_{prod}(t) \cdot A}{\Delta t} + \dot{H2}_{prod\_rated} \cdot B, \qquad \forall \ H2_{prod}(t) \leq \dot{H2}_{prod\_limit} \cdot \Delta t$$

$$P_E(t) = \frac{H2_{prod}(t) \cdot A \cdot \left(1 + F \cdot \left(\dfrac{\dfrac{H2_{prod}(t)}{\Delta t} - \dot{H2}_{prod\_limit}}{\dot{H2}_{prod\_rated}}\right)\right)}{\Delta t} + \dot{H2}_{prod\_rated}$$
$$\cdot B,$$

$$\forall \ H2_{prod}(t) > \dot{H2}_{prod\_limit} \cdot \Delta t$$

For example, if you change the values to: A = 41 kW/kg/h, B = 3 kW/kg/h, $\dot{H2}_{prod_{limit}}$ = 5% of rated hydrogen mass flow and factor F = 0.45, values which fit with the efficiency of a 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:
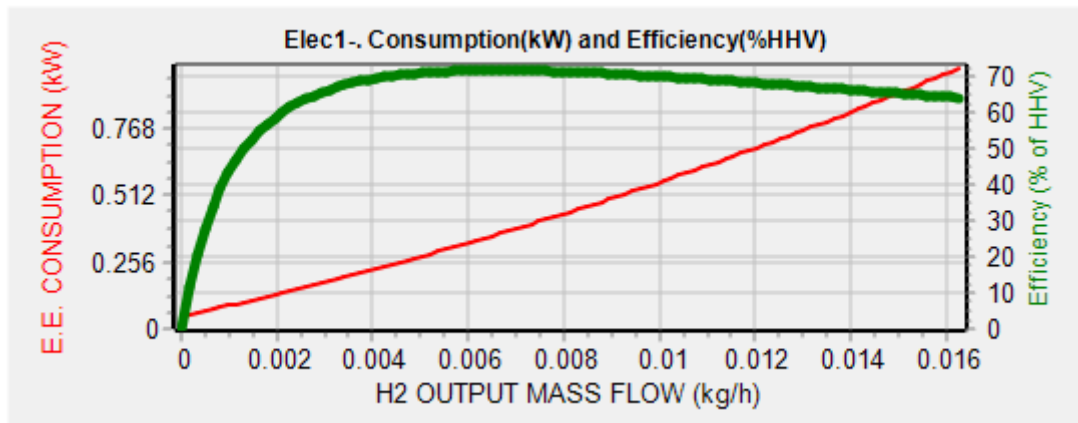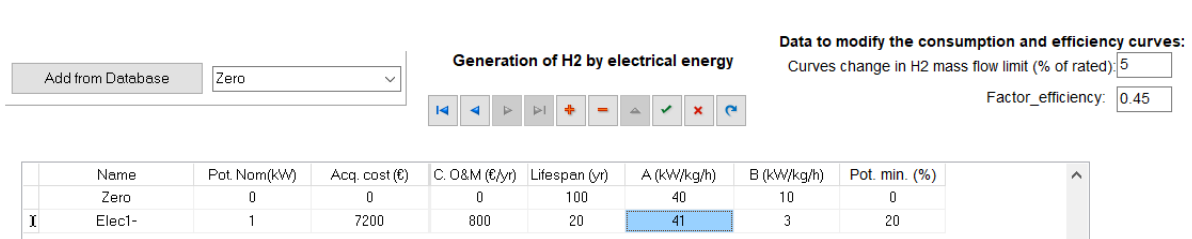
By default, when the electrolyzer does not work, it is in stand-by, which means that it will consume electricity (default 10% of its nominal power): in the simulations you will see that there is a load consumption by the electrolyzer that must be supplied by the rest of the system, it this load is not covered it will be counted as unmet load. You can change the percentage:

Power consumption in stand-by: 10   % of nominal power

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):

Water cost (€/kg_H2): 0

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 acquisition cost) 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:

Stack replacement cost (% of acq. cost): 40

Cold start time (minutes) and equivalent extra ageing (minutes) due to each cold start must also be set:

Cold start time (min): 20 ; Each cold start equiv. to extra ageing (min) 100

With the button Availability 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 electricity consumption and efficiency of the electrolyzer that is selected in the table. Below the graph it shows the nominal H2 mass flow (kg/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 0.2 kW to begin generating hydrogen. In the simulation, if during a given time no more than 0.2 kW of power is available to operate the electrolyzer, it cannot generate hydrogen during that time (and therefore it will not work during 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 electrical 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.

3.16.3 H₂ tank.

When iHOGA 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, iHOGA 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).

By clicking in the "H2 Tank" tab, we can see:

Fuel Cells   Electrolyzers   H2 Tank

Acquisition cost: 1000   €/kg of max. cap.

Maximum allowed size: 10   kg   Minimum level of H2 (% of max. size):   0
☐ H2 tank size is the maximum allowed size   (Fuel Cell will not run if tank level lower)

Capacity at the beginning of the simulation: 0   kg

Lifespan 25   years

O&M Cost 500   €/yr

☐ In H2 generating systems, do not consider H2 tank (costs 0, infinite allowed size)

The tank cost must be estimated, in €/kg of capacity, and a maximum allowed tank size must be set. 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 kg, as well as of the expected lifespan and the operation and maintenance costs for the tank.

Green H2 generating systems:

If the following checkbox is checked (default in high power projects), all the data disappears:

☑ In H2 generating systems, do not consider H2 tank (costs 0, infinite allowed size)

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 fuel 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 iHOGA, 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 iHOGA, 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).

3.17 PRE-SIZING.

After setting the load, resources and types of PV modules or 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.
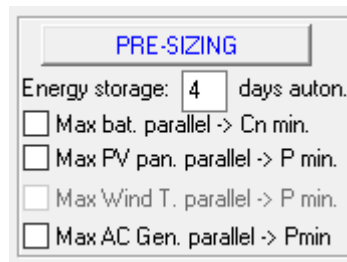
By clicking on the "PRE-SIZING" button button it displays a window with information of the maximum power recommended for the different components:
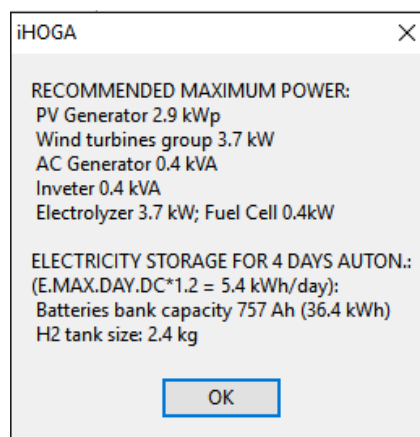
The following recommendations are for systems that must cover a specific load consumption. If the system sells electricity and/or H2, these recommendations can be not suitable.

- iHOGA 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 photovoltaic modules, losses in wires, etc. defined in the PV window; if there is no MPPT an extra factor of 1.3 is added). This peak power (in the example 2.9 kWp) should be the maximum power of the photovoltaic group that iHOGA can be allowed for optimization. For example, if we use 100 W, 12 V modules, and the DC voltage of the system is 48 V (so there will always be 48/12 = 4 modules in series), in the main screen, where we select the maximum allowed

number of Modules in parallel, we should not put a number much higher than 2900 / (100 · 4) = 7.25, for example, we could set 8 as the maximum number of parallel modules allowed.

-iHOGA 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 3.7 kW, so in the wind turbine screen we could include a wind turbine of around 1 kW and some other of around 2 kW, 3 kW and 4 kW but not much more power as it probably would be unnecessary.

- 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 photovoltaic 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.

iHOGA 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, iHOGA informs you of the maximum numbers of allowed components being updated on the main screen.
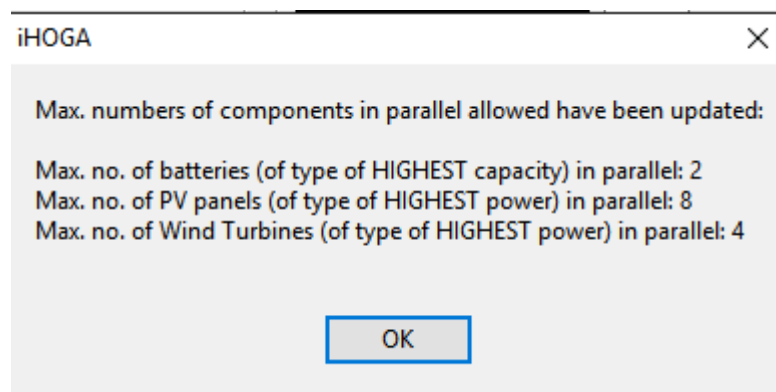
The updated values appear in red:

3.18 HDI and Job creation

Pressing the "HDI and Jobs" button accesses the screen where you can enter the data for the calculation of the Human Development Index (HDI) and Job Creation of the different technologies.

On the left side (HDI), you must enter the number of persons of the community from which the installation is to be supplied, in addition to the parameters for calculating the HDI.

The HDI can be calculated considering the use of excess energy, considering a usable excess factor (by default 20%) and a maximum usable (default 35% of total load), following the methodology set out in the article (Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016a).

In the right part, the job creation data of each technology (number of jobs per GWh of generated energy) is entered.

The default data were obtained from the doctoral thesis of Juan Carlos Rojas Zerpa (Rojas-Zerpa, 2012). Employment created by photovoltaic and wind power by default is considered in jobs per MW of peak power, as was considered in (Rodolfo Dufo-López, Cristóbal-Monreal, et al., 2016a).

3.19 Sensitivity analysis. ==Only in PRO+ version==

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):
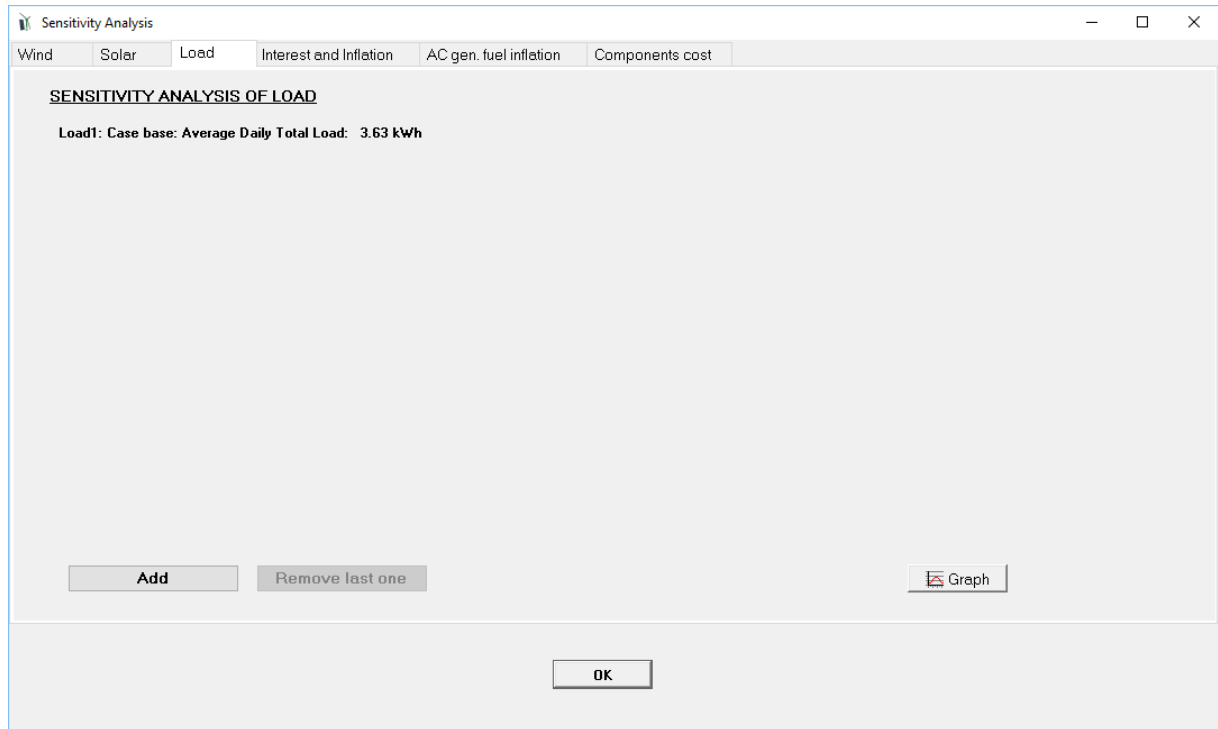
The screen has 6 tabs where you can enter the data so that iHOGA performs the sensitivity analysis..

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. iHOGA 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) iHOGA 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 iHOGA 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 iHOGA 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).
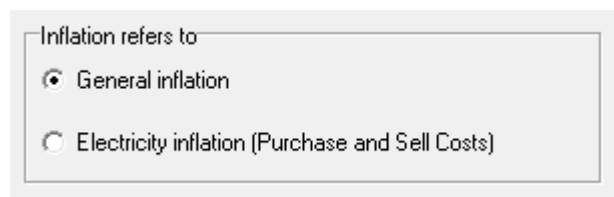
By clicking on the button on the bottom right "Graph" the different series are plotted.

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.

3.20 Probability Analysis. Only in PRO+ version

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:
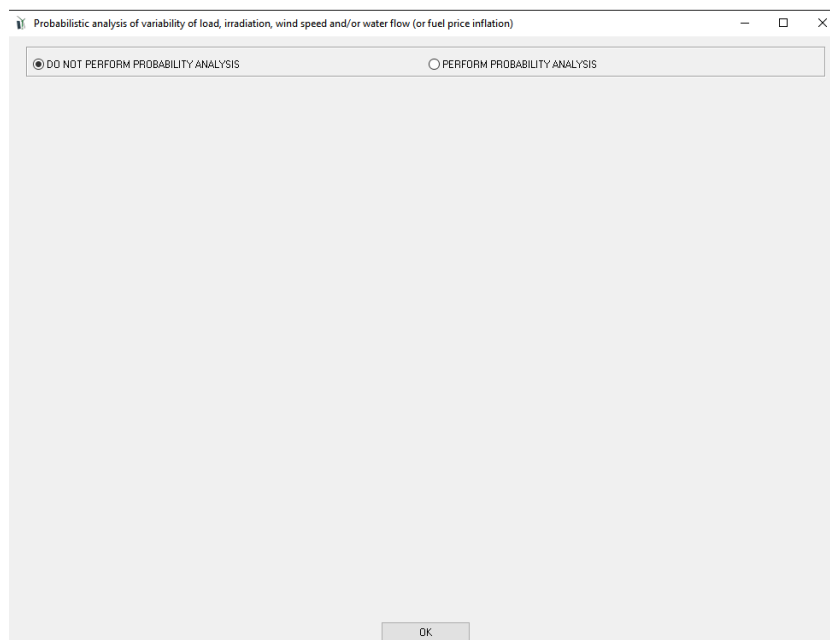
By default the probability analysis is not ready. To indicate we want probability analysis, click on "PERFORM PROBABILITY ANALYSIS" and the following screen appears, in which the checkboxes "Analyze variability of the average value of load", "Analyze the variability of the average value of irradiation", "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.
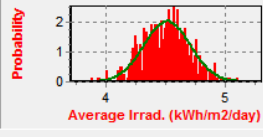
With this analysis, for each combination of components and control strategy to be studied, N combinations of different time series of load and resources (and fuel inflation) will be performed using Monte Carlo Simulation, according to the methodology presented in the works (Rodolfo Dufo-López, Pérez-Cebollada, 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 backup 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.

iHOGA 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 water 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:

In the probability analysis report, in the last two charts, show the probability distribution of:

Hours running AC Generator (h/yr)	⌄	Annual cost of fuel of AC Generator (currency/yr)	⌄

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 ☐ When clicking at any cell of the results table, do not update results is checked, the results will not be updated.

If the box ☐ When clicking on simulation button, do not consider the characteristic cases 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. <u>OPTIMIZATION OF THE HYBRID SYSTEM</u>

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.
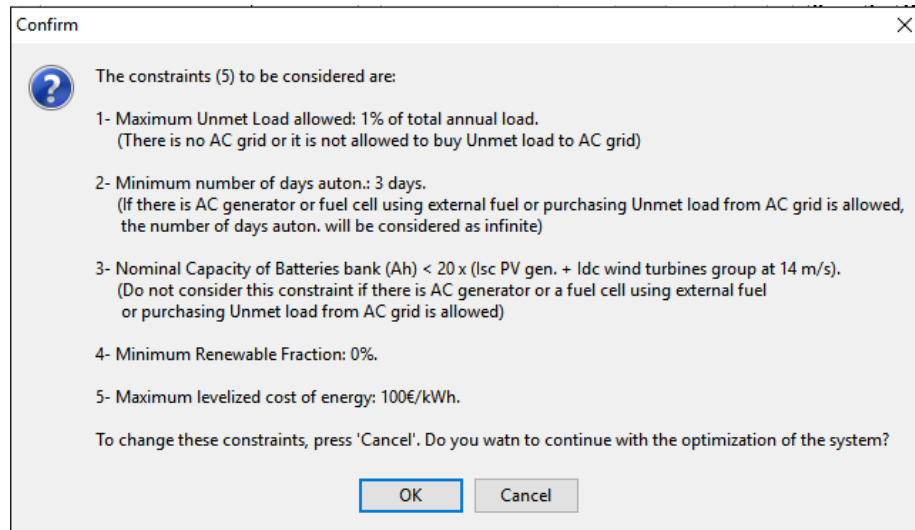
If it had already been calculated, it asks if we want to calculate, since the previous results will be lost.
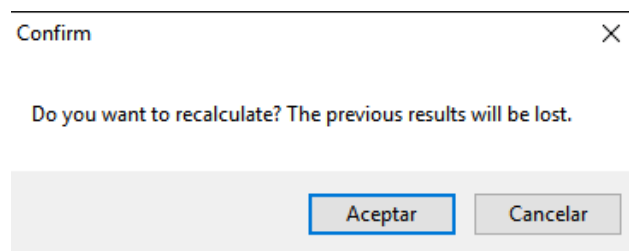
If we accept, the program begins to perform the optimization.

It should be noted that if there are results (we have previously optimized the system), clicking on "CALCULATE" and accepting the confirmation requested by iHOGA, 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 cannot be resumed, but a new calculation must be started.

4.1 Mono-objective optimization using genetic algorithms.

In the case of the mono-objective optimization there is a unique objective: minimize NPC or maximize NPV.

The following screen shows an example of mono-objective optimization. In this example the components of the system are photovoltaic modules, batteries, auxiliary (PV batt. charger, rectifier), inverter, AC generator and fuel cell (with electrolyzer). In addition, the maximum execution time has been set at 1 minute, but the number of possible combinations would take in evaluating 8'38", so that the genetic algorithm method is used to find the optimum without evaluating all combinations, and the best solution found for each generation is being shown during the optimization (in the figure it have already passed 4 generations of a total of 15 to be executed).

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".
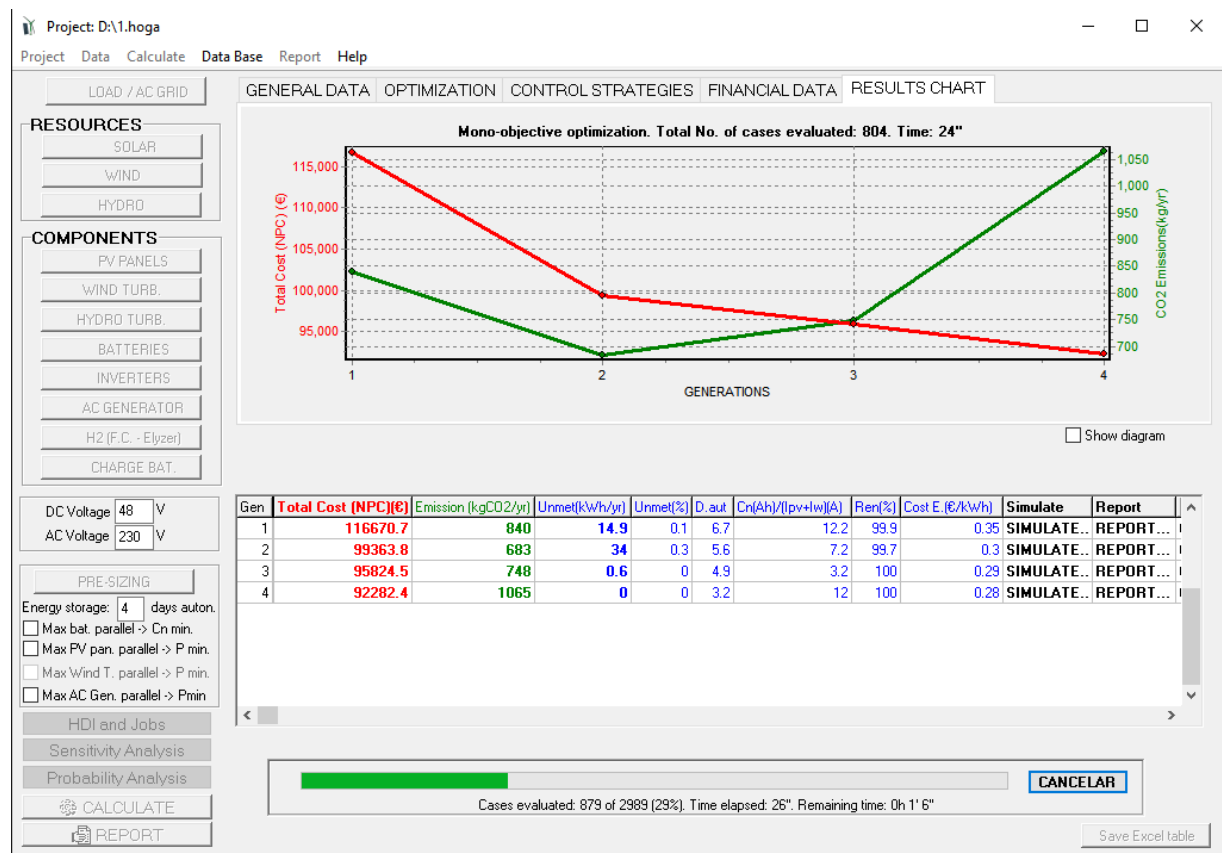
Each row of the table collects the best solution found during each generation.

At the end of the simulation the panel disappears with the progress bar and instead the description of the best solution found (the best of the last generation) appears.

In the case of minimization of NPC project, the graph shows the total cost (NPC) of the system (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) for the best solution of each generation. In the table, in blue it is shown the unmet load (in kWh/year and in %), the days of autonomy (of daily average annual load), the value of the division

between the nominal capacity of the battery bank and the sum of the short-circuit current of the photovoltaic generator and the DC current produced by the group of wind turbines at 14 m/s, Cn (Ah)/(Ipv+Iw) (A), the renewable fraction covering the demand load (%). Also levelized cost of energy (€/kWh) is shown. These values, besides many others, are also observed in the table.

If the optimization type is Maximization of NPV, the NPC column is replaced by the NPV, some restriction columns disappear and appear columns of IRR (internal rate of return) and Investment.

In the case of any row (or all) in the column of Total Cost (NPC) (€) the INF value is shown, it means that this combination of components and control strategy does not comply with the constraints we have indicated (maximum unmet load, minimum autonomy, nominal battery bank capacity > N times Isc PV generator, minimum renewable fraction or maximum cost of energy) and iHOGA penalizes that solution, giving it infinite cost (1E10). If any row has this value, it means that in its generation no solution evaluated comply with all the constraints. This usually occurs when loads are high and the elements of the system are "small". It is represented graphically with total cost (NPC) = 0. If the optimization type is Maximization of NPV, if a solution does not match with the constraint (max. investment), its NPV is assigned a –infinite value (represented graphically with total NPV = 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 .
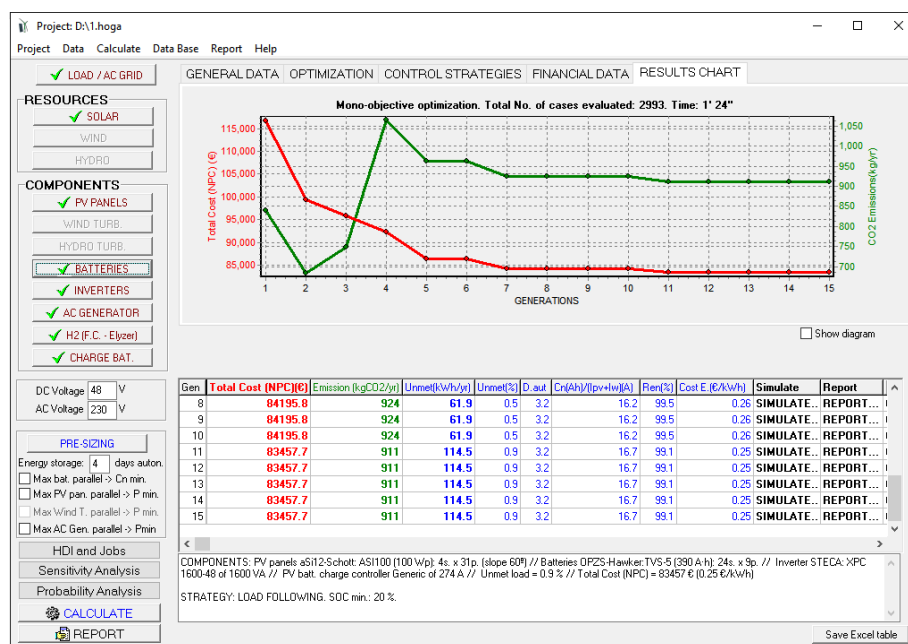
In the case we have selected in the main screen, in the tab "GENERAL DATA" the field "Comparing with Worst Month Method (PV-only)", it also shows the characteristics of the photovoltaic-battery calculated according to the method of the worst month.

Calculation with probability analysis: Only in PRO+ version

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:

A1				fx	Project: 1									
	A	B	**C**	D	**E**	F	**G**	H	**I**	J	**K**	L	**M**	N	O
1	Project: 1														
2	Gen.#		NPC(€)		Em.CO2(kg/yr)		Unmet(kWh/yr)		Unmet(%)		Days auton.		Cn(Ah)/(Isc+Idc)(A)		Renewa
3															
4	0		116670.7		840.27		14.91		0.11		6.68		12.18		!
5	1		99363.8		683.81		33.96		0.26		5.63		7.18		!
6	2		95824.54		748.34		0.61		0		4.93		3.19		
7	3		92282.37		1065.2		0		0		3.15		12.02		
8	4		86393.77		962.8		0		0		3.15		14.77		
9	5		86393.77		962.8		0		0		3.15		14.77		
10	6		84195.8		924.4		61.86		0.47		3.15		16.15		!
11	7		84195.8		924.4		61.86		0.47		3.15		16.15		!
12	8		84195.8		924.4		61.86		0.47		3.15		16.15		!
13	9		84195.8		924.4		61.86		0.47		3.15		16.15		!
14	10		83457.68		911.6		114.49		0.86		3.15		16.68		!
15	11		83457.68		911.6		114.49		0.86		3.15		16.68		!
16	12		83457.68		911.6		114.49		0.86		3.15		16.68		!
17	13		83457.68		911.6		114.49		0.86		3.15		16.68		!
18	14		83457.68		911.6		114.49		0.86		3.15		16.68		!

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, iHOGA asks if we are sure, since the previous results will be lost.
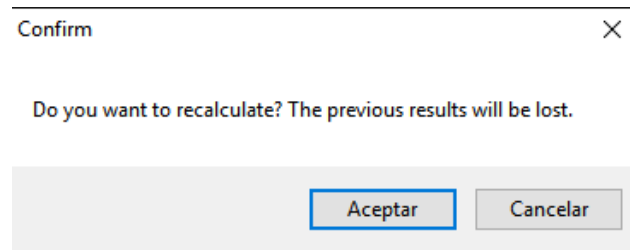
If we want to recalculate, we accept. If we want to save the previous results, press Cancel, save the project, save it as with another name and in the new project we can calculate without losing the results of the original project.

4.2 Mono-objective optimization evaluating all the combinations.

There are two genetic algorithms (main to optimize the combination of components, and secondary to optimize the control strategy). 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 case, the maximum allowed time for the execution of the optimization is the default that appears in the software (15 min), however, in 2 seconds all combinations of components and control strategies are evaluated (there are "few" possible combinations, only 54), so the enumerative method is used.

OPTIMIZATION PARAMETERS SELECTED BY:

◉ iHOGA   ○ USER

Maximum execution time:

`0` h. `15` min.   [Parameters]

☑ Minimum time for the Genetic Algorithms

NUMBER OF CASES AND TIME EXPECTED

Computation speed: 25 cases/second

	EVAL. ALL	POP. (% ALL)	GEN. ALG. (% ALL)
MAIN ALG. (COMB. COMPONENTS):	54 (1x54)	10 (18.52%)	140 (259.26%)
SEC. ALG. (COMB. STRATEGIES):	1	30 (3000%)	408 (40800%)

	MAIN ALG.	SEC. ALG.	NUMBER OF CASES	%	TIME EXPECTED
OPTION 1:	EVAL. ALL	EVAL. ALL.	54	100 %	**0h 0' 2"**
OPTION 2:	EVAL. ALL	GEN. ALG.	22032	40800 %	0h 14' 41"
OPTION 3:	GEN. ALG.	EVAL. ALL.	140	259.3 %	0h 0' 6"
OPTION 4:	GEN. ALG.	GEN. ALG.	57120	105777.8 %	0h 38' 4"

Optimization by means of enumerative method (evaluating all combinations). It is guaranteed to obtain the optimal solution

If we check the "EVALUATE ALL COMB." Option of the main genetic algorithm (in the secondary we also mark it), or if the maximum execution time we allow is sufficient and iHOGA selects the enumerative method (evaluate all the combinations), the system performs all possible combinations of components, and for each one of them it looks for the strategy, by means of the secondary algorithm if it has not been marked the option of "EVALUATE ALL COMB." for the control strategy or evaluating all the possible strategies if that option has been marked. In any case, at the end of evaluating all the combinations, the best N combinations of components, ordered from lowest to highest cost, each with their best strategy, are represented in the table and in the graph. If N is very high, it can take a long time to represent all the solutions. However, since the first solutions represented are the lowest cost and therefore the best solutions, it can be cancelled by the corresponding button, and the representation is stopped.

The following figure shows an example.
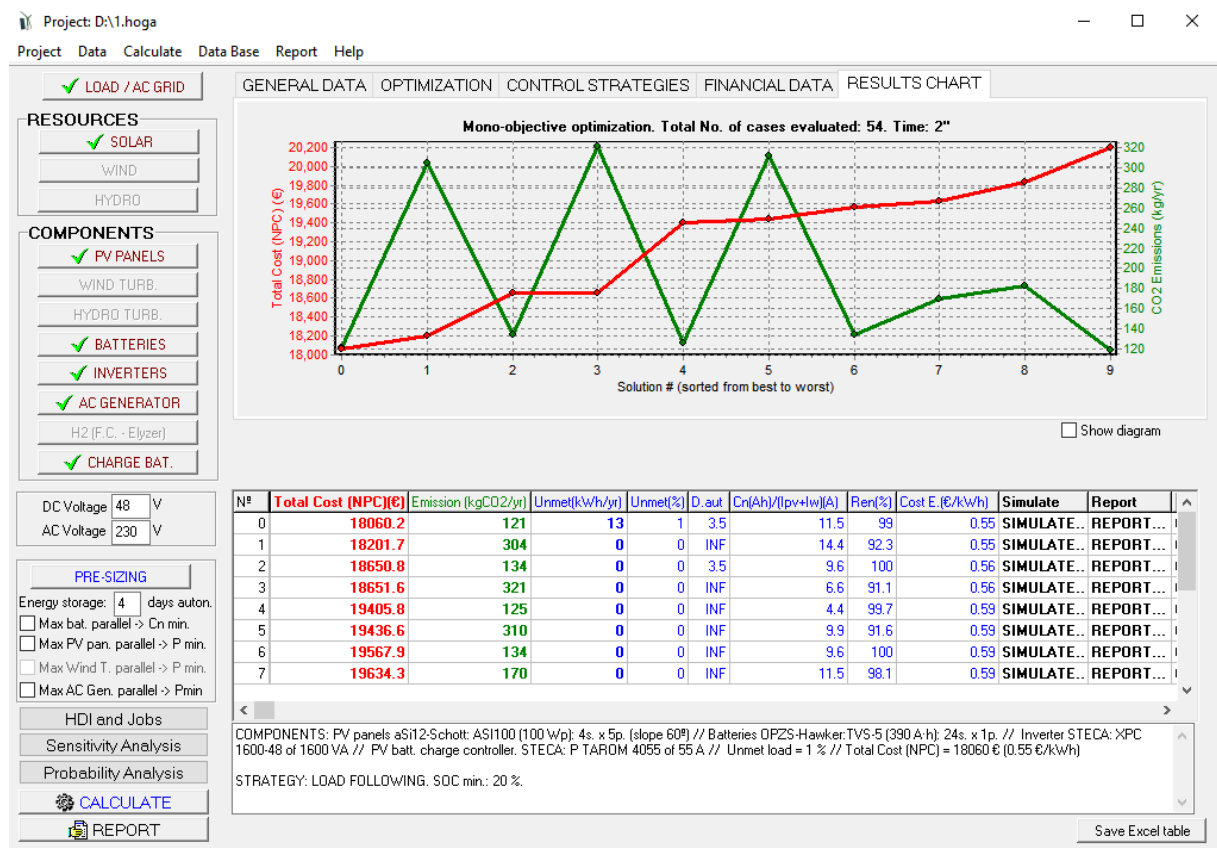
Solutions that do not comply with the constraints (maximum allowed unmet load or other constraints) are assigned the infinite NPC value (1E10). However, to represent graphically it is done with NPC = 0.

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.

4.3 Multi-objective optimization.

In the case of multi-objective optimization, it is intended to minimize (or maximize) different objectives.

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 dominate 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) or other type including the objectives of maximizing the HDI or job creation.

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.
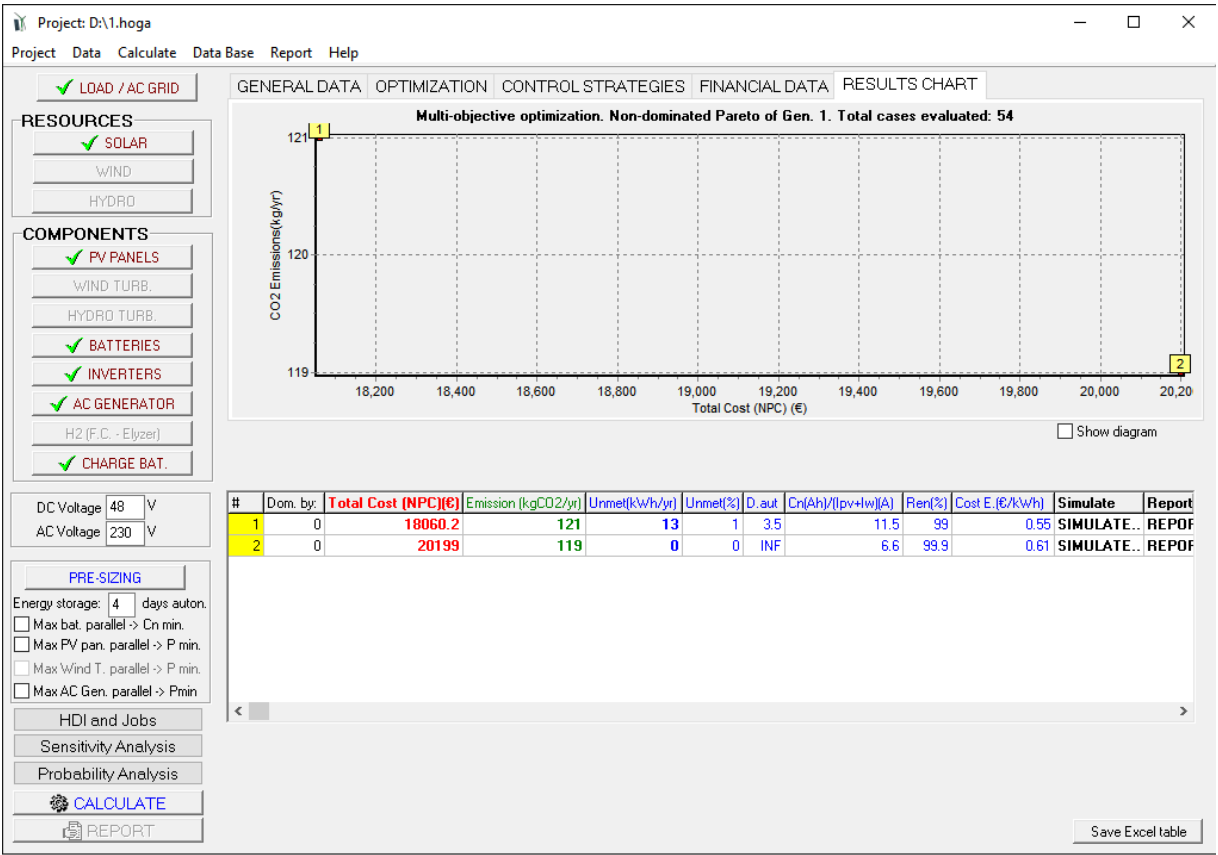
4.4 Results table.

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 (kWh or MWh/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)(€)	Emission (kgCO2/yr)	Unmet(kWh/yr)	Unmet(%)	D.aut	Cn(Ah)/(Ipv+Iw)(A)	Ren(%)	Cost E.(€/kWh)	Simulate	Report
0	53786	2221	0	0	INF	7.2	72.3	0.54	SIMULATE..	REPORT...
1	56887.5	2246	0	0	INF	3.3	72.1	0.57	SIMULATE..	REPORT...
2	56973.8	2237	0	0	INF	5	72.2	0.57	SIMULATE..	REPORT...
3	62329.7	2845	0	0	INF	8.2	63.1	0.63	SIMULATE..	REPORT...
4	65406.7	2866	0	0	INF	5.7	63	0.66	SIMULATE..	REPORT...
5	65695	2881	0	0	INF	3.8	62.9	0.66	SIMULATE..	REPORT...
6	69998.7	3494	0	0	INF	9.6	53.8	0.7	SIMULATE..	REPORT...
7	71988.9	3500	0	0	INF	6.6	53.7	0.72	SIMULATE..	REPORT...

- Maximization of NPV: in blue there is the unmet load (kWh or MWh/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 (€ or k€, which must comply with the constraint) and the LCOE (€/kWh).

Next on the right are the "SIMULATE", "REPORT" and "COSTS" cells that, when clicked, the simulation, report or cost screens are accessed. Next are the results of Human Development Index (HDI) and Jobs created during the life of the system. Then there are the characteristics of the components of each solution (number of modules in series x parallel x power of each panel; slope of the PV modules; number of batteries in series x parallel x capacity of each battery, number of AC generators in parallel x power of each generator, etc).

Simulate	Report	Costs	HDI	Jobs	P. PV pan. (Wp)	Slope(º)	Cn Bat. (Ah)	P. Gen (VA)	P. inv (VA)	P. Wind T. (W
SIMULATE..	REPORT...	COSTS...	0.6212	0.0098	4x8x100	60	24x1x390	1x1900	1600	1x0
SIMULATE..	REPORT...	COSTS...	0.6212	0.0098	4x8x100	60	24x1x180	1x1900	1600	1x0
SIMULATE..	REPORT...	COSTS...	0.6212	0.0098	4x8x100	60	24x1x270	1x1900	1600	1x0
SIMULATE..	REPORT...	COSTS...	0.6212	0.0086	4x7x100	60	24x1x390	1x1900	1600	1x0
SIMULATE..	REPORT...	COSTS...	0.6212	0.0086	4x7x100	60	24x1x270	1x1900	1600	1x0
SIMULATE..	REPORT...	COSTS...	0.6212	0.0086	4x7x100	60	24x1x180	1x1900	1600	1x0
SIMULATE..	REPORT...	COSTS...	0.6212	0.0075	4x6x100	60	24x1x390	1x1900	1600	1x0
SIMULATE..	REPORT...	COSTS...	0.6212	0.0075	4x6x100	60	24x1x270	1x1900	1600	1x0

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) (€) ", there is the column "C. Sec. (€)", which gives an idea of the variable costs that depend on the control strategy (costs of replacement of batteries, AC backup generator, etc., costs of operation and maintenance, fuel ...), that is, costs that are not fixed but depend on the control strategy.

C.sec(€)	STRATEGY	Plim_charge	P2 (W)	P1gen (W)	P1FC (W)	Pmin_gen (W)	Pmin_FC (W)	Disch-FC-first	Pcri_gen (V
37033	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	
41356	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	
39799	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	
46167	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	
48823	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	
50754	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	
54532	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	
56100	LOAD FOLLOWING	INF	925	INF	INF	570	0	0	

- 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.

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 (kWh/year or MWh/year), in blue: Total energy consumed by the load (Etotal), energy generated by renewable sources (Eren) (in low power projects it is not the same as the renewable energy that covers the demand, since the energy generated by renewables can be higher, as there are losses due to efficiencies and conversion from DC to AC), Energy generated by photovoltaic modules (Epv), Energy generated by wind turbines (Ew), Energy generated by the hydraulic turbine (Et), Energy that could be exported to the grid (or energy in excess, 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(kWh/yr)	Eren(kWh/yr)	Epv(kWh/yr)	Ew(kWh/yr)	Et(kWh/yr)	E excess (kWh/yr)	E Sell (kWh/yr)	E Buy (kWh/yr)	E ch. bat (kWh/yr)
3974	3574	3574	0	0	0	0	0	15
3974	3574	3574	0	0	0	0	0	15
3974	3574	3574	0	0	0	0	0	15
3974	3127	3127	0	0	0	0	0	12
3974	3127	3127	0	0	0	0	0	12
3974	3127	3127	0	0	0	0	0	12
3974	2680	2680	0	0	0	0	0	10
3974	2680	2680	0	0	0	0	0	10

It should be noted that sometimes not all excess (export) power can be sold to the AC grid, since some of that excess power may be on the DC bus and the inverter is not enough to evacuate it all to the AC bus. Also the maximum power that can be injected in the grid can be 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 Gen.	Bat. life (yr)	Hours Ch. Bat.	Hours Disch. Bat.	Hours FC	Hours Elyzer.	C. Fuel Gen.(€/yr)	C. Fuel FC(€/yr)	E Buy (€/yr)	E Sell
2444.32	13.05	4257	4298	0	0	720.88	0	0	
2460.33	5.29	4263	4292	0	0	725.58	0	0	
2453.73	8.22	4260	4295	0	0	723.59	0	0	
3189.11	16.88	4102	4316	0	0	952.62	0	0	
3196.89	9.47	4103	4313	0	0	955.08	0	0	
3203.5	5.64	4107	4308	0	0	957.07	0	0	
3938.43	16.28	3751	4501	0	0	1186.29	0	0	
3944.56	11.41	3753	4495	0	0	1188.49	0	0	

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) (€/year or k€/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.(€/yr)	C. Fuel FC(€/yr)	E Buy (€/yr)	E Sell (€/yr)	Sell H2 (€/yr)	C. PV (NPC) (€)	C. Bat. (NPC) (€)	C. Aux. (NPC) (€)	C. Inv.
720.88	0	0	0	0	4995	7467	4860	
725.58	0	0	0	0	4995	10504	4860	
723.59	0	0	0	0	4995	10495	4860	
952.62	0	0	0	0	4469	6779	4860	
955.08	0	0	0	0	4469	9709	4860	
957.07	0	0	0	0	4469	10084	4860	
1186.29	0	0	0	0	3942	6828	3291	
1188.49	0	0	0	0	3942	8685	3291	

Next are the columns also in red that indicate 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)(€ or k€), if maximization of NPV all these columns are called "NPV"+ the element + (€ or k€).

For example, in the case of minimization of NPC, "C PV (NPC) (€)" is the total cost (NPC) of the PV generator, C Bat. (NPC) (€) 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) (€)" 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 because they are revenues and not costs. In the case of net metering actually the cost for the producer-consumer will be the subtraction of both columns (E buy - E sell).

C. PV (NPC) (€)	C. Bat. (NPC) (€)	C. Aux. (NPC) (€)	C. Inv. (NPC) (€)	C. Gen. (NPC) (€)	C. WindT (NPC)	C. Hydro (NPC) (€)	C. FC (NPC) (€)	C. Elyz. (NPC) (€)
4995	7467	4860	3159	10763	0	0	0	0
4995	10504	4860	3159	10827	0	0	0	0
4995	10495	4860	3159	10801	0	0	0	0
4469	6779	4860	3159	14009	0	0	0	0
4469	9709	4860	3159	14040	0	0	0	0
4469	10084	4860	3159	14076	0	0	0	0
3942	6828	3291	3159	17262	0	0	0	0
3942	8685	3291	3159	17286	0	0	0	0

4.4.1. Simulation screen.

We can visualize the simulation of each solution found by iHOGA, 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.

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.
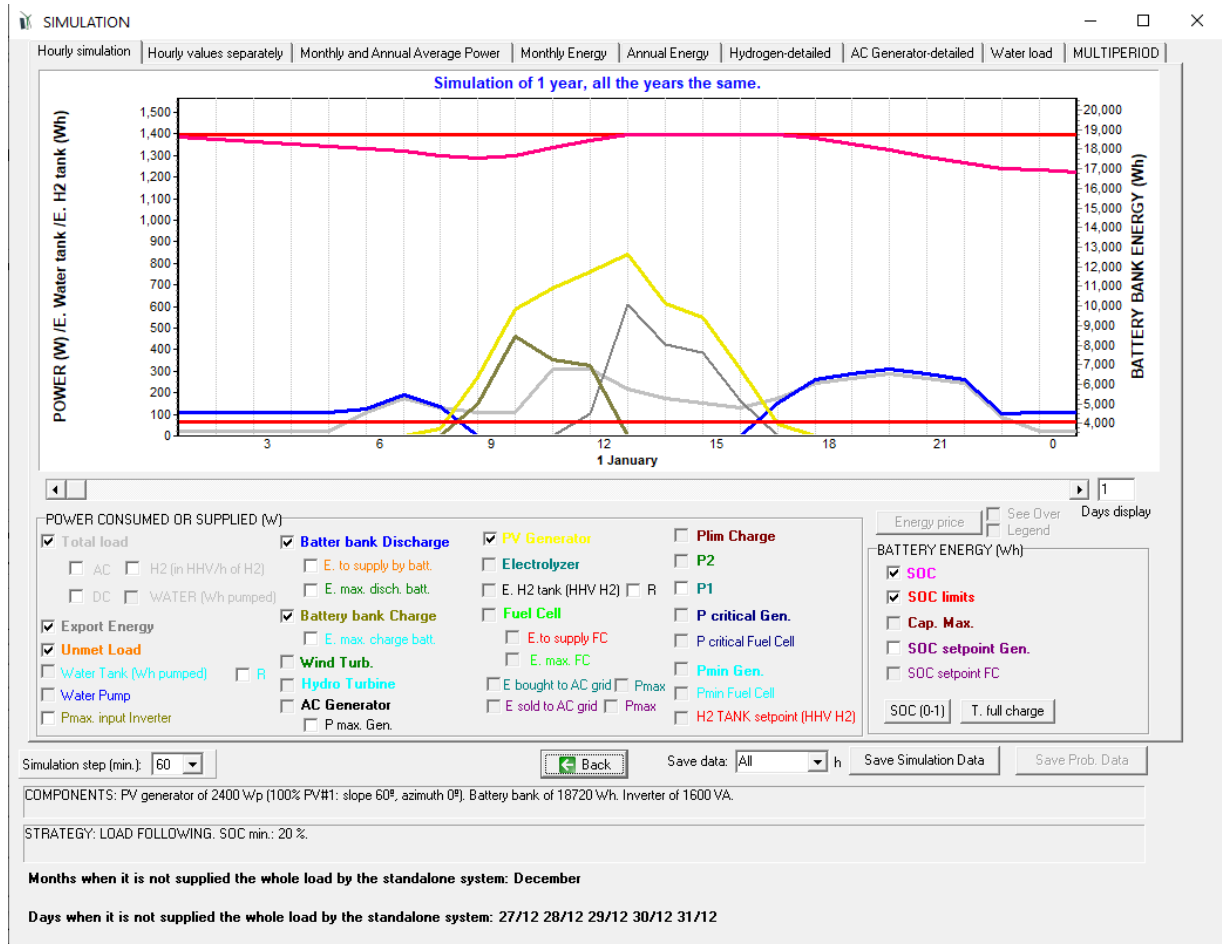
If the battery model is not the Schiffer model, the simulation is seen during 1 year in the time steps that have been used in the optimization. If the model is Schiffer, the simulation is seen during the life of the batteries.

In PRO+ version you can change the simulation time step (under the legend, left):

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, W). The state of charge (SOC) of the batteries refers to the right axis (energy in the battery bank, Wh).

In the case of consumption of H2, the energy of the H2 tank in each moment (Wh) is displayed (referred to the left axis), converted to energy by multiplying by the available H2 kg at each moment by 39400 Wh/kg, this value being the H2 HHV. In this case the value of the variable H2TANKstp, also converted to Wh, 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. If the time step is 1 h and for example on January 1st at 0 h the AC generator supplies 0 W and at 1 h supplies 2000 W (ie 2000 W for 1 h), this is represented by a ramp, which leaves from 0 W to 0 h and reaches 2000 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 2000 W.

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 (Wh) 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 P1, E H2 tank and H2 TANK setpoint). In that case, deselect the box corresponding to that variable to better observe the other variables.

The following figure shows the 10-day display.
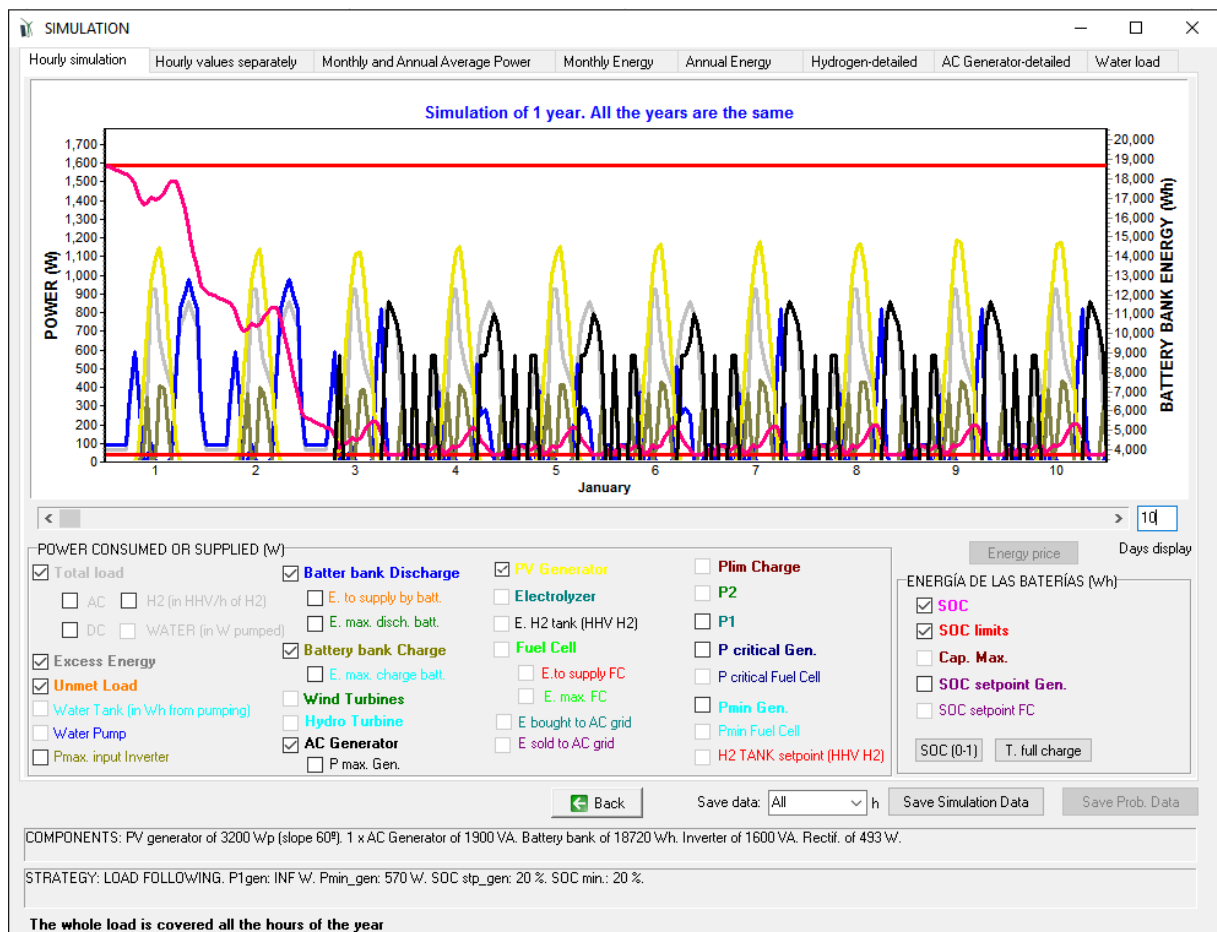
The two buttons on the right side show the battery SOC and the time since the last full charge of the batteries.

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.
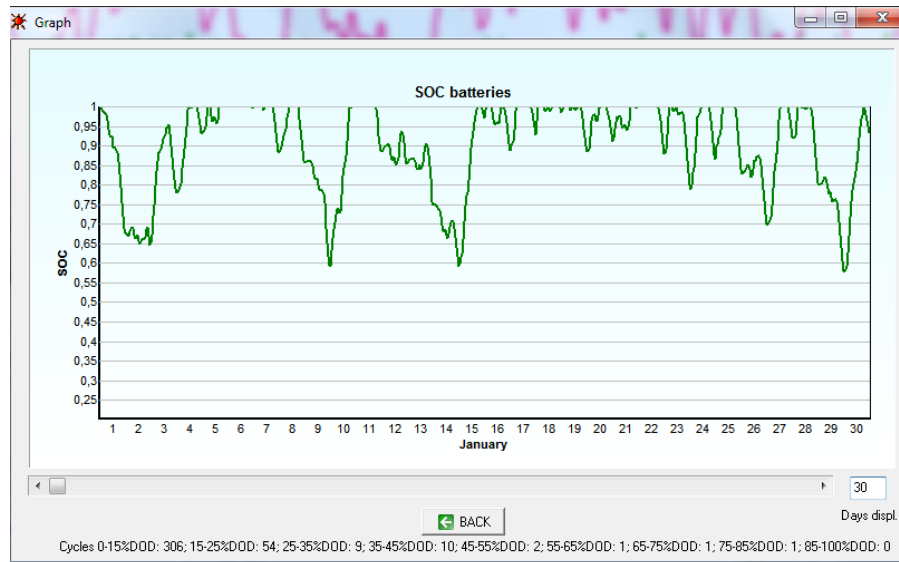
By clicking the "T. full charge" button the following screen appears, in which 100 days are displayed. The number of days since the last complete charge (SOC> 0.95 by default but can be changed on the battery screen) of the batteries (green curve) and the number of complete cycles (blue curve) are displayed.
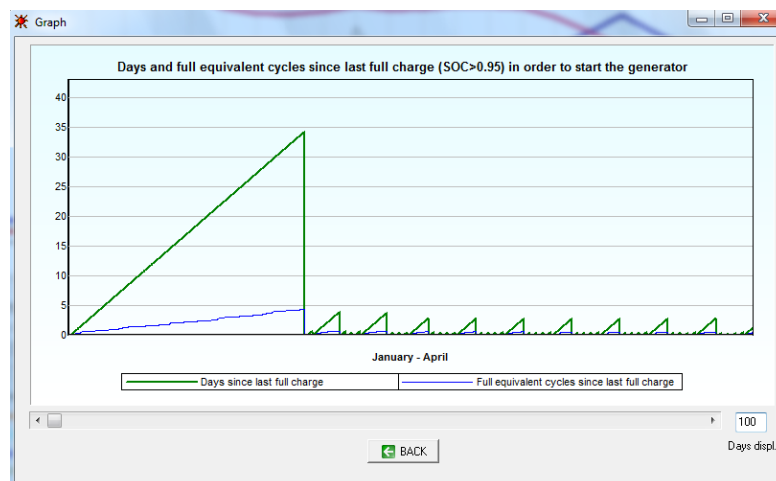
Below the simulation chart, it informs about the components and the control strategy. It also informs of the months and specific days in which the demand load could not be covered in full.

"Hourly values separately" tab:

This tab shows the hourly values for the different energies of the system, each in a different graph.

(*This example of simulation corresponds to a system different from the simulation shown before*)
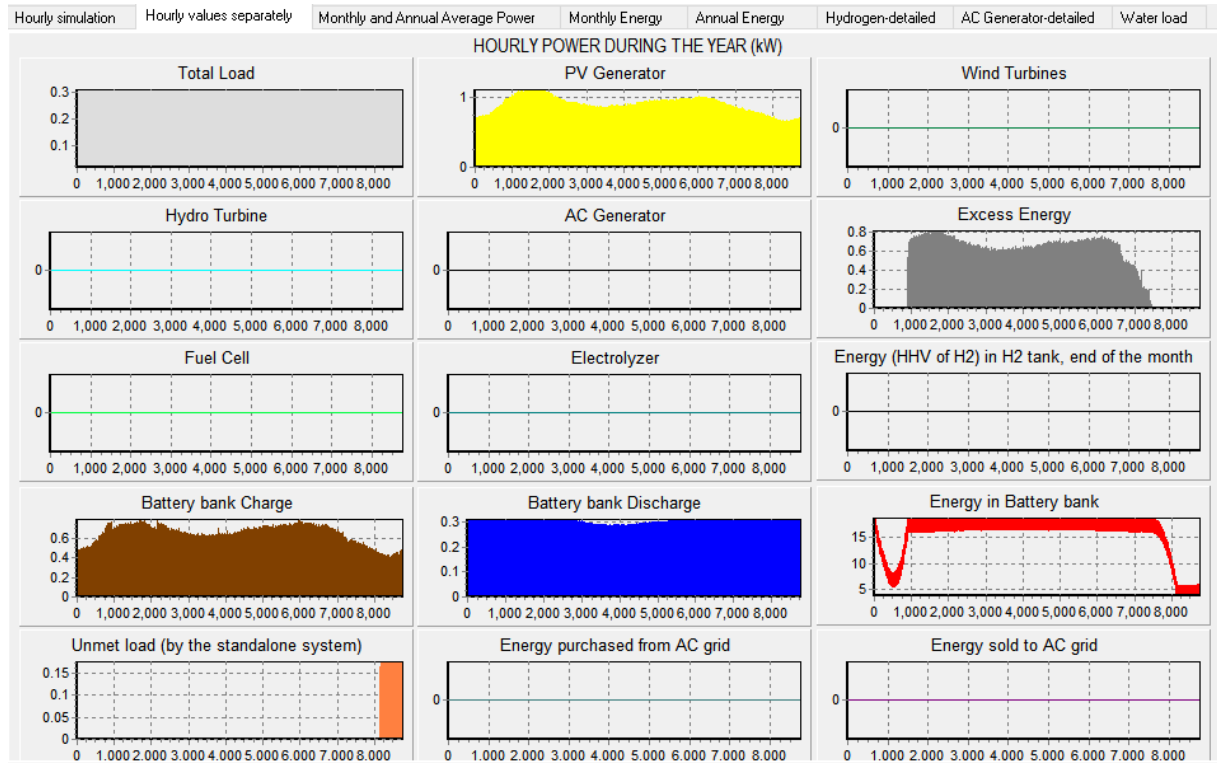
"PDF" tab:

This tab shows the probability density function (PDF) graphs vs. power during the year or vs. energy during the year, for the different power and energy of the components.

By default, this graph is not shown. To show this, go to the OPTIONS (main menu of the software, Project -> OPTIONS) and check the box "**In the simulation window, show the probability density function (PDF) of the main results**":

In multiperiod simulation and/or small time steps, it can take a high extra time to show the simulation screen, this is why this option is by default unselected.

When this option is selected, we see something like this in the third tab of the simulation screen:
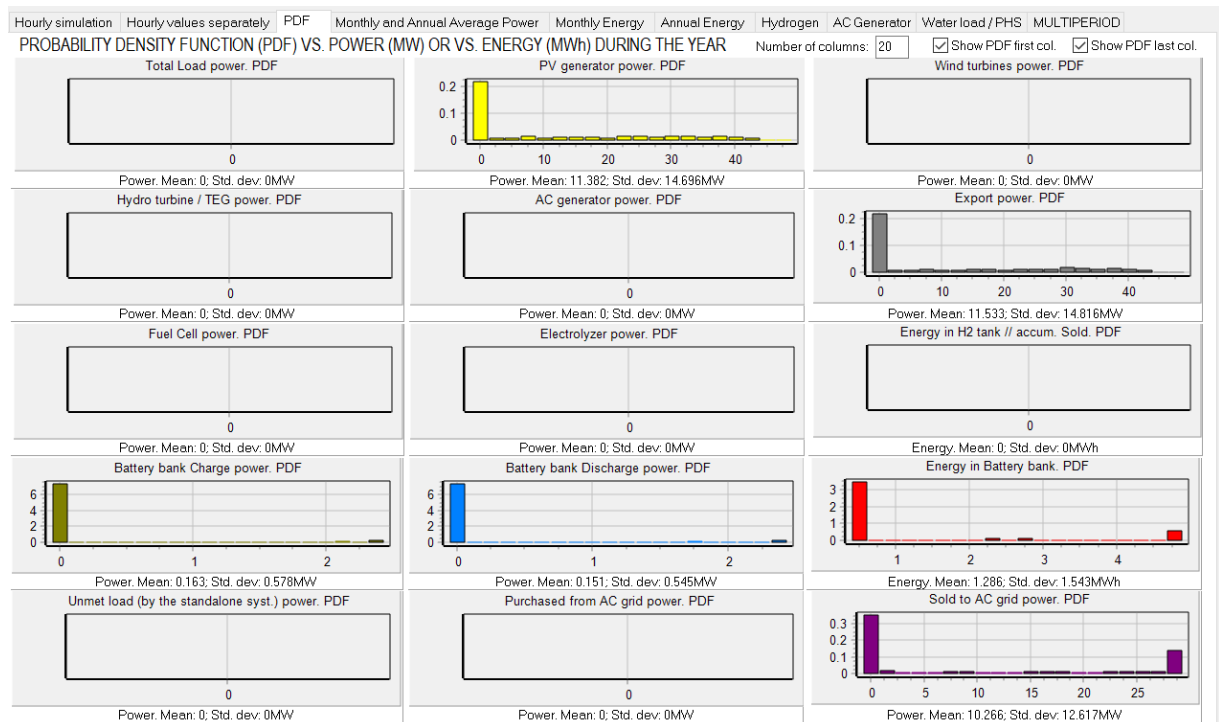
For each component, its power (or energy in the case of the energy in battery bank and energy in H2 tank) during the year is shown in probability density terms (bottom axis is power or energy, left axis is probability density). Of course, as every PDF graph, the integral of each curve is 1 (full probability). Under each graph, the mean of the power or energy during the year and its standard deviation are shown.

In the upper right area, you can change the number of columns to be shown in each graph and you can set the options to show the first column and the last column of each graph.

For example, if you uncheck "**Show PDF first col.**", for the PV generator it won't show the first column (which includes the values of power 0, that is, it won't show the column of the night hours).
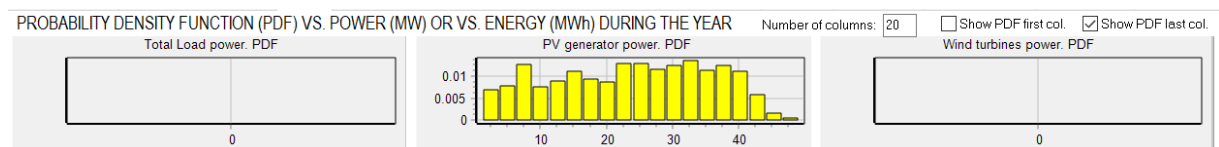
"Monthly and Annual Average Power" tab:

This tab shows, for each month (1 to 12) and for the total of the year, the average values of power (kW) 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).
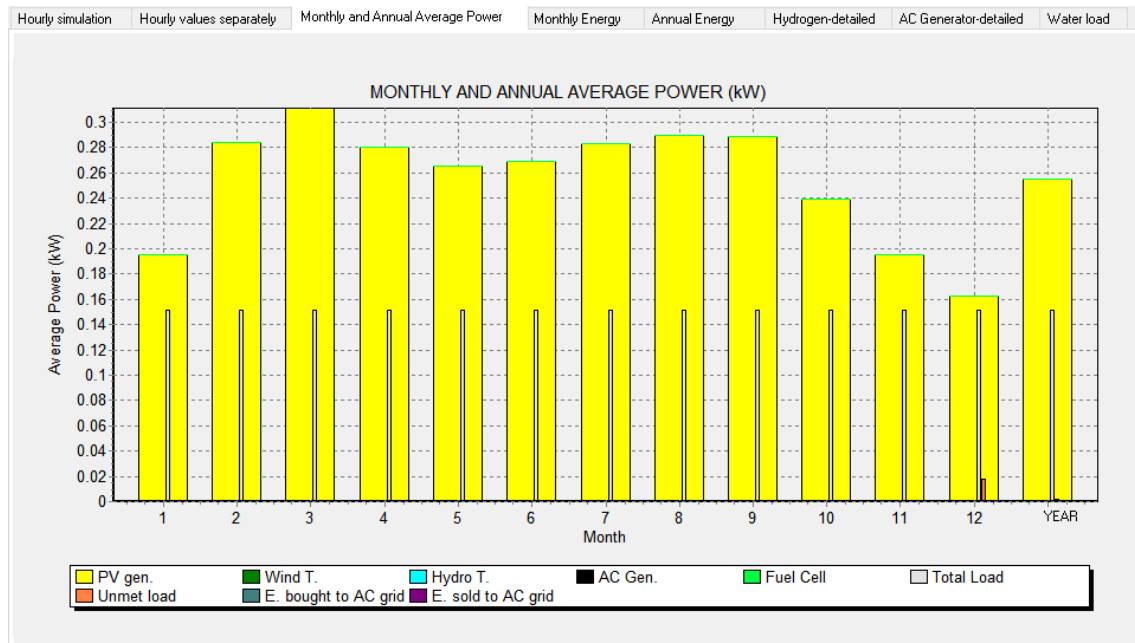
"Monthly Energy" tab:

This tab displays for each month (1-12), monthly energy values (kWh).
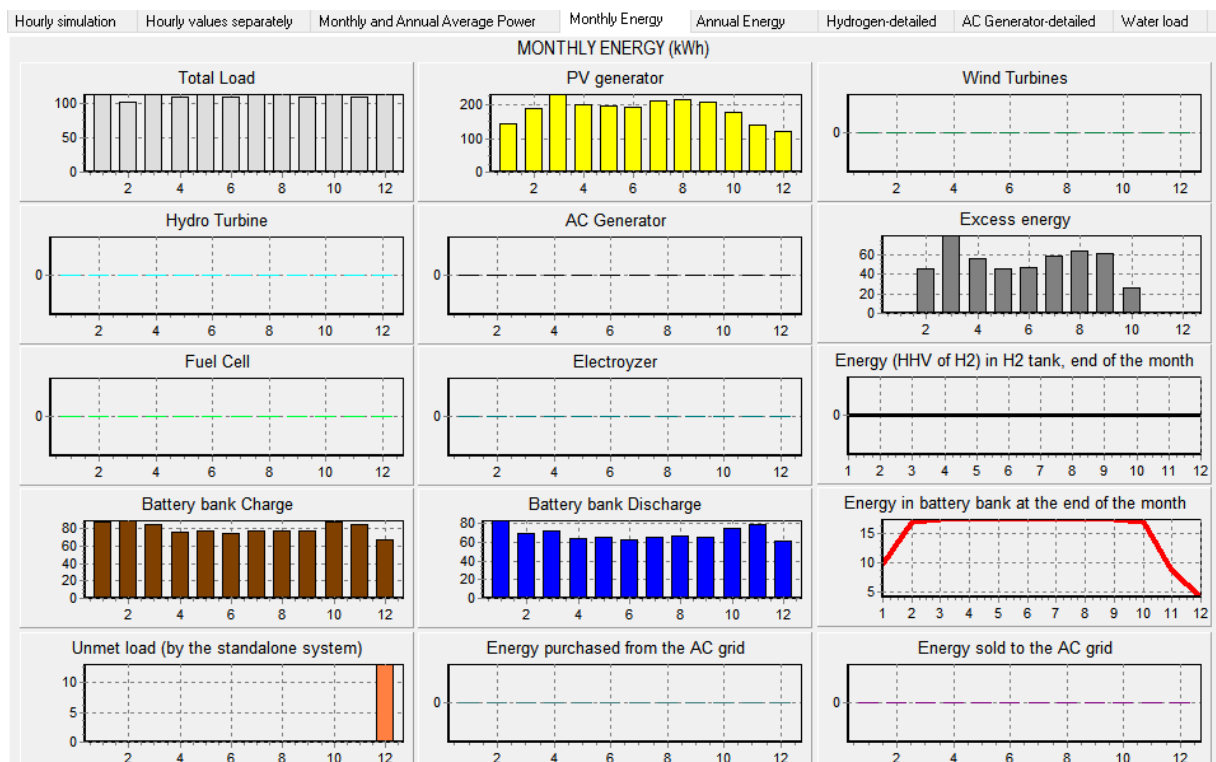
"Annual Energy" tab:

This tab displays total annual energy (kWh) for each component
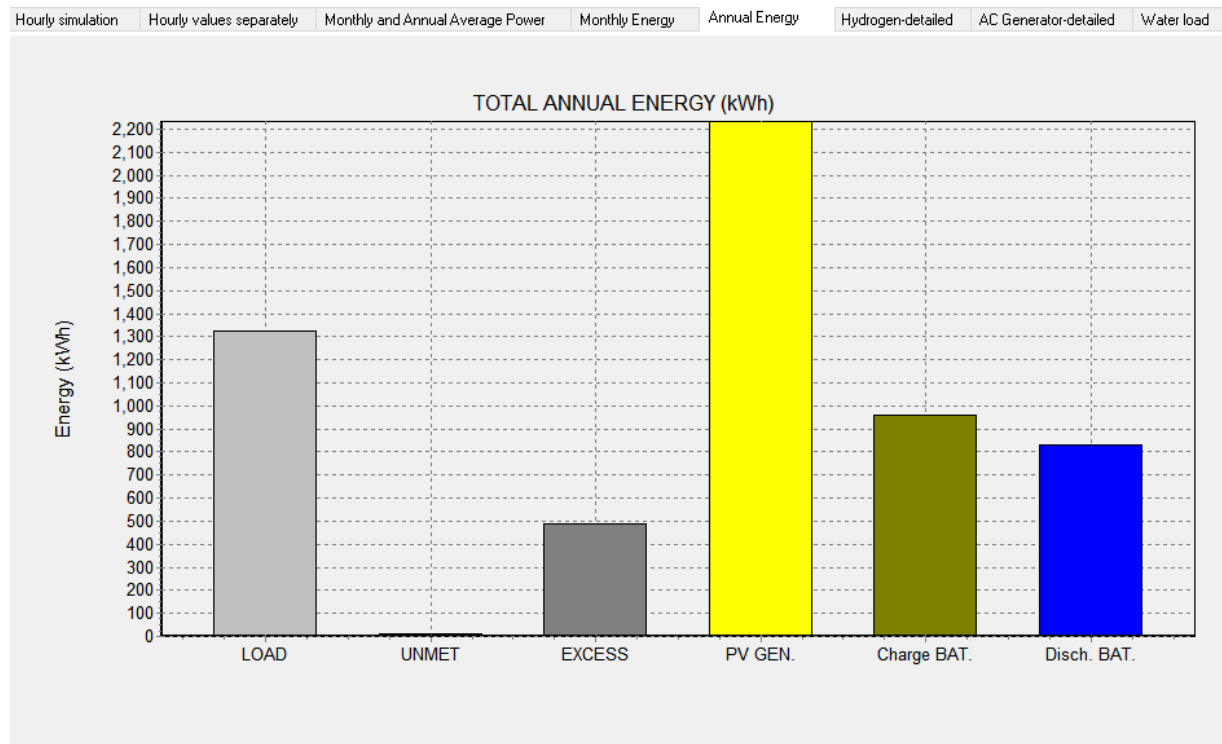
Hydrogen - detailed tab:

Values of hydrogen consumed and generated for each month, in kg and kWh 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*).
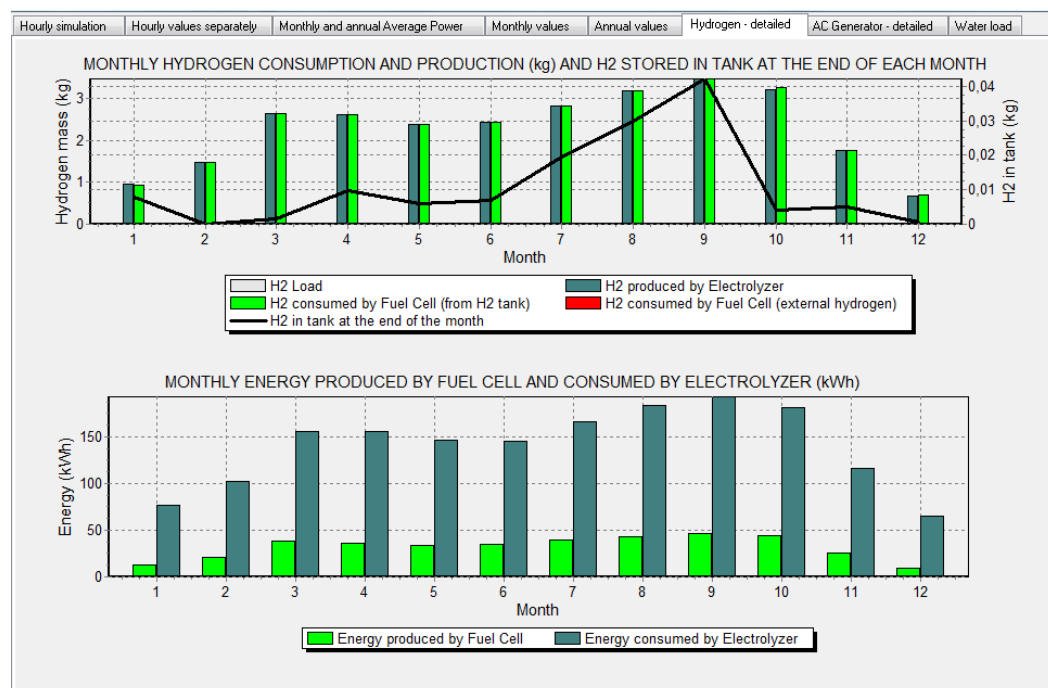
AC generator - detailed tab:

Showing details on consumption and AC generator power. (*The example figure of this simulation corresponds to a system different from the simulation seen before*)**.**
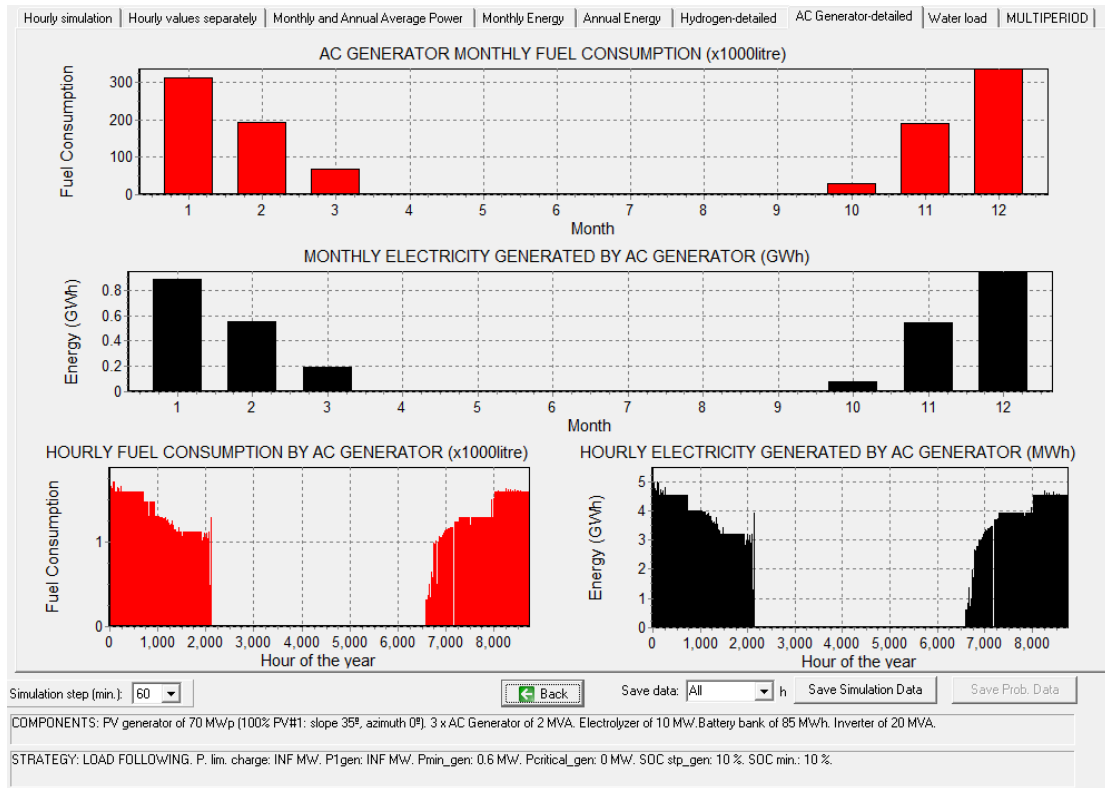
Water load tab:

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 dam3 and MWh 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*)**.**
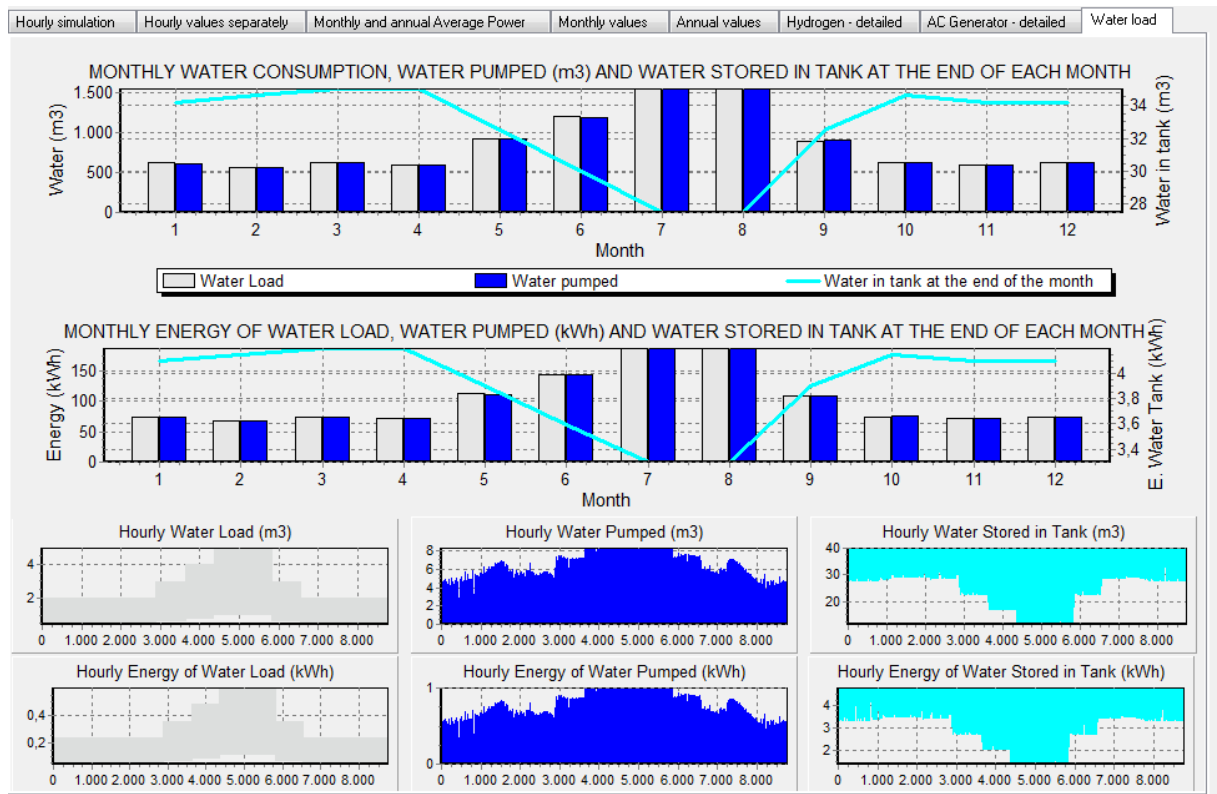
Save simulation data: <mark>Only in PRO+ version</mark>

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

).
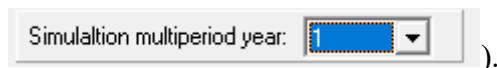
You can save all data used in the simulation or in higher temporal intervals (if the interval is greater than the one used in the simulation, the average of the values of that interval is performed). They are stored in rows (one row for each time interval), in each column the different results of the simulation.
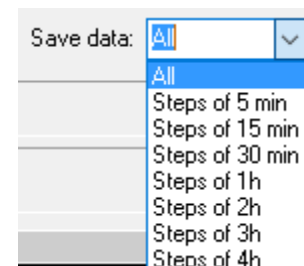
You can choose to save as an Excel file (.xls) or as a text file (.txt). In case of saving as an Excel file, once saved, if we open the file with Microsoft Excel, it reports a message, you must answer "Yes" and it opens correctly.

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.

Project: 1.hoga. Solution # 0

COMPONENTS: PV generator: 3240 Wp (slope 60º). Wind turbines group DC: 546 W. AC Generator: 1900 VA. Batteries bank: 9360 Wh. Inverter: 500 VA. Rectifier(AC/DC): 496 W.

ESTRATEGY: LOAD FOLLOWING. P1gen: INF W. Pmin_gen: 570 W. SOC stp_gen: 20 %. SOC min.: 20 %.

ENERGY HOURLY VALUES. All hourly values of energy are expressed in Wh (H2.Load in HHV of H2). Fuel consumption of AC Generator (Fuel.Gen) is expressed in litre. Prices of selling and purchasing E fo

Cost of AC Generator fuel (Cost.Fuel), and cost of external fuel for 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 $.

Load of Hydrogen (H2_kg.load), H2 used by fuel cell, from H2 tank (Fuel.FC) or externally purchased (Fuel.ext_FC), hydrogen generated by the electrolyzer (Prod_H2) and hydrogen stored in H2 Tank (H2

Date	Hour	Load	AC_load	DC_load	H2_load	H2_kg.load	Water_l	PV	Wind	Hydro	Gener.	Fuel.Gen.	Cost.Fuel.	F.C.	Fuel.
01-ene	0:00	69.96	22	0	0	0	47.96	0	61.63	0	0	0	0	0	0
01-ene	1:00	69.96	22	0	0	0	47.96	0	35.93	0	0	0	0	0	0
01-ene	2:00	69.96	22	0	0	0	47.96	0	18.33	0	0	0	0	0	0
01-ene	3:00	69.96	22	0	0	0	47.96	0	9.2	0	0	0	0	0	0
01-ene	4:00	69.96	22	0	0	0	47.96	0	19.72	0	0	0	0	0	0
01-ene	5:00	69.96	22	0	0	0	47.96	0	10.92	0	0	0	0	0	0
01-ene	6:00	349.8	110	0	0	0	239.8	0	7.04	0	0	0	0	0	0
01-ene	7:00	295.9	176	0	0	0	119.9	0	24.61	0	0	0	0	0	0
01-ene	8:00	251.9	132	0	0	0	119.9	56.87	12.23	0	0	0	0	0	0
01-ene	9:00	181.94	110	0	0	0	71.94	309.42	8.59	0	0	0	0	0	0
01-ene	10:00	181.94	110	0	0	0	71.94	571.72	5.77	0	0	0	0	0	0
01-ene	11:00	403.92	308	0	0	0	95.92	787.64	2.11	0	0	0	0	0	0
01-ene	12:00	427.9	308	0	0	0	119.9	909.31	0.26	0	0	0	0	0	0
01-ene	13:00	411.84	220	0	0	0	191.84	909.31	0	0	0	0	0	0	0
01-ene	14:00	367.84	176	0	0	0	191.84	787.64	0	0	0	0	0	0	0
01-ene	15:00	273.9	154	0	0	0	119.9	571.72	0.3	0	0	0	0	0	0
01-ene	16:00	203.94	132	0	0	0	71.94	309.42	0	0	0	0	0	0	0
01-ene	17:00	223.96	176	0	0	0	47.96	56.87	0.66	0	0	0	0	0	0
01-ene	18:00	289.96	242	0	0	0	47.96	0	0	0	0	0	0	0	0
01-ene	19:00	383.9	264	0	0	0	119.9	0	18.37	0	0	0	0	0	0
01-ene	20:00	453.86	286	0	0	0	167.86	0	11.67	0	0	0	0	0	0
01-ene	21:00	431.86	264	0	0	0	167.86	0	14.22	0	0	0	0	0	0
01-ene	22:00	337.92	242	0	0	0	95.92	0	7.95	0	0	0	0	0	0
01-ene	23:00	135.96	88	0	0	0	47.96	0	2.96	0	0	0	0	0	0
02-ene	0:00	69.96	22	0	0	0	47.96	0	0.93	0	0	0	0	0	0
02-ene	1:00	69.96	22	0	0	0	47.96	0	0	0	0	0	0	0	0
02-ene	2:00	69.96	22	0	0	0	47.96	0	0.9	0	0	0	0	0	0
02-ene	3:00	69.96	22	0	0	0	47.96	0	0	0	0	0	0	0	0
02-ene	4:00	69.96	22	0	0	0	47.96	0	0	0	0	0	0	0	0

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.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
8772	TOTAL MONTHLY VALUES AND TOTAL ANUAL. All energy values are in kWh. Fuel consumption of AC Gen. is expressed in litre. H2 load, H2 used by fuel cell (external or from H2 tank) and H2 generation by electrolyzer are in kg. Co																	
8773	MONTH		Load	AC_load	DC_load	H2_load	H2_load_kg	Water_l	PV	Wind	Hydro	Gener.	Fuel.Gen.	Cost.Fuel	F.C.		Fuel.FC	Fuel.ext_FC C.Fuel.ext
8774	1		186.9	112.5	0	0	0	74.3	182.1	14.9	0	10.8	5.6	9.5	0		0	0
8775	2		168.8	101.6	0	0	0	67.1	208.9	14.3	0	0	0	0	0		0	0
8776	3		186.9	112.5	0	0	0	74.3	301.1	12.5	0	0	0	0	0		0	0
8777	4		180.8	108.9	0	0	0	71.9	302.7	14	0	0	0	0	0		0	0
8778	5		224	112.5	0	0	0	111.5	299.7	6.9	0	0	0	0	0		0	0
8779	6		252.8	108.9	0	0	0	143.9	296.5	4.5	0	0	0	0	0		0	0
8780	7		298.4	112.5	0	0	0	185.8	322.6	6	0	0	0	0	0		0	0
8781	8		298.4	112.5	0	0	0	185.8	343.8	5.9	0	0	0	0	0		0	0
8782	9		216.8	108.9	0	0	0	107.9	358	6	0	0	0	0	0		0	0
8783	10		186.9	112.5	0	0	0	74.3	340	8.9	0	0	0	0	0		0	0
8784	11		180.8	108.9	0	0	0	71.9	234.8	9.6	0	0	0	0	0		0	0
8785	12		186.9	112.5	0	0	0	74.3	161.2	15.5	0	31.3	16.2	27.4	0		0	0
8786	YEAR		Load	AC_load	DC_load	H2_load	H2_load_kg	Water_l	PV	Wind	Hydro	Gener.	Fuel.Gen.	Cost.Fuel	F.C.		Fuel.FC	Fuel.ext_FC C.Fuel.ext
8787	TOTAL		2568.3	1324.9	0	0	0	1243.4	3351.5	119	0	42.2	21.8	36.9	0		0	0
8788																		
8789																		
8790																		
8791	Mettering energy purchased and sold to AC grid: No Net Mettering																	
8792																		
8793	RESULTS FOR HOURLY PERIODS OF PURCHASING AND SELLING ENERGY TO THE AC GRID:																	
8794																		
8795	HOURLY PERIOD P1:																	
8796	MONTH		Unmet Load		Excess E.		Sell E to AC grid		Purchase E from AC grid	Incomes selling E		Cost purchasing E						
8797	1		0		1.26		0		0	0		0						
8798	2		0		24.84		0		0	0		0						
8799	3		0		100.5		0		0	0		0						
8800	4		0		112.05		0		0	0		0						
8801	5		0		58.39		0		0	0		0						
8802	6		0		24.69		0		0	0		0						
8803	7		0		5.55		0		0	0		0						
8804	8		0		26.24		0		0	0		0						
8805	9		0		122.33		0		0	0		0						
8806	10		0		136.85		0		0	0		0						
8807	11		0		37.97		0		0	0		0						
8808	12		0		0		0		0	0		0						
8809	YEAR		Unmet Load		Excess E.		Sell E to AC grid		Purchase E from AC grid	Incomes selling E		Cost purchasing E						
8810	TOTAL		0		650.65		0		0	0		0						
8811																		

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.

8813											
8814	CYCLES OF CHARGE-DISCHARGE OF BATTERIES DURING 1 YEAR:										
8815	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	
8816	Cycles:	326	39	0	0	0	0	0	1	0	
8817											
8818											
8819	MONTHS WITH UNMET LOAD (NOT ALL THE LOAD CAN BE COVERED BY THE STAND-ALONE SYSTEM):										
8820	December										
8821											
8822	MONTHS WITH UNMET LOAD (NOT ALL THE LOAD CAN BE COVERED BY THE STAND-ALONE SYSTEM):										
8823	December, day 27										
8824	December, day 28										
8825	December, day 29										
8826	December, day 30										
8827	December, day 31										
8828											
8829											

4.4.2. Simulation in the case of multiperiod optimization. Only in PRO+ version

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: .

4.4.3. Simulation in case of probability analysis. <mark>Only in PRO+ version</mark>

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 analysis), 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.
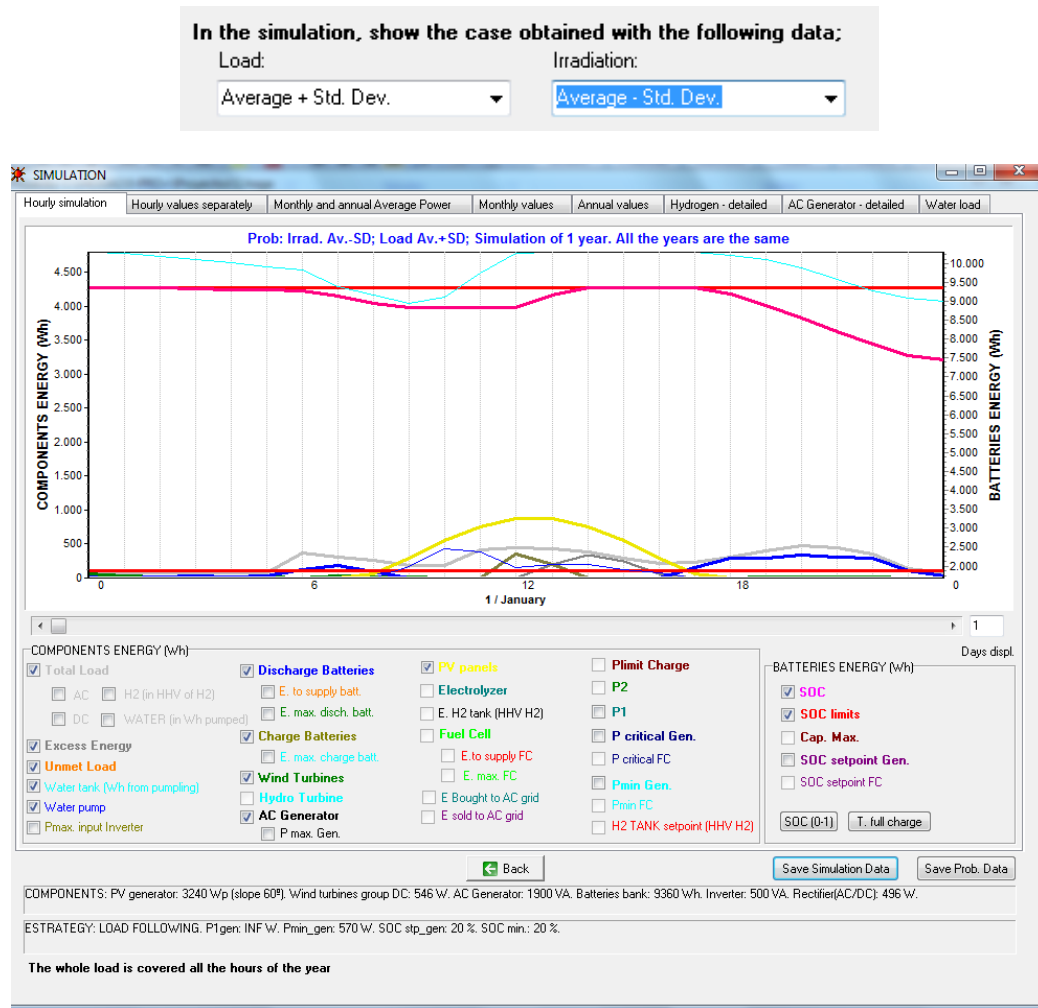
If you click the button **"Save Prob. Data"**, the results of the N+5$^{\text{number probability variables}}$ series are saved in Excel format.

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 analysis, 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.

| A1 | fx | Project: 1.hoga. Solution # 0 |

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Project: 1.hoga. Solution # 0														
2	COMPONENTS: PV generator: 3240 Wp (slope 60º). Wind turbines group DC: 546 W. AC Generator: 1900 VA. Batteries bank: 9360 Wh. Inverter: 500 VA. Rectifier(AC/DC): 496 W.														
3	ESTRATEGY: LOAD FOLLOWING. P1gen: INF W. Pmin_gen: 570 W. SOC stp_gen: 20 %. SOC min.: 20 %.														
4															
5	RESULTS FOR THE DIFFERENT COMBINATIONS OF THE PROBABILITY ANALYSIS:														
6	First 500 rows are the results corresponding to random data series. Next 25 rows correspond to characteristical cases. Next row correspond to the case shown in simulation. Finally MINIMUM, MAXIMUM														
7															
8	Results corresponding to random data series:														
9	Case prob. #		Rad.(kWh/m2/day)		Wind(m/s)		W_flow(l/s)		Load(kWh/day)		C.total(NPV)($)		Energy_cost($/kWh)		Emission(kgCO2/y
10	0		4.65		3.32		3		7.04		28915.1		0.45		299.8
11	1		4.91		3.32		3		7.04		28143.2		0.438		273.5
12	2		4.91		3.32		3		6.77		27479.4		0.445		252.7
13	3		4.7		3.32		3		6.85		28272.6		0.452		277.7
14	4		4.55		3.32		3		7.39		31483.4		0.467		385
15	5		4.82		3.32		3		7.54		30027.8		0.436		335.7
16	6		4.52		3.32		3		7.03		29560.9		0.461		319.5
17	7		4.63		3.32		3		6.87		28525.8		0.455		286.5
18	8		4.44		3.32		3		7.11		30513.5		0.471		352
19	9		4.63		3.32		3		6.31		27192.8		0.473		243
20	10		4.76		3.32		3		7.3		29432.4		0.442		315.5
21	11		4.48		3.32		3		6.45		27856.1		0.474		265.6
22	12		4.86		3.32		3		6.98		28136.4		0.442		273.4
23	13		4.73		3.32		3		6.89		28302.8		0.45		278.7
24	14		4.72		3.32		3		7.52		30795.1		0.449		361.6
25	15		4.8		3.32		3		7.38		29578.8		0.44		320.1
26	16		4.65		3.32		3		7.26		29791.5		0.45		327.4
27	17		4.43		3.32		3		6.98		29683.5		0.466		325.8
28	18		4.86		3.32		3		7.13		28500.1		0.438		285.6
29	19		4.81		3.32		3		7.17		28784		0.44		295.2
30	20		4.64		3.32		3		6.83		28356.2		0.455		280.8
31	21		4.54		3.32		3		7.38		31544.8		0.468		387.3
32	22		4.78		3.32		3		6.92		28204.2		0.447		275.6
33	23		4.48		3.32		3		6.76		28744.3		0.466		294
34	24		4.64		3.32		3		6.54		27604.4		0.463		257
35	25		4.55		3.32		3		6.71		28355.3		0.463		280.7
36	26		4.58		3.32		3		7		29104		0.456		306.1
37	27		5.06		3.32		3		7.03		27691.6		0.432		258.3
38	28		4.69		3.32		3		6.79		28171.7		0.455		274.2

3.xks

Listo   100%

| A1 | fx | Project: 1.hoga. Solution # 0 |

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
509	499		4.45		3.32		3		7.34		32187.2		0.481		408.7
510	Results corresponding to characteristic cases (combinations of data: AVERAGE, AVERAGE+StdDv, AVERAGE+3StdDv, AVERAGE-StdDv, AVERAGE-3StdDv):														
511	Case #		Rad.(kWh/m2/day)		Wind(m/s)		W_flow(l/s)		Load(kWh/day)		C.total(NPV)($)		Energy_cost($/kWh)		Emission(kgCO2/y
512	500		4.65		3.32		3		7.04		28915.1		0.45		299.8
513	501		4.65		3.32		3		7.34		30204.3		0.451		341.5
514	502		4.65		3.32		3		7.94		35763.6		0.494		526.4
515	503		4.65		3.32		3		6.74		28078.9		0.457		273.1
516	504		4.65		3.32		3		6.14		27007.7		0.482		236.6
517	505		4.85		3.32		3		7.04		28276.3		0.44		277.9
518	506		4.85		3.32		3		7.34		29184.8		0.436		306.8
519	507		4.85		3.32		3		7.94		32599.8		0.45		420.9
520	508		4.85		3.32		3		6.74		27542.7		0.448		254.8
521	509		4.85		3.32		3		6.14		26751		0.478		228
522	510		5.25		3.32		3		7.04		27255.8		0.424		245.2
523	511		5.25		3.32		3		7.34		27908.7		0.417		265.2
524	512		5.25		3.32		3		7.94		29621.7		0.409		321.9
525	513		5.25		3.32		3		6.74		26949.8		0.438		234.4
526	514		5.25		3.32		3		6.14		25911.5		0.463		219.4
527	515		4.45		3.32		3		7.04		30002.7		0.467		334.7
528	516		4.45		3.32		3		7.34		32187.2		0.481		408.7
529	517		4.45		3.32		3		7.94		39263.6		0.542		643
530	518		4.45		3.32		3		6.74		28776.2		0.468		295
531	519		4.45		3.32		3		6.14		27225.7		0.486		244.1
532	520		4.05		3.32		3		7.04		35469.5		0.552		518.5
533	521		4.05		3.32		3		7.34		39035.6		0.583		637.5
534	522		4.05		3.32		3		7.94		47546.6		0.657		904.7
535	523		4.05		3.32		3		6.74		31968.1		0.52		401.6
536	524		4.05		3.32		3		6.14		28364.6		0.507		282.7
537	Results corresponding to case shown in simulation:														
538	Case #		Rad.(kWh/m2/day)		Wind(m/s)		W_flow(l/s)		Load(kWh/day)		C.total(NPV)($)		Energy_cost($/kWh)		Emission(kgCO2/y
539	525		4.45		3.32		3		7.34		32187.2		0.481		408.7
540															
541	Values MINIMUM, MAXIMUM, AVERAGE and STD. DEV. of each result obtained in the 500 series:														
542	VALUE		Rad.(kWh/m2/day)		Wind(m/s)		W.flow(l/s)		Load(kWh/day)		C.total(NPV)($)		Energy_cost($/kWh)		Emission(kgCO2/y
543	MINIMUM:		4.03		3.32		3		6.09		26845.8		0.417		231.2
544	MAXIMUM:		5.19		3.32		3		7.99		37378.2		0.571		581.1
545	AVERAGE:		4.67		3.32		3		7.03		29215.5		0.455		309.5
546	STD.DEV.:		0.19		0		0		0.3		1598.2		0.017		52.9

3.xks

Listo   100%

4.4.4. Simulation in the case of "Schiffer" lead-acid battery model. <mark>Only in PRO+ version</mark>

In the case of using the battery model "Schiffer" (for lead-acid batteries), the simulation is performed until the end of the lifespan of the batteries. For example, in the case of the figure below, the batteries lifespan is 9.31 years.
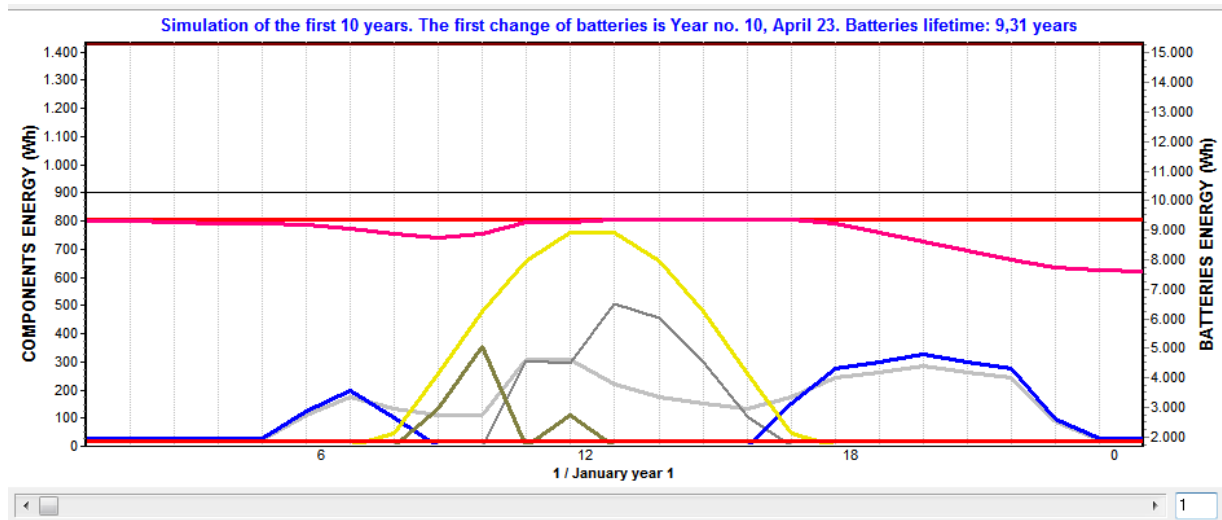
The following figure shows the simulation of the first 10 years (3649 days display). You can see how in the year 10, on April 23, the maximum capacity of the battery (brown curve) has dropped to 80% of its nominal value (9360Wh * 80/100 = 7494 Wh), indicating that battery has exhausted its useful life and must be replaced. This day the batteries are replaced.
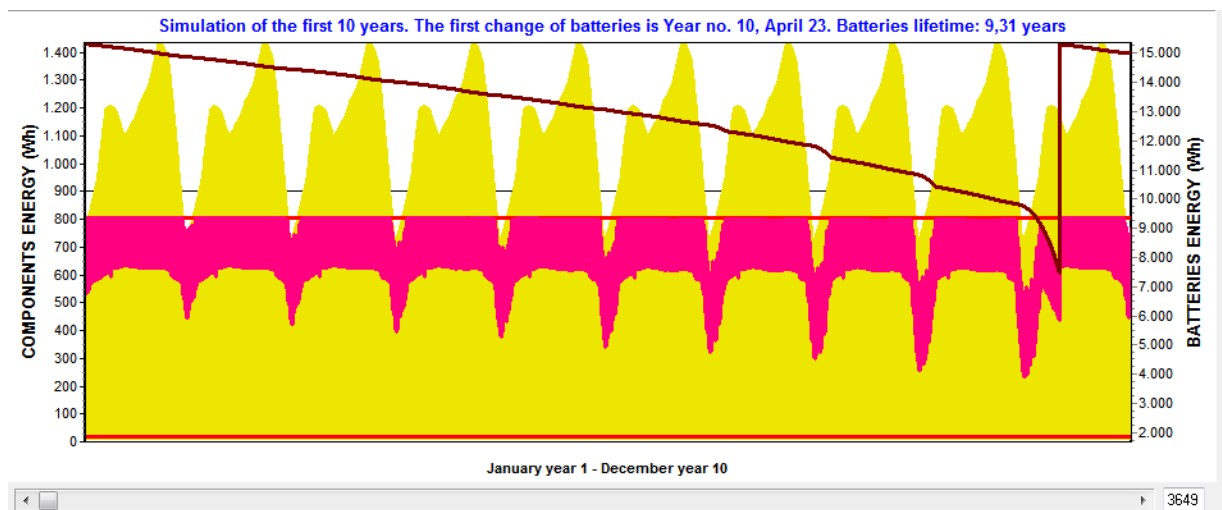
By clicking on the buttons on the right of the screen simulation, different variables appears in a new simulation screen:

- SOC(0-1): SOC of the battery bank, in per unit (in Figure 10 years displyed, 3649 days):
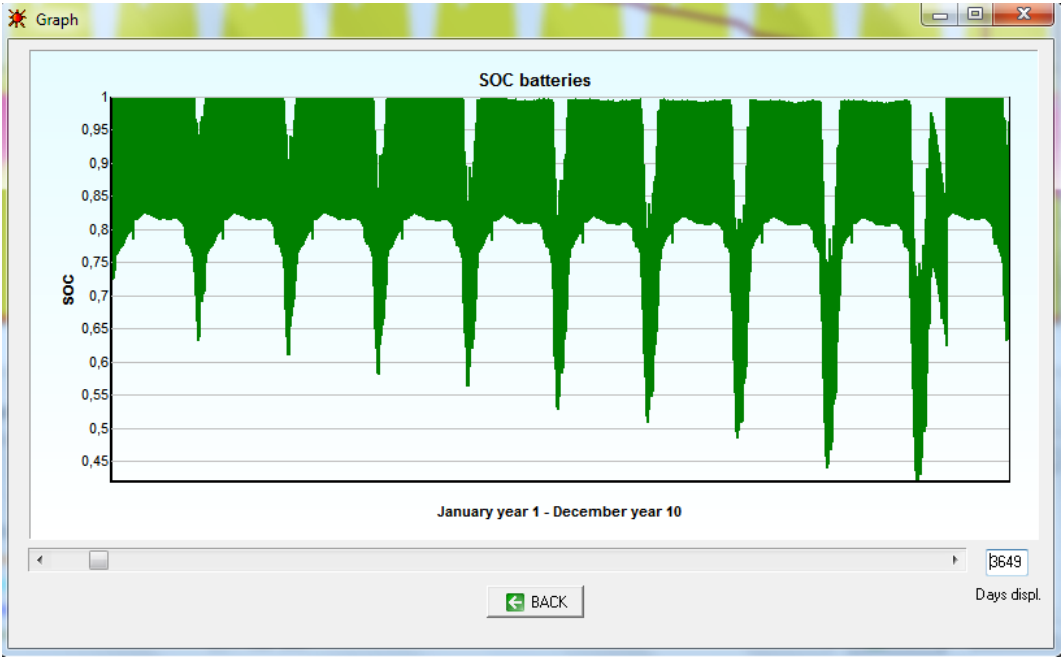
- T. full charge: Time and equivalent cycles since the last full charge
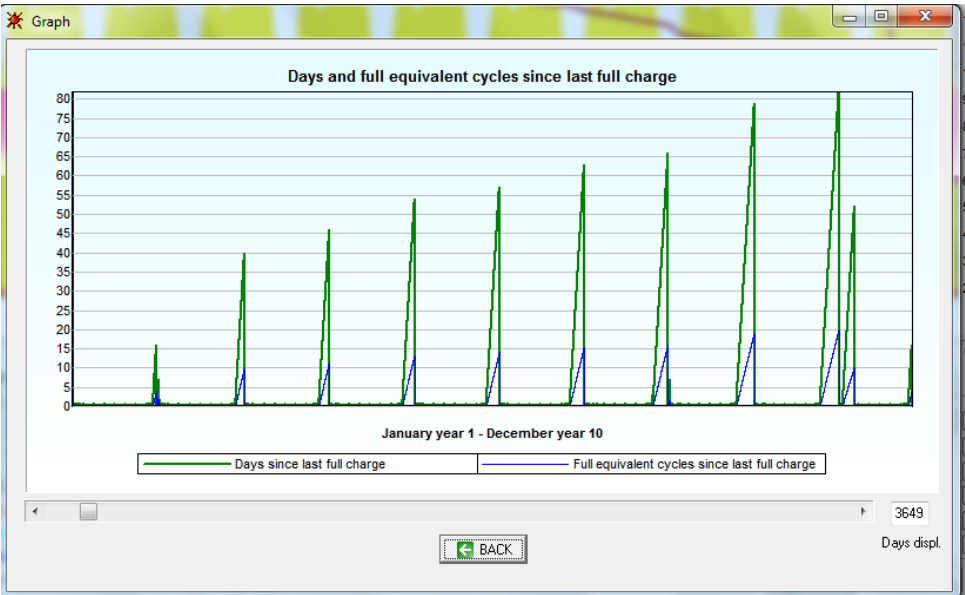
- V Battery: Battery voltage and cutting limits (in Figure 1 days display):
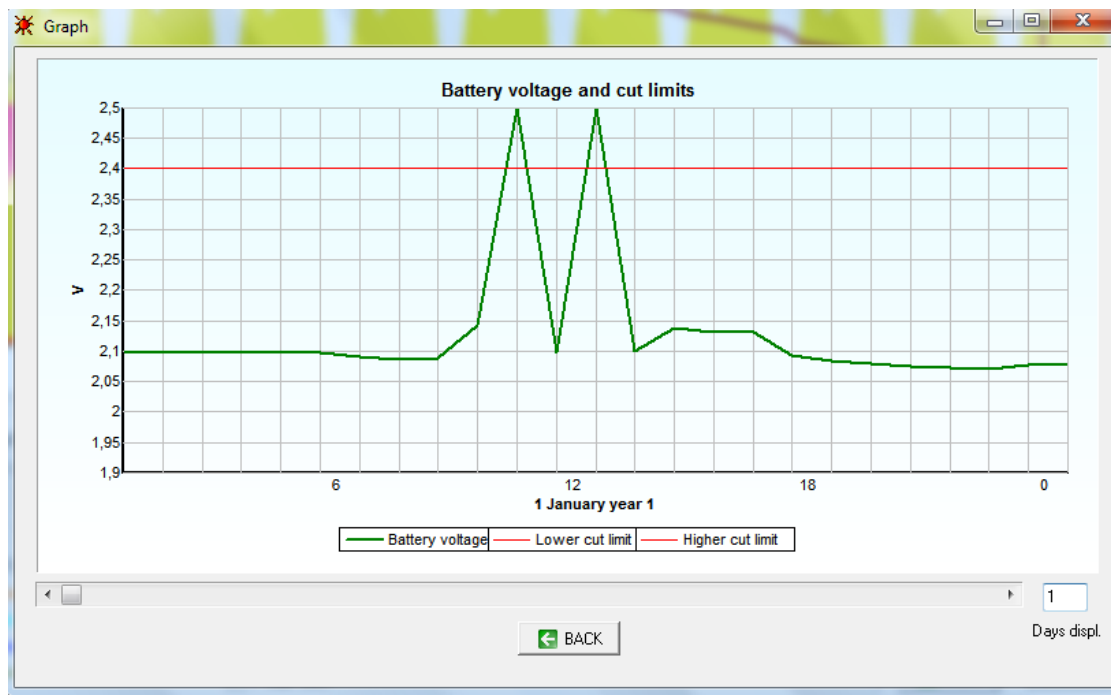
- Capacity. Is displayed (in Figure 10 years displayed, 3649 days):
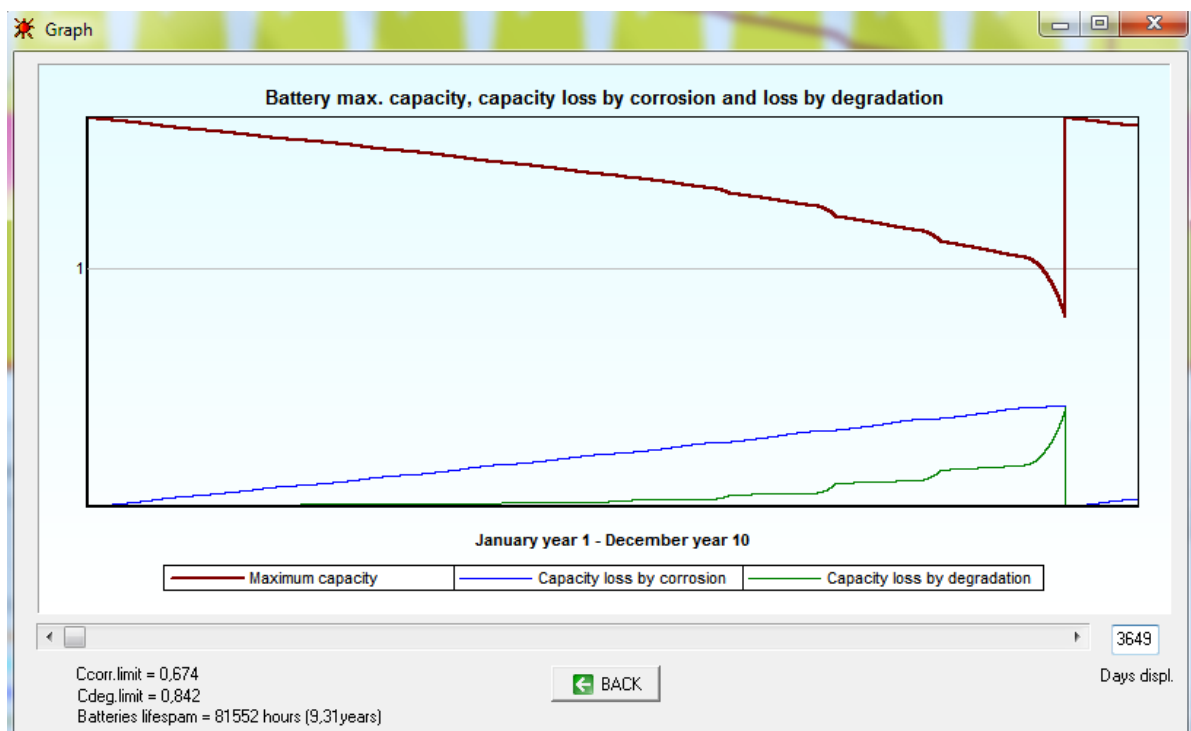
It is shown the maximum capacity in brown, with the end of lifespan when it reaches 80%, the loss of capacity for degradation (green curve) and the loss of capacity due to corrosion (blue curve). It is noted that, in this case, the capacity loss due to corrosion is far greater than by

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):
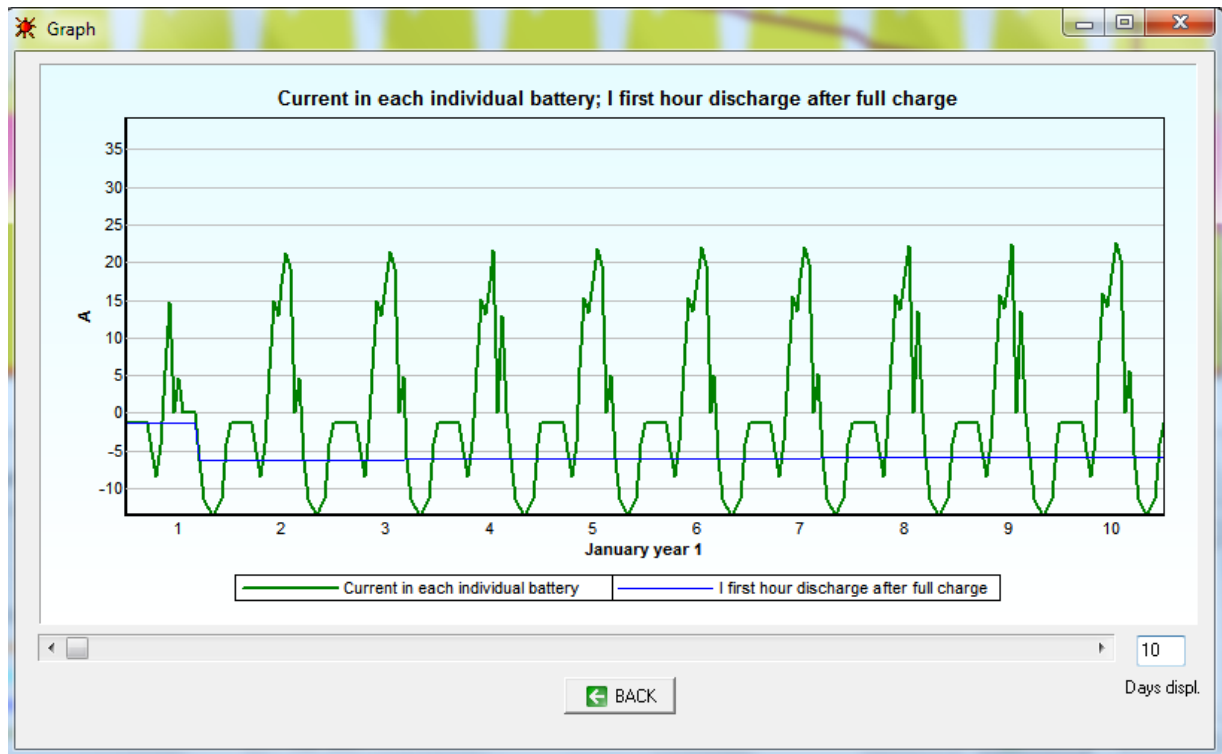
It is shown the current for each individual battery (green curve) and the discharge current for the first hour after full charge (blue curve), very important parameter for calculating the current factor and quantify the effect of sulfation and its degradation effect.

- Factors: factors used in the Schiffer model (in figure display 100 days):
FSOC, FI, Facid, Fplus, Fminus
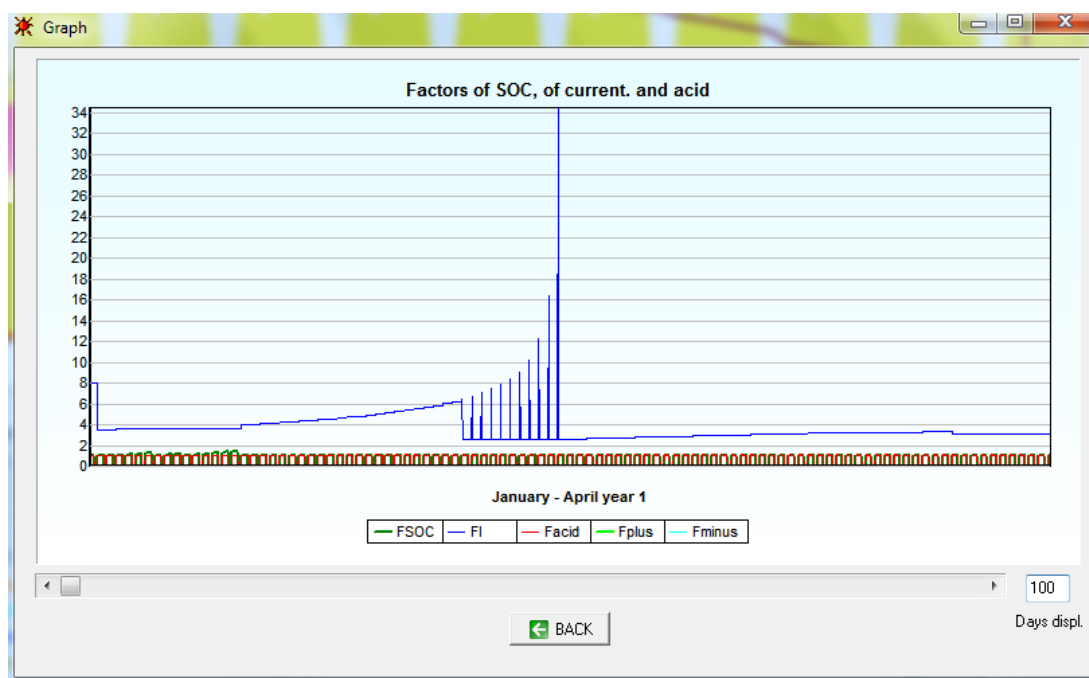
- Cycles: full cycles performed by the batteries (in the figure, displayed 10 years):

It is shown the cycles without weight factors (curve green) and the weight cycles (blue curve).
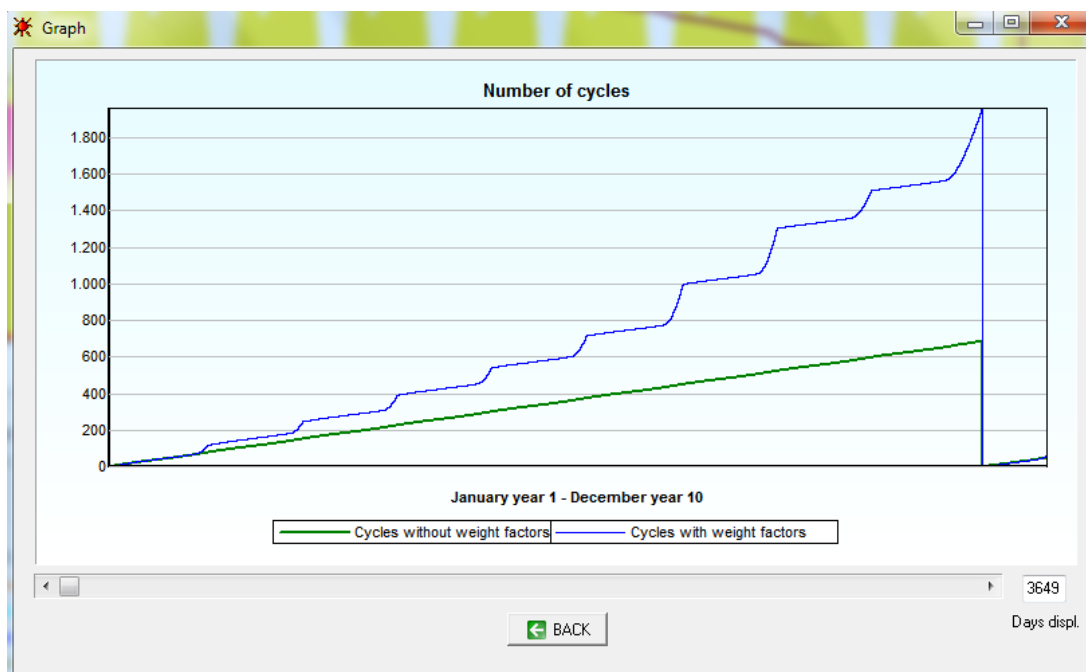
- Bad ch.: Number of bad recharges (not achieved 99% of SOC) (in the figure, displayed 10 years):
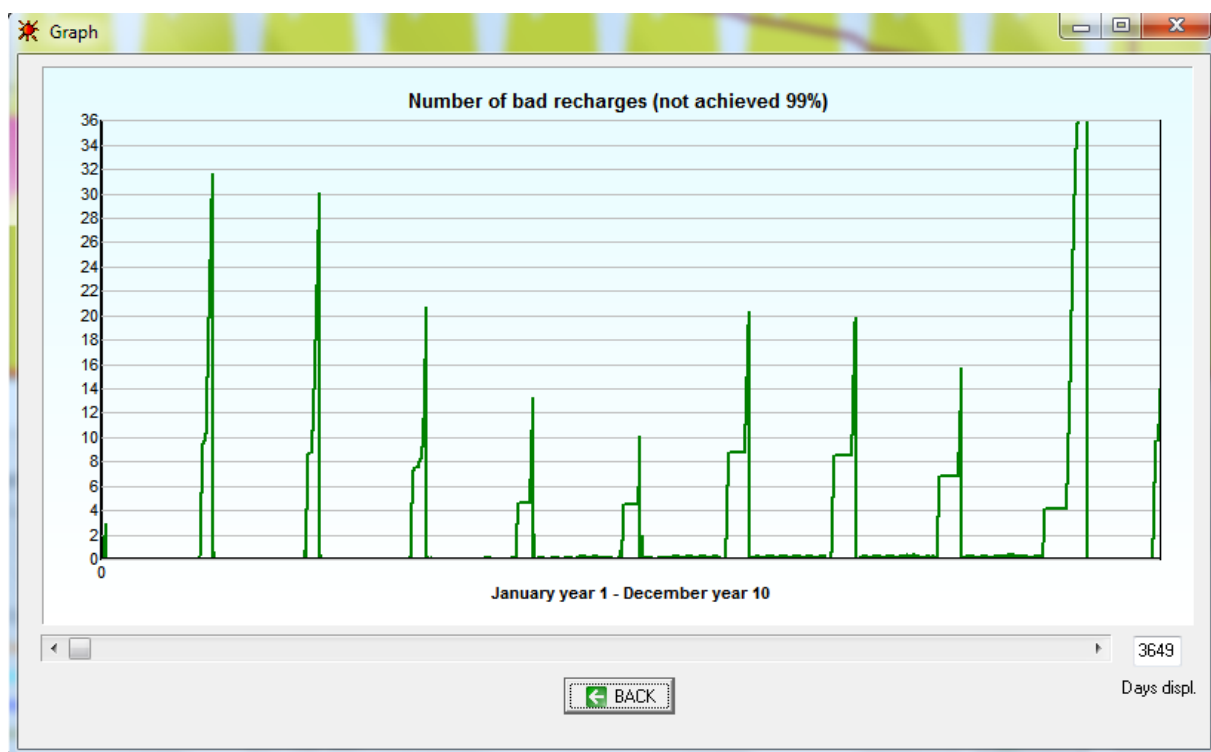
- Resist.: Resistances (charge, discharge and corrosion layer) (in the figure, 10 years of viewing):
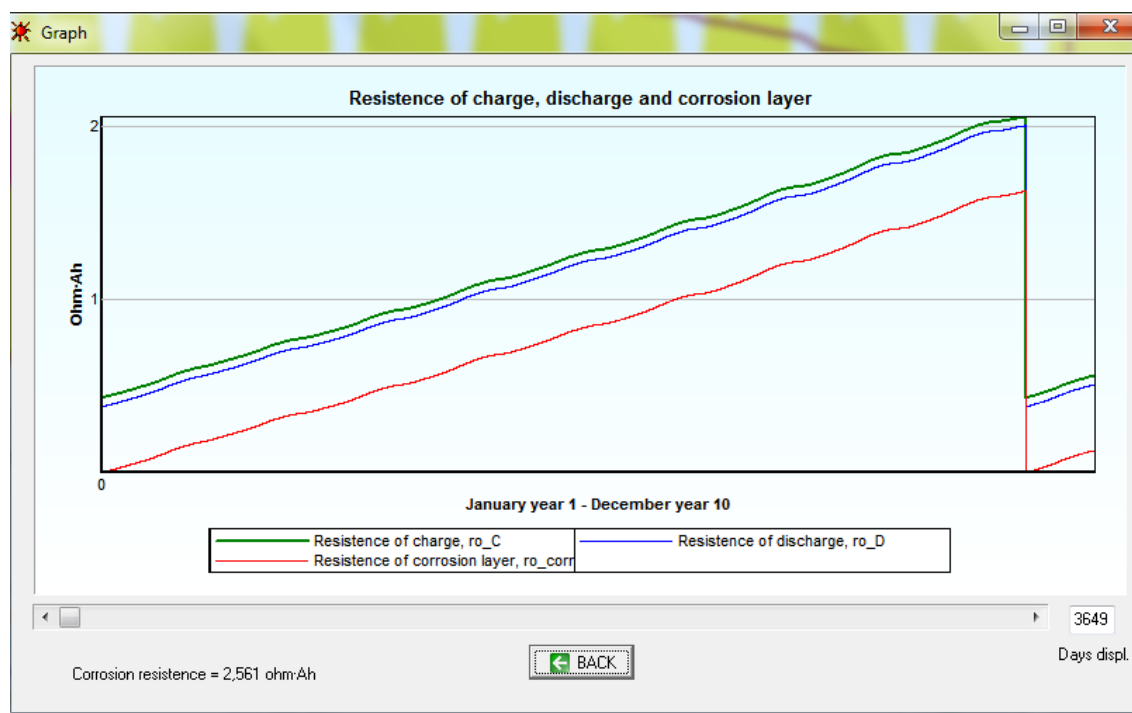
The simulation results shown in the other tabs of the simulation screen (separate hourly values, etc.) refer to last year of the simulation.

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 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.
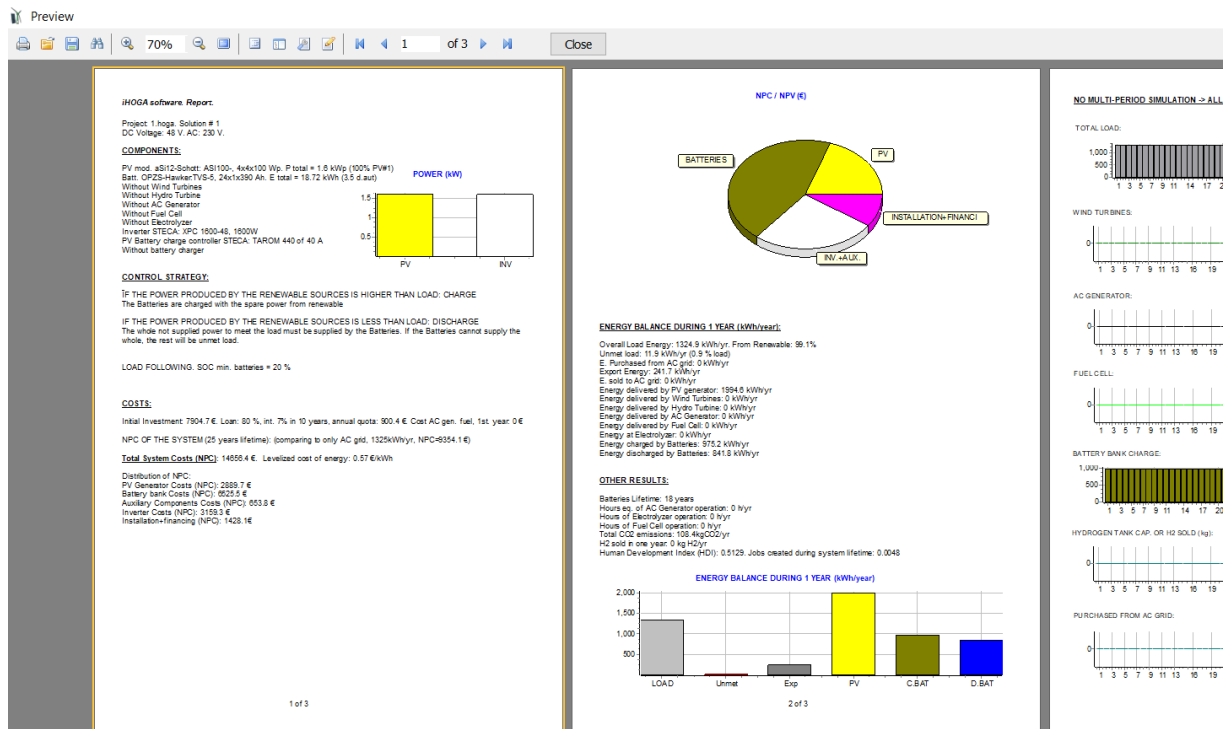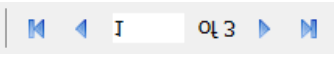
When closing the report, a message appears asking us if we want to save the report in a .rtf file (which can be open by Microsoft Word or other text processors).

Extra Report in the case of probability analysis: <mark>Only in PRO+ version</mark>

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.
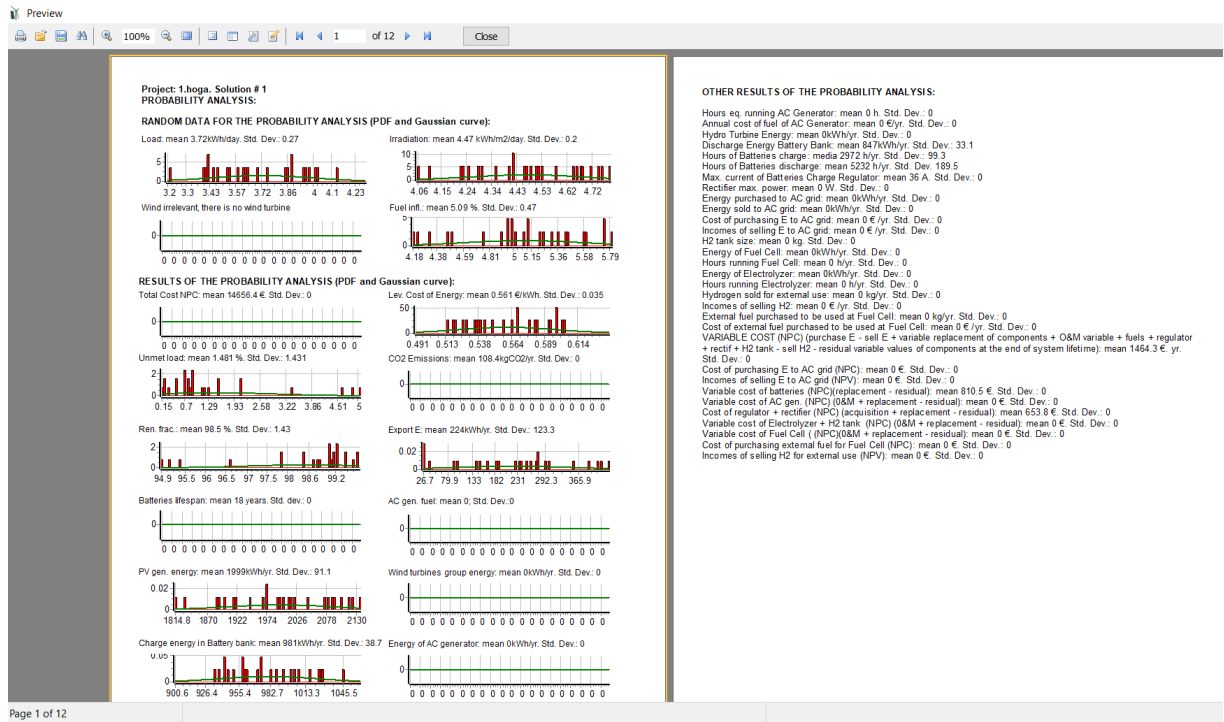
When we close the probability report, a screen appears asking if we want to save the results of the analysis of probability as Microsoft Excel file (same Excel file as the one which is saved when clicking the button **"Save Prob. Data"** in the simulation window shown in section 4.4.2).

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.

Please, note that the cost of the electricty 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.
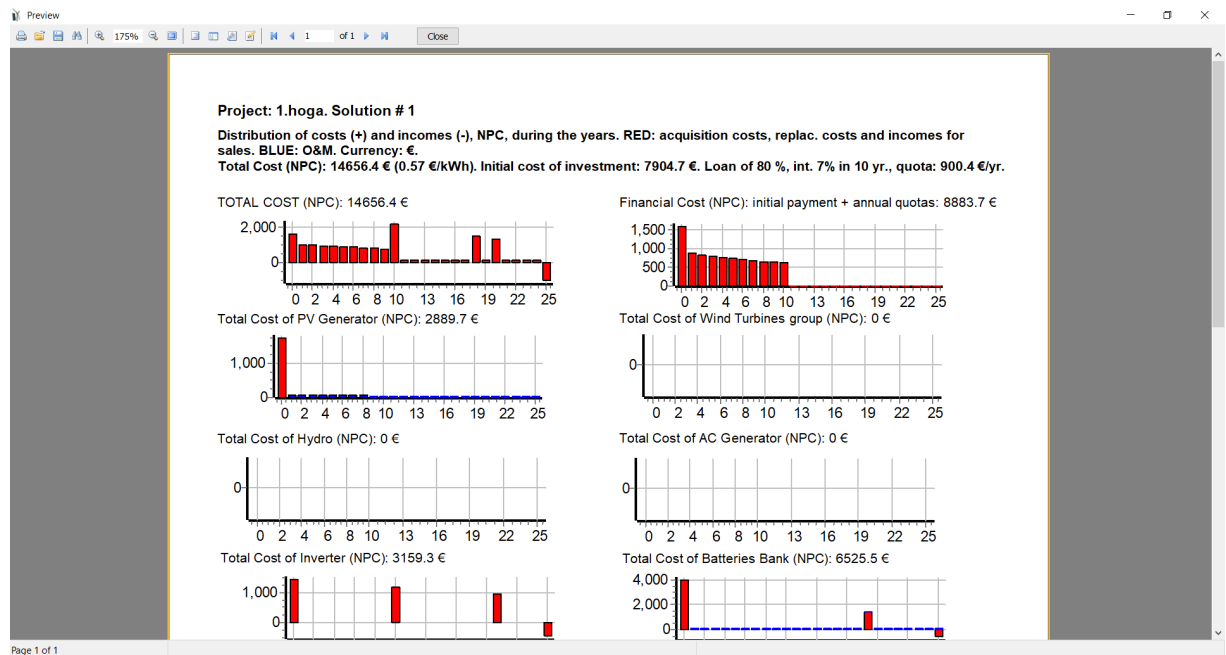
When you close the report a screen appears asking if you want to save the results of the cash flows in the form of Microsoft Excel.
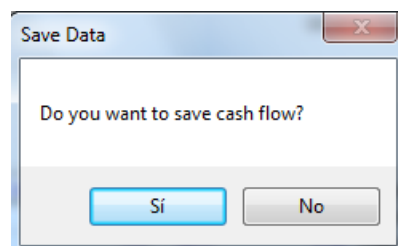
If you click "Yes", you save the file and, when you open it, the cash flow of costs (+ or -, depending on the project type) and incomes (- or +) of the years of the system lifetime are shown for each component, and also for purchasing or selling energy from the AC grid, etc. For each cost or income, 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.

A1 — Project: 1.hoga. Solution # 0

Project: 1.hoga. Solution # 0

CASH FLOW THROUGHOUT SYSTEM LIFETIME.
CASH FLOW OF COSTS (+) AND INCOMES (-):
Initial cost of investment: 15884,3 $(included installation and initial variable costs of 693,8 $). Loan of 80 %
All values in currency: $. Costs +, Incomes -. For each component cahs flow includes initial acquisition cost (year 0), replacement costs (years when the component must be replaced) and incomes of selling the component at th

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 In
	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 ye
0	8642.4	8642.4	0	0	1241.5	1241.5	0	0	0	0	0	0	1040	1040	0	0	0
1	0	0	141.2	135.8	0	0	66.3	63.8	0	0	0	0	0	0	16.7	16.1	
2	0	0	144	133.2	0	0	67.6	62.5	0	0	0	0	0	0	17	15.8	
3	0	0	146.9	130.6	0	0	69	61.3	0	0	0	0	0	0	17.4	15.5	
4	0	0	149.8	128.1	0	0	70.4	60.1	0	0	0	0	0	0	17.7	15.2	
5	0	0	152.8	125.6	0	0	71.8	59	0	0	0	0	0	0	18.1	14.9	
6	0	0	155.9	123.2	0	0	73.2	57.9	0	0	0	0	0	0	18.4	14.6	
7	0	0	159	120.8	0	0	74.7	56.7	0	0	0	0	0	0	18.8	14.3	
8	0	0	162.2	118.5	0	0	76.2	55.6	0	0	0	0	0	0	19.2	14	
9	0	0	165.4	116.2	0	0	77.7	54.6	0	0	0	0	0	0	19.6	13.8	
10	0	0	168.7	114	740.7	500.4	79.2	53.5	0	0	0	0	0	0	20	13.5	6
11	0	0	172.1	111.8	0	0	80.8	52.5	0	0	0	0	0	0	20.4	13.2	
12	0	0	175.6	109.7	0	0	82.4	51.5	0	0	0	0	0	0	20.8	13	
13	0	0	179.1	107.5	0	0	84.1	50.5	0	0	0	0	0	0	21.2	12.7	
14	0	0	182.6	105.5	0	0	85.8	49.5	0	0	0	0	0	0	21.6	12.5	
15	0	0	186.3	103.4	0	0	87.5	48.6	0	0	0	0	0	0	22	12.2	
16	0	0	190	101.5	0	0	89.2	47.6	0	0	0	0	0	0	22.5	12	
17	0	0	193.8	99.5	0	0	91	46.7	0	0	0	0	0	0	22.9	11.8	
18	0	0	197.7	97.6	0	0	92.8	45.8	0	0	0	0	0	0	23.4	11.5	
19	0	0	201.7	95.7	0	0	94.7	44.9	0	0	0	0	0	0	23.9	11.3	
20	0	0	205.7	93.9	669.9	305.7	96.6	44.1	0	0	0	0	0	0	24.3	11.1	7
21	0	0	209.8	92.1	0	0	98.5	43.2	0	0	0	0	0	0	24.8	10.9	
22	0	0	214	90.3	0	0	100.5	42.4	0	0	0	0	0	0	25.3	10.7	
23	0	0	218.3	88.6	0	0	102.5	41.6	0	0	0	0	0	0	25.8	10.5	
24	0	0	222.6	86.9	0	0	104.5	40.8	0	0	0	0	0	0	26.3	10.3	
25	0	0	227.1	85.2	-318.5	-119.5	106.6	40	0	0	0	0	0	0	26.9	10.1	-4
TOTAL	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 In
NPC		8642.4		2715		1928.1		1274.9		0		0		1040		321.3	

TOTAL COST (NPC) = 29441,5 $
LEVELIZED COST OF ENERGY = 0,46 $/kWh

A1 — Project: 1.hoga. Solution # 0

k	O&M H2 Tank		Costes Fuel of AC. Gen		Costs ext. Fuel for F.C.		Costs Purchasing E to AC	Incomes Selling E to AC g	Incomes Selling H2		Financial Costs		TOTAL(Costs-Incomes)	
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
0	0	0	0	0	0	0	0	0	0	0	0	0	3176.9	3176.9	3176.9	3176.9
0	0	0	49.6	47.7	0	0	0	0	0	0	0	0	1809.2	1739.7	2177.7	2093.9
0	0	0	54.6	50.4	0	0	0	0	0	0	0	0	1809.2	1672.8	2189	2023.9
0	0	0	60	53.3	0	0	0	0	0	0	0	0	1809.2	1608.4	2201	1956.6
0	0	0	66	56.4	0	0	0	0	0	0	0	0	1809.2	1546.6	2213.6	1892.2
0	0	0	72.6	59.7	0	0	0	0	0	0	0	0	1809.2	1487.1	2227	1830.4
0	0	0	79.9	63.1	0	0	0	0	0	0	0	0	1809.2	1429.9	2241.1	1771.2
0	0	0	87.9	66.8	0	0	0	0	0	0	0	0	1809.2	1374.9	2256.2	1714.5
0	0	0	96.6	70.6	0	0	0	0	0	0	0	0	1809.2	1322	2272.1	1660.2
0	0	0	106.3	74.7	0	0	0	0	0	0	0	0	1809.2	1271.2	2289.1	1608.3
0	0	0	116.9	79	0	0	0	0	0	0	0	0	1809.2	1222.3	4863.9	3285.9
0	0	0	128.6	83.6	0	0	0	0	0	0	0	0	0	0	517.3	336
0	0	0	141.5	88.4	0	0	0	0	0	0	0	0	0	0	537.9	336
0	0	0	155.6	93.5	0	0	0	0	0	0	0	0	0	0	560	336.3
0	0	0	171.2	98.9	0	0	0	0	0	0	0	0	0	0	583.6	337
0	0	0	188.3	104.6	0	0	0	0	0	0	0	0	0	0	609	338.2
0	0	0	207.2	110.6	0	0	0	0	0	0	0	0	0	0	636.3	339.7
0	0	0	227.9	117	0	0	0	0	0	0	0	0	0	0	665.6	341.7
0	0	0	250.7	123.7	0	0	0	0	0	0	0	0	0	0	697.1	344.1
0	0	0	275.7	130.9	0	0	0	0	0	0	0	0	0	0	2622.7	1244.9
0	0	0	303.3	138.4	0	0	0	0	0	0	0	0	0	0	3651.3	1666.4
0	0	0	333.6	146.4	0	0	0	0	0	0	0	0	0	0	807.4	354.3
0	0	0	367	154.9	0	0	0	0	0	0	0	0	0	0	850.2	358.8
0	0	0	403.7	163.8	0	0	0	0	0	0	0	0	0	0	896.6	363.8
0	0	0	444.1	173.2	0	0	0	0	0	0	0	0	0	0	946.8	369.4
0	0	0	488.5	183.2	0	0	0	0	0	0	0	0	0	0	-1703.5	-639
k	O&M H2 Tank		Costes Fuel of AC. Gen		Costs ext. Fuel for F.C.		Costs Purchasing E to AC	Incomes Selling E to AC g	Incomes Selling H2		Financial Costs		TOTAL(Costs-Incomes)	
0		0		2532.9		0		0		0		0		17851.5		29441.5

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).
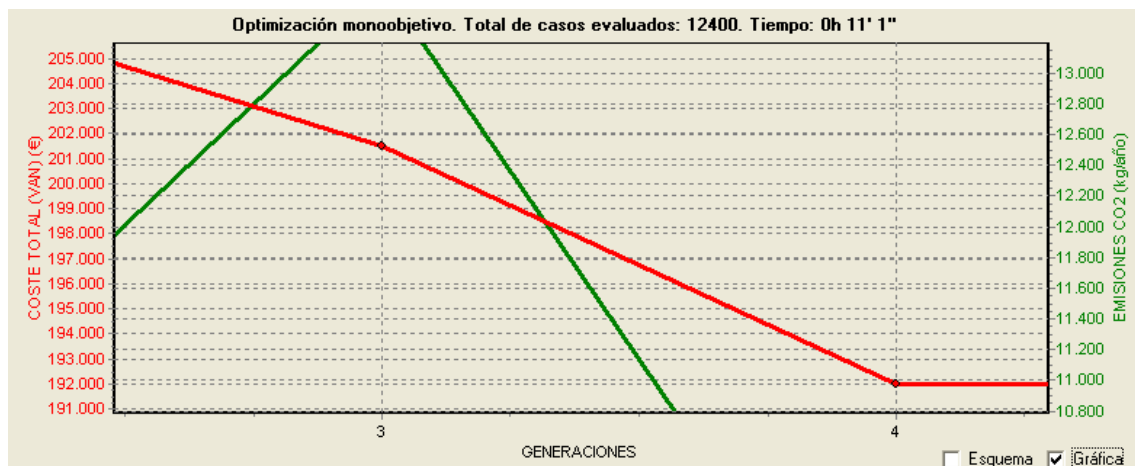
To undo the zoom window, click and drag from bottom right to top left.

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.
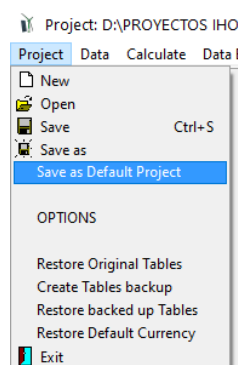
You can save another project as a default project later.

4.7 Sensitivity Analysis.

If the sensitivity analysis is performed, i.e. if cases have been entered on the sensitivity analysis screen, iHOGA 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 analysis (the number of optimizations) that iHOGA will perform is 3x2x3x2x2x3 = 216 projects.

The figure below shows a screen during the course of the calculation in which the number of optimizations (sensitivity analysis number) is 6. At that time it goes through the sensitivity analysis number 2 (corresponding to Wind.1, Rad.1, Load.2 (I-g)1, Inf.F.1, Pr.1), in that analysis in that moment it is in generation 5th of the genetic algorithm. Between the figure and the table it shows the number of the sensitivity analysis being carried out at that moment and the combination of the sensitivity cases.
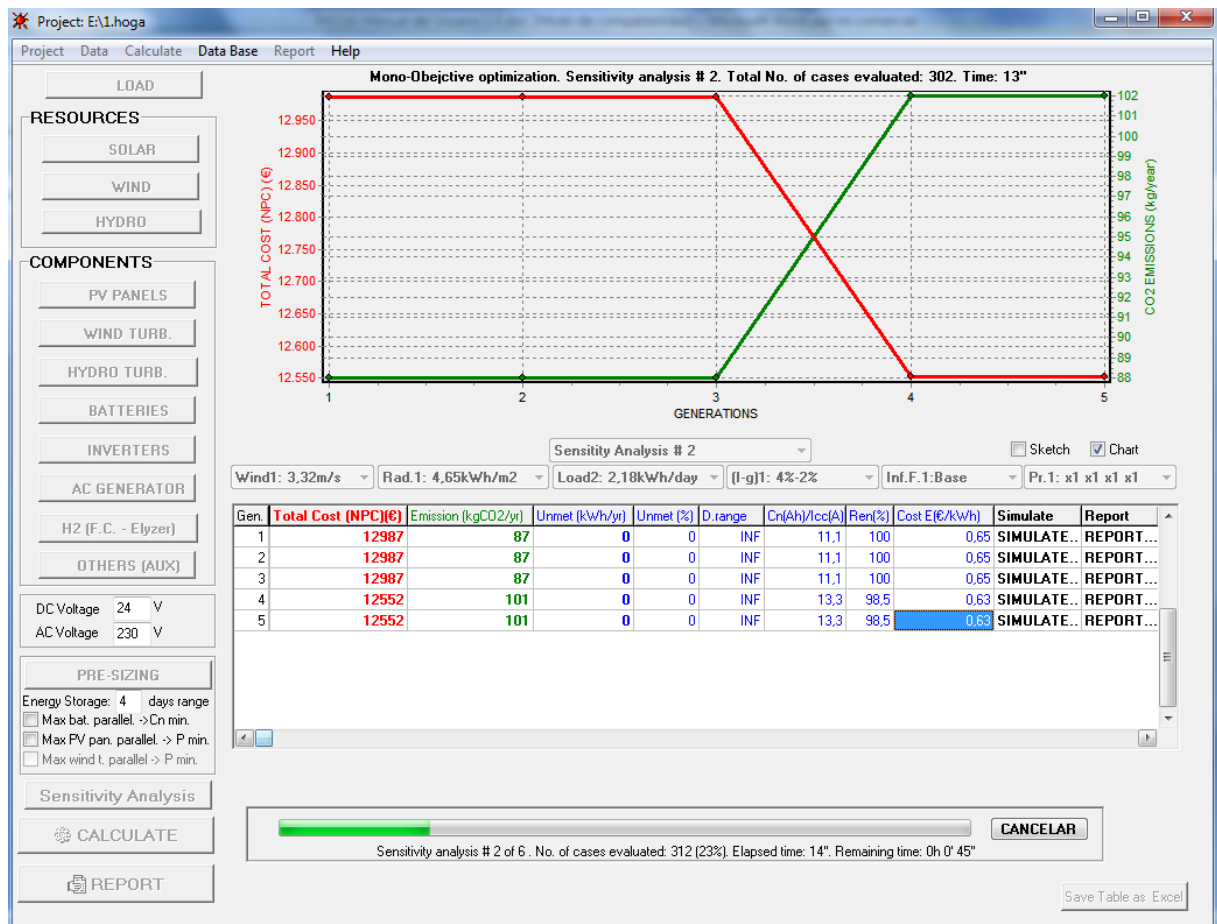
Upon completion all the sensitivity analysis, it is shown in the table of results the results of the analysis No. 1 (the basis of all cases), next figure.
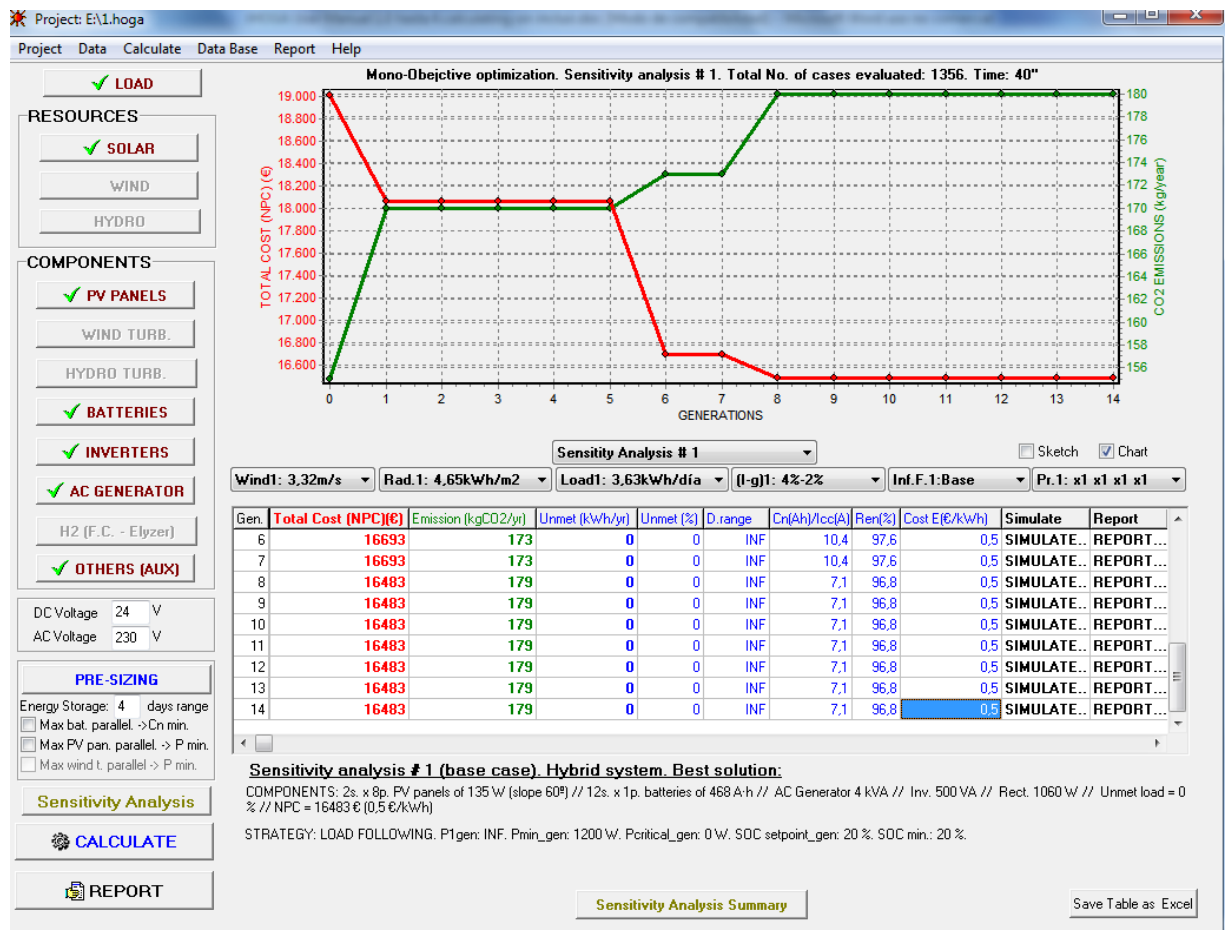
We can see the results of any other analysis by selecting the number of analysis down or selecting each individual case analysis variables. For example, in the following screen it is selected Sensitivity Analysis # 3 (corresponding to Wind.1, Rad.2, Load.1, (I-g) 1, Inf.F.1, Pr.1, and results are shown in the table (next figure).
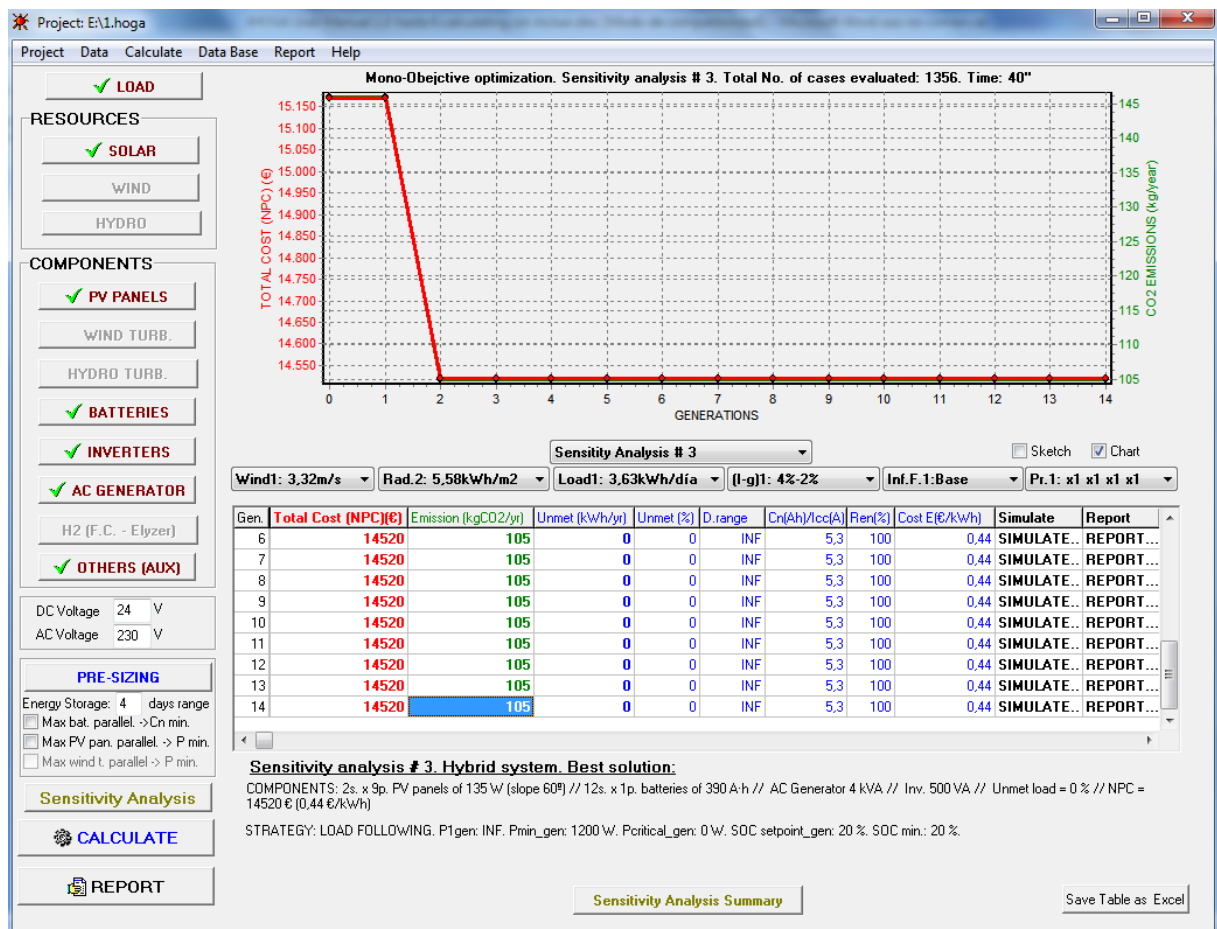
4.8 Summary of the sensitivity analysis.

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 9. 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. Scrolling with the vertical scroll you can see all 9 results in text.
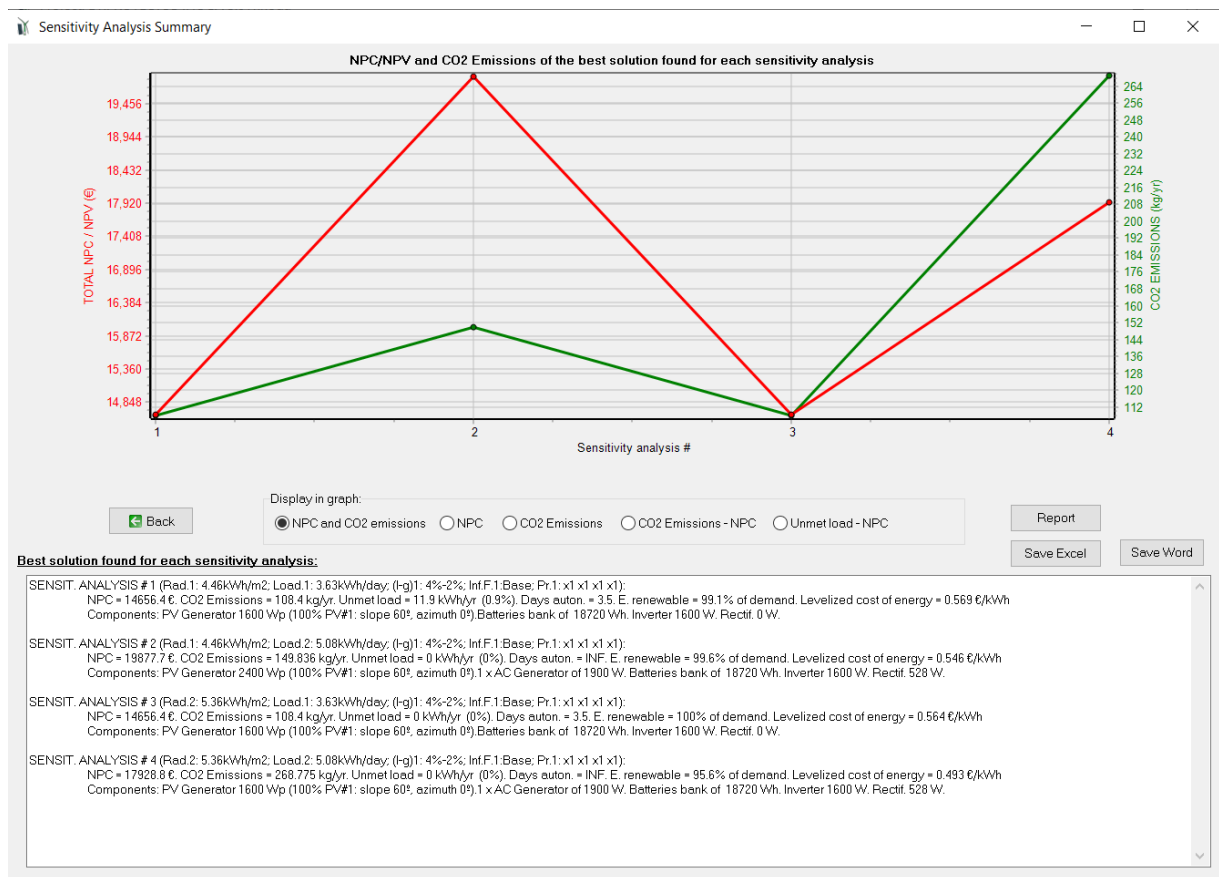
By clicking on the **"Report"** button on the screen of sensitivity analysis summary, it displays a report that can be printed or saved as pdf (if we have a virtual pdf printer installed on the computer).
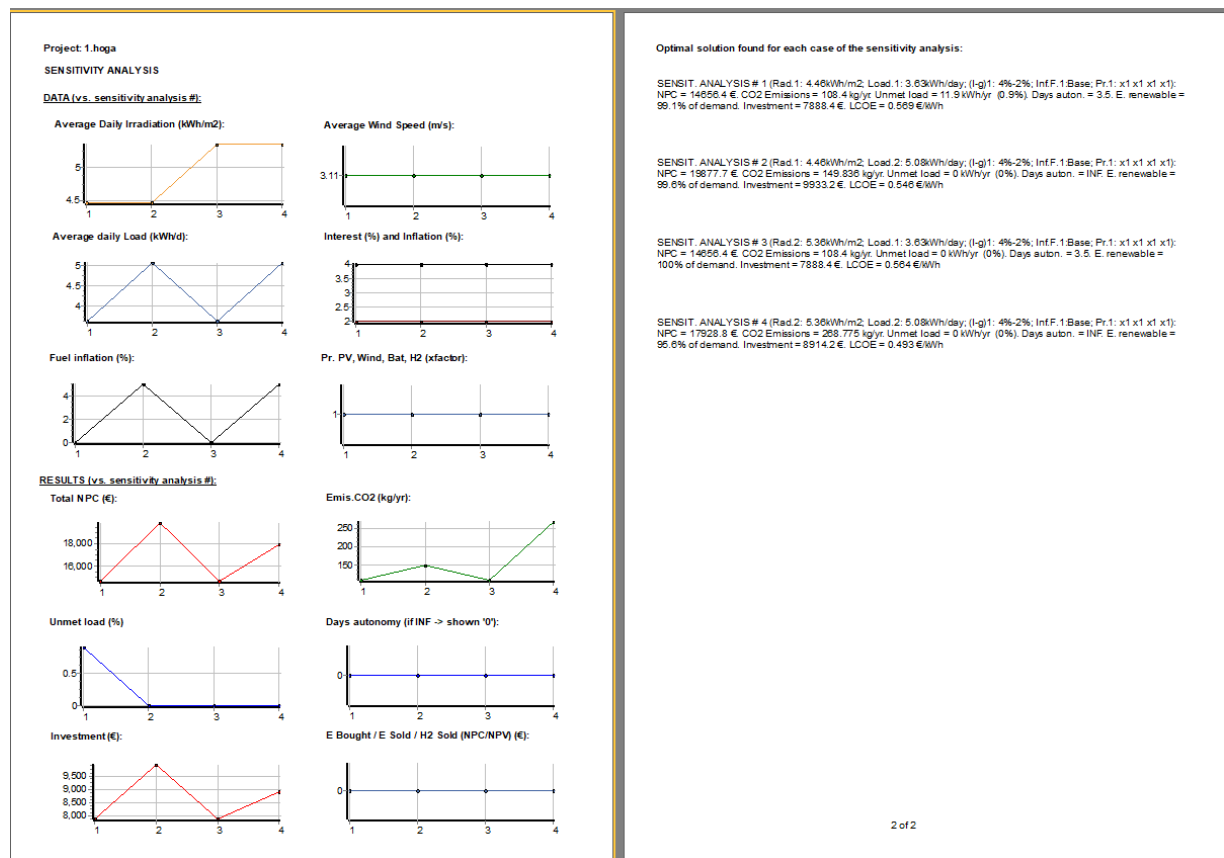
Clicking on the button "**Save Excel**" on the screen of the summary of the sensitivity analysis, a detailed table with the results of the sensitivity analysis (best combination found for each sensitivity analysis) can be saved in format .xls or format .txt. If we keep it as. .xls, when opening the file 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.

By clicking in "**Save word**" button we can save the report in .rtf format, which can be open by Microsoft Word, for example:

5. <u>FREQUENTLY ASKED QUESTIONS</u>

1. Can iHOGA only be used to simulate and optimize 'small', low consumption systems?

No, you can simulate and optimize systems of any size up to 5 MW. For high power projects, when creating a new project, select that option.

2. Does iHOGA only serve to simulate and optimize stand-alone (off-grid) systems?

No, you can also simulate and optimize systems connected to the AC grid, with or without energy storage. If AC grid is available, and the option to buy the unmet load from the AC grid is selected, the unmet load (energy that cannot be supplied by the stand-alone system) is purchased from the AC grid. If the option to sell the excess energy (energy produced by the renewable sources and not consumed by the load nor stored) to the AC grid is marked, all the energy that cannot be used by the load or by the storage is sold to the grid. Both options are independent, can be marked only one or both. It is also possible to take into account net metering, annual or monthly, so that it will only be allowed to sell to the AC grid at most the energy purchased from the grid, annually or monthly. There are up to 8 possible options for the net metering, depending on the legislation in place at the installation site.

There is also the possibility to simulate and optimize systems with battery storage and connected to the AC grid, so that the batteries can be charged with electricity from the AC grid (when the price is cheap) and discharged by supplying the load when the price of the electricity from the AC grid is expensive (we can even model the batteries to inject them into the AC grid at those times).

In systems where there is no load consumption (generating installations connected to the AC grid, where the energy consumption of the installation is 0 kWh or a low value compared to the energy injected to the AC grid), you should select the project type of Maximization of NPV (menu Project->Options), in that case the optimization tries to obtain the system with highest NPV (you could select to minimize LCOE instead of maximize NPV).

3. 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. PRE-SIZING button helps you to choose the maximum number of components in parallel.

4. 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.

5. 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 iHOGA 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.

6. Where can I obtain data on system components, such as characteristics, prices, etc?

iHOGA includes a database, but you can add more components. Apart from iHOGA databases and manufacturers' web sites and renewable energy shops, you may download Retscreen http://www.retscreen.net where information is available on the characteristics, estimated costs, ... for different renewable-energy components.

7. 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, iHOGA will use genetic algorithms.

iHOGA 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 modules, 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).

8. 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, 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 modules, batteries, wind turbines or AC 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.

9. 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 3.16.2). 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, see section 3.16.3), the electrolyzer will not work (hydrogen will not be generated as it cannot be stored).

10. 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. See section 3.16.1.

12. How to optimize systems selling electricity to the AC grid, without load consumption?

In systems where there is no load consumption (generating installations connected to the AC grid, where the energy consumption of the installation is 0 kWh or a low value compared to the

energy injected to the AC grid), you should select the project type of Maximization of NPV (menu Project->Options), in that case the optimization tries to obtain the system with highest NPV (you could select to minimize LCOE instead of maximize NPV).

In the window of load consumption "LOAD/ AC GRID", choose for data source "Load profile", and select the profile "Zero" (no load). On the same window, tab "PURCHASE/SELL E" check the "Sell excess energy to AC grid".

13. Which battery model should I select?

LEAD-ACID BATTERIES:

For lead-acid batteries, you should use Schieffer 2007 for the battery model and Schieffer ageing model for the ageing model (only in PRO+ version). This way, iHOGA 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.
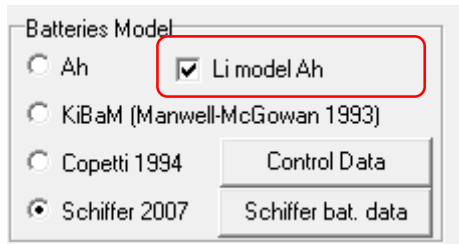
For the ageing model, you can select several models: Wang, Grot or Naumann for LiFePO4, Saxena for LiCoO2 or generic models (Full equivalent cycles or Rainflow).

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).
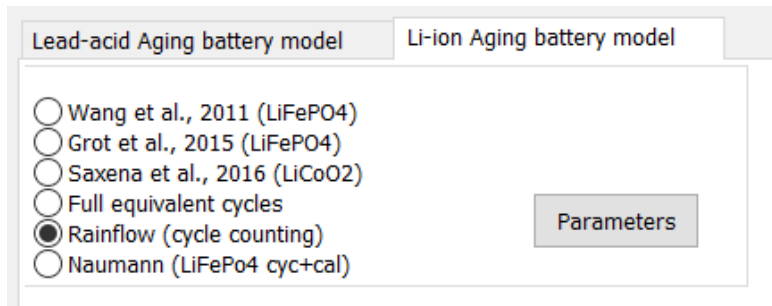
Full equivalent cycles or Rainflow models are generic models, and they consider the number of cycles to failure of the battery data.

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 iHOGA?

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.

iHOGA 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) [2] for the system, in mono-objective optimization (for multi-objective optimization iHOGA will seek

---

[2]   In most cases where optimization is applied through iHOGA, cash flows are usually expenses only (purchasing, replacement, maintenance, and fuel costs, etc), with no income. The different costs throughout the whole of the study period are referred to the initial time of the investment using the discount rate (approx. interest rate minus inflation rate), thereby producing the NPC. The lower the NPC value, the better the investment .

        It is possible to use the option in iHOGA to sell surplus hydrogen and electric energy to the AC grid (it is also possible to purchase energy from the grid to compensate for unmet load by the hybrid system). In those cases, sales are accounted for within iHOGA as negative values, since they must be subtracted from component, replacement, and maintenance expenses. We may thus achieve an income from energy sales which is higher than system costs, resulting in a negative value for "NPC". This means that our facility will achieve a net benefit (positive values meant expenses, i.e. costs). A larger negative value for our "NPC" will indicate a more profitable system. However, if you select in the menu Project-> Options to maximize NPV, it calculates the NPV where incomes are positive and costs negative values.

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 modules in parallel

- Type of PV modules

- Number of Wind Turbines in parallel

- Type of Wind Turbines

- Type of Hydraulic Turbine or TEG (not possible using in the same project hydro turbinte and TEG).

- 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 iHOGA 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:

$$Combinations\_main\_alg=$$

$$= No.\_Pv\_Panel\_Types*(1+No.\_max\_Pv\_Modules\_parallel- No.\_min\_Modules\_parallel)*$$

$$*No.\_Wind\_T\_types*(1+No.max\_Wind\_T\_parallel – No.min\_ Wind\_T\_parallel)*$$

$$*No.\_battery\_tpes*(1+No.max\_batteries \_parallel – No.min\_batteries\_parallel)* No.\_AC\_gen\_types*No.$$

$$Hyd\_T\_types*No.\_electroliz\_types*No.\_Fuel\_Cell\_types*Combinations\_secondary\_alg$$

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 earlier versions of HOGA made use 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 et al., 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.
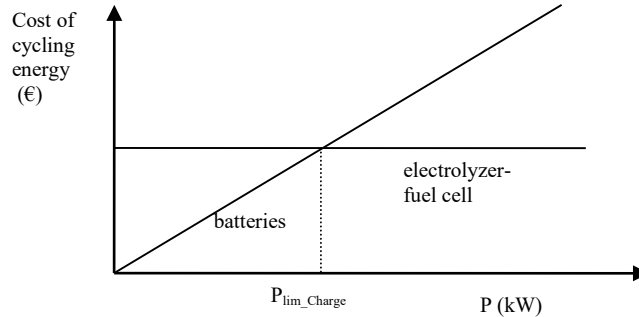
Cost of cycling energy

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**.

iHOGA 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.
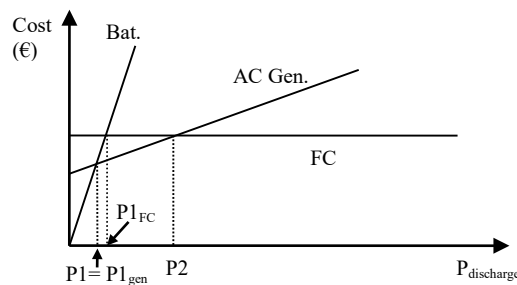
Costs of supplying energy (DISCHARGE process)

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 2nd element cannot supply the rest of the power, a 3rd 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.

REFERENCES

Aguiar, R., & Collares-Pereira, M. (1992). TAG: A time-dependent, autoregressive, Gaussian model for generating synthetic hourly radiation. *Solar Energy*, *49*(3), 167–174. https://doi.org/https://doi.org/10.1016/0038-092X(92)90068-L

Barley, C., & Winn, C. (1996). Optimal dispatch strategy in remote hybrid power systems. *Solar Energy*, *58*((4-6)), 165–179.

Bernal-Agustín, J. L., & Dufo-López, R. (2009a). Efficient design of hybrid renewable energy systems using evolutionary algorithms. *Energy Conversion and Management*, *50*(3), 479–489. https://doi.org/10.1016/j.enconman.2008.11.007

Bernal-Agustín, J. L., & Dufo-López, R. (2009b). Multi-objective design and control of hybrid systems minimizing costs and unmet load. *Electric Power Systems Research*, *79*(1), 170–180. https://doi.org/10.1016/j.epsr.2008.05.011

Bernal-Agustín, J. L., & Dufo-López, R. (2009c). Simulation and optimization of stand-alone hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, *13*(8), 2111–2118. https://doi.org/10.1016/j.rser.2009.01.010

Bernal-Agustín, J. L., Dufo-López, R., & Rivas-Ascaso, D. M. (2012). Design of isolated hybrid systems minimizing costs and pollutant emissions. *Renewable Energy*, *44*, 215–224. https://doi.org/10.1016/j.renene.2012.01.011

Champier, D. (2017). Thermoelectric generators: A review of applications. *Energy Conversion and Management*, *140*, 167–181. https://doi.org/10.1016/j.enconman.2017.02.070

Coello, C. A., Veldhuizen, D. A. V., & Lamont, G. B. (2002). *Evolutionary Algorithms for Solving Multi-Objective Problems* (Kluwer Aca). New York.

Collares Pereira, M., & Rabl, A. (1979). The average distribution of solar radiation correlations between diffuse and hemispherical and between daily and hourly insolation values. *Solar Energy*, *22*, 155–164.

Copetti, J., & Chenlo, F. (1994). Lead/acid batteries for photovoltaic applications. Test results and modeling. *Journal of Power Sources*, *47*(1–2), 109–18.

Copetti, J., Lorenzo, E., & Chenlo, F. (1993). A general battery model for PV system

simulation. *Prog Photovoltaic*, *1*(4), 283–292.

Cristóbal-Monreal, I. R., & Dufo-López, R. (2016). Optimisation of photovoltaic-diesel-battery stand-alone systems minimising system weight. *Energy Conversion and Management*, *119*, 279–288. https://doi.org/10.1016/j.enconman.2016.04.050

Downing, S., & Socie, D. (1982). Simple Rainflow Counting Algorithms. *International Journal of Fatigue*, *4*(1).

Dufo-lópez, R., Champier, D., Gibout, S., Lujano-rojas, J. M., & Domínguez-navarro, J. A. (2019). Optimisation of off-grid hybrid renewable systems with thermoelectric generator. *Energy Conversion and Management*, *196*(June), 1051–1067. https://doi.org/10.1016/j.enconman.2019.06.057

Dufo-lópez, R., & Lujano-rojas, J. M. (2025). Optimization of Size and Operation of Stand-Alone Renewable-Based Systems with Diesel and Hybrid Pumped Hydro Storage – Battery Storage Considering Uncertainties. *Batteries*, *11*(70). Retrieved from https://www.mdpi.com/2313-0105/11/2/70

Dufo-López, R, Lujano-Rojas, J. M., & Bernal-Agustín, J. L. (2023). 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

Dufo-López, Rodolfo. (2007). *Dimensionado y control óptimos de sistemas híbridos aplicando algoritmos evolutivos. Tesis doctoral.* University of Zaragoza.

Dufo-López, Rodolfo. (2015). Optimisation of size and control of grid-connected storage under real time electricity pricing conditions. *Applied Energy*, *140*, 395–408. https://doi.org/10.1016/j.apenergy.2014.12.012

Dufo-López, Rodolfo, & Bernal-Agustín, J. L. (2005). Design and control strategies of PV-diesel systems using genetic algorithms. *Solar Energy*, *79*(1), 33–46. https://doi.org/10.1016/j.solener.2004.10.004

Dufo-López, Rodolfo, & Bernal-Agustín, J. L. (2008). Multi-objective design of PV-wind-diesel-hydrogen-battery systems. *Renewable Energy*, *33*(12), 2559–2572. https://doi.org/10.1016/j.renene.2008.02.027

Dufo-López, Rodolfo, & Bernal-Agustín, J. L. (2011). *Generación de energía eléctrica con fuentes renovables. Optimización de sistemas híbridos renovables con almacenamiento energético mediante algoritmos genéticos. Editorial Académica Española. LAP*

LAMBERT Academic Publishing GMBH & Co. KG, Saarbrücken, Ale.

Dufo-López, Rodolfo, & Bernal-Agustín, J. L. (2012). New methodology for the generation of hourly wind speed data applied to the optimization of stand-alone systems. *Energy Procedia*, *14*(2011), 1973–1978. https://doi.org/10.1016/j.egypro.2011.12.887

Dufo-López, Rodolfo, & Bernal-Agustín, J. L. (2015a). A comparative assessment of net metering and net billing policies. Study cases for Spain. *Energy*, *84*, 684–694. https://doi.org/10.1016/j.energy.2015.03.031

Dufo-López, Rodolfo, & Bernal-Agustín, J. L. (2015b). Techno-economic analysis of grid-connected battery storage. *Energy Conversion and Management*, *91*, 394–404. https://doi.org/10.1016/j.enconman.2014.12.038

Dufo-López, Rodolfo, Bernal-Agustín, J. L., & Contreras, J. (2007). Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage. *Renewable Energy*, *32*(7), 1102–1126. https://doi.org/10.1016/j.renene.2006.04.013

Dufo-López, Rodolfo, Bernal-Agustín, J. L., Yusta-Loyo, J. M., Domínguez-Navarro, J. a., Ramírez-Rosado, I. J., Lujano, J., & Aso, I. (2011). Multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV-wind-diesel systems with batteries storage. *Applied Energy*, *88*(11), 4033–4041. https://doi.org/10.1016/j.apenergy.2011.04.019

Dufo-López, Rodolfo, Cristóbal-Monreal, I. R., & Yusta, J. M. (2016a). Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation. *Renewable Energy*, *94*, 280–293. https://doi.org/10.1016/j.renene.2016.03.065

Dufo-López, Rodolfo, Cristóbal-Monreal, I. R., & Yusta, J. M. (2016b). Stochastic-heuristic methodology for the optimisation of components and control variables of PV-wind-diesel-battery stand-alone systems. *Renewable Energy*, *99*, 919–935. https://doi.org/10.1016/j.renene.2016.07.069

Dufo-López, Rodolfo, Fernández-Jiménez, L. A., Ramírez-Rosado, I. J., Artal-Sevil, J. S., Domínguez-Navarro, J. A., & Bernal-Agustín, J. L. (2017). Daily operation optimisation of hybrid stand-alone system by model predictive control considering ageing model. *Energy Conversion and Management*, *134*, 167–177. https://doi.org/10.1016/j.enconman.2016.12.036

Dufo-López, Rodolfo, & Lujano-Rojas, J. M. (2024). Simulation and Optimisation of Utility-Scale PV-Wind Systems with Pumped Hydro Storage. *Applied Sciences (Switzerland)*, *14*(7033). https://doi.org/https://doi.org/10.3390/app14167033

Dufo-López, Rodolfo, Lujano-Rojas, J. M., & Bernal-Agustín, J. L. (2014). Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems. *Applied Energy*, *115*, 242–253. https://doi.org/10.1016/j.apenergy.2013.11.021

Dufo-López, Rodolfo, Pérez-Cebollada, E., Bernal-Agustín, J. L., & Martínez-Ruiz, I. (2016). Optimisation of energy supply at off-grid healthcare facilities using Monte Carlo simulation. *Energy Conversion and Management*, *113*, 321–330. https://doi.org/10.1016/j.enconman.2016.01.057

Durusoy, B., Ozden, T., & Akinoglu, B. G. (2020). Solar irradiation on the rear surface of bifacial solar modules: a modeling approach. *Scientific Reports - Nature*, *10*(1), 1–10. https://doi.org/10.1038/s41598-020-70235-3

Erbs, D., Klein, S., & Beckman, W. (1983). Estimation of Degree-Days and ambient temperature bin data from monthly-average temperature. *ASHRAE JOURNAL*, *25*(6), 60–65.

Erbs, D., Klein, S., & Duffie, J. (1982). Estimation of the Diffuse Radiation Fraction for Hourly, Daily and Monthly average Global Radiation. *Solar Energy*, *28*(4), 293–302.

Favarel, C., Bédécarrats, J.-P., Kousksou, T., & Champier, D. (2016). Experimental analysis with numerical comparison for different thermoelectric generators configurations. *Energy Conversion and Management*, *107*, 114–122. https://doi.org/10.1016/j.enconman.2015.06.040

González-Longatt, F., Wall, P. P., & Terzija, V. (2012). Wake effect in wind farm performance: Steady-state and dynamic behavior. *Renewable Energy*, *39*(1), 329–338. https://doi.org/10.1016/j.renene.2011.08.053

Goupil, C., Ouerdane, H., & Apertet, Y. (2013). Thermoélectricité - Thermodynamique et applications. *Techniques De L'Ingenieur*.

Graham, V. A., & Hollands, K. G. T. (1990). A method to generate synthetic hourly solar radiation globally. *Solar Energy*, *44*(6), 333–341. https://doi.org/10.1016/0038-092X(90)90137-2

Green, H. ., & Manwell, J. (1995). HYBRID2- A versatile model of the performance of hybrid power systems. In *WindPower'95. Washington, DC*.

Gregory, J., Peterson, R., Lee, J., & Wilson, G. (1994). Modeling wind and relative humidity effects on air quality. In *International Specialty Conference on Aerosols and Atmospheric Optics: Radiative Balance and Visual Air Quality*.

Groot, J., Swierczynski, M., Stan, A. I., & Kær, S. K. (2015). On the complex ageing characteristics of high-power LiFePO4/graphite battery cells cycled with high charge and discharge currents. *Journal of Power Sources*, *286*, 475–487. https://doi.org/10.1016/j.jpowsour.2015.04.001

Hay, J. E., & Davies, J. A. (1978). Calculations of the solar radiation incident on an inclined surface. In J. E. Hay and T. K. Won (Ed.), *First Canadian Solar Radiation Data Workshop*. Toronto, Canada.

Kopp, M., Coleman, D., Stiller, C., Scheffer, K., Aichinger, J., & Scheppat, B. (2017). Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis. *International Journal of Hydrogen Energy*, *42*(19), 13311–13320. https://doi.org/10.1016/j.ijhydene.2016.12.145

Lander, J. (1956). Further studies on the anodic corrosion of lead in H2SO4 solutions. *J. Electrochem. Soc*, *103*, 1–8.

Leloux, J., Lorenzo, E., García-Domingo, B., Aguilera, J., & Gueymard, C. A. (2014). A bankable method of assessing the performance of a CPV plant. *Applied Energy*, *118*, 1–11. https://doi.org/10.1016/j.apenergy.2013.12.014

Liu, B., & Jordan, R. (1960). The interrelationships and characteristic distributions of direct, diffuse, and total solar radiation. *Solar Energy*, *4*, 1–19.

Manwell, J., & McGowan, J. (1993). A Lead Acid Battery Storage Model for Hybrid Energy Systems. *Solar Energy*, *50*(5), 399–405.

Meteonorm. Global meteorological database. Handbook part II: Theory. Version 7.1. (2015).

Naumann, M., Schimpe, M., Keil, P., Hesse, H. C., & Jossen, A. (2018). Analysis and modeling of calendar aging of a commercial LiFePO4/graphite cell. *Journal of Energy Storage*, *17*, 153–169. https://doi.org/10.1016/j.est.2018.01.019

Naumann, M., Spingler, F., & Jossen, A. (2020). Analysis and modeling of cycle aging of a

commercial LiFePO4/graphite cell. *Journal of Power Sources*, *451*(January), 227666. https://doi.org/10.1016/j.jpowsour.2019.227666

Petit, M., Prada, E., & Sauvant-Moynot, V. (2016). Development of an empirical aging model for Li-ion batteries and application to assess the impact of Vehicle-to-Grid strategies on battery lifetime. *Applied Energy*, *172*, 398–407. https://doi.org/10.1016/j.apenergy.2016.03.119

Rietveld, M. (1978). A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine. *Agricultural Meteorology*, *19*, 243–252.

Rivas-Ascaso, D. (2004). Aplicación informática para el diseño de sistemas híbridos de generación de energía eléctrica" Proyecto fin de carrera, Ingeniería Industrial, C.P.S. Univ. Zaragoza.

Rojas-Zerpa, J. C. (2012). *Planificación del suministro eléctrico en áreas rurales de los países en vías de desarrollo: un marco de referencia para la toma de decisiones. Tesis Doctoral*. University of Zaragoza.

Ruetschi, P. (2004). Aging mechanisms and service life of lead–acid batteries. *Journal of Power Sources*, *127*(1–2), 33–44. https://doi.org/10.1016/j.jpowsour.2003.09.052

Saxena, S., Hendricks, C., & Pecht, M. (2016). Cycle life testing and modeling of graphite / LiCoO 2 cells under different state of charge ranges. *Journal of Power Sources*, *327*, 394–400. https://doi.org/10.1016/j.jpowsour.2016.07.057

Schiffer, J., Sauer, D. U., Bindner, H., Cronin, T., Lundsager, P., & Kaiser, R. (2007). Model prediction for ranking lead-acid batteries according to expected lifetime in renewable energy systems and autonomous power-supply systems. *Journal of Power Sources*, *168*(1), 66–78. https://doi.org/10.1016/j.jpowsour.2006.11.092

Schuhmacher, J. (1993). INSEL – Interactive Simulation of Renewable Electrical Energy Supply Systems-, Reference Manual. University of Oldenburg, Renewable Energy Group, Dept. of Physics.

Skarstein, O., & Ulhen, K. (1989). Design Considerations with Respect to Long-Term Diesel Saving in Wind/Diesel Plants. *Wind Engineering*, *13*(2).

Swierczynski, M., Stroe, D. I., Stan, A. I., Teodorescu, R., & Kær, S. K. (2015). Lifetime Estimation of the Nanophosphate LiFePO4/C Battery Chemistry Used in Fully Electric Vehicles. *IEEE Transactions on Industry Applications*, *51*(4), 3453–3461.

https://doi.org/10.1109/TIA.2015.2405500

Wang, J., Liu, P., Hicks-Garner, J., Sherman, E., Soukiazian, S., Verbrugge, M., … Finamore, P. (2011). Cycle-life model for graphite-LiFePO4 cells. *Journal of Power Sources*, *196*(8), 3942–3948. https://doi.org/10.1016/j.jpowsour.2010.11.134

Zitzler, E., & Thiele, L. (1999). Multiobjective evolutionary algorithms: a comparative case study and the strength Pareto approach. *IEEE Transactions on Evolutionary Computation*, *3*(4), 257–271.