GETTING STARTED. MHOGA 4.0.

Updated Dec. 21, 2024

Several example projects are shown to illustrate how MHOGA works. ***You can find more information in the User's Manual*** (https://ihoga.unizar.es/en/descarga/)

This guide is designed to follow sequentially.

Sections 41 and 42 could be done regardless the previous sections.

CONTENTS:

BEFORE STARTING TO WORK:

MHOGA needs to run:

- Internet connection to check the license validity (and to import irradiation, temperature and wind speed data).

- A printer (physical or virtual) installed in the computer. This is necessary to print the reports. You can install a virtual pdf printer, for example the free doPDF (http://www.dopdf.com/es/)

Virtual machines:

MHOGA software does not run under virtual machines or hypervisors. Even if you do not use it, virtualization is enabled by default in many new computers BIOS.

Deactivate virtual machines or hypervisors if, after installing, when you open the software you obtain the following message "**Failed to start the trial: The function failed because this instance of your program is running inside a viertual machine / hypervisor and you've prevented the function from running inside a VM.**" (*it can happen due to the default virtualization activation in the computer BIOS, in this case you must disable it in BIOS, see the last page of the following document*):

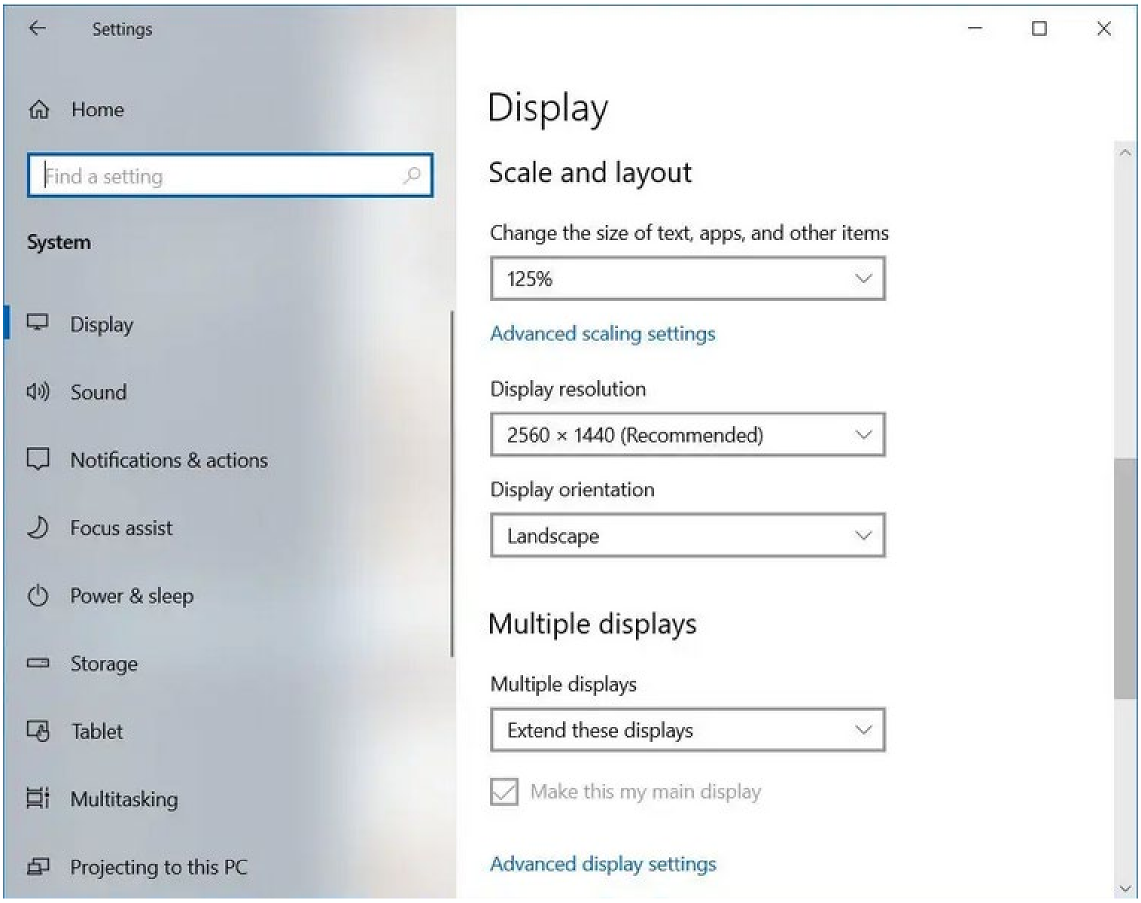
How to deactivate virtual machine / hypervisor

Screen settings:

In Windows, select **Settings > System > Display > Scale and layout** (in your language).

Usually the optimal display resolution is the recommended value, but in some cases the software visualization improves with other values. Also, in the field "**Change the size of text, apps, and other items**" usually it is better to use 125% or even higher. We recommend using at least 125 percent scaling on 1080p display resolutions and higher to make it easier on your eyes, but find the scaling that works best for you.

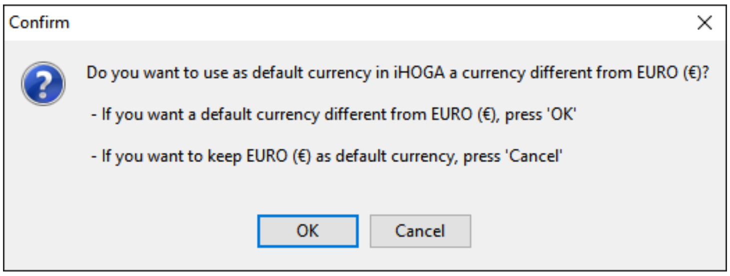
Depending on these settings, the visualization of the software will be better or worse.



1. Create a new project.

In the top menu, click **Project->New**.

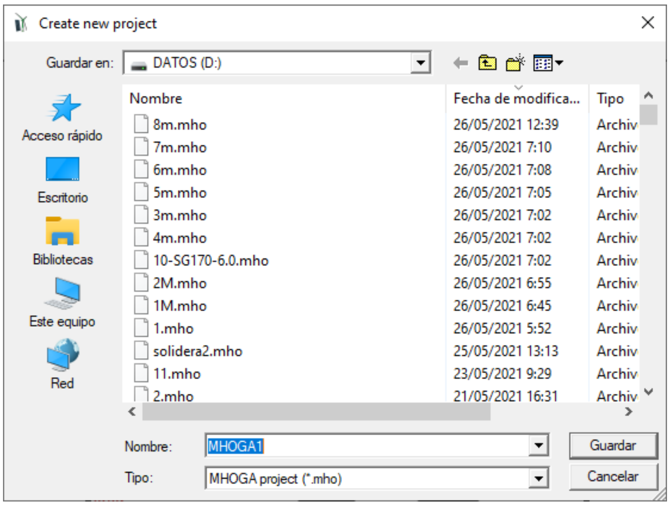
The first time we create a project, MHOGA asks us if we want to change the default currency (which is EURO).



This starting guide is prepared with the EURO currency, so we set the EURO as the default currency, by clicking "**Cancel**". However, if you prefer another currency you can click on "**OK**" and change the default currency to another by following the steps on section 3 of the user manual (https://ihoga.unizar.es/en/descarga/). In that case the economic results that will appear later in this guide (in €) will be different from yours (in another currency).

After selecting the default currency, a window appears where we must indicate the location of the project and its name. MHOGA projects are files with extension **.mho**.

The full path from the root directory to the file .mho that will be created should not contain more than 60 characters, otherwise an error may occur.

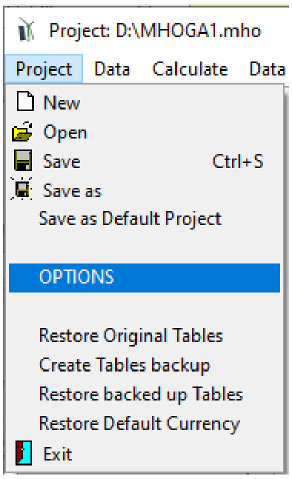


In our case we create it directly in the root directory (or in the folder where you want provided the full path should not be longer than 60 characters) and call it "**MHOGA1.mho"**, then clicking on "**Save**".

Note that, in some computers, writing in C: needs administrator permission. If MHOGA reports an error related to writing access, you should close the software, open it again, create the project again and save it in another root (D:, E:…).

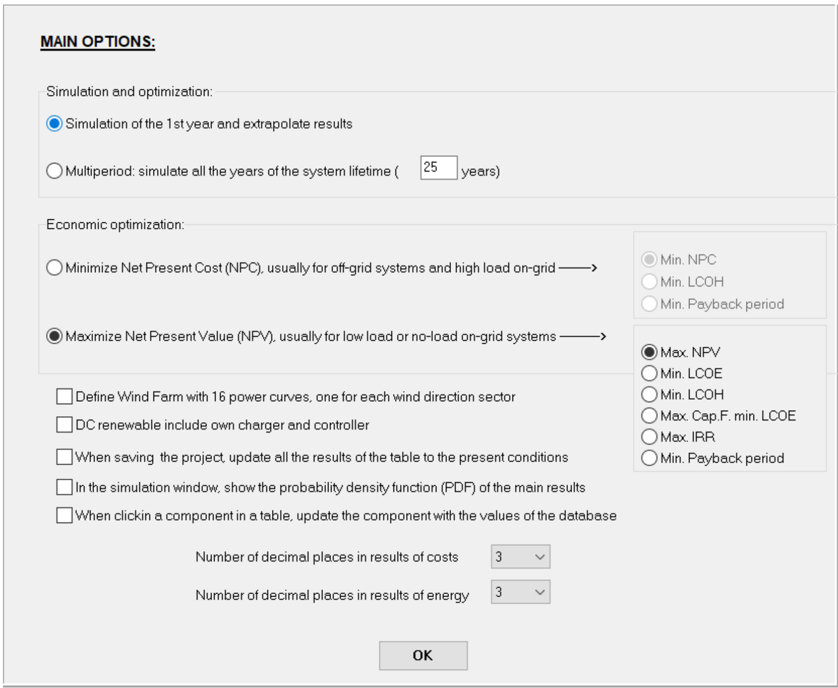
You can check that the file MHOGA1.mho will be created in the folder selected, and a folder with the same name (MHOGA1) will also be created. If, later, after closing the project, you want to move or copy your project to another folder or share it with another person, you must move / copy / share the .mho file and also the folder with the same name (in this case, you must move / copy / share MHOGA1.mho file and MHOGA1 folder).

We can choose general options of the project (upper menu **Project-> OPTIONS**):



A window appears, where:

In the **Simulation and optimization** selection, we can select that the simulation is just for one year (extrapolating the results of that year, by default) or multiperiod, simulating the whole lifetime of the system (by default 25 years). We leave the default value.

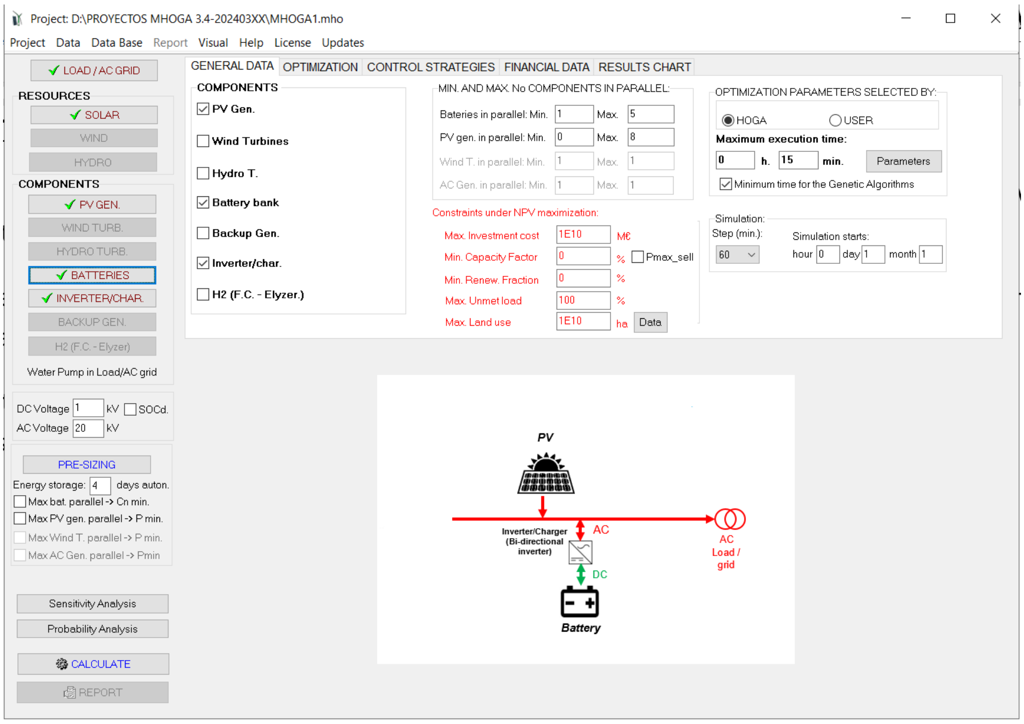


In the **Economic optimization** selection, we can choose between minimizing the net present cost (NPC) of the system (for off-grid systems of grid-connected systems with load consumption) or maximizing the net present value (NPV) of the system (for grid-connected power generators without load or with low load, as default).

We leave the default value. For maximizing NPV projects, we can choose between maximizing NPV (default) or minimizing LCOE or optimizing other variables (LCOH, IRR…) we leave the default value.

We click **OK**.

The default project is a Photovoltaic-Battery grid-connected power generating system, without any load consumption. However, later we can change any of the data that appears by default.

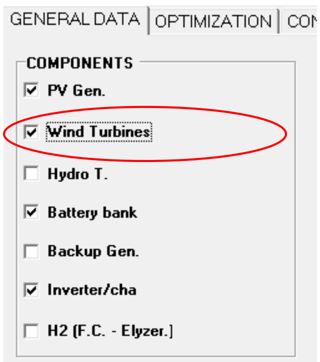


2. Type of system.

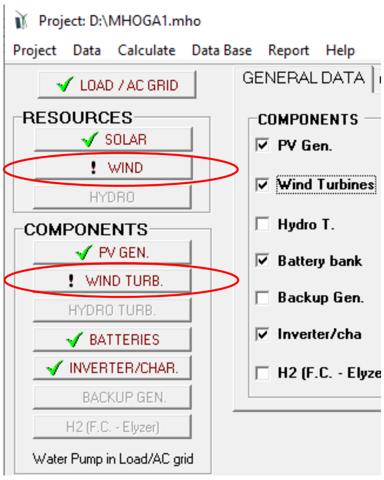
By default, the system to be optimized would be the grid-connected PV generator with batteries, evaluating different combinations of systems.

We are going to assume that we are also interested in testing combinations with wind turbines, that is, that the system can be **PV-wind-batteries**.

In the main screen, in the default tab (**GENERAL DATA**), we click "**Wind turbines**", this way the system will also consider them.



In the group of buttons on the left, the buttons "WIND" and "WIND TURB." are enabled, showing the "**!**" symbol indicating that data must be entered for wind speed and wind turbines.



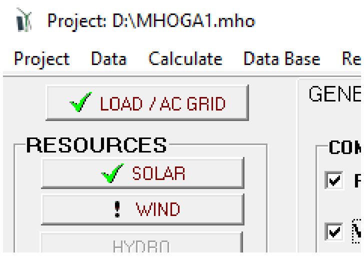
3. DC and AC nominal voltages.

In the main screen, under the components buttons (central left zone), the nominal DC and AC bus voltages of the system are defined. DC bus voltage will be the voltage of the battery bank. Let's use the ones that appear by default.

If the check box "SOC d." is marked, the DC voltage will vary depending on the state of charge (SOC) of the lead-acid batteries, situation more similar to the real one than if we consider DC voltage is fixed (without marking that checkbox). However, as we will use Li-ion batteries, we will leave this check box unchecked.

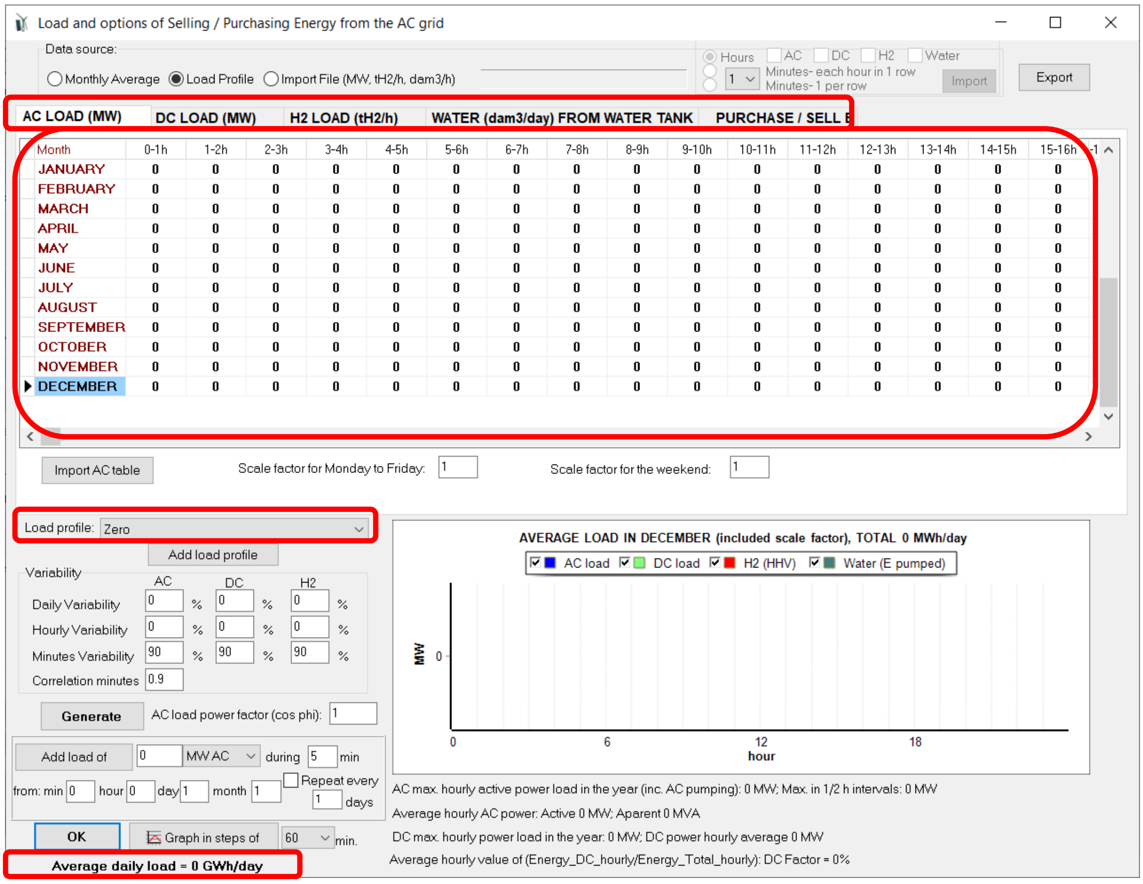
4. Load data and options to purchase / sell electricity to the AC grid.

By clicking on the "**LOAD / AC GRID**" button, we can modify the load data (electrical demand AC and/or DC, hydrogen loads for external consumption or water consumption pumped from a river or a well to a water storage tank or reservoir) and the data of purchasing and selling electrical energy to the AC grid or selling surplus hydrogen.



Into the window of the LOAD / AC GRID, “**AC LOAD**” tab is selected by default.

By default, the load profile “Zero” is selected, this means no load consumption in our system. The default tab shown is the AC LOAD (MW), we see this load is 0 for all the hours of the different months. If we click in the different tabs of DC LOAD, H2 LOAD and WATER, we see there is no load (in the WATER tab the daily water consumption in dam3/day is 0 for all the months).



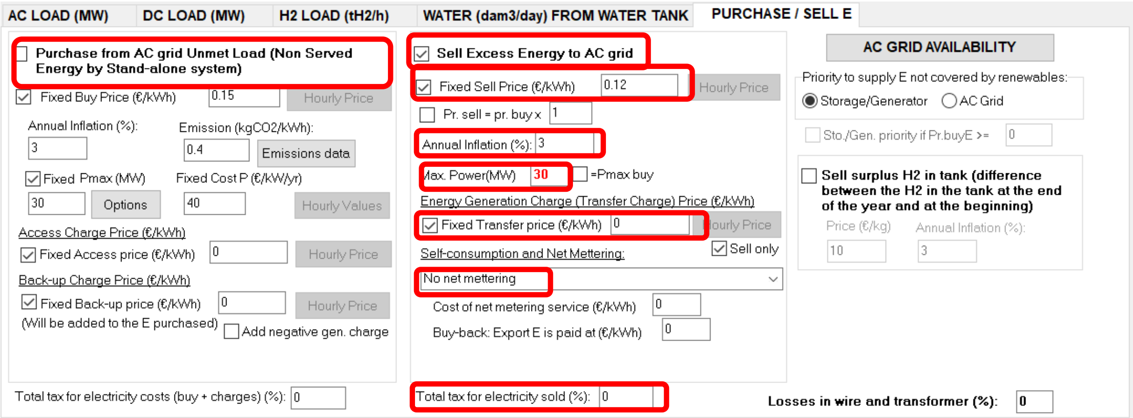
At the bottom of the screen it is shown the average daily total load, which is now 0 GWh/day.

We could use a different load profile (selecting it where now is “Zero” selected).

For each type of load, we could introduce the data by importing from a table file with the hourly load profile of each month. We could also import from a file with the data of the whole year in hourly or in lower time steps (see the user manual for details).

However, in this case we will suppose there is no load and we will not add any load.

To see the options of purchasing and selling electricity to the AC grid, click on the last tab ("**PURCHASE / SELL E**").



By default, the purchase from AC grid is not allowed (the box "**Purchase from AC grid Unmet Load** …" is unchecked) therefore our system won't import any power from the AC grid. We don't need it as there is no load, however, in projects with load consumption you should check that box so that the system could import power from the AC grid.

By default, injecting (selling) electricity to the AC grid is allowed (the box "**Sell Excess Energy to AC grid**" is checked). There is a fixed default price for the electricity sold to the AC grid (0.12 €/kWh), with a 3% annual inflation and a maximum power for the grid-connection of 30 MW. By default, no energy generation charge (transfer charge) is applied (it is fixed at 0 €/kWh) (in some countries, for generating systems a generation charge is applied for each kWh it injects into the AC grid, but we won't consider this). Also no net metering policy is applied and no taxes area applied.

In all MHOGA data boxes, the decimal spacing must be entered as defined in the Windows environment. The computer with which this guide was made has in Windows the decimal spacing as the dot (".") so for example the fixed sell price is "0.12" €/kWh; if your computer uses comma as decimal spacing, you will see "0,12" in that box.

5. Hourly price and other options for the electricity sold to the AC grid.

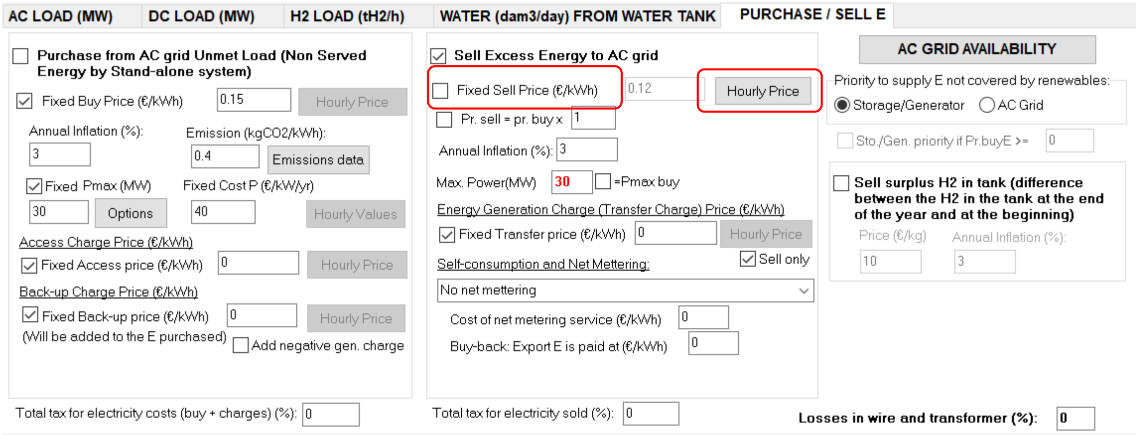
We can change these values related to the electricity sold to the AC grid.

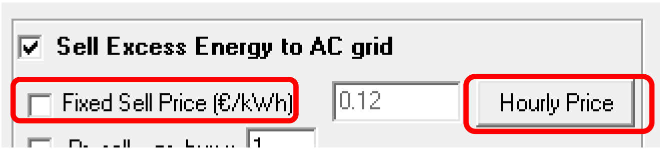
Now let's suppose that the electricity sell price is hourly (real time pricing tariff) and it has high differences between the minimum and maximum hourly price of each day. This hypothetical hourly price file can be downloaded here:

http://ihoga.unizar.es/Desc/Hypothetical_hourly_pirce.zip

Download and unzip, you will get "Hypothetical_hourly_pirce.txt" file.

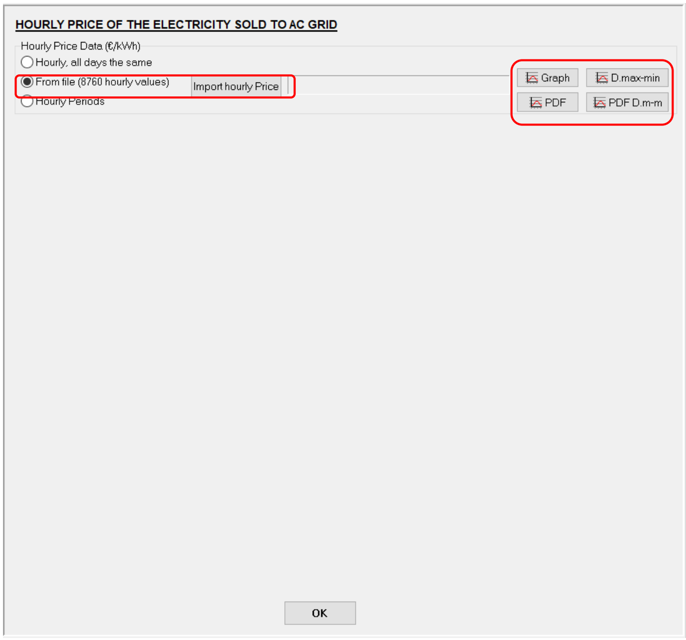
In the LOAD / AC GRID window, PURCHASE / SELL E tab, uncheck "**Fixed Sell Price**" and click in "**Hourly Price**" button.



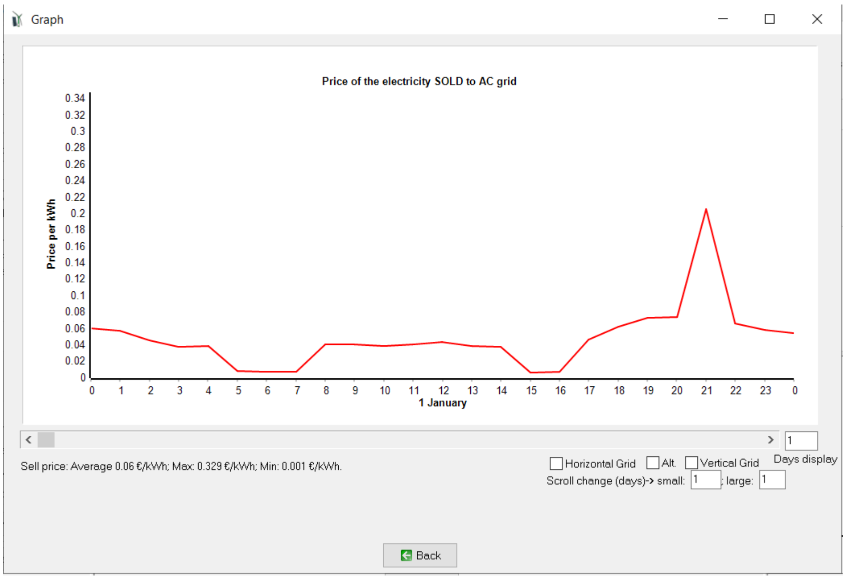


When clicking in “**Hourly Price**” button, a small window appears, where you can import the downloaded hourly file. Click in “**From file (8760 hourly values)**” and click in the button “**Import hourly file**” and import the “Hypothetical_hourly_pirce.txt” file you downloaded.

When MHOGA imports a file, the decimal spacing of the values of the file must ALWAYS BE DOT (.). If you open the downloaded file, you will see the dot as the decimal spacing. Even if your computer uses comma as decimal spacing, ***in the files that MHOGA will import the DECIMAL SPACING MUST BE DOT (.).***



After importing the file, you can click in the button “**Graph**” and see the hourly sell price:

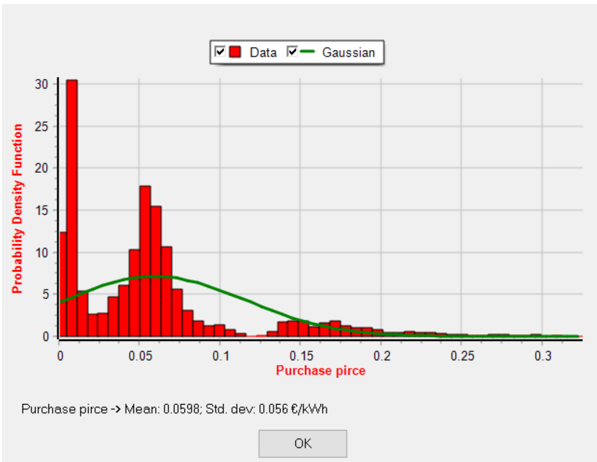


In all the graphs, you can **zoom** in the graph (draw a window with your mouse over the area to be enlarged: click from top left to bottom right); later you can undo the zoom (click and drag from bottom right to top left).

We can see that average hourly price is 0.06 €/kWh, its maximum is 0.329 and its minimum 0.001 €/kWh.

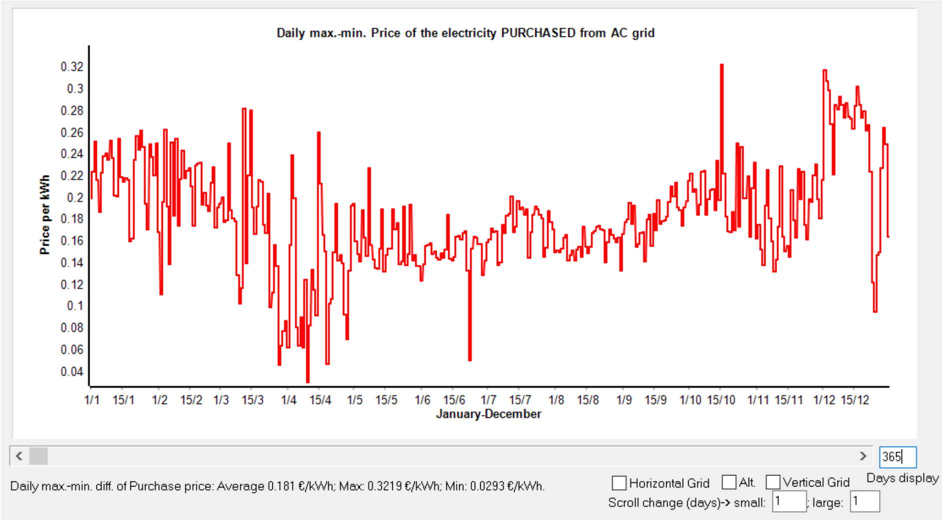
Click “**Back**”.

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).

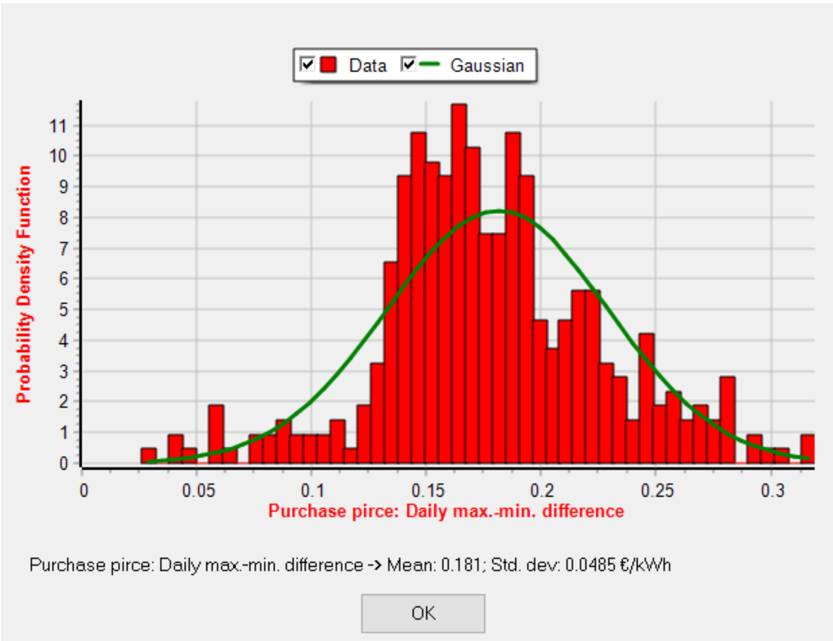


Click “**OK**”.

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:

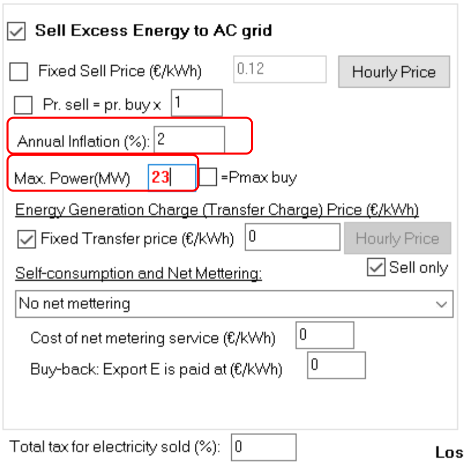


With the button "**PDF Dm-m**" it shows the probability density function (PDF) of the previous graph (values of difference between the maximum price and the minimum price of that day), showing also the mean and standard deviation (and, with these values, it shows in green the Gaussian curve). In next 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.



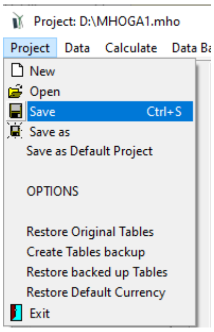
Click "**OK**" to return to the options of selling electricity to the AC grid.

Let's suppose that the annual inflation price of the electricity sold to the AC grid is 2%, we change it. Also, the maximum power to be injected to the grid (the limit of the injecting point) is 23 MW. We leave the taxes in 0%, therefore we suppose the hourly price we introduced includes taxes.



Now we have defined everything we need of LOAD / AC GRID, so we can return to the main screen of the software by clicking in "**OK**" button (left bottom corner).

<u>Remember to save the project periodically (in the main screen, upper menu **Project-> Save**):</u>

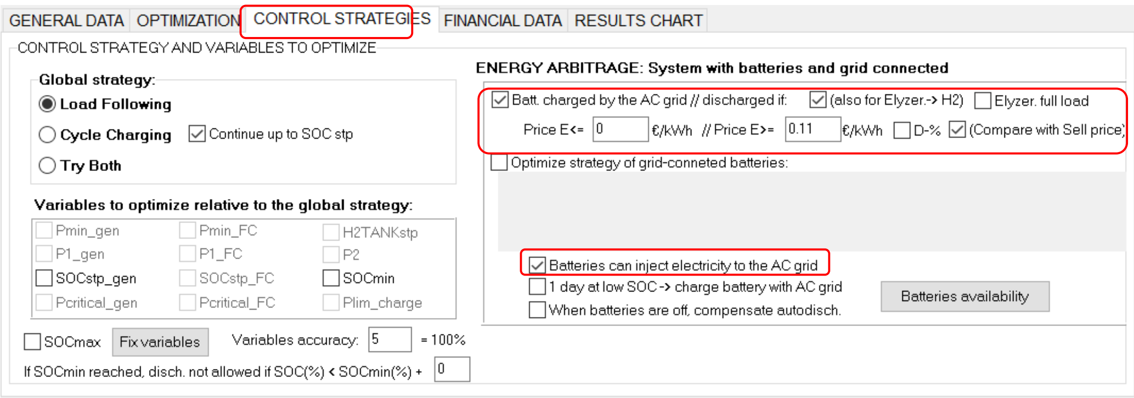


<u>6. Grid-connected battery management.</u>

In the main screen, **CONTROL STRATEGIES** tab, we can set the options for the control strategies. The left part of this tab (global strategy and variables to optimize relative to the global strategy) is only used when there is consumption load: the control strategy selects which component must supply the load when the renewable sources cannot do it, etc. This has no sense in the cases without load consumption, therefore in our case we will not consider anything of this.

In the right part of this tab we can set the energy arbitrage (management of the grid-connected batteries), as we have in our project batteries and grid connection.

We can set the conditions so that the batteries will be charged by the AC grid and the conditions to discharge them, in terms of electricity price. <u>As the checkbox "(Compare with Sell price)" is checked (by default), the electricity price to be considered in the control strategy is the sell price, and this also implies that batteries will never be charged from the grid (they will be charged just from the renewable sources), even if the purchasing electricity price from the grid was lower than the limit</u>.



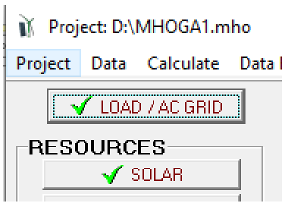
By default:

- The batteries never charge from the grid ("(Compare with Sell E)" is selected) and they will never be charged from the renewable sources (they would be charged when sell price E <= 0 €/kWh, that is, never); however, they will be charged from the renewable sources when the renewable power is higher than the maximum power that can be injected to the AC grid (defined in previous section, 23 MW) with the surplus power.
- Batteries are discharged, injecting electricity to the grid ("Batteries can inject electricity to the AC grid" is selected) when the price of the electricity sold to the grid is higher than 0.11 €/kWh.

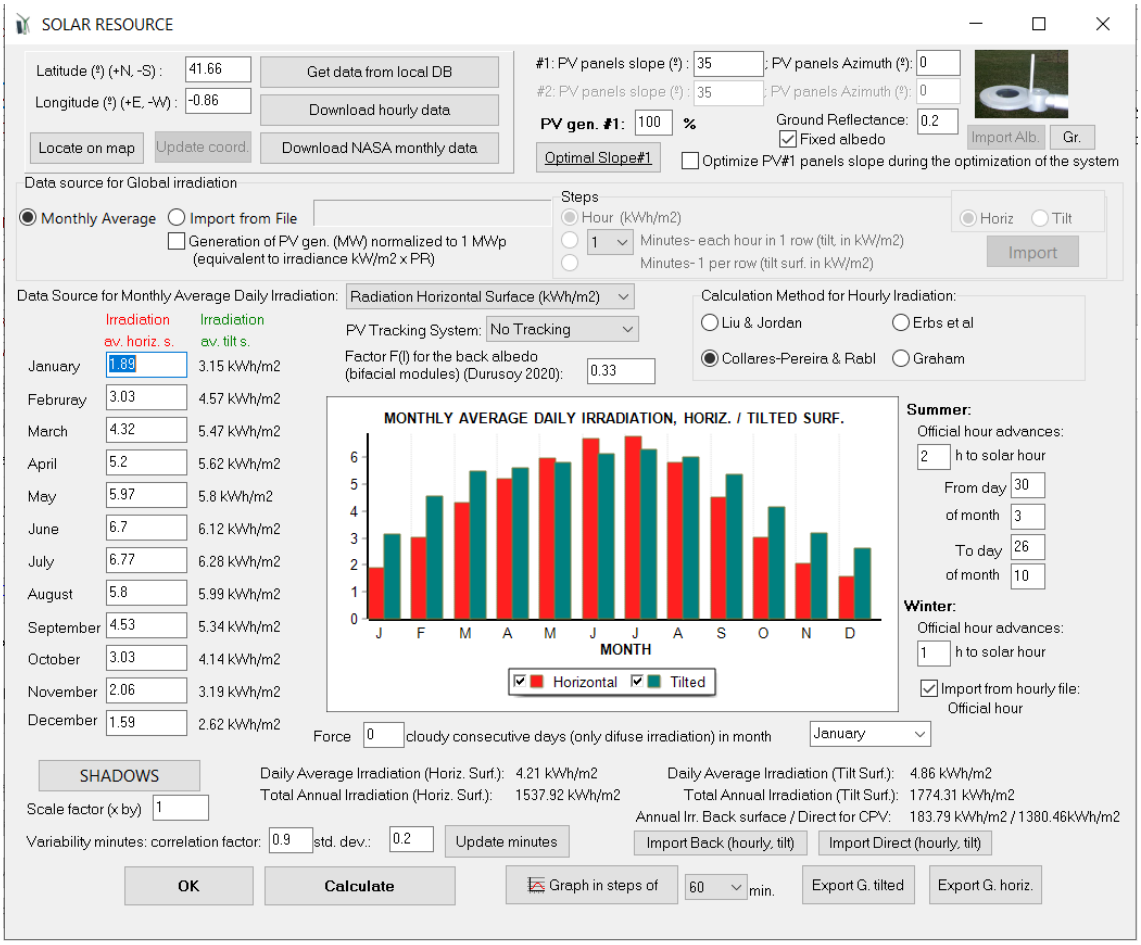
Therefore, energy arbitrage will be: the batteries will only be charged with the power from the renewable sources that cannot be injected to the grid, if it is higher than 23 MW (the maximum power allowed to inject to the grid), and the batteries will inject their energy to the grid when the sell price is higher than 0.11 €/kWh.

7. Irradiation data.

In the main screen, by clicking on the "**SOLAR**" button we can modify the solar resource data.



The following screen appears:

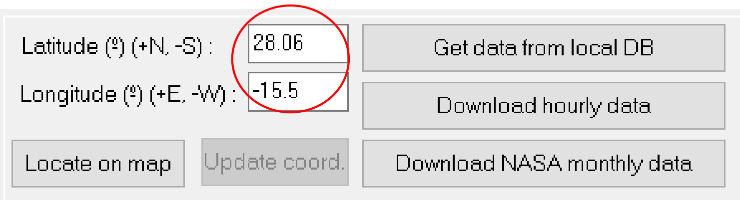


Within the irradiation screen, we must indicate the latitude and longitude of our location (left top corner). If we know them, we indicate them directly.

If we do not know them, we can obtain them directly with the button "**Locate on map**" (the first time they must introduce a Google Maps JavaScript API key, which can be obtained free of charge as shown in the *user manual*, section 3.3.2), then Google Maps open in your web browser, you click in the location, click in the “Confirm” button of the web and go back to MHOGA, irradiation screen, and click in “**Update coord**” button, then the coordinates are updated to the value of the location selected in the web (more info in the *user manual*, section 3.3.2).

If you don’t want to use that option, you can search in [https://www.**google**.com/**maps**](https://www.google.com/maps) the location, once found, click the right button and you will see the latitude and longitude.

Suppose that the system will be near Las Palmas de Gran Canaria, latitude 28.06 ° (north, positive) and longitude -15.5 ° (west, negative). Enter these values (top left corner of the screen):



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

- Monthly average data:

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

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

- Hourly data:

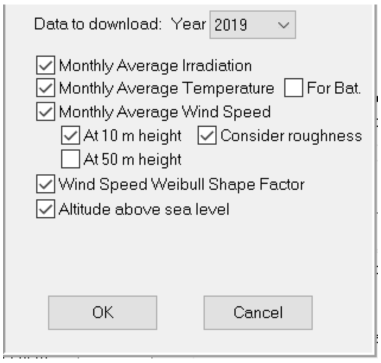
  -PVGIS (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html)

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

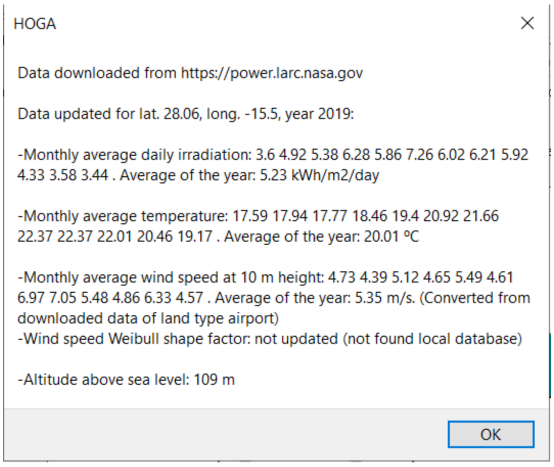
  - NASA (https://power.larc.nasa.gov/)

First we will use NASA monthly average data.

Then click on "**Download NASA monthly data**". A window appears asking us what data we want to download (we can also choose the year of the data to be downloaded):



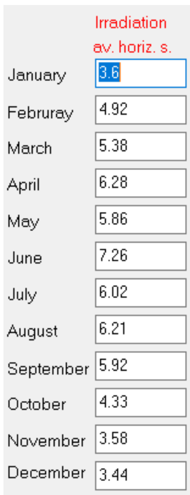
We use the default values (2019 data) and click "**OK**". After some seconds (be patient, it can take even 30 seconds) the confirmation of the downloaded data appears:



Note that these values are average values of year 2019 for 1º lat x 1º long. around the location (solar data source is a global 1° x 1° latitude/longitude grid while the meteorological data sources are ½° x ⅝° latitude/longitude grid). Weibull shape factor will only appear if you have previously installed the local database, available in the download area of the iHOGA / MHOGA website (not necessary at the moment).

By clicking "**OK**", we return to the irradiation screen.

In this screen the average monthly data of irradiation in kWh/m2 have been updated:

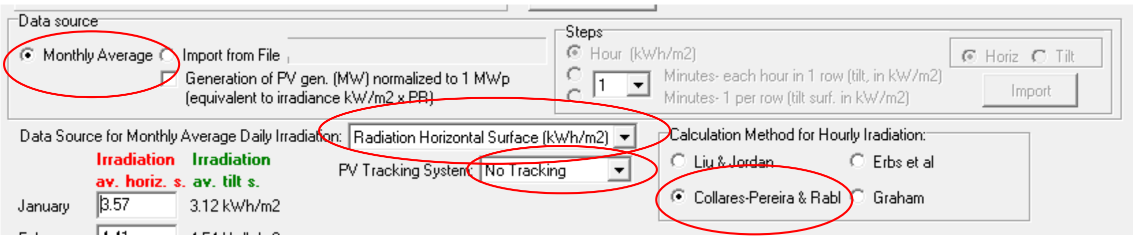


If NASA database fails (server error), you can introduce the data manually. We won't do it, but you could use the local database of iHOGA/MHOGA (you must have previously installed the database by downloading and executing the self-extracting rar file "RESOURCES-ENG.exe", installing into the MHOGA installation folder, subfolder "RESOURCES". (Availalbe in https://www.dropbox.com/s/p3sd0t3ru19lros/RESOURCES-EDU-eng.exe?e=1&dl=0)..

*To use the local database, in the irradiation screen, click on the button "**Get data from local DB**".*

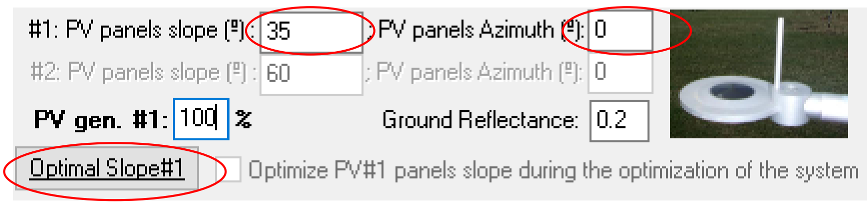
We could use as input data source data a file with data of global irradiation on horizontal surface (hourly values, file of 8760 rows, in each row the value in kWh/m^2 of each hour), a file with data in minutes (inclined surface) or average monthly data (12 data, one for each month, in different formats).

When downloading from NASA (monthly values) we obtain average daily data per month in kWh/m^2, so we don't change the default option "**Monthly average**", Radiation Horizontal Surface (kWh/m^2).

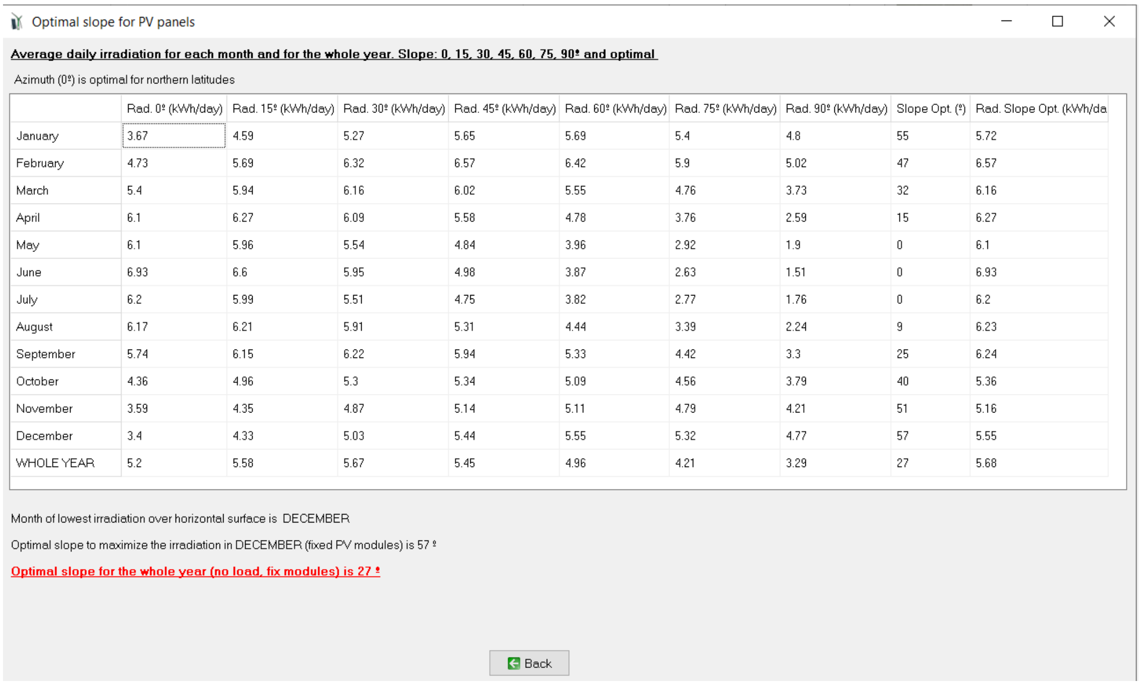


In this case we will assume that there is no solar tracking system (modules with fixed orientation and slope) and we will use the method of calculation of the hourly irradiation of Collares-Pereira and Rabl (default values).

We must indicate the slope and the azimuth of the PV modules. You can use two zones for the PV generator, with different slope and azimuth, PV gen. #1 (100% default) and PV gen. #2 (0% default). By default, all the PV modules will be in #1 (100%), but we could change it. We leave 100% for zone #1 as default, defining 35º for the slope and 0º for the azimuth (that is, south oriented).



The optimal azimuth will be 0º (for northern hemisphere, that is, orientation towards the south) but maybe the slope is not optimal. The optimal inclination for our case will be obtained by pressing the button "Optimal slope#1". After some seconds 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	3.67	4.59	5.27	5.65	5.69	5.4	4.8	55	5.72
February	4.73	5.69	6.32	6.57	6.42	5.9	5.02	47	6.57
March	5.4	5.94	6.16	6.02	5.55	4.76	3.73	32	6.16
April	6.1	6.27	6.09	5.58	4.78	3.76	2.59	15	6.27
May	6.1	5.96	5.54	4.84	3.96	2.92	1.9	0	6.1
June	6.93	6.6	5.95	4.98	3.87	2.63	1.51	0	6.93
July	6.2	5.99	5.51	4.75	3.82	2.77	1.76	0	6.2
August	6.17	6.21	5.91	5.31	4.44	3.39	2.24	9	6.23
September	5.74	6.15	6.22	5.94	5.33	4.42	3.3	25	6.24
October	4.36	4.96	5.3	5.34	5.09	4.56	3.79	40	5.36
November	3.59	4.35	4.87	5.14	5.11	4.79	4.21	51	5.16
December	3.4	4.33	5.03	5.44	5.55	5.32	4.77	57	5.55
WHOLE YEAR	5.2	5.58	5.67	5.45	4.96	4.21	3.29	27	5.68

Month of lowest irradiation over horizontal surface is DECEMBER

Optimal slope to maximize the irradiation in DECEMBER (fixed PV modules) is 57 º

Optimal slope for the whole year (no load, fix modules) is 27 º

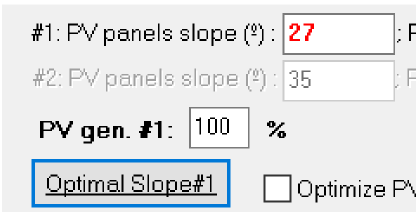
Back

If the screen does not appear, but the main screen of the program appears, click on the MHOGA icon in the Windows taskbar (lower part of the computer screen) and the screen shown 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.

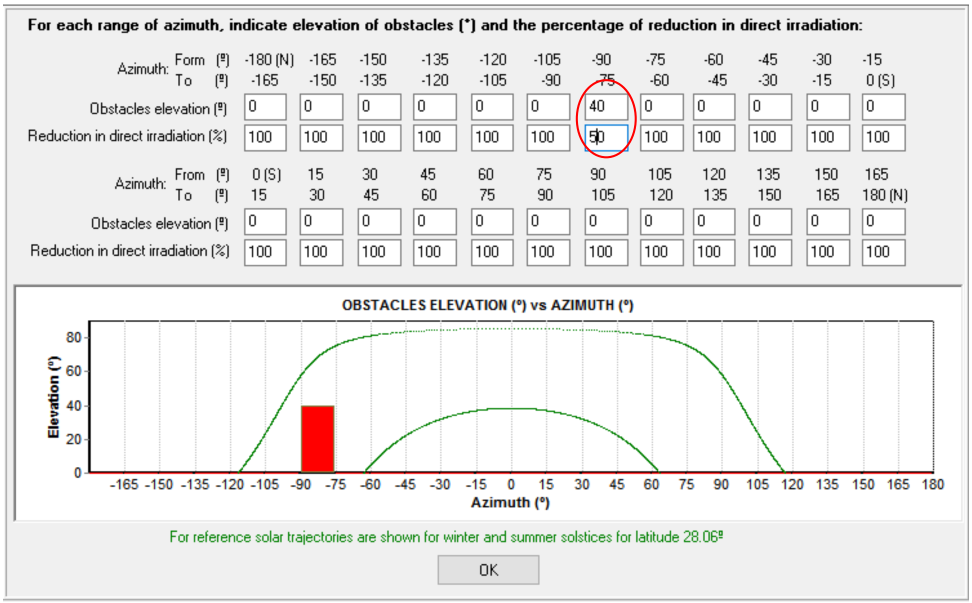
In generating systems (as our case), with no load, in red it is shown the optimal slope for maximizing the PV generation during the whole year, in our case 27º.

We click "**Back**" to return to the irradiation screen. A message appears showing that the slope of the PV modules has been updated to the optimal value. We see the change in red.



Shadows that affect our PV generator must be defined before calculating the irradiation or before downloading hourly irradiation data from PVGIS, Renewables Ninja or NASA.

By clicking the button "**SHADOWS**" (down left) we access a window where we can define the existing obstacles that can shade the photovoltaic modules. Suppose that between -75 and -90° azimuth exists a 40° elevation obstacle, and that this obstacle eliminates 50% of the direct irradiation (because it occupies the middle of the strip between -75 and -90° of azimuth), we introduce these data:



By clicking "**OK**", we return to the irradiation screen.

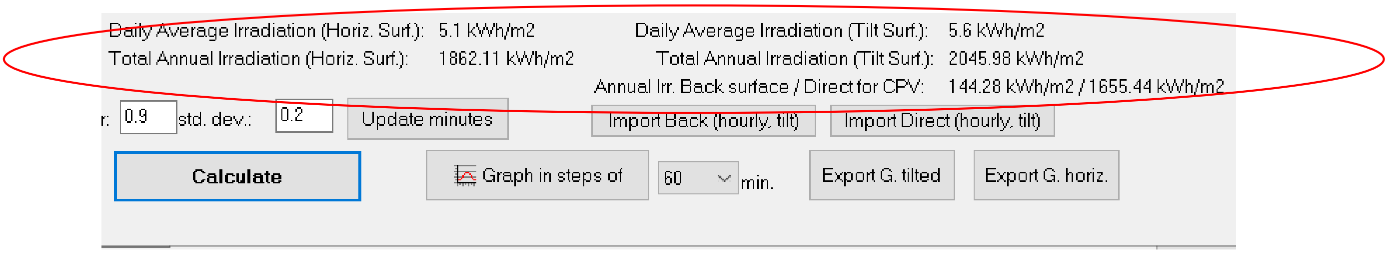
We are using irradiation in monthly average values. The software must convert it to hourly values and later in minute values so that any time step can be used in the simulations and optimizations.

Before clicking on the “Calculate” button, we must define how the irradiation values of each minute will be obtained, since a first order autoregressive model is used. We must indicate the correlation factor and the standard deviation (kW/m^2). We use the default values (down left):

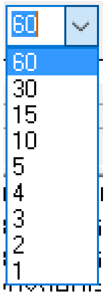
Then click the "**Calculate**" button (down) to obtain the 8760 values of hourly radiation on the tilted surface (26°) and for all the minutes within each hour:

The software also calculates the irradiation of the back surface (needed if we would consider bifacial PV modules) and the direct irradiation over the tilt surface (needed if we would consider concentrating PV, CPV).

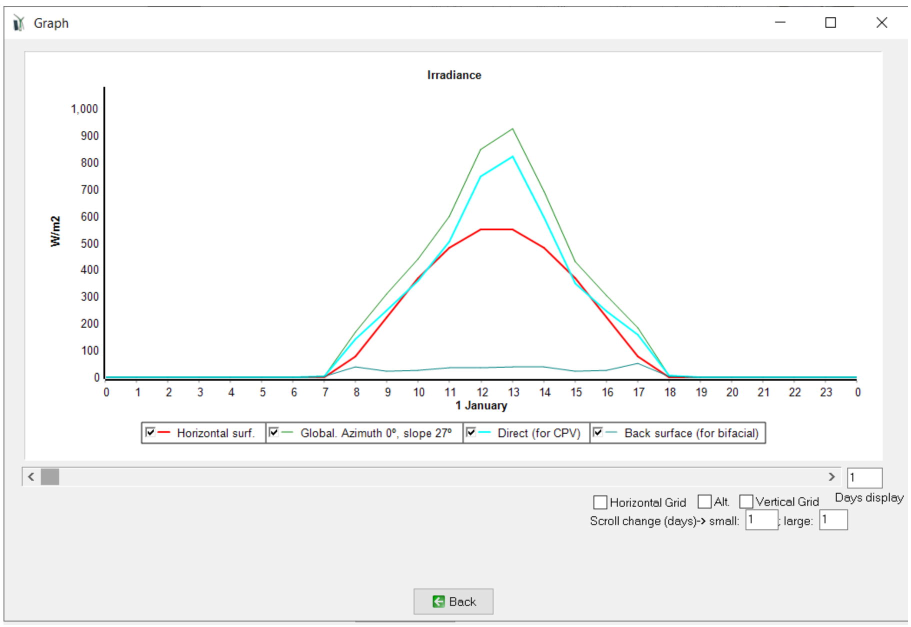
After calculation, it is shown (above the button Calculate) the daily global average and annual irradiation on horizontal surface and on tilted surface, the total annual irradiation over the back surface of the modules and the total direct irradiation over the titl surface, for CPV (***note that the user can obtain values slightly different because a correlation factor and standard deviation have been applied, implying that a randomness is applied; it will also happen in the next sections***).



The "**Graph in steps of**" button is enabled. The display can be in intervals of between 1 minute and 60 minutes.

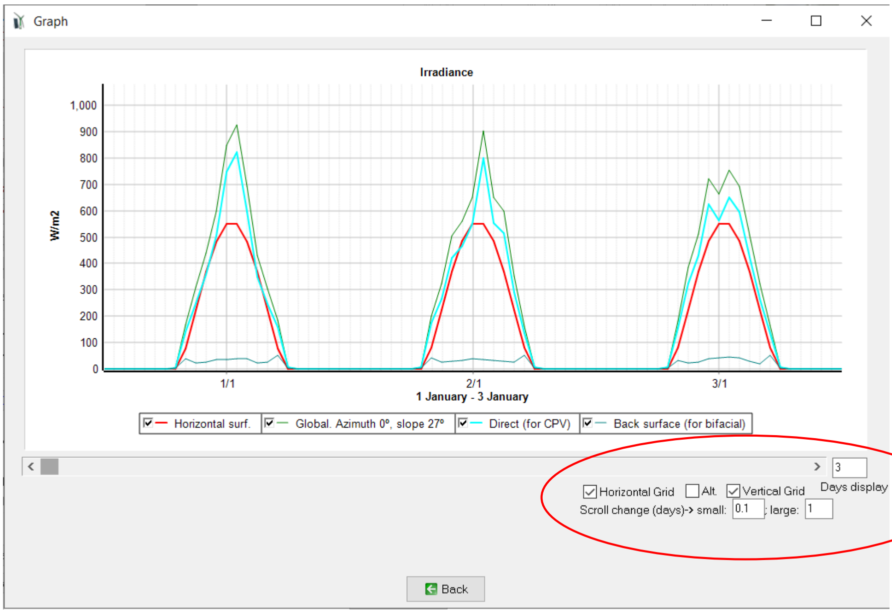


We use 60 minutes and when clicking in "**Graph in steps of**" the representation of the global irradiation on the tilted surface (27º) in shown in green, the irradiation on horizontal surface in red (without random variability), the direct irradiation over the tilt surface (for CPV) in blue and the global irradiation over the back surface in teal.

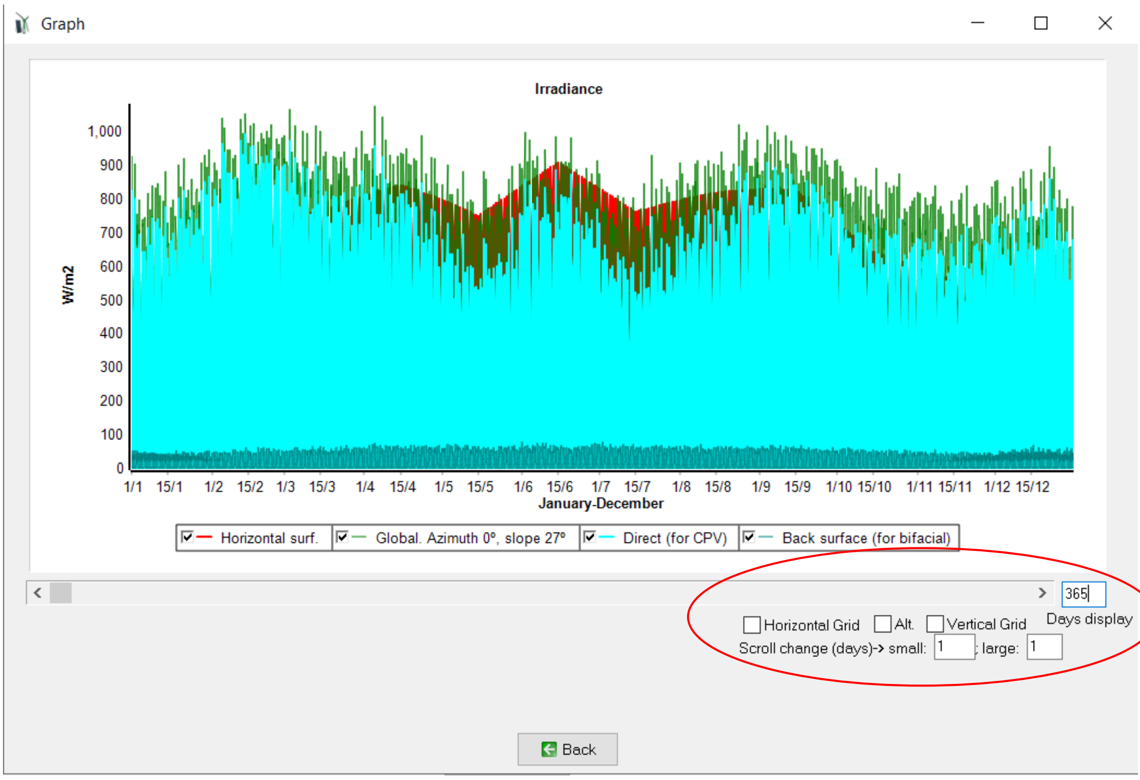


You can see the horizontal grid by clicking on the "Horizontal grid" checkbox. Horizontal axis labels can be seen in alternate positions by clicking on "Alt" checkbox (if you have select less than 60 min. for the graph, you will see the hours and the half hours). Vertical grid is shown by clicking on "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).

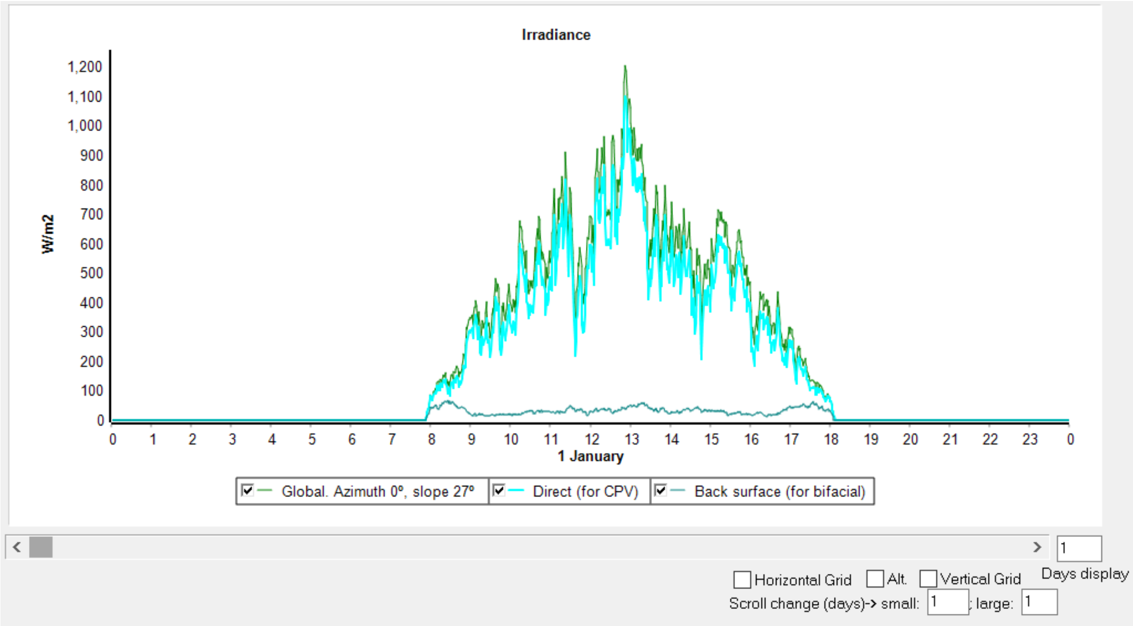
For example, we can see 3 days at the same time (3 Days display), with horizontal grid (darker grey at 12:00 h of each day if more than 1 day displayed) and vertical grid, and each time we click in the scroll arrow the graph will move 0.1 days, and each time we move the scroll cursor the graph will move 1 day):



If we change the days of visualization to 365, we see the distribution of the irradiation during a whole year:



We change again the days of visualization to 1, we return ("**Back**" button) and change to 1 minute and click again on "**Graph in steps of**" button, after some seconds (be patient, please) we obtain the graph in minutes of the global irradiation on tilted surface, the global over the back surface and the direct over the tilted surface.



By clicking "**Back**" we return to the irradiation screen.

We could use these values of irradiation for our simulations and optimizations. But we could also download hourly values from PVGIS, Renewable Ninja or NASA.

8. Using hourly irradiation and wind speed data from Renewable Ninja, PVGIS or NASA.

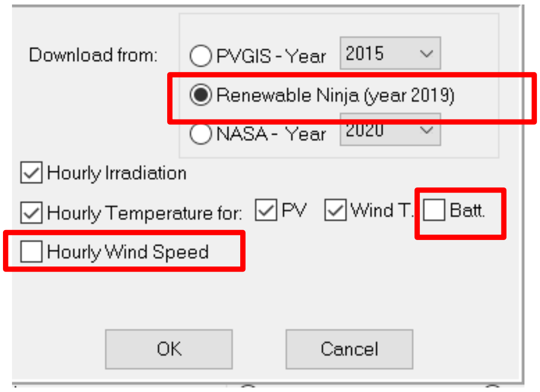
We can use hourly data for irradiation, temperature and wind speed data obtained from the databases of PVGIS, Renewable Ninja or NASA.

In the SOLAR resource windows, click in "**Download hourly data**".

Then a small window appears, showing the database to choose (PVGIS, Renewable Ninja or NASA) and the that can be downloaded.

Renewable Ninja hourly data:

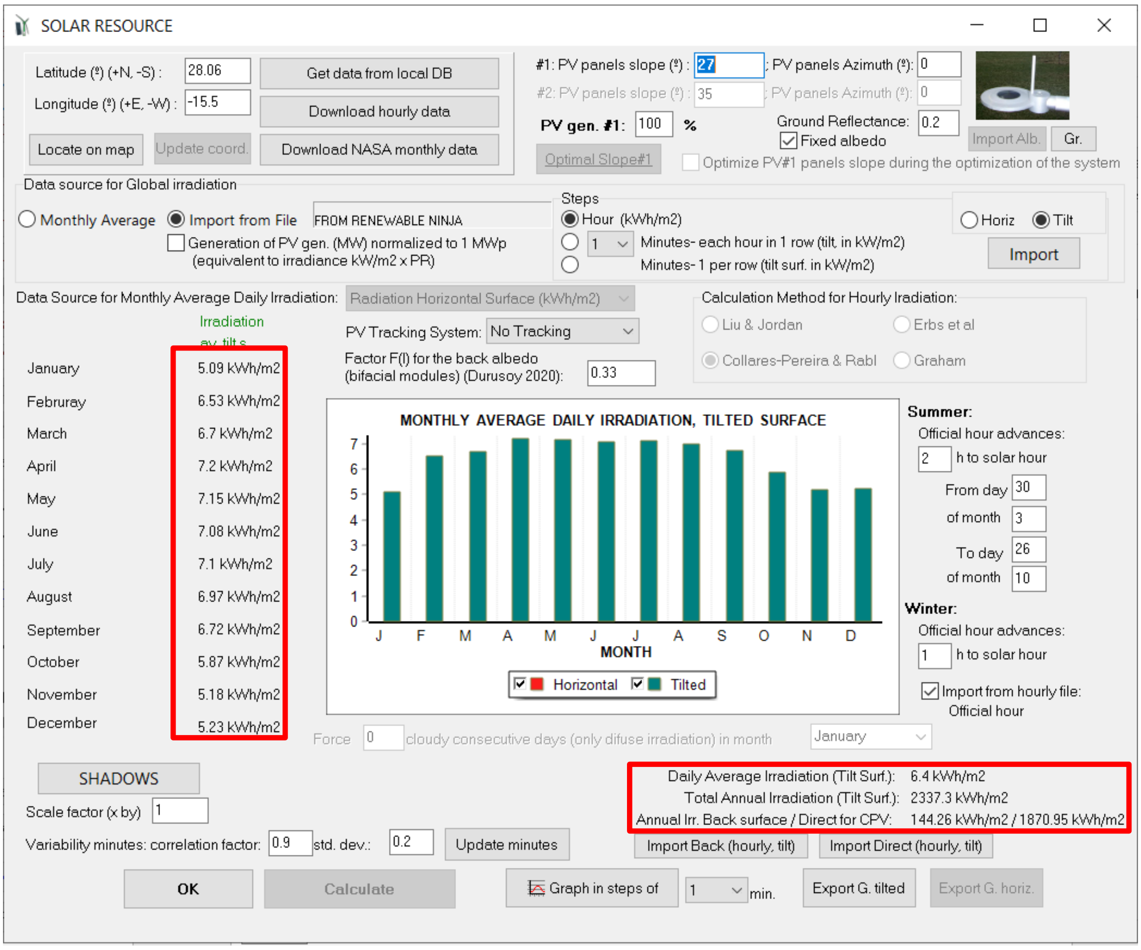
First we select the database of Renewable Ninja (year 2019). This database has some restrictions: with this database we can only download data of year 2019, and we can do only 5 downloads per day (each download of irradiation/temperature is counted and also each download of wind speed is counted) however if you can change your IP (for example using a free VPN service as https://www.tunnelbear.com/) you can do 5 downloads each time you have a new IP. These restrictions are not for PVGIS or NASA databases.



We could download irradiation, temperature and also wind speed. However, as now we only want to download irradiation and temperature, we uncheck “Hourly Wind Speed”. The temperature of the batteries is not checked and we will leave it, because we can suppose the batteries temperature is different from ambient temperature, assuming they are into a building and not in the outdoor (their temperature will be defined later in the batteries window).

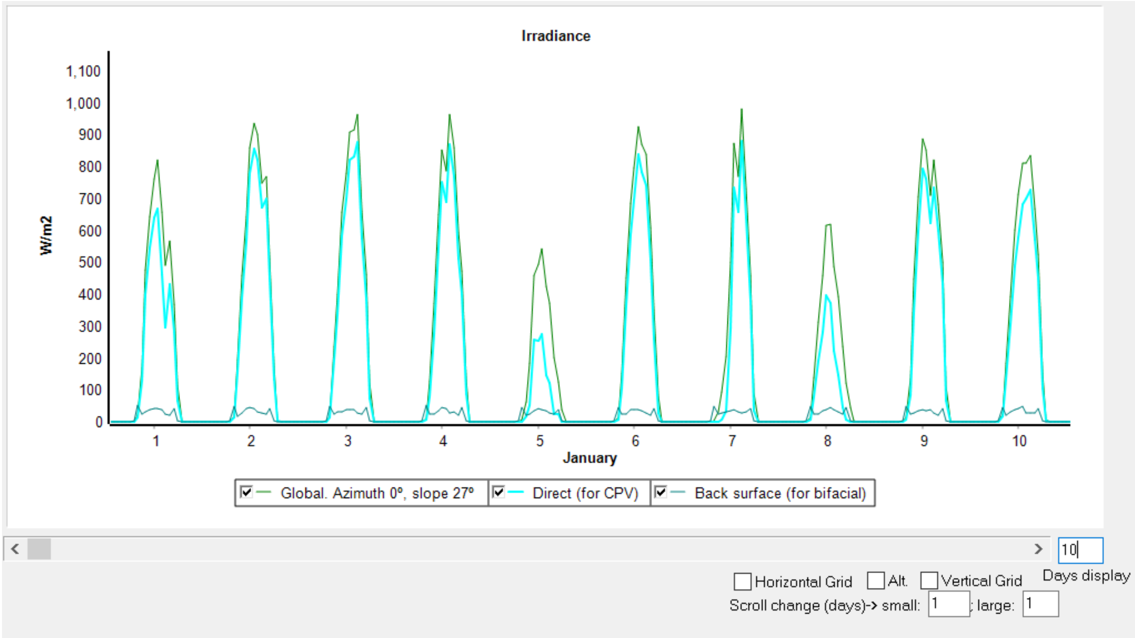
By clicking “**OK**”, an info message appears, we click “**OK**” again and hourly data of irradiation and temperature are downloaded.

In the irradiation window we see the average values of the downloaded irradiation over tilted surface (daily average for each month and annual).



Total annual irradiation over the inclined surface is 2337 kWh/m^2, compared to 2046 kWh/m^2 obtained with NASA monthly data (obtained in the previous section).

If we click on the button "**Graph in septs of**" (60 min.) we see the hourly irradiation downloaded from Renewable Ninja:

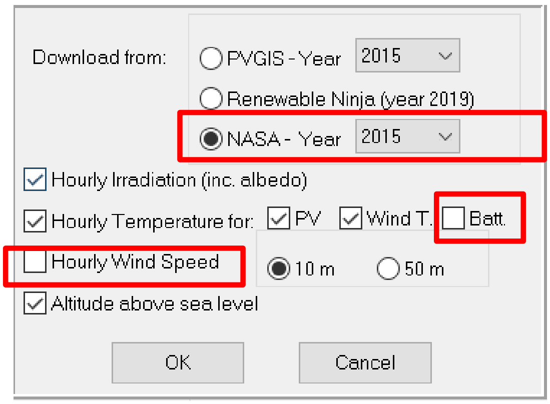


We could use the data form Renewable Ninja for the simulations or optimizations, we could also use the data from PVGIS or NASA. We can see the difference in irradiation is low.

Now we will download NASA hourly data to see the difference with the other databases.

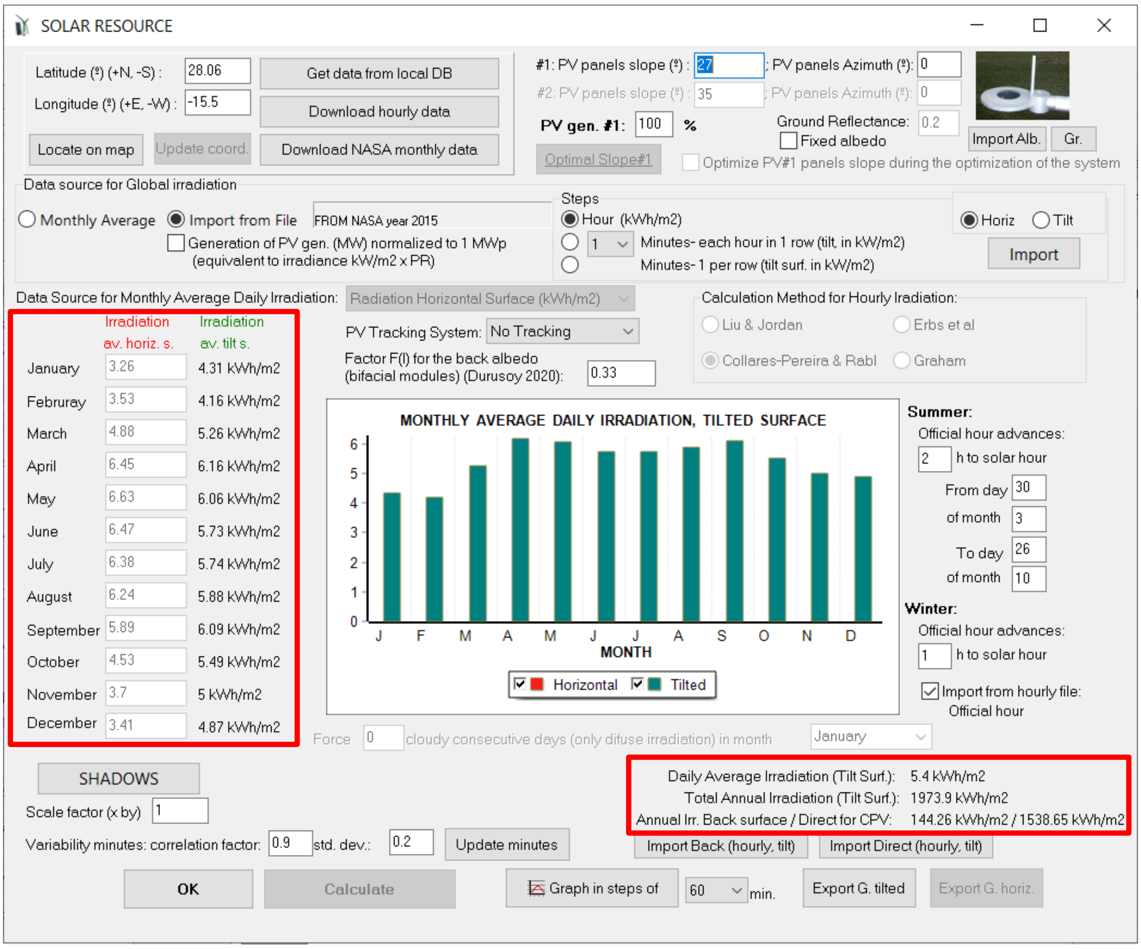
NASA hourly data:

Click in "**Download hourly data**" button. Now we select the database of NASA. We can select any year from 1990 to 2020, for example select 2015. We leave unchecked "Batt." We could also download wind speed data at 10 or 50 m height (not at any height as Renewable Ninja can do), but we will not do it later.



By clicking "**OK**" an info message appears, we click "**OK**" again and hourly data of irradiation and temperature are downloaded. *Be patient, it can take even more than one minute*.

After downloading, in the irradiation window we see the average values of the downloaded irradiation over horizontal surface (downloaded) and over tilted surface (calculated by MHOGA).

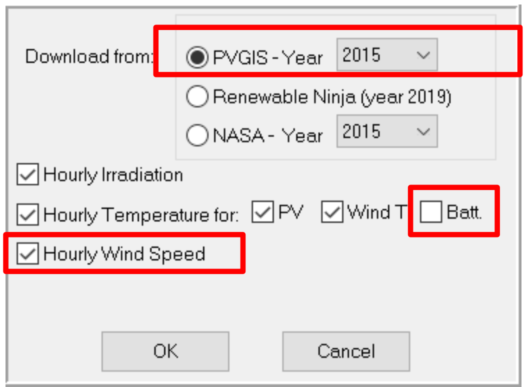


Total annual irradiation over the inclined surface is 1974 kWh/m^2, compared to 2337 kWh/m^2 obtained with Renewables Ninja and 2046 kWh/m^2 obtained with NASA monthly data.

Now we will download PVGIS hourly data to see the difference with the other databases.

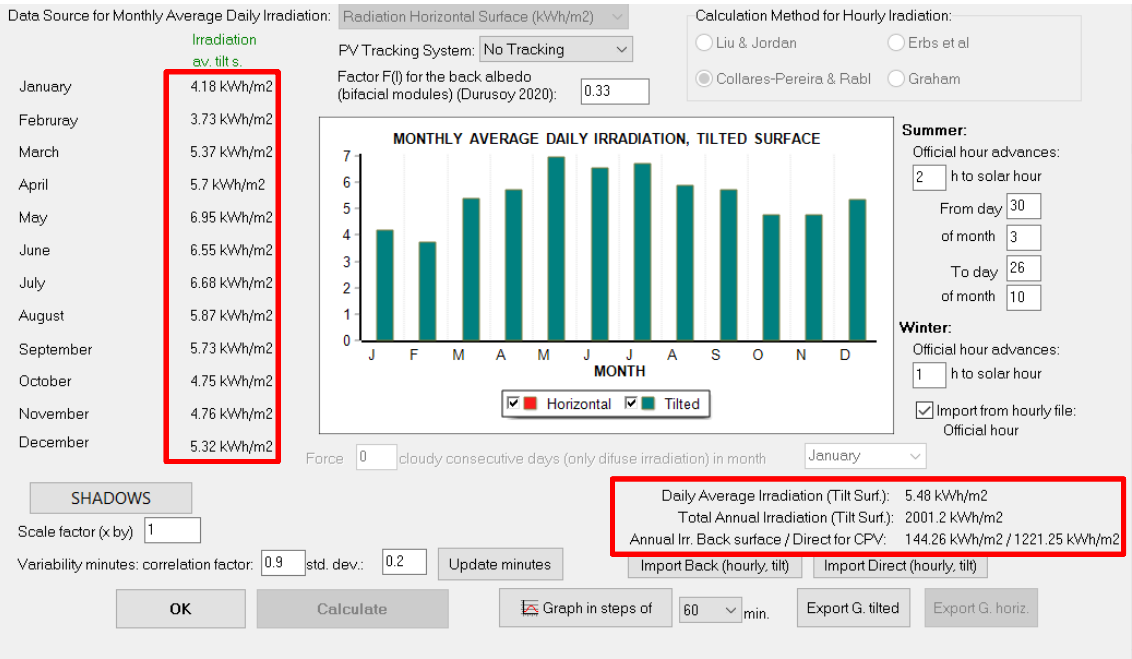
<u>PVGIS hourly data:</u>

Click in "**Download hourly data**" button. Now we select the database of PVGIS. We can select any year from 2007 to 2015, for example select 2015. We leave unchecked "Batt." But we check "Hourly Wind Speed" so that the wind speed at height 10 m will also be downloaded from PVGIS (in PVGIS we cannot change the height at which the wind speed was measured, PVGIS database only supplies wind speed at 10 m height).



By clicking "**OK**" an info message appears, we click "**OK**" again and hourly data of irradiation and temperature are downloaded.

In the irradiation window we see the average values of the downloaded irradiation over tilted surface (daily average for each month and annual).



Total annual irradiation over the inclined surface is 2001 kWh/m^2, compared to 1974 kWh/m^2 from hourly NASA, 2337 kWh/m^2 obtained with Renewables Ninja and 2046 kWh/m^2 obtained with NASA monthly data.

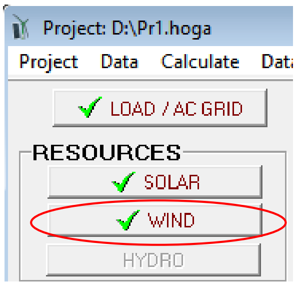
As before, we could see the downloaded data in hourly steps by clicking “**Graph in steps of**”.

Finally, we will use these data for irradiation (PVGIS year 2015).

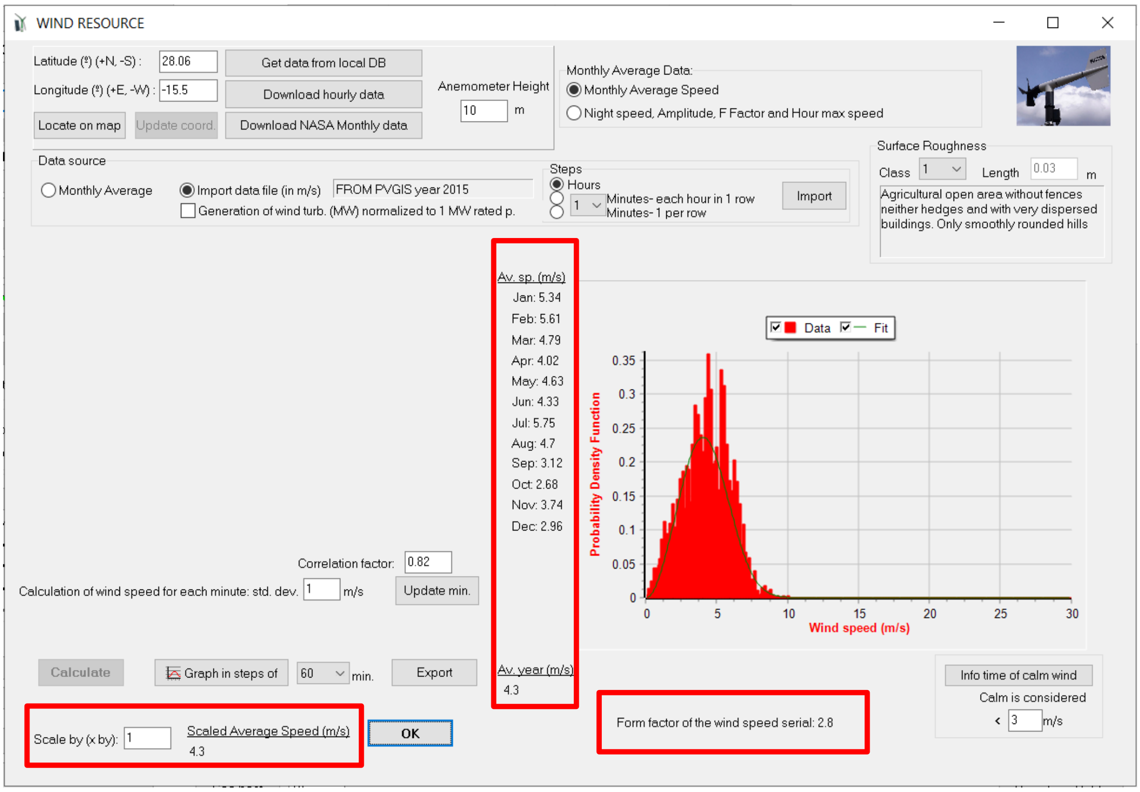
Clicking "**OK**" it returns to the main screen of the program.

9. Wind speed data.

By clicking on the "WIND" button we can define the wind resource data.



The Wind screen appears.



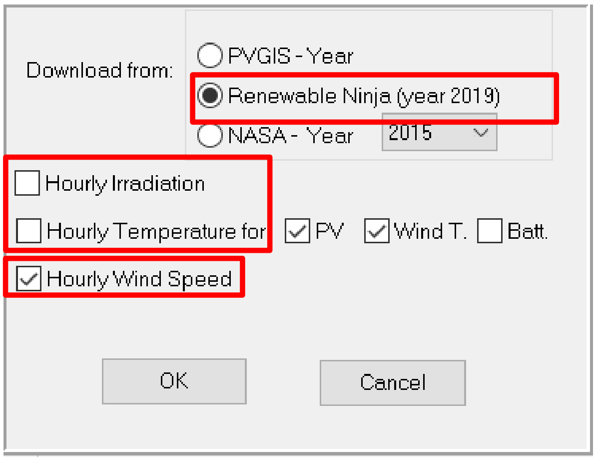
The data downloaded previously from PVGIS in the irradiation screen are already placed here: latitude and longitude, Anemometer height (10 m) and Monthly average wind speed (m/s). The distribution of the downloaded wind speed at 10 m height is shown in the probability density function (PDF). Average monthly values of the downloaded data are shown close to the PDF, and annual average (4.3 m/s at 10 m height). Weibull shape factor of the Weibull curve that best fits the downloaded data is 2.8 (shown under the probability density function PDF).

A scale factor could be set to multiply the wind speed downloaded (for example, to see the effect of having a wind speed 20% higher than the downloaded, we would set 1.2 for the “Scale by (x by)”. In this case, we will use the data downloaded, “Scale by (x by)” 1.

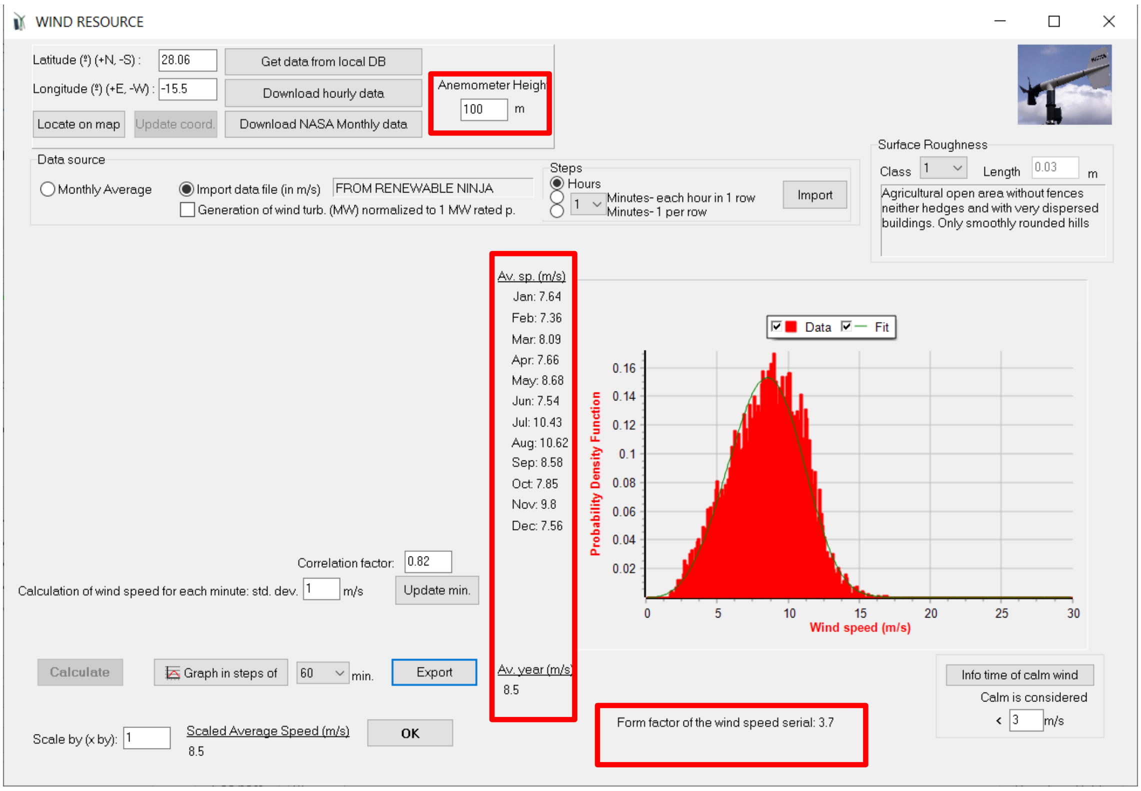
Renewables Ninja wind speed data is usually more accurate than PVGIS and NASA, also it can be downloaded for any hub height. As we will use wind turbines of hub height 100 m, we will download data at that height.

First, we set the height of the anemometer:

Then, we click in “**Download hourly data**” button, selecting just wind speed (irradiation and temperatures were already downloaded from PVGIS). We select Renewable Ninja (year 2019) as the database, and we uncheck “Hourly Irradiation” and “Hourly Temperature for”, leaving “Hourly Wind Speed” as the only one checked.



We click "OK" and the wind speed data at 100 m height is downloaded:



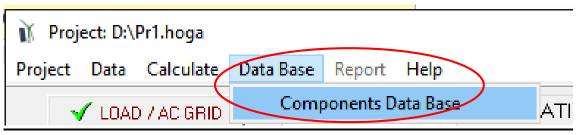
Annual average wind speed is 8.5 m/s at 100 m height and the Weibull shape factor of the Weibull curve that best fits the downloaded data is 3.7.

These data will be the wind speed data that we will use in the simulations and optimizations of this guide.

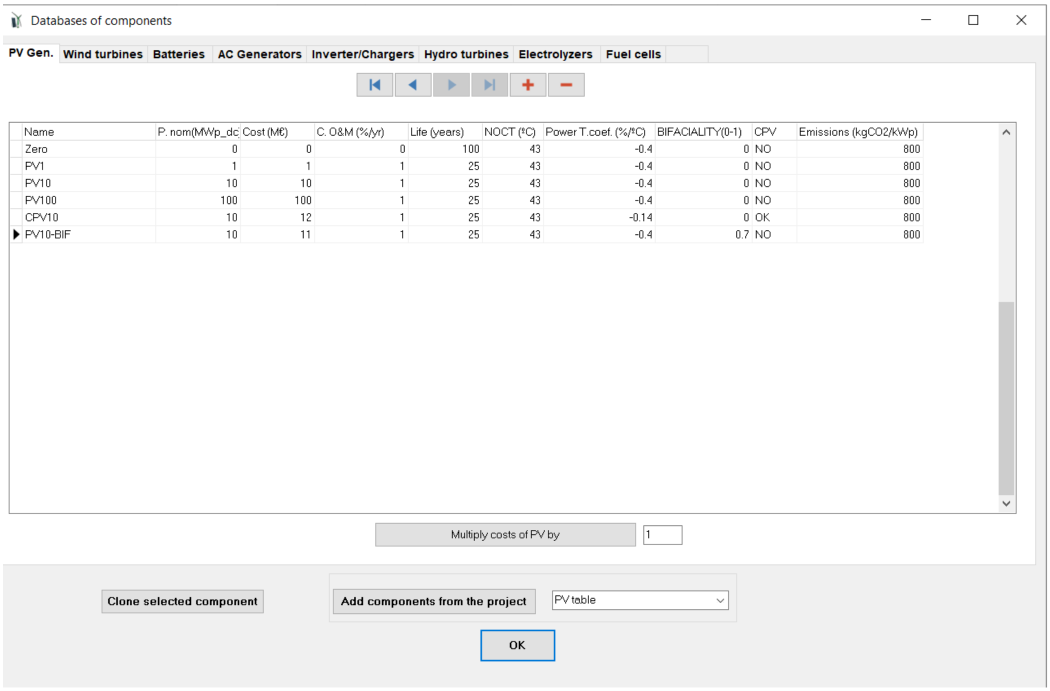
Finally clicking "**OK**" return to the main screen of the program.

10. Components Databases.

By clicking on the top menu **Data Base -> Components Data Base** it displays the components defined in the databases.



The following screen appears:



The different tabs show the components stored in the databases. We can modify the data of each component, eliminate components or add others. We can also multiply all the prices of a given component by a factor, clone a selected component (and later changing whatever you want) or adding components from the project.

It should be noted that the prices of the components vary by country, even within the same country it depends on different variables. Therefore, the designer must verify or modify the prices conveniently.

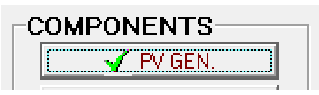
All the data are "generic", and the user can change them to his/her specific situation.

We will leave everything as it is by default, later the designer can change what he/she wants.

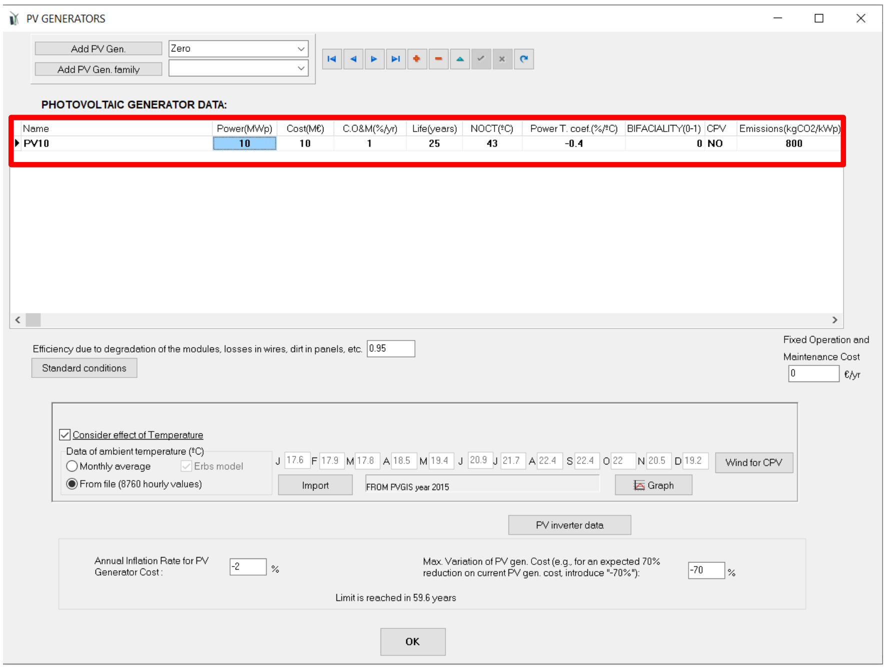
Finally clicking "**OK**" it returns to the main screen of the program.

11. PV generators data.

By clicking on the "**PV GEN.**" button we can define the different photovoltaic generators to take into account into the simulations and optimizations.



The following screen appears:



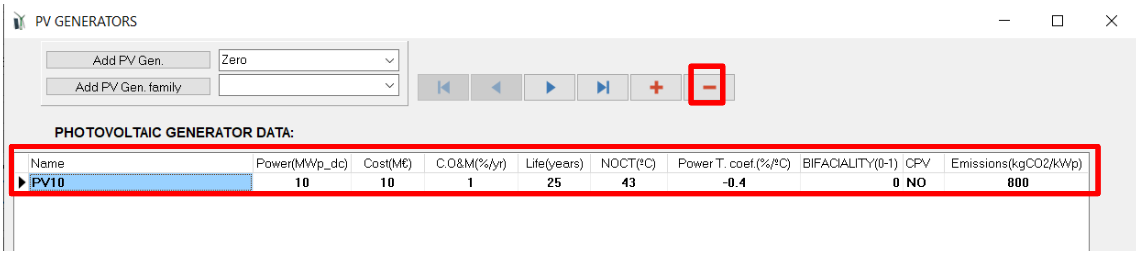
By default, there is only one type of photovoltaic generator to consider, as, by default, there is just one row in the table, the one of 10 MWp (in the optimization there will be several of this type in parallel, later we will define the minimum and maximum number in parallel allowed). We could add more different generators in the table using the button "+" of the button set in the upper area, and defining their values. We could also add from the database using the buttons "Add PV Gen" or "Add PV Gen. family". We could delete rows of the table with the button "-".

Suppose we think the size of the PV generator is too high and we want more precision, wanting to use several of 1 MWp in parallel instead of several of 10 MWp in parallel.

Then, we delete the generator of 10 MWp:

Step 1: Select with your mouse the row of the table.

Step 2: Click in "-"

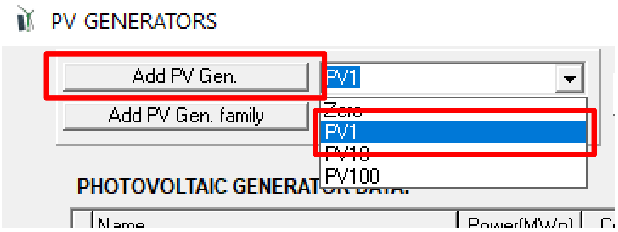


MHOGA ask you "Delete record?". Respond yes and the generator will be deleted.

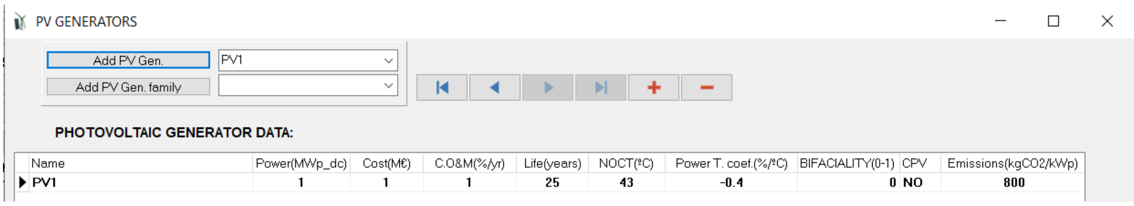
Now we want to add from the database the PV generator of 1 MWp. The quickest way to add it is:

Step 1. Select from the list close to the "Add PV Panel" button the type "PV1", which is the one of 1 MWp.

Step 2. Click on the button "**Add PV Gen.**".



Now the project will take into account the type of 1 MWp (later we will define how many of them in parallel will be allowed):



Suppose in our case we want to consider that the cost of the PV generator of 1 MWp is not the one that appears (1 M€) but it is 1.2 M€ (take into account that this would be the total cost of the PV generator of 1MWp, including PV modules, mounting structures, inverters, wiring, protections, transformers, buildings, etc).

We can modify it in the database (see point 8) and then, in the PV screen, add it from the database (if in Project->Options it is checked the box “When clicking a component in a table…”, by clicking on the row of this PV generator, its cost would be updated).

Another option is to change the name on the screen (for example, add "-mod") and change the price. If in Project->Options it is checked the box “When clicking a component in a table…”, if we do not change the name, any changes we make will not be effective because the software will consider the data in the database. Keep in mind that the number of characters in the name is limited.

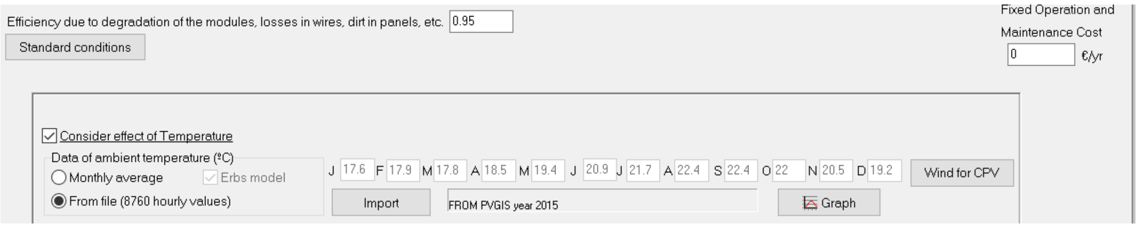
We change the name by clicking in the cell and adding at the end of the name “-mod”:

And then we change the cost to 1.2 M€ (if the decimal spacing of your computer is dot, write “1.2”; if it is comma you should write “1,2”).

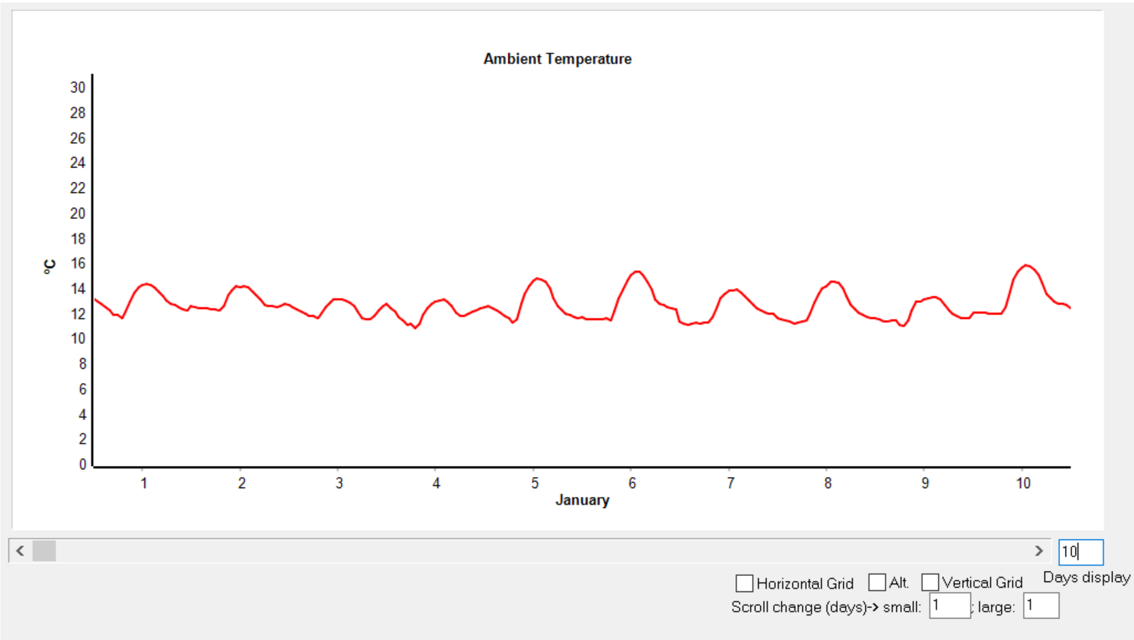
We can see in the table that O&M annual cost (OPEX) is 1% of the CAPEX (which now is 1.2 M€), that is, now it will be 12,000 €/year. We could change this percentage, but we will leave in 1%.

It is important to note that, when you change the values of the tables (the tables of the components, tables of the database and tables of load), the changes done in the tables will remain even if you do not save the project.

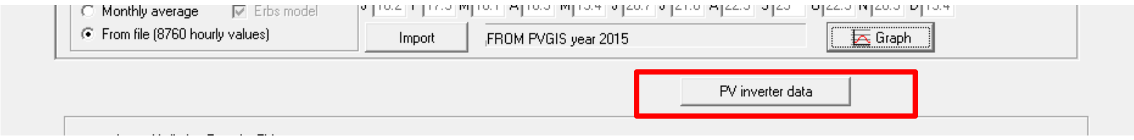
In the central area of the screen we see the efficiency due to degradation, losses, dirt (default 0.95), the fixed O&M cost (default 0 €/year, this is a fixed cost which is added to the total O&M cost of the group of individual PV generators of 1 MWp in parallel) and the button "Standard conditions" (where the standard conditions for the PV and CPV data are set).



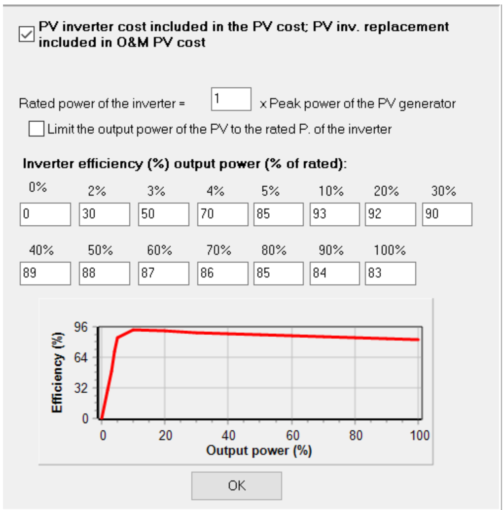
Also the effect of the temperature is by default taken into account (we could uncheck the "Consider effect of Temperature" check box in order to not consider it). We will consider it so we leave that check box checked. The ambient temperature is from hourly file as we have downloaded it previously by PVGIS, year 2015. By clicking the "**Graph**" button we can see the temperature downloaded:



Back in the PV generators screen, in the bottom of the screen we can set the PV inverter data, by clicking in the "**PV inverter data**" button.

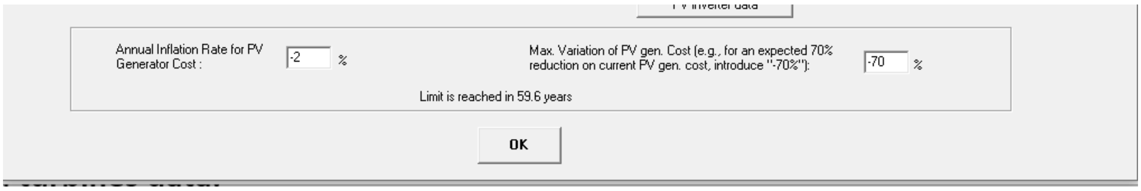


A small window appears, where we must define if the PV inverter cost is included in the PV cost (by default it is), we must set the rated power of the inverter in times the peak power of the PV generator (default 1) and the inverter efficiency (%) vs. the output power (% of rated) curve.



We leave the default inverter data and click “**OK**”.

At the top bottom of the PV generators window we can set the annual inflation rate for the PV generators CAPEX (default -2%, this means that each year we expect that the PV generator cost will be reduced in 2%) and the maximum variation of that cost, by default -70% (reduction of 70%). This means that after 59.6 years (shown below, as $(1-0.02)^{59.6}=0.3$), the cost will be 30% of the initial cost, i.e., reduction of a 70%. This limit of -70% in the PV cost reduction will be reached in 59.6 years, then after that year the technology will be considered as mature and the cost will be increased with general inflation.

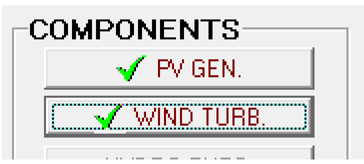


This values would be used to calculate the replacement cost of the PV generator, if its lifetime was lower than system lifetime (it is not our case, as PV generator lifetime is 25 years, the same as the system lifetime). If, for example, we had defined the system lifetime (study period of the system) to be 40 years, then in the year 25 the PV generator should be replaced, and the replacement cost would be the initial investment cost multiplied by $(1-0.02)^{25}$. And in the year 40 the residual cost would be also calculated considering this inflation rate.

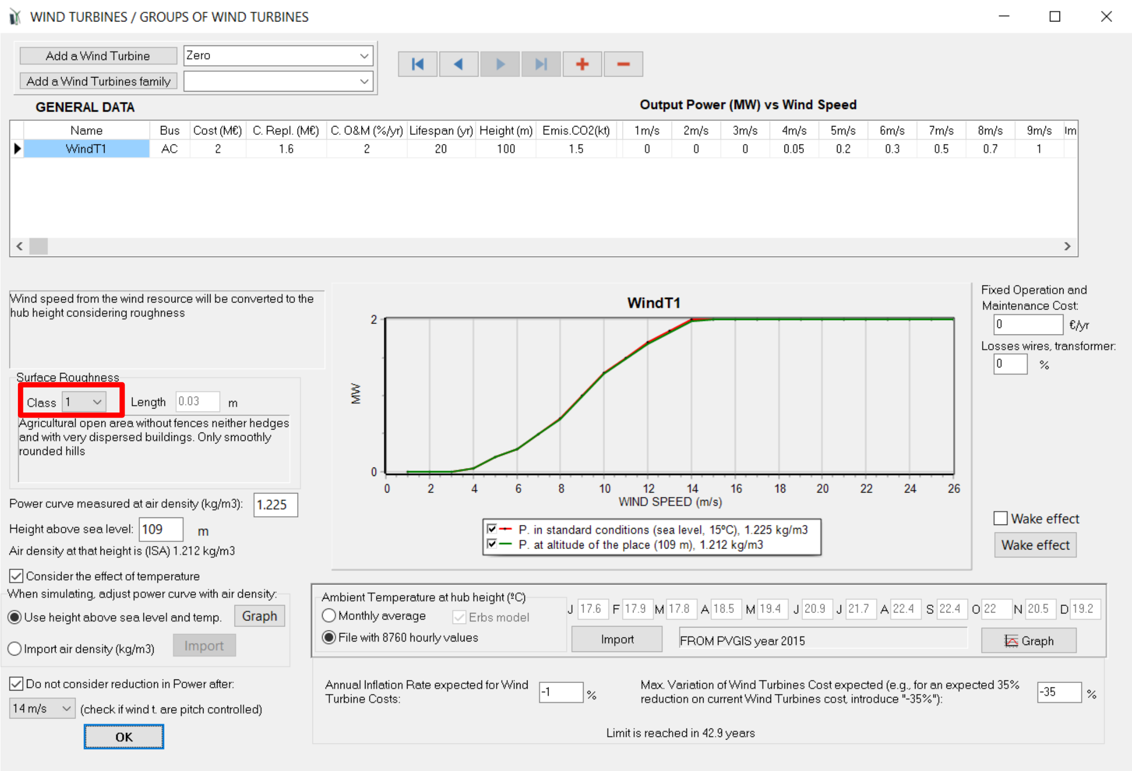
Finally clicking "**OK**" it returns to the main screen of the program.

12. Wind turbines data.

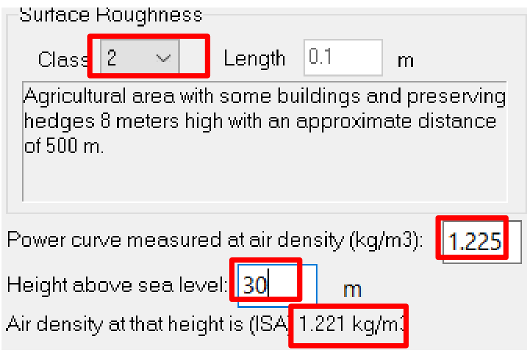
By clicking on the "**WIND TURB.**" button we can define the wind turbines to take into account.



A screen appears with a table where a predetermined wind turbine of 2 MW with a tower of 100 m is shown. As we did with the PV generator, we could change to another wind turbine, but we will leave the default values. The cost ("Cost (M€)") is the CAPEX, which should include all the costs relates to the wind turbines. The ("C. Repl.") is the replacement cost, as when its lifetime ends it is usual that not all the components are replaced, therefore replacement cost (referred to the installation time) is lower than the CAPEX.



We must indicate the kind of roughness of the surface of the terrain (already chosen on the wind screen, but here it could be changed). Let's suppose the terrain is of Class 2, we change it:

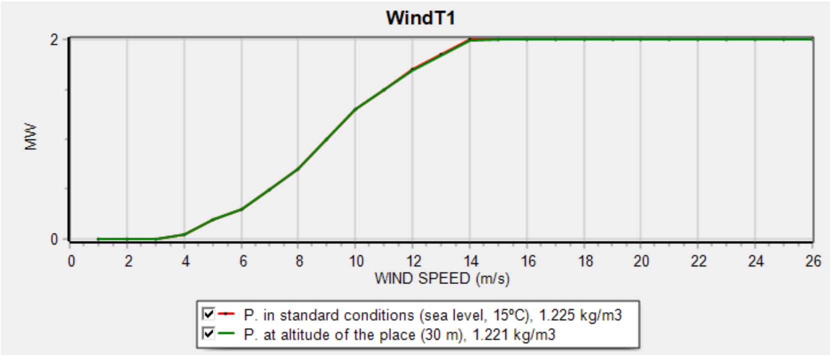


In our case it will have no effect as the wind speed was downloaded at 100 m height, same height as the wind turbine height, therefore the wind speed will not have to be converted to the hub height.

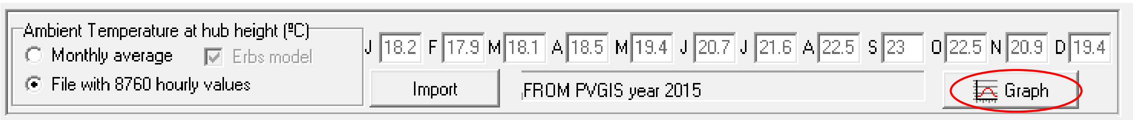
We suppose the air density conditions of the power curve supplied by the wind turbines manufacturer is the default at standard conditions, sea level and 15ºC, that is, 1.225 kg/m^3, therefore we don't change it.

The altitude above sea level was already updated when we obtained data from NASA, in our case 109 m above sea level. This is an average value for several km^2, let's suppose we know the height for our location and it is 30 m, we change to this value.

MHOGA shows the air density at the height above sea level (in our case 1.221 kg/m3) and it shows the power curve of the wind turbine selected by the mouse in red in standard conditions and in green (over the other curve) the power curve considering the air density at the height above sea level of our case. In our case, as the altitude above sea level is 30 m (very low), the two curves are practically the same.

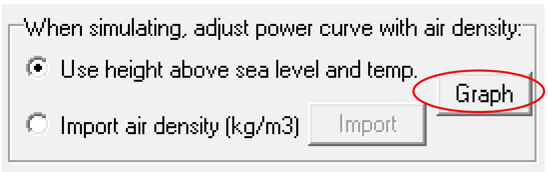


We will consider the effect of the ambient temperature (the corresponding box is selected by default), using the previously PVGIS temperature downloaded.

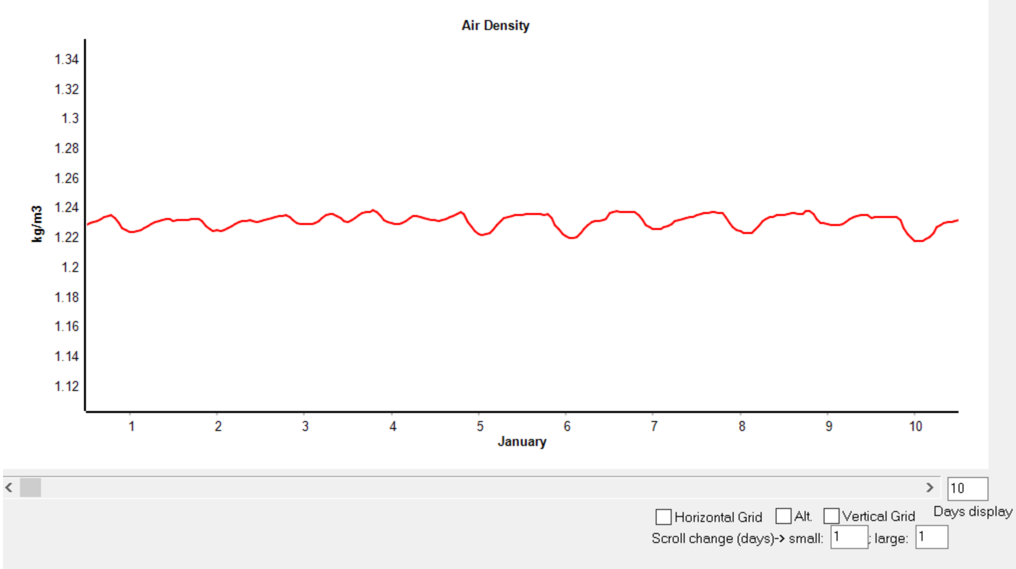


If we click on "**Graph**" we see the representation of the hourly temperature, same as the shown for the PV generator. Click on “**Back**” to return to the wind turbines screen.

When MHOGA performs the simulation of the different combinations of components (when optimizing the system), for each hour of the year it will adjust the power curve of the wind turbines to the air density of that hour. We can choose to calculate the hourly air density by using the height above sea level and temperature (if the temperature effect is considered by checking its checkbox, as default) or we can import the air density hourly file (8760 rows, in each row the hourly air density in kg/m^3). We don’t change it.

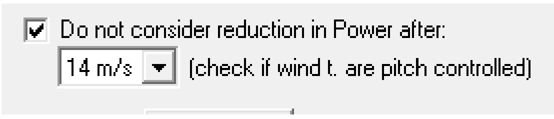


By clicking the “**Graph**” button we can see the hourly air density, calculated for each hour considering the height above sea level and the hourly temperature:

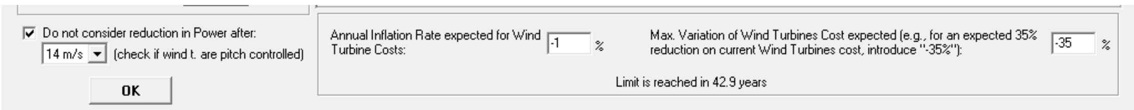


Click “**Back**” to return to the wind turbines screen.

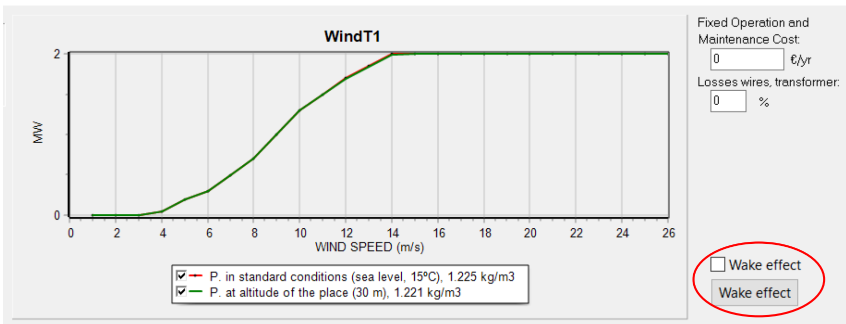
In the bottom of the wind turbines screen we can select (as default) not to consider the reduction in the output power of the wind turbine (due to the density lower than standard) after a specific wind speed. It must be selected if the wind turbine is pitch controlled (usual for wind turbines as the one of 2 MW), as the output power above around 14 m/s is limited to its rated power, so after that wind speed the power curve isn’t reduced. We leave this check box checked, as by default.



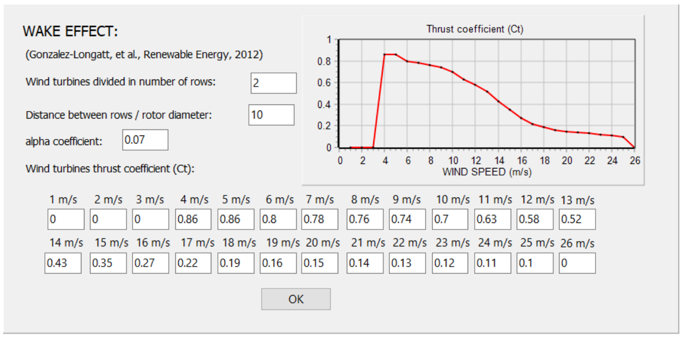
Also in the bottom of the screen we should set the annual inflation rate expected for the wind turbine costs (default -1%) and the maximum variation expected for that rate (default -35%). We leave the default values and MHOGA informs us that this maximum reduction in cost will be achieved in 42.9 years: $(1\text{-}0.01)^{42.9}$=0.65. These data will be used to calculate the replacement cost when the wind turbines must be replaced (after 20 years lifetime) and to calculate the residual value of the wind turbines when the system lifetime ends (in the year 25).



In the right part of the window we can select to consider wake effect in the wind farm by selecting the checkbox “**Wake effect**”.



By clicking in the button “Wake effect” we can see the parameters to be considered in the wake effect.



In this case we will not consider the wake effect (we suppose all the wind turbines are in the same row” therefore we will not check the “wake effect” checkbox).

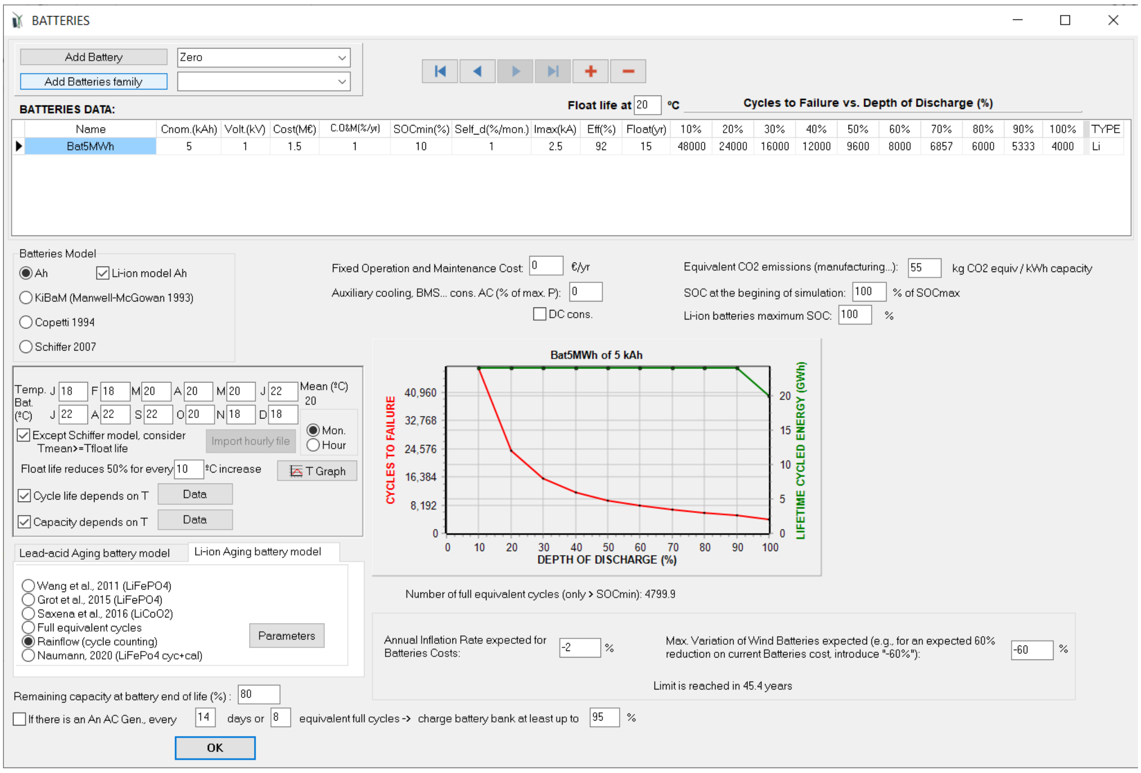
Finally clicking "**OK**" it returns to the main screen of the program.

13. Batteries data.

By clicking on the button "**BATTERIES**" we can define the batteries to be taken into account in the project.

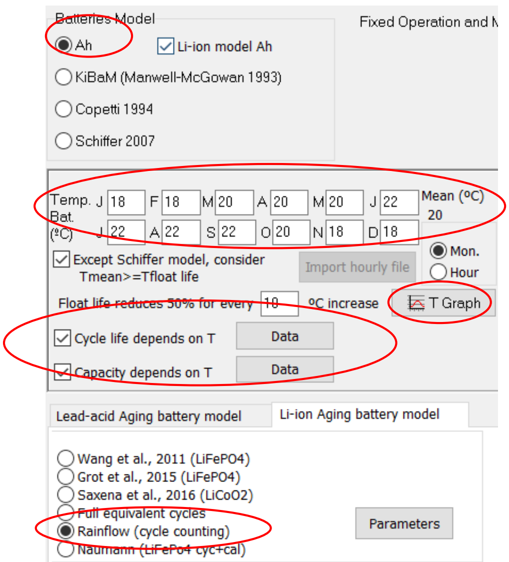
The battery screen shows a table where by default just one type of battery is taken into account. It is a battery of 5 MWh (5 kAh x 1 kV = 5 MWh), with an acquisition cost (CAPEX) of 1.5 M€ and an annual O&M cost (OPEX) of 1% of the CAPEX. The minimum SOC allowed is 10% and the self-discharge is 1%/month. Its maximum allowed current is 2.5 kA (that is, C/2), roundtrip efficiency 92% and float life at 20º of 15 years (conservative value). The cycles to failure vs. depth of discharge (DOD) curve is shown in the table, from 10% DOD to 90% DOD (shown in the graph below in red, while in green it is shown the cycled energy during its lifetime, under the graph the average value of the full equivalent cycles is shown, in this case 4799.9 cycles).

We could change some of these data (first modifying the name) and we could add more batteries to the table, but we will not do it.



In the last column of the table it is seen that the battery is Li-ion type (defined by “Li”).

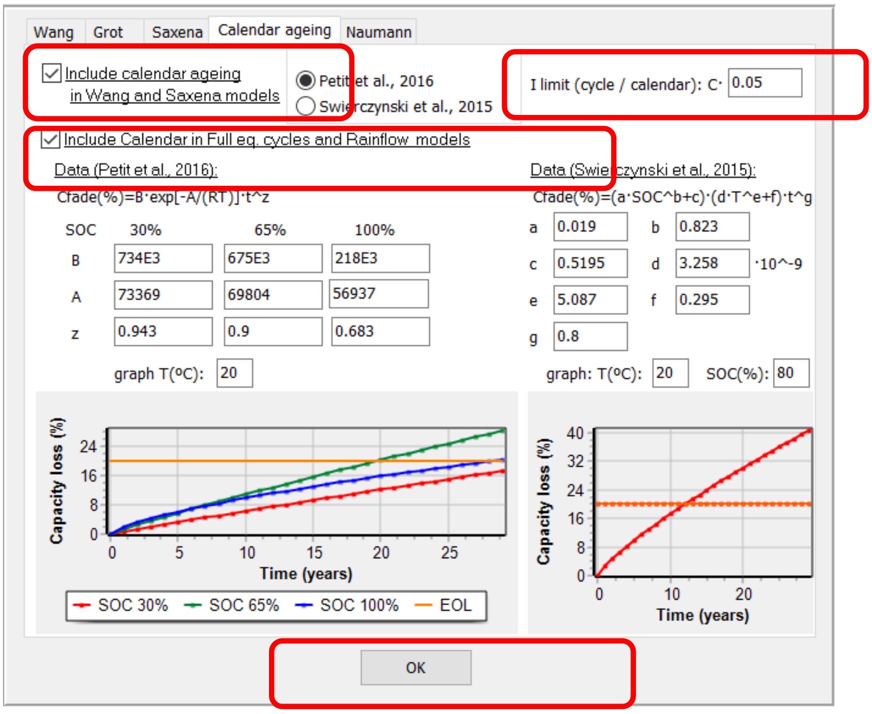
We will take into account the standard **Ah** battery model. Regarding the average monthly temperature, we leave the default values, taking into account that the temperature is the average at which the batteries are estimated to be (we could import hourly values but we will not do it, we will use the same value for all the hours of each month, considering the batteries are into a building and the temperature is similar for all the hours of the month; we can see the graph by clicking “**T Graph**” button). The lifespan of the Li-ion batteries will be calculated according to the **Rainflow** (cycle count) aging model.



Cycle life depends on temperature, we leave the checkboxes “**Cycle life depends on T**” and “**Capacity depends on T**” checked.

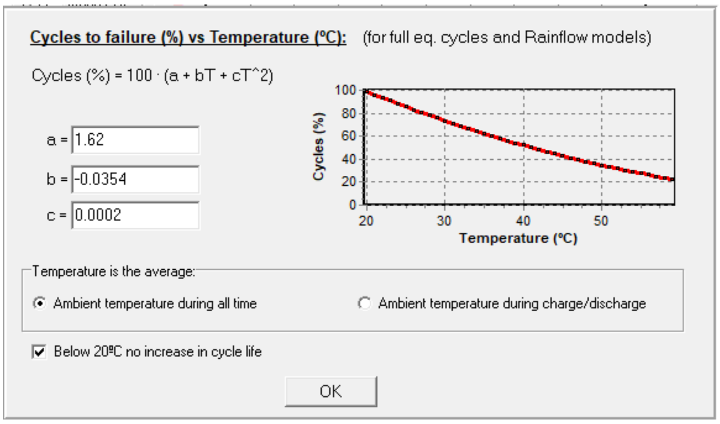
With lithium-ion batteries, we can use specific ageing models, however if we are not sure our battery is the same as the one tested in the different models, the best option would be to use **Rainflow model** (it will consider the cycle life vs depth of discharge DOD).

After you select the model, click in "**Parameters**" button and **you should be sure that the calendar ageing model is included**, then both 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.

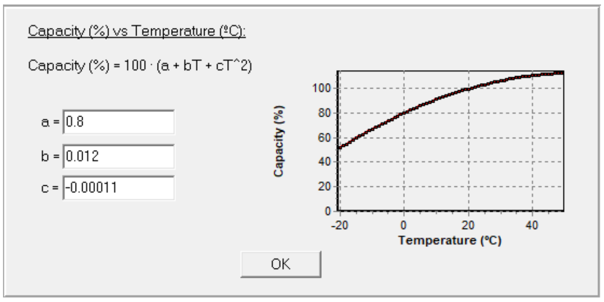


You should set a threshold limit to consider cycle or calendar ageing, by default a C-rate of 0.05 is the limit (we leave the default value). During the simulation of each combination of components, in the time steps when the C-rate is lower than this value calendar ageing will be considered and when it is higher cycle ageing will be considered. Then click "**OK**" to save the changes.

If we click in "**Data**" button close to "**Cycle life depends on T**", we can see the following window, where the parameters a, b and c show the temperature dependence of the cycles to failure (%), being 100% for 20ºC and being reduced as temperature increases (curve obtained from https://midsummer.ie/pdfs/fronius-performance-solar-battery.pdf). By default, the temperature considered is the temperature during all time (not only during charge/discharge), and below 20ºC there is not considered any increase in cycle life. We leave the default values.

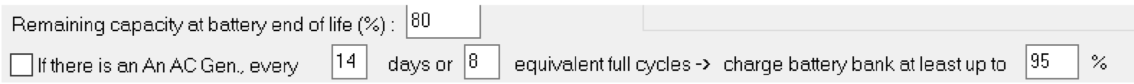


If we click in "**Data**" button close to "**Capacity depends on T**", we can see the following window, where the parameters a, b and c show the temperature dependence of the capacity (%), being 100% for 20ºC. In the simulations, considering the hourly temperature of the battery, the maximum capacity (energy that the battery could discharge if it was at full SOC) during each time step will be calculated with this curve.

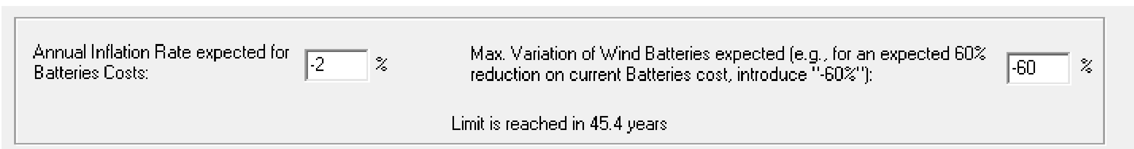


At the bottom, we can set the remaining capacity at battery end of life (default 80%), that is, we consider that when the remaining capacity is 80% the battery will be dead and it must be replaced, we leave the default value.

Also, we can check the box "If there is an AC Gen., every ...." so that the backup generator will charge the batteries after a specific number of days without full charge or after a specific number of full equivalent cycles. In this case we leave this unchecked, as this has no sense because there is no load consumption, there is no AC generator and we have the AC grid.



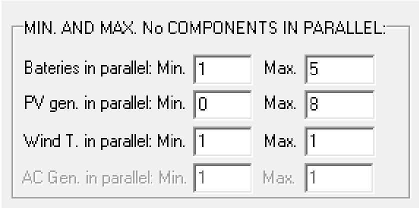
An annual decrease of the battery acquisition cost of 2% is set by default, with a limit of -60% (reached in 45.4 years), therefore when the batteries must be replaced, the acquisition cost will be obtained considering this reduction.



We will use the rest of the default data. Finally, we click "**OK**" to return to the main screen.

14. Minimum and maximum number of components allowed in parallel.

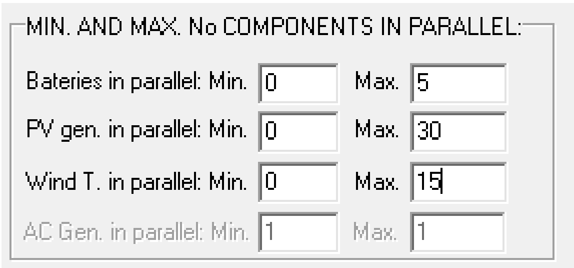
In the main screen of the software, GENERAL DATA tab, we can see a box where we must set the minimum and maximum number of components allowed in parallel. Default numbers are:



These values must be selected by the designer, depending on the minimum and maximum size he/she wants to allow of the different components.

In our case, we want to consider the possibility of not having batteries nor wind turbines in the system, therefore min. number of batteries and wind turbines in parallel will be changed to 0. The maximum number of batteries in parallel is 5, it is ok (if 5 in parallel, the whole battery bank will be of 5 parallel x 5 MWh = 25 MWh). As the maximum output power to be injected in the grid (defined previously) is 23 MW, 8 PV generators of 1 MWp in parallel can be too few. We change the max. number of PV gen. in parallel to 30 (therefore the maximum PV generator will be of 30 x 1 MWp = 30 MWp). We will change the max. number of wind turbines in parallel to 15 (therefore the maximum wind turbines group will be of 15 x 2 MW = 30 MW).

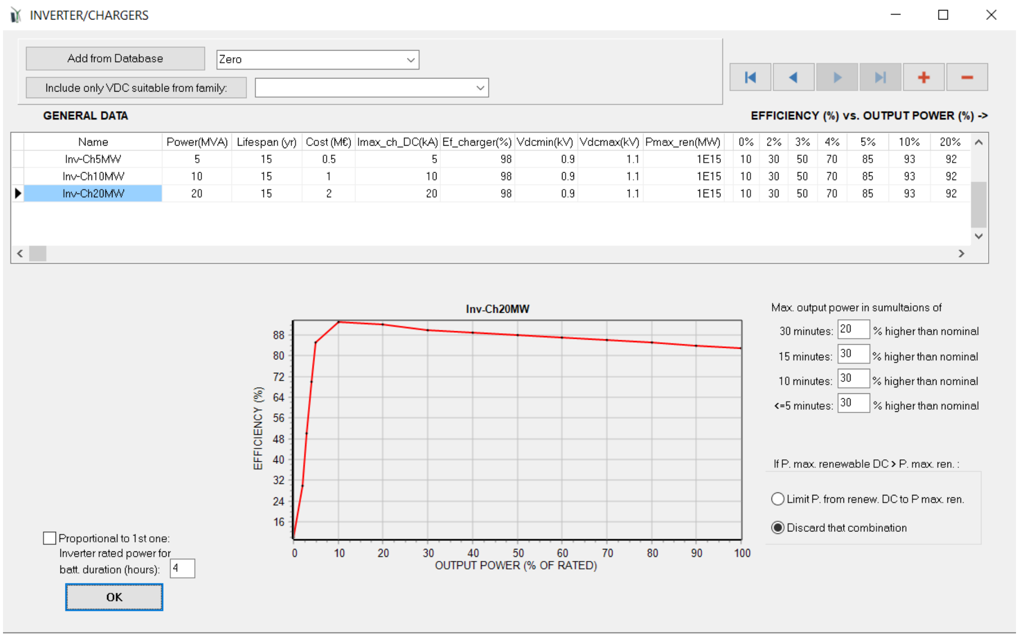
Therefore, the final values will be:



15. Inverter-chargers data.

By clicking on the "**INVERTER/CHAR.**" button we can define the inverter-chargers to take into account in the project.

The table shows three inverter/chargers considered by default, of 5, 10 and 20 MW.



We can see, for the different inverter/chargers, nominal power (MVA), lifespan (15 years), CAPEX, maximum current in DC (kA, we can see it is the same as the power in MVA as voltage is 1 kV), charger efficiency (%), minimum and maximum DC voltage (as DC bus voltage was defined 1 kV, these limits must be around this value), and efficiency vs. output power of the inverter.

As the maximum capacity of the battery bank can be 25 MWh (max. 5 in parallel of 5 MWh) with a maximum power of 5x2.5=12.5 kW, the maximum inverter power (20 MW) is enough, also considering that the maximum output power to be injected to the grid is 23 MW. We will add an inverter of Zero to consider the possibility of not including inverter (select in the list close to the "**Add from database**" button and then click that button):

GENERAL DATA — **EFFICIENCY (%) vs. OUTPUT POWER (%) ->**

Name	Power(MVA)	Lifespan (yr)	Cost (M€)	Imax_ch_DC(kA)	Ef_charger(%)	Vdcmin(kV)	Vdcmax(kV)	0%	2%	3%	4%	5%	10%	20%	30%	40%
Inv-Ch5MW	5	15	0.5	5	98	0.9	1.1	10	30	50	70	85	93	92	90	89
Inv-Ch10MW	10	15	1	10	98	0.9	1.1	10	30	50	70	85	93	92	90	89
Inv-Ch20MW	20	15	2	20	98	0.9	1.1	10	30	50	70	85	93	92	90	89
Zero	0	100	0	0	100	0.9	1.1	100	100	100	100	100	100	100	100	100

Finally clicking "**OK**" it returns to the main screen of the program.

16. Constraints.

In the main screen, in the "**GENERAL DATA**" tab, there are five possible restrictions:

-The maximum investment cost (maximum system CAPEX). Let's suppose we don't want it to be higher than 100 M€ (combinations with total investment cost higher than this value will be discarded). We change the value to 100.

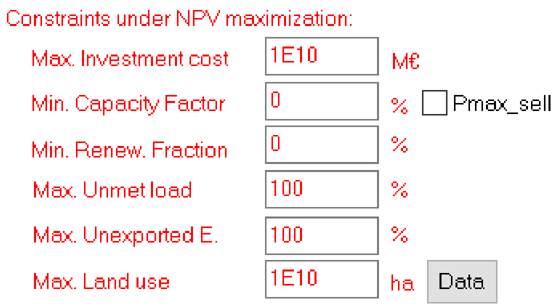
- The minimum renewable capacity factor (annual energy sold divided by the peak renewable power multiplied by 8760 h) (by default 0%, so by default this constraint is not considered). We leave the default value. If you check the box "Pmax_sell", then the capacity factor will be calculated as the annual energy sold divided by the maximum power that can be exported to the AC grid (23 MW in our case) and multiplied by 8760 h.

- The minimum renewable fraction (by default 0%, so by default this constraint is not considered). It is calculated as the annual energy injected to the grid minus the annual energy injected to the grid by the fossil fuel generator, divided by the annual energy injected to the grid.

- The maximum unmet load (load energy not served, by default allowed 100%, so by default this constraint is not considered). This is the unmet load that cannot be supplied by the system nor by the AC grid. In our case we have no load therefore it has no meaning.

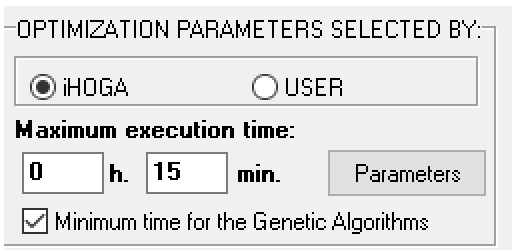
- The maximum unexported energy (by default 100%, so by default this constraint is not considered %). Unexported energy (%) id defined as: (Exported_energy-Sold_energy)/Exported_energy*100.

- The maximum land use (by default a very high value, that is 1E10 ha, so by default this constraint is not considered). We leave the default value. With button "Data" we can set the land occupied by each technology.

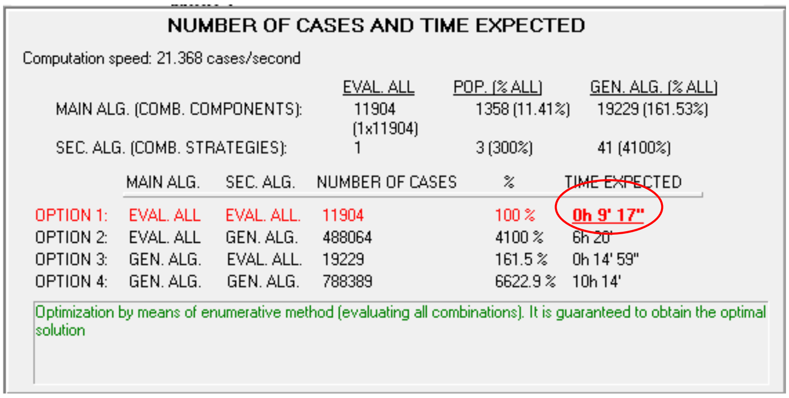


17. Maximum execution time allowed.

In the main screen, in the "**GENERAL DATA**" tab we should set the maximum execution time (maximum time the optimization can last) and who (the user or MHOGA) must set the optimization parameters (recommended MHOGA). The longer the time allowed the more likely it is that all the possible combinations can be evaluated and thus obtain the global optimum. If sufficient time was not allowed, genetic algorithms metaheuristic technique will be used to optimize the system (without evaluating all combinations) in the allowed time. We will leave the 15 minutes by default, enough time in this case so that all possible combinations can be evaluated (enumerative method).



If we pass with the mouse on the zone of maximum and minimum number of components in parallel (see section 14) we are informed that the method chosen for the optimization will be the enumerative method (EVAL. ALL, to evaluate all the possible combinations), since the allowed time (15 minutes) is greater than that needed to evaluate all the combinations. There are 11904 possible combinations: 1 type of PV gen. multiplied by 31 possible cases in parallel (from 0 to 30) multiplied by 1 type of wind turbine multiplied by 16 possible cases in parallel (from 0 to 15) multiplied by 1 type of battery multiplied by 6 possible cases in parallel (from 0 to 5) multiplied by 4 types of inverter/chargers. In this computer the estimated calculation speed is 21.3 cases per second, so in 9'17'' it is expected that all combinations will be evaluated and the optimum will be found.



18. Financial data.

In the main screen, in the "**FINANCIAL DATA**" tab, we must set several economic variables (nominal interest rate or nominal discount rate, general inflation, study period, currency, installation costs, and loan). Let's leave the data by default.

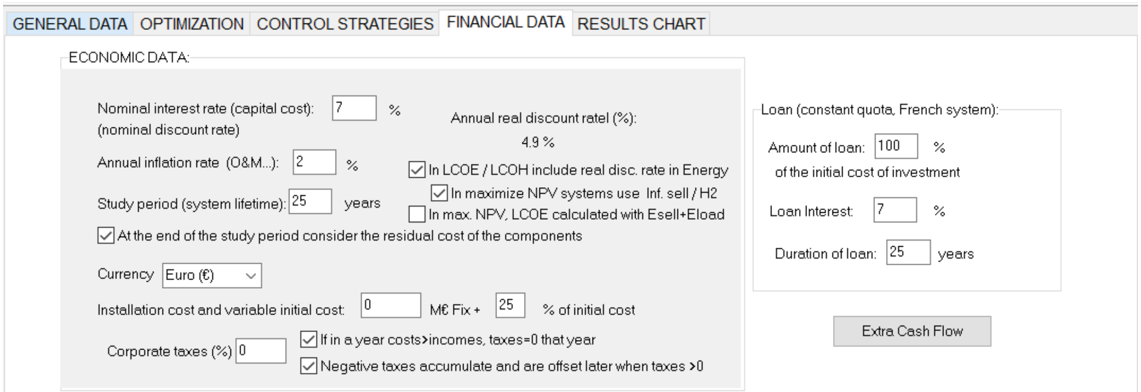
By default, at the end of the study period (25 years) the residual cost of the components will be considered as incomes.

Also, by default the LCOE (levelized cost of energy) and the LCOH (levelized cost of hydrogen) will be calculated considering in the energy the real discount rate (see user manual, section 3.1.4). By default, in maximize NPV systems, for calculating LCOE or LCOH it will use the electricity sell price inflation and the hydrogen sell inflation instead of the general inflation.

The installation cost and variable initial cost considered is 25% of the initial cost. This means that the total CAPEX of all the components will be multiplied by 1.25 to obtain the investment cost.

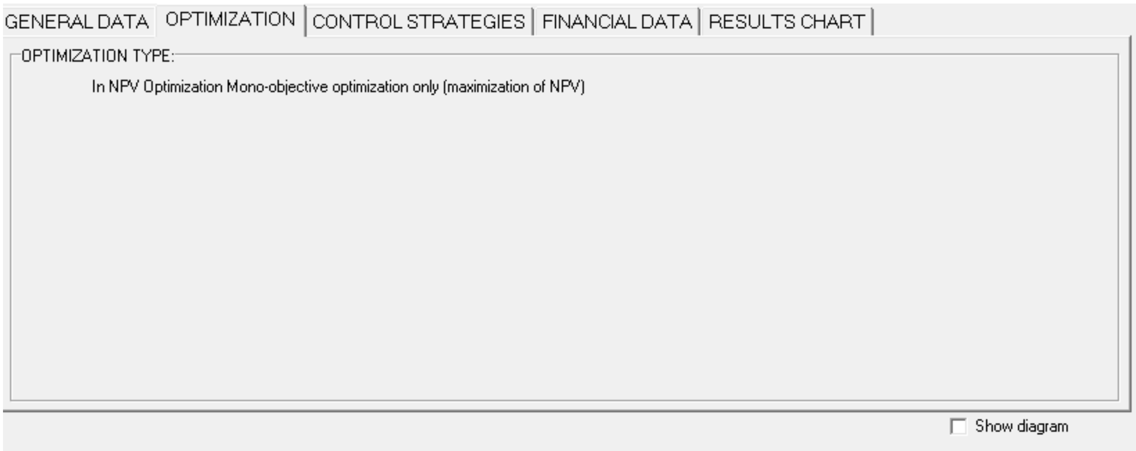
Also, by default, 100% of the CAPEX is obtained with a loan of interest 7% and duration 25 years.

No corporate taxes are considered by default (0%).



18. Optimization type.

In the main screen, tab "**OPTIMIZATION**" we can see that for maximization of NPV projects just mono-objective optimization (economic optimization) is allowed.



If the project type was maximization of NPC, multi-objective optimization could be chosen.

19. Calculate (optimize the system).

Before calculating, it is recommended to save the project (in the main screen, upper menu **Project-> Save**). Also, periodically you should save the project.

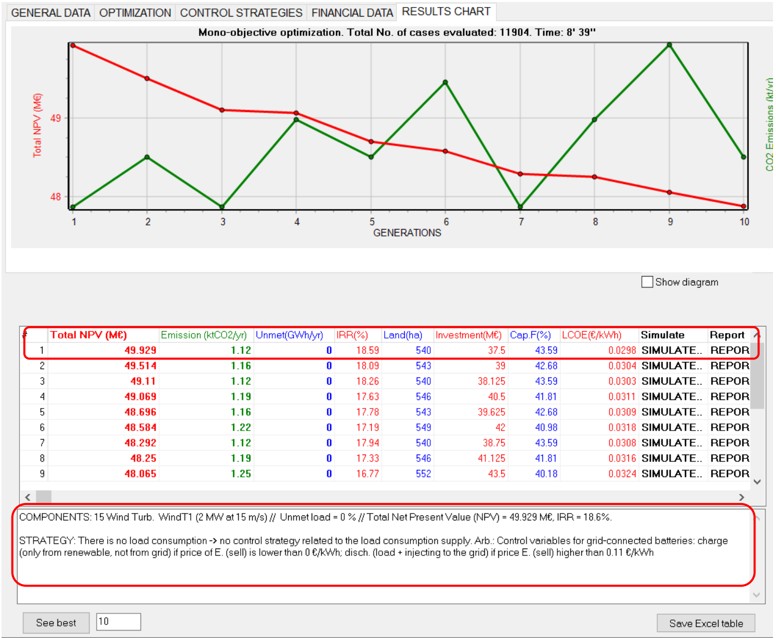
In the general screen, clicking on the "**CALCULATE**" button, the calculation of the optimization begins. In our case, the only restriction is the maximum investment cost allowed.

20. Results. Best solution found

MHOGA evaluates all the possible combinations of components and control strategies (but in this case the control strategy is the grid-connected batteries management for energy arbitrage, fixed in this case). Each combination is simulated during a whole year, in this case in steps of 1 hour. If that simulation meets the constraint (max. investment allowed is 100 M€), then it calculates the Net Present Value (NPV), considering all the costs and incomes during the lifetime of the system (25 years) and converting all of them to the first year (taking into account inflation and interest rate). The combinations that do not meet the constraint are discarded, assigning them a NPV of –infinite (and showing them in the results graph with 0 NPV).

The optimization time depends on the computation speed of the computer. In this case the real computation time has been a bit lower than the expected time.

Once the evaluation of the different combinations is finished, the results are shown.

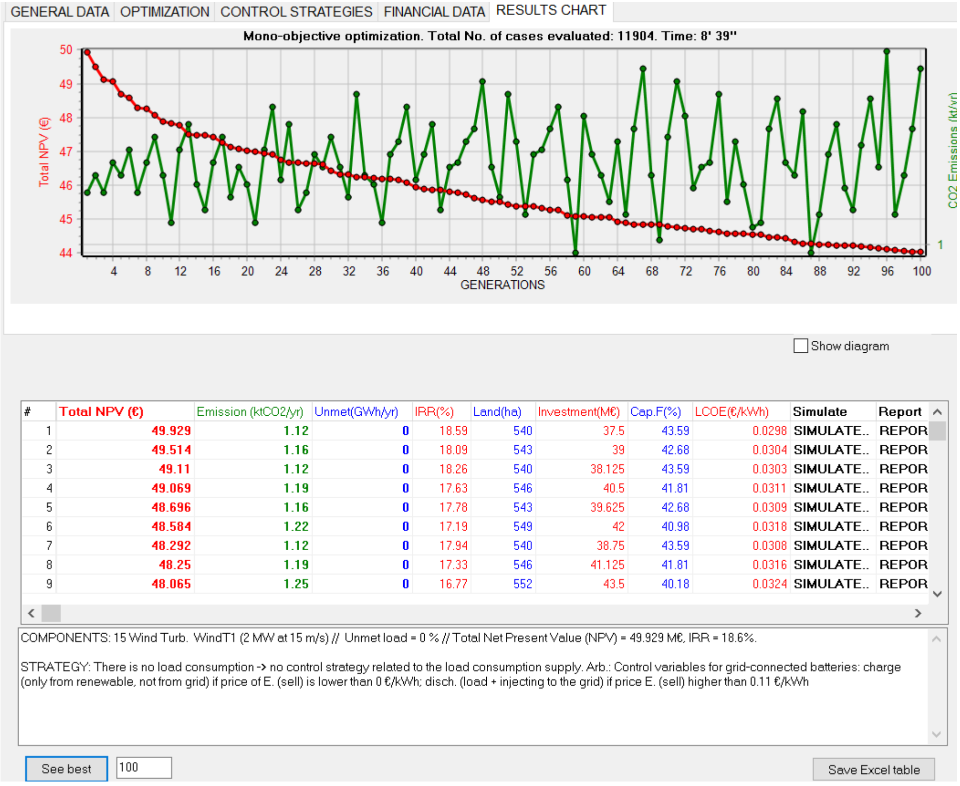


Note that the user can obtain values slightly different because a correlation factor and standard deviation have been applied in the internal calculation of the 1-minute step irradiation and wind speed, implying that a randomness is applied. It will also happen in the next sections.

In the "**RESULTS CHART**" tab it is shown the graph of the total cost of the best solution (in red) and of the life cycle annual CO2 equivalent emissions (green) of the 10 best solutions found. MHOGA has used the ENUMERATIVE METHOD, that is, all possible combinations have been evaluated. In addition, instead of the scheme of the components, a table with the results of the best combinations appears. The table shows the 10 best combinations ordered from best to worst: the best is the first of the table (#1), second best is the #2,….

The number of the best combinations shown (in this case the 10 best ones) can be modified in the text field of the bottom left corner, and then clicking in the button "**See best**". For example, change it to 100 and click that button:

The first 100 best solutions are shown now:



#	Total NPV (€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	49.929	1.12	0	18.59	540	37.5	43.59	0.0298	SIMULATE..	REPOR
2	49.514	1.16	0	18.09	543	39	42.68	0.0304	SIMULATE..	REPOR
3	49.11	1.12	0	18.26	540	38.125	43.59	0.0303	SIMULATE..	REPOR
4	49.069	1.19	0	17.63	546	40.5	41.81	0.0311	SIMULATE..	REPOR
5	48.696	1.16	0	17.78	543	39.625	42.68	0.0309	SIMULATE..	REPOR
6	48.584	1.22	0	17.19	549	42	40.98	0.0318	SIMULATE..	REPOR
7	48.292	1.12	0	17.94	540	38.75	43.59	0.0308	SIMULATE..	REPOR
8	48.25	1.19	0	17.33	546	41.125	41.81	0.0316	SIMULATE..	REPOR
9	48.065	1.25	0	16.77	552	43.5	40.18	0.0324	SIMULATE..	REPOR

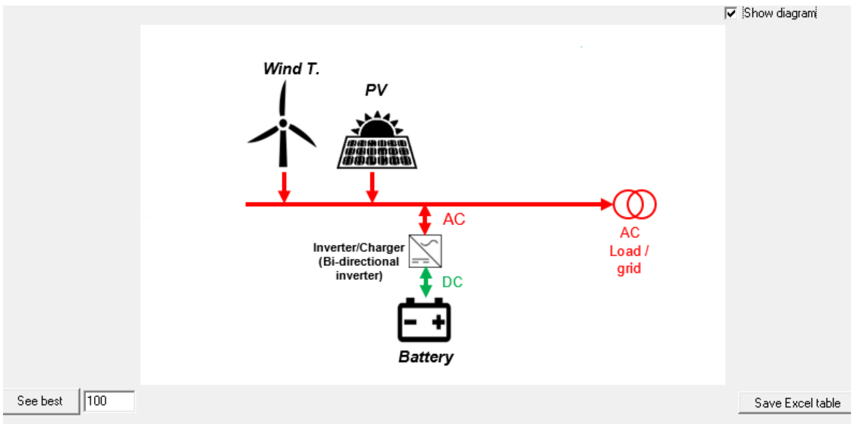
COMPONENTS: 15 Wind Turb. WindT1 (2 MW at 15 m/s) // Unmet load = 0 % // Total Net Present Value (NPV) = 49.929 M€, IRR = 18.6%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. Arb.: Control variables for grid-connected batteries: charge (only from renewable, not from grid) if price of E. (sell) is lower than 0 €/kWh; disch. (load + injecting to the grid) if price E. (sell) higher than 0.11 €/kWh

See best | 100 | Save Excel table

To see the diagram of the components, click on the "**Show diagram**" button above the table, on the right:

Appearing again the diagram instead of the table:



To see the results table again, uncheck "**Show diagram**".

Below the table the characteristics of the optimal solution (corresponding to the first row of the table) are shown. This text can be copied (select and Ctrl + C).

COMPONENTS: 15 Wind Turb. WindT1 (2 MW at 15 m/s) // Unmet load = 0 % // Total Net Present Value (NPV) = 49.929 M€, IRR = 18.6%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. ARB.: Control variables for grid-connected batteries: charge (only from renewable, not *from grid) if price of E. (sell) is lower than 0 €/kWh; disch. (load + injecting to the grid) if price E. (sell) higher than 0.11 €/kWh*

We can see the best solution (first row) in this case is a wind farm of 15 wind turbines, without PV nor batteries. If we move through the table with the bottom bar, and focus on the 1st row, we can see there is no PV (0x1 MWp, that is, 0 in parallel), no battery (1x0x5 Ah, that is, 1 series x 0 in parallel), no inverter.

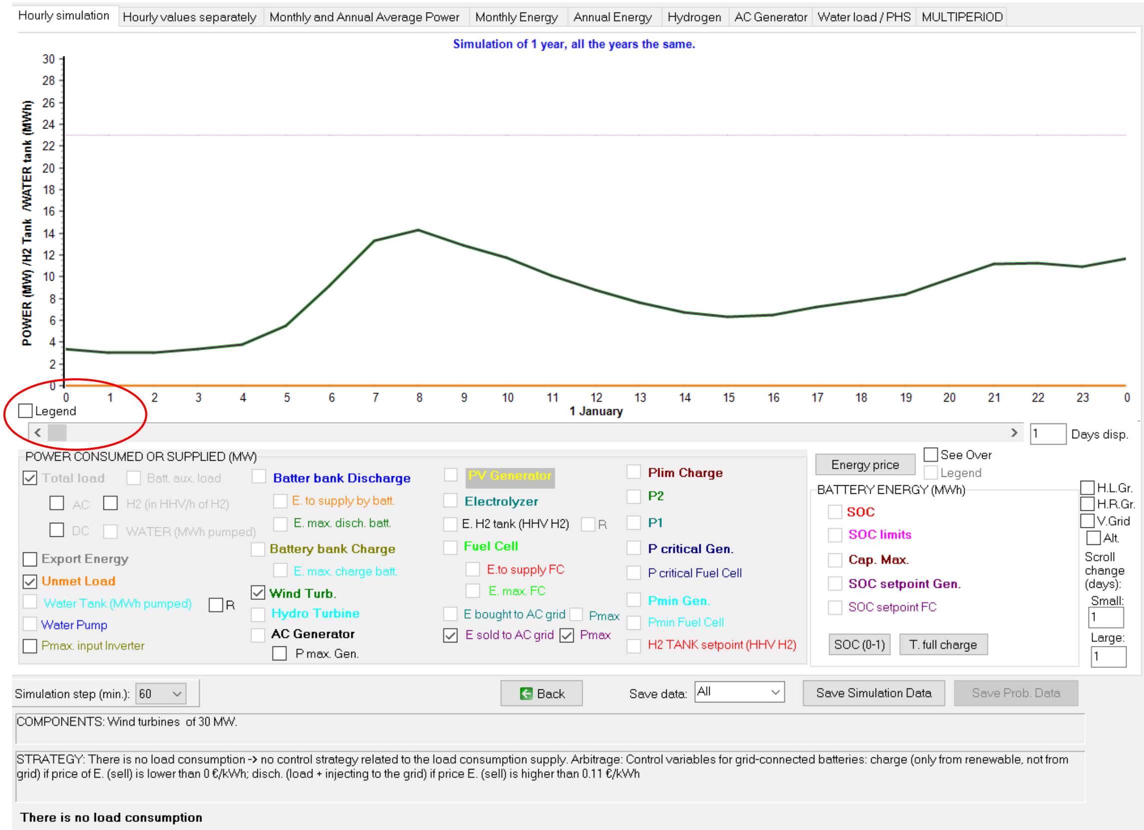
Costs	P. PV (MWp_dc)	Slope#1(º)	Cn Bat. (kAh)	P. Gen (MW)	P. Inv (MW)	P. Wind T. (MW)	F. Turb (m3/s)	P. FC (MW)	P. Elyz. (MW)	H2 tank (t)
COSTS...	0x1	27	1x0x5	1x0	0	15x2	0	0	0	

21. Simulation of the best solution.

We can see the simulation of the operation of the optimal solution (first row) by clicking on the first row of the table, in "**SIMULATE**":

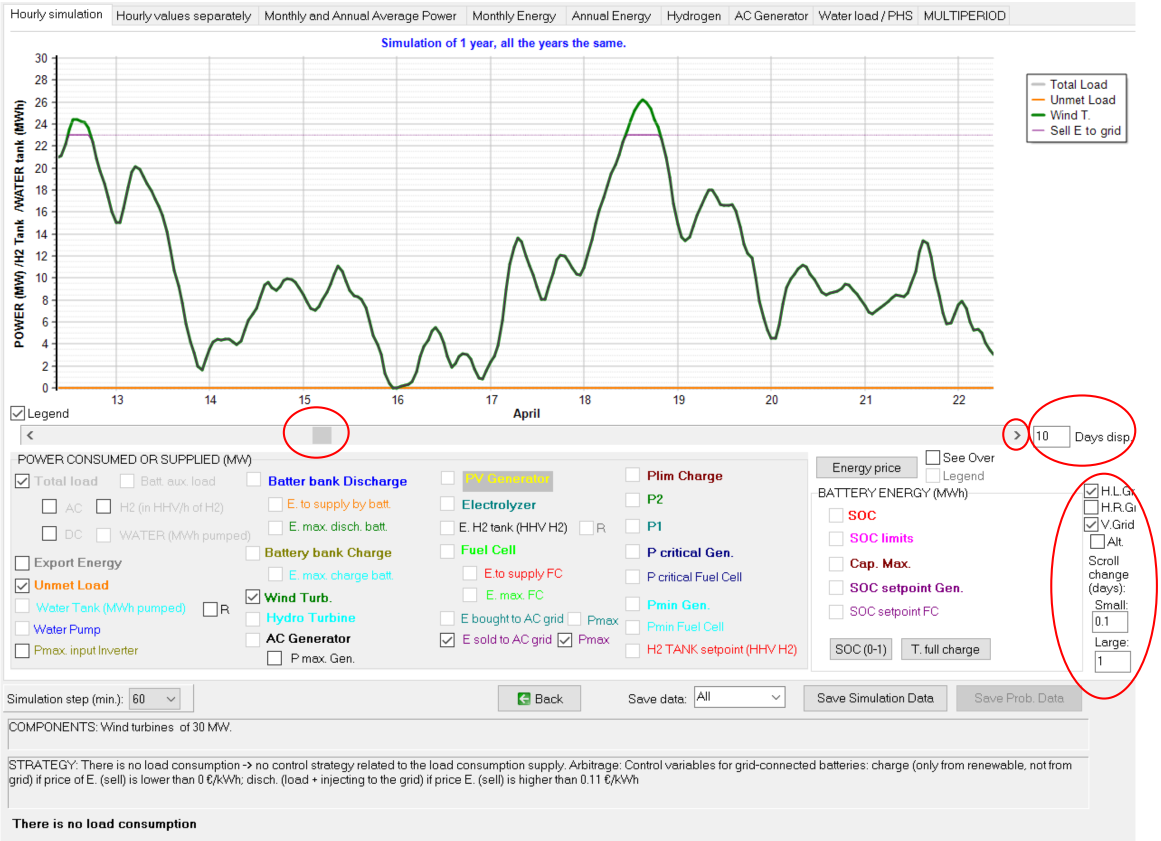
#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	49.593	1.12	0	18.52	540	37.5	43.46	0.0299	SIMULATE..	REPOR

The simulation screen appears as shown below (if it has not appeared, click on the HOGA icon in the taskbar at the bottom of the computer screen and the simulation screen will appear):

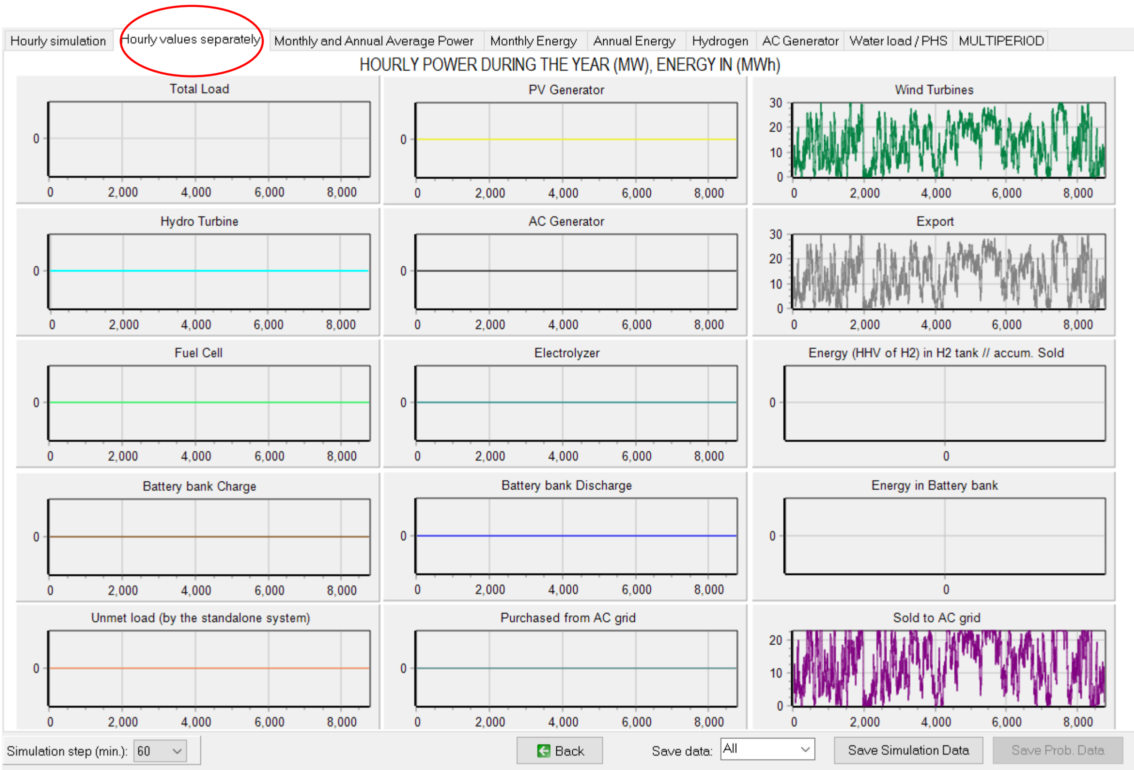


We can move through the days of the year moving the bottom bar cursor or clicking in the bottom bar. We can see the legend clicking in "**Legend**" at the left bottom corner of the graph.

We can see several days in the screen changing the number of days to display, for example to 10. Also, clicking in the "**H.L.Gr**" se see the horizontal left axis grid, clicking in the "**V.Grid**" we see the vertical grid, and with Scroll change (days) Small: 0.1, each time we click the scroll arrow it moves 0.1 day, and with Large: 1, each time we click in the scroll it moves 1 day. Moving the scroll we can see for example the days 13-23 of April. We can check to make visible and uncheck to make invisible the checkboxes of the different variables (load, wind turbines power generation, electricity sold to the grid…).



We can see the different tabs of the simulation screen ("Export" is the energy which can be exported, that is, excess energy not used by the system). As we have no load, no storage, the system does not use any energy, so all the energy generated by the sources is export energy. However, not all the export energy is sold to the grid, because in our case we have a grid limit power of 23 MW, and during some time steps the generation is higher (up to 30 MW), therefore there is a small curtailment which cannot be sold to the grid (sold power limited to 23 MW).



In the third tab, the PDF (probability density function) graphs, by default, are not shown. To show them, 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**":

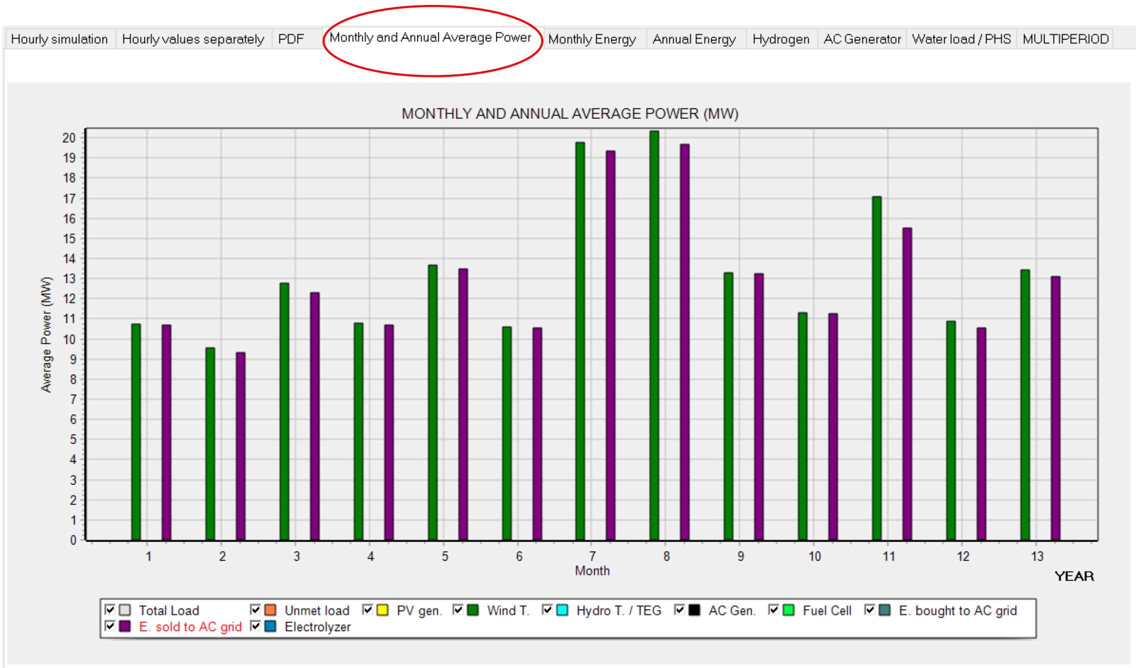
When this option is selected, we see something like the following figure, third tab of the simulation screen.

Each PDF graphs shows the probability density for each interval between the minimum and the maximum of the power / energy of that variable. For example, for the wind turbines output power, we can see the minimum column is for the interval between the minimum power and the minimum power+ (maximum power – minimum power) / Number of columns. As min. power is 0 and max. is around 30 MW, the first column is for the interval between 0 and 0 + (30-0)/20 = 1.5 MW, that is, interval 0 MW – 1.5 MW. We can see that, for that interval, probability density is around 0.04. For each PDF graph, the area (integral of the PDF graph) is 1. Below the graphs we can see the mean power / energy and the standard deviation (for the wind turbines output, mean 13.432 MW, standard deviation 7.999 MW).

We can see in the last PDF graph (lower right area) that the sold power during the year is a lot of time the maximum power allowed by the grid (23 MW).

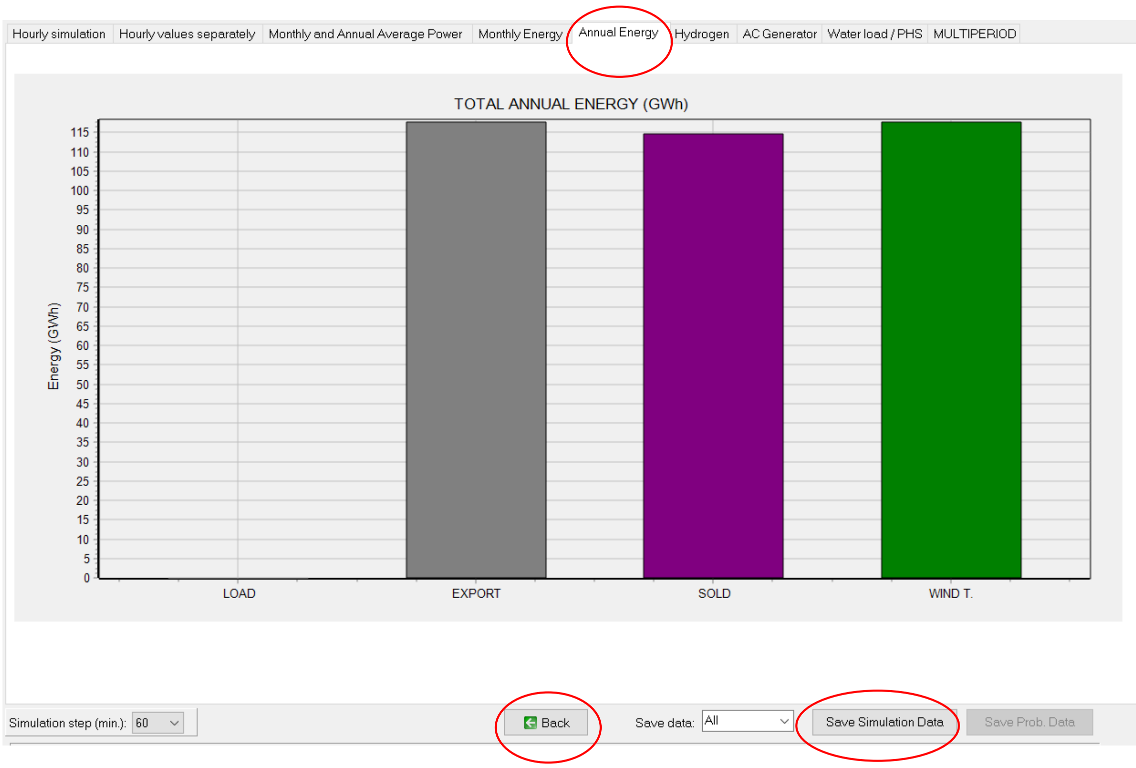
In the upper right area, we can change the number of columns of the PDF graphs and we can set the first column of each PDF not to be shown, and also for the last column. For example, if we had PV generator (it is not our case), as the most of the time its power is 0 (night time), we can uncheck “**Show PDF first col.**” and we will see the PDF of the PV power without the first column.

The monthly and annual average power (fourth tab):



The monthly energy:

The annual energy:



We can save the simulation data in Microsoft Excel format. To do this, click the "**Save Simulation Data**" button. Once the Excel file has been saved, when opening the Excel file it warns us about opening the file, to which we respond "**Yes**".

The Excel file opens perfectly, showing for each hour of the year the different power of the different components. At the end it shows the monthly and total annual values, the values of the purchase and sale of energy to the AC grid (if any)...

We must save this file by the option "Save As" of Microsoft Excel in Excel file (*.xlsx) and the next time we open it, it will no longer show the previous warning.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Project: D:\PROYECTOS MHOGA 3.4-202403XX\MHOGA1.mho. Solution # 1																		
2																			
3	COMPONENTS: Wind turbines of 30 MW.																		
4	STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. Arbitrage: Control variables for grid-connected batteries: charge (only from renewable, not from grid) if price of E. (sell) is lower than 0 €/kWh; disch. (load + injecting to																		
5																			
6	HOURLY VALUES. All power values are expressed in MW (H2.load is in MW referring to the HHV of H2). The SOC data of the batteries in energy (MWh).																		
7	Water tank (Water_tank) is energy needed to pump the water (MWh) while (Water_tank_volume) is the volume stored (dam3).																		
8	No.Gen_on is the number of AC generators that are running during this time step. Hours_eq_Gen is the number of equivalent hours (including out-of-range penalty and start-up penalty) of AC generators. The fuel consumption of the Gen. AC (Fuel.Gen) is expressed in x1E6litr																		
9	Costs of purchasing energy to the grid, the fuel cost of the AC Gen. (Fuel.Cost), the cost of the external fuel used by the fuel cell (C.fuel.ext_FC) and incomes of selling E and costs of buying E to the AC grid (Inc.Sell and Cost.Buy) are expressed in M€. They are cash flow values																		
10	Load of Hydrogen (H2_load_mass) is expressed in t/h of H2. H2 in tank (H2_Tank_mass), H2 used by fuel cell, from H2 tank (Fuel.FC) or externally purchased (Fuel.ext_FC) and hydrogen generated by the electrolyzer (Prod_H2) are expressed in t of H2.																		
11	Hydrogen stored in H2 Tank (H2_Tank_HHV) is expressed in MWh HHV of H2																		
12	Date	Hour	Load(MW)	AC_load(MW)	DC_load(MW	H2_load(HHV	H2_load_mas	Water_load(N	PV(MW)	Wind(MW)	Hydro(MW)	Ef_turb(perce	AC.Gen.(MW)	No.Gen_on	Hours_eq_Ge	Cons.Fuel(x1E	Fuel.Cost(M€)	F.C.(MW)	Fuel.FC(t)
13	01-January	0:00	0	0	0	0	0	0	0	3.34	0	1	0	0	0	0	0	0	0
14	01-January	1:00	0	0	0	0	0	0	0	3.08	0	1	0	0	0	0	0	0	0
15	01-January	2:00	0	0	0	0	0	0	0	3.05	0	1	0	0	0	0	0	0	0
16	01-January	3:00	0	0	0	0	0	0	0	3.34	0	1	0	0	0	0	0	0	0
17	01-January	4:00	0	0	0	0	0	0	0	3.81	0	1	0	0	0	0	0	0	0
18	01-January	5:00	0	0	0	0	0	0	0	5.53	0	1	0	0	0	0	0	0	0
19	01-January	6:00	0	0	0	0	0	0	0	9.21	0	1	0	0	0	0	0	0	0
20	01-January	7:00	0	0	0	0	0	0	0	13.35	0	1	0	0	0	0	0	0	0
21	01-January	8:00	0	0	0	0	0	0	0	14.26	0	1	0	0	0	0	0	0	0
22	01-January	9:00	0	0	0	0	0	0	0	12.94	0	1	0	0	0	0	0	0	0
23	01-January	10:00	0	0	0	0	0	0	0	11.73	0	1	0	0	0	0	0	0	0
24	01-January	11:00	0	0	0	0	0	0	0	10.12	0	1	0	0	0	0	0	0	0
25	01-January	12:00	0	0	0	0	0	0	0	8.76	0	1	0	0	0	0	0	0	0
26	01-January	13:00	0	0	0	0	0	0	0	7.62	0	1	0	0	0	0	0	0	0
27	01-January	14:00	0	0	0	0	0	0	0	6.77	0	1	0	0	0	0	0	0	0
28	01-January	15:00	0	0	0	0	0	0	0	6.29	0	1	0	0	0	0	0	0	0
29	01-January	16:00	0	0	0	0	0	0	0	6.46	0	1	0	0	0	0	0	0	0
30	01-January	17:00	0	0	0	0	0	0	0	7.25	0	1	0	0	0	0	0	0	0
31	01-January	18:00	0	0	0	0	0	0	0	7.78	0	1	0	0	0	0	0	0	0
32	01-January	19:00	0	0	0	0	0	0	0	8.41	0	1	0	0	0	0	0	0	0

Sim

In the simulation screen, clicking in "**Back**" button we return to the main screen.

22. Report of the best solution.

If we move through the table with the bottom bar, and focus on the 1st row (optimal solution), we can see many results. In blue we can see the results of the annual energy, all of them in GWh: load (Etotal); energy from renewable generation (Eren); energy from PV generation (Epv); energy from wind turbines generation (Et); energy that can be exported, from renewables + from backup generator + from the storage, that cannot be used by the load, in this case all the energy (E export); energy injected and sold to the AC grid (E Sell); energy bought to the AC grid (E Buy)... We can see E Sell is lower than Eexport because during many hours the power generated by the wind turbines is higher than the maximum power that can be injected to the AC grid (23 MW), therefore these hours the injected power is limited to 23 MW.

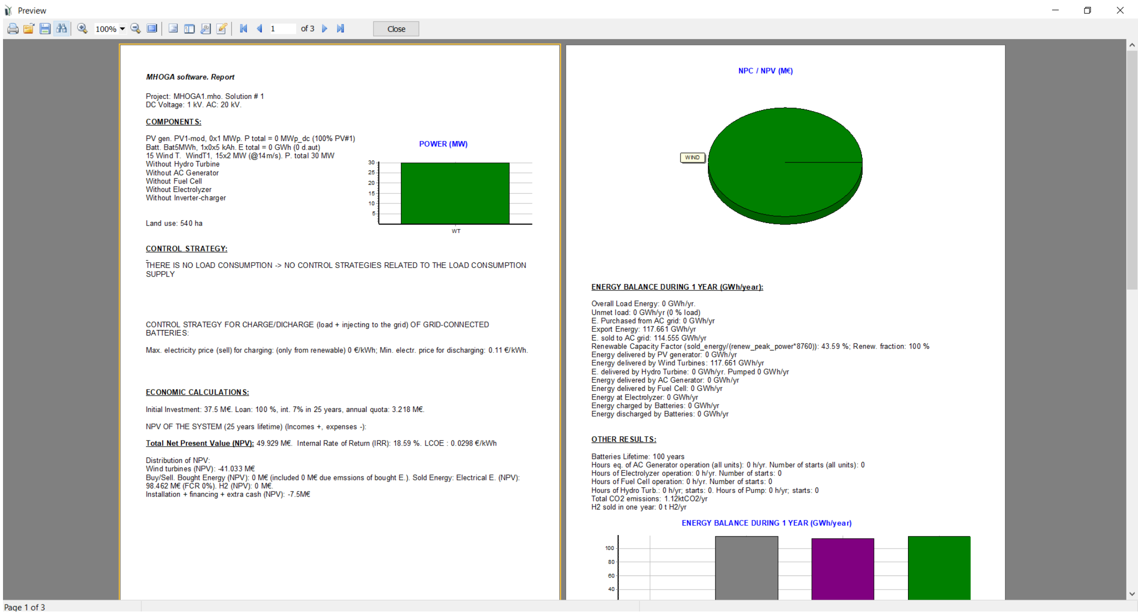
Etotal(GWh)	Eren(GWh)	Epv(GWh)	Ew(GWh)	Et(GWh)	E export(GWh)	E Sell(GWh)	E Buy(GWh)	E ch. bat(GWh)
0	117.661	0	117.661	0	117.661	114.555	0	
0	119.212	1.551	117.661	0	119.212	115.89	0	
0	117.661	0	117.661	0	117.661	114.555	0	
0	120.762	3.101	117.661	0	120.762	117.193	0	
0	119.212	1.551	117.661	0	119.212	115.89	0	
0	122.313	4.652	117.661	0	122.313	118.457	0	
0	117.661	0	117.661	0	117.661	114.555	0	
0	120.762	3.101	117.661	0	120.762	117.193	0	
0	123.863	6.202	117.661	0	123.863	119.687	0	

We can see the report of the optimal solution by clicking on the first row of the table, in "**REPORT**".

Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
49.929	1.12	0	18.59	540	37.5	43.59	0.0298	SIMULATE...	REPORT...

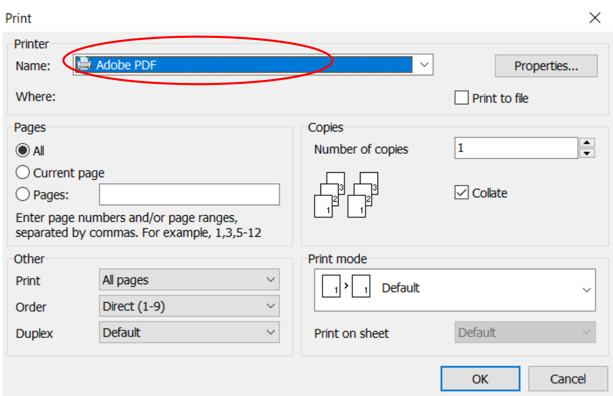
The screen of the report of the best solution appears.

(The same report would have been obtained if we click in the bottom left corner button REPORT showing this button the best solution found)



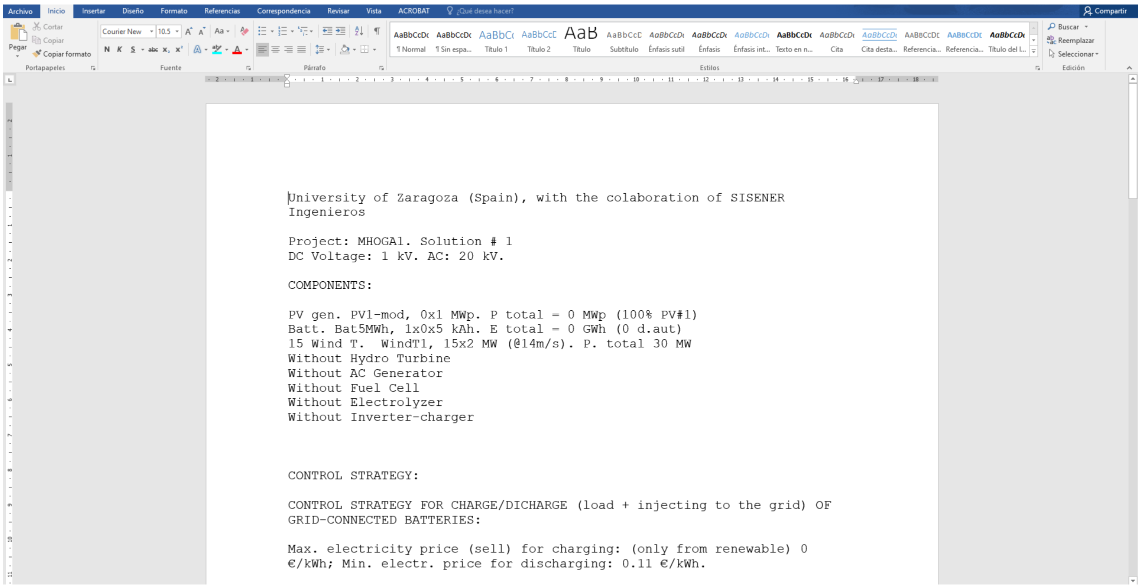
The report can be printed, on paper or in PDF format (if you have installed a virtual Pdf printer, for example Adobe Acrobat or doPDF, which is free).

Press the print button  and then select the physical or vitual printer (in the example, Adobe PDF):



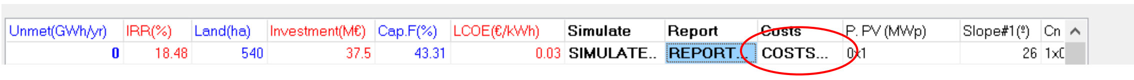
Once the printer is selected (physical or virtual PDF), the report is printed or the PDF file is created by clicking OK (a dialog appears in the Windows taskbar, where you must select the location of the PDF file).

By clicking on the "**Close**" button, the software ask us if we want to save the report in word format (.doc or .rtf) or in .txt format. We click YES, save in .doc format, we save it and then we can open it with Word:

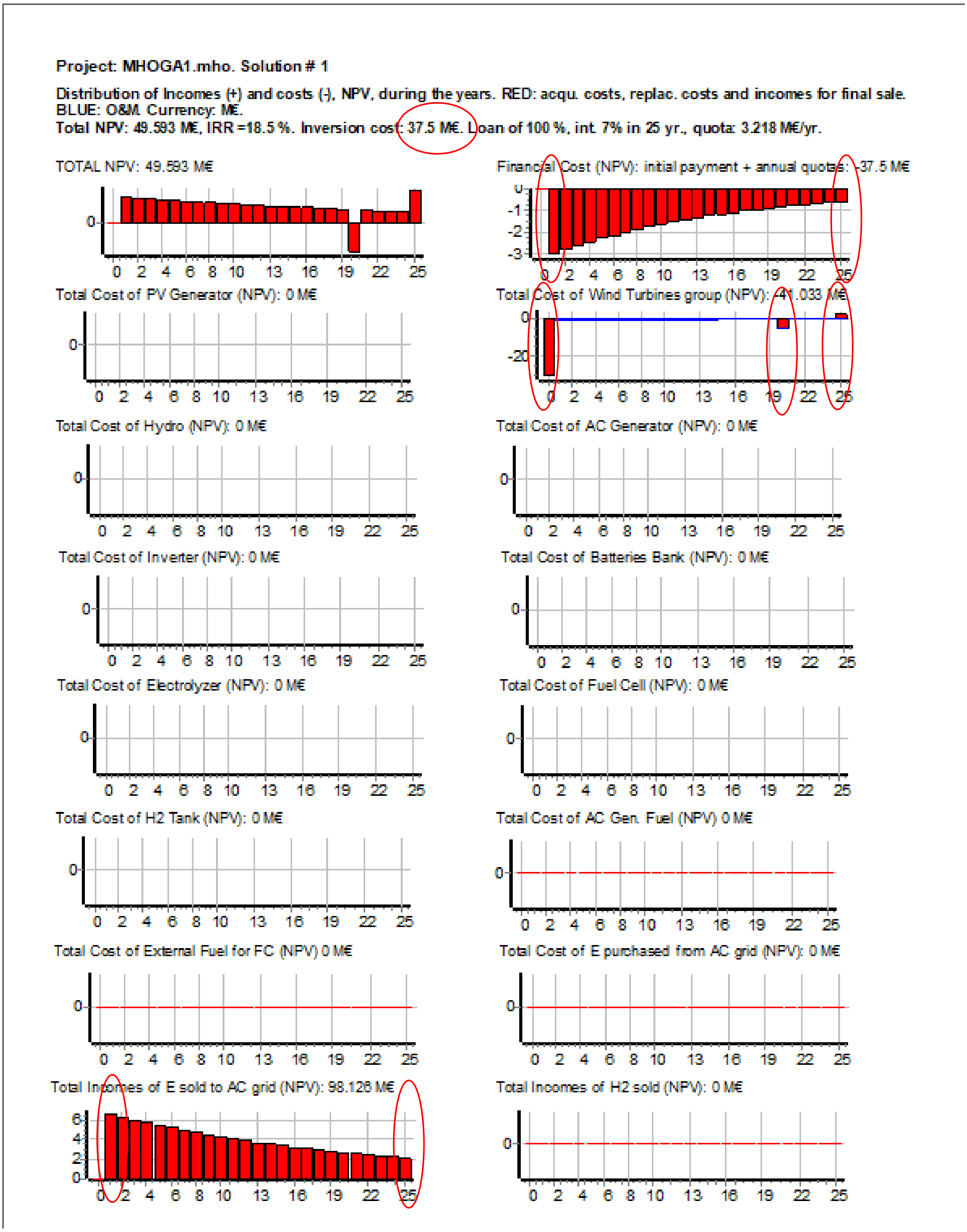


23. Costs of the best solution

In the main screen, we click on the "COSTS" button of the results table (close to "REPORT" button), in the first row:



The following screen appears, informing us graphically of the different costs throughout the life of the system:



We can see the investment costs are 37.5 M€, that is, CAPEX of the wind turbines (2 M€/wind turbine * 15 wind turbines = 30 M€) multiplied by 1.25 (we set in the FINANCIAL DATA tab that a 25% would be added to the initial cost of the system): 30*1.25 = 37.5 M€.

All the costs shown are present cost or present value. For costs or incomes that are the same all the years (but updated by their inflation), the cash flow corresponding to the year 0 is converted to the cash flow of year y multiplying by $(1\text{+interest rate})^{y}$, and this cash flow is converted to present cost or present value dividing by $(1\text{+inominal discount rate})^{y}$.

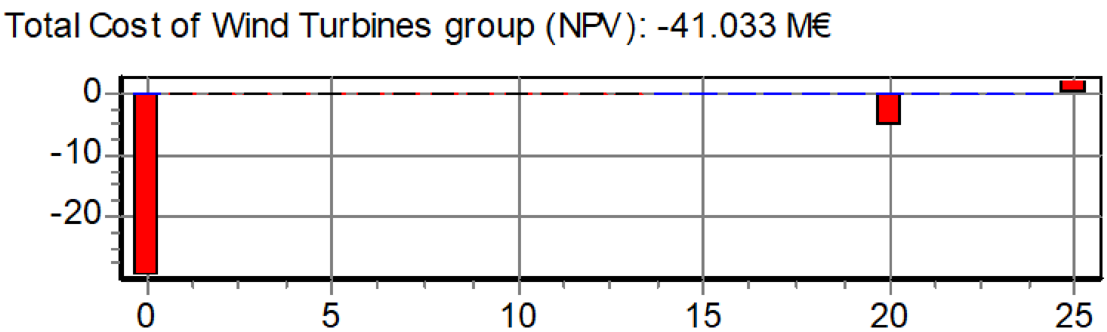
We suppose all the costs and incomes are paid at the end of each year, except for the CAPEX of the different components, which would be paid at year 0 (beginning of the system lifetime) if there was no loan. All the costs defined in the different windows of the software are for the year 0 (beginning of the system lifetime).

For example, for the OPEX costs of the first year, or the incomes due to selling electricity to the AC grid of the first year, the costs defined must be updated with the inflation of 1 year, as the payments and the incomes are at the end of the first year.

Costs due to the wind turbines:

In the graph of the costs of wind turbines we can see all the costs related to the wind turbines: the year 0 (when the system lifetime starts) the cost is the CAPEX (2 M€/wind turbine * 15 wind turbines = 30 M€). Costs are represented as negative values as the type of project is maximization of NPV.

From year 1 to 19 the costs are OPEX (operation and maintenance, O&M): during year 1 the OPEX would be 1% of the wind turbines CAPEX, therefore 30·0.01 = 0.6 M€, but it is paid at the end of the year adding the general inflation (2%). Therefore, the wind turbines OPEX during the 1st year is 0.6 M€, but it is converted to cash flow at the end of the 1st year, it is $0.6 \cdot 1.02^1 = 0.612$ M€; this cash flow will be converted to present cost considering the nominal discount rate of 7%, that is: $0.612/1.07^1 = 0.572$ M€ (it cannot be correctly seen in the graph due to the low value). The same for the rest of the years, changing the number of the year.



In year 20, a reposition cost must be considered, as wind turbines lifetime ends. The replacement cost set in the wind turbines window is 1.6 per wind turbine -> 24 M€, but this cost would be in year 0, however in year 20 this value will be different. We set in the wind turbines window an annual inflation rate for wind turbines costs of -1%, with a limit of -35% (limit would be reached in 42.9 years, see wind turbines window). That means that, in year 20, the 24 M€ are converted to $24 \cdot (1-0.01)^{20} = 19.63$ M€ of cash flow in year 20. However, we must convert this cash flow to present cost dividing by 1.07^{20}, obtaining $19.63/1.07^{20} = 5.073$ M€, shown in the graph.

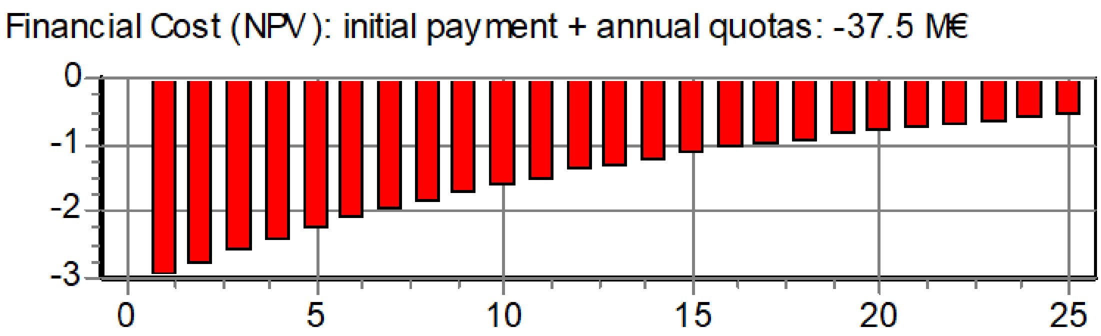
In year 25, there are incomes due to the residual cost of the components, in this case the wind turbines will be working for 5 years (from year 20 to 25), therefore 15 years of useful life will be remaining, with a cash flow value of 24 M€*15/20 = 18 M€ (value referred to year 0). In year 25, considering the annual inflation rate for wind turbines costs of -1% (with a limit of -35%), the cash flow will be $18 \cdot (1-0.01)^{25} = 14.001$ M€ of cash flow at the end of year 25. This cash flow must be converted to present cost by dividing by 1.07^{25}, obtaining $14.001/1.07^{25}$ = 3.618 M€, shown in the graph (value positive as it is an income).

Financial costs:

In our case, in FINANCIAL DATA tab we set that 100% of the initial cost of components and installation (100% of the total initial CAPEX) would be financed by a loan of 7% interest rate and 25 years. As the interest rate is the same as the nominal discount rate and the years are the same as the system lifetime, the effect in the NPV would be the same as if the CAPEX payment would be done in year 0 (37.5 M€). However, in other cases the effect would be different.

If the percentage of the initial cost financed was lower than 100%, in year 0 (the beginning of the system) there would be a financial cost corresponding to the non-financed cost. However, in this case, as 100% is financed, in year 0 there is no financial cost.

In the top right graph, we can see the financial costs, which are the costs during the years (in present cost values) that the owner of the system must pay to cover the CAPEX of the system.



The annual quota (a) is calculated as:

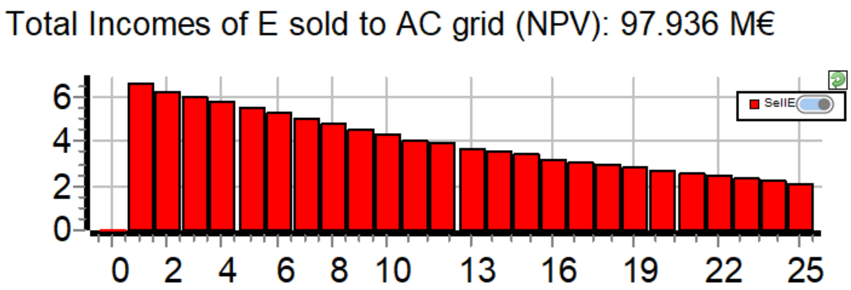
$$a = C_0 \frac{i}{1-(1+i)^{-n}}$$

Where Co is the total financed cost (37.5 M€), i is the interest rate of the loan (7%) and n is the number of years to return (25). The annual constant quota is a = 3.218 M€, which will be the cash flow of each of the 25 years. But this must be converted to present cost, dividing by 1.07^{y}, obtaining for year 1 the present cost of $3.218/1.07^{1}$ = 3.007 M€ and for the last year $3.218/1.07^{25}$ = 0.593 M€, shown in the graph.

Incomes of selling electricity:

We can see the incomes due to selling electricity to the AC grid (bottom left corner graph).

The year 0 (when the system lifetime starts) these incomes would be 6.8803 M€ (sum of the energy injected by the grid multiplied by its cost, which is variable as we introduced an hourly file). In our case the inflation of the price of the electricity sold to the AC grid was set to 2% and the nominal discount rate is 7%. The first year (as always, the payment is at the end of the first year), the cash flow received at the end of the 1st year (as it has passed one year since the beginning, the costs and incomes are supposed to be incremented by inflation) will be $6.8803 \cdot 1.02^{1}$= 7.018 M€. It is converted to present value by dividing by 1.07^{1}, obtaining $7.018/1.07^{1}$= 6.559 M€. The same for the rest of the years, changing the number of year, for the last year (25) it would be the cash flow $6.8803 \cdot 1.02^{25}$= 11.289 M€ and the present value $11.289/1.07^{25}$= 2.08 M€. The sum of all these present value incomes is 97.936 M€.

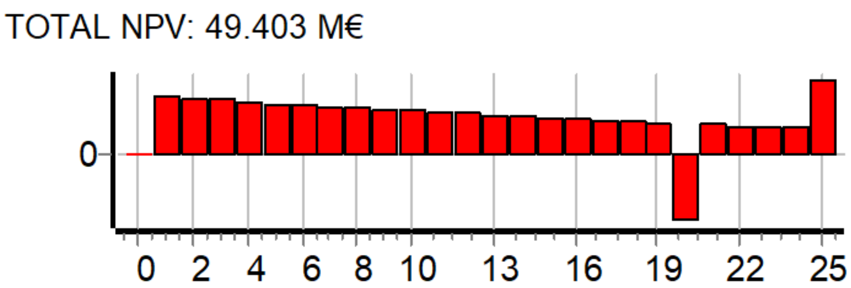


Total NPV:

In the top left graph we can see the total NPV for the different years (all the values added are the NPV of the system, 49.403 M€).

In this case, the CAPEX is financed 100%, we have also OPEX costs (each year OPEX of the wind turbines) and cost of replacement of the wind turbines in year 20, incomes of residual cost of wind turbines in year 25 and incomes are just the incomes from the selling electricity to the AC grid, therefore the value of each year will be the present value of the incomes of selling electricity minus the present cost of the financial minus the OPEX present cost of the wind turbines (in year 20 also minus the replacement cost of the wind turbines; in year 25 plus the incomes of residual cost of the wind turbines).

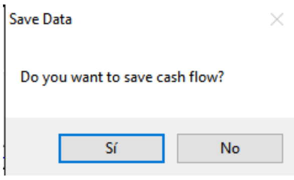
The 100% of the CAPEX of the wind turbines (plus the 25%, that is, the total CAPEX of 37.5 M€) are in the financial costs. Therefore, in year 0 (at the beginning of the system) there is no cost (0 incomes – 0 cost of CAPEX (100% CAPEX is financed) – 0 cost of wind turbines OPEX).



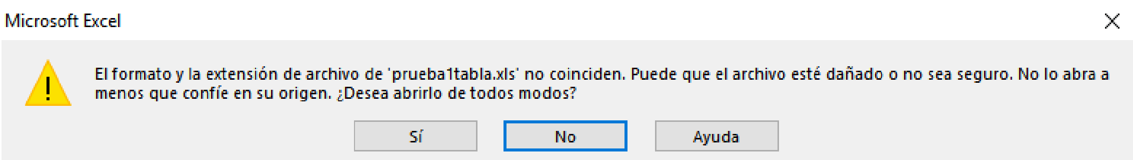
For year 1: 6.559 M€ incomes (present value of incomes of year 1) - 3.007 M€ (present cost of the financial cost of year 1) - 0.572 M€ (present cost of the wind turbines OPEX of year 1) = 2.98 M€ (seen in the graph for year 1).

If we save the results of the cost (when closing the costs window we will be asked), we can see the values calculated previously in an Excel file.

As in the case of the report screen, you can print or create the PDF. If we close (“**Close**” button) it asks if we want to save the cash flows in Excel.

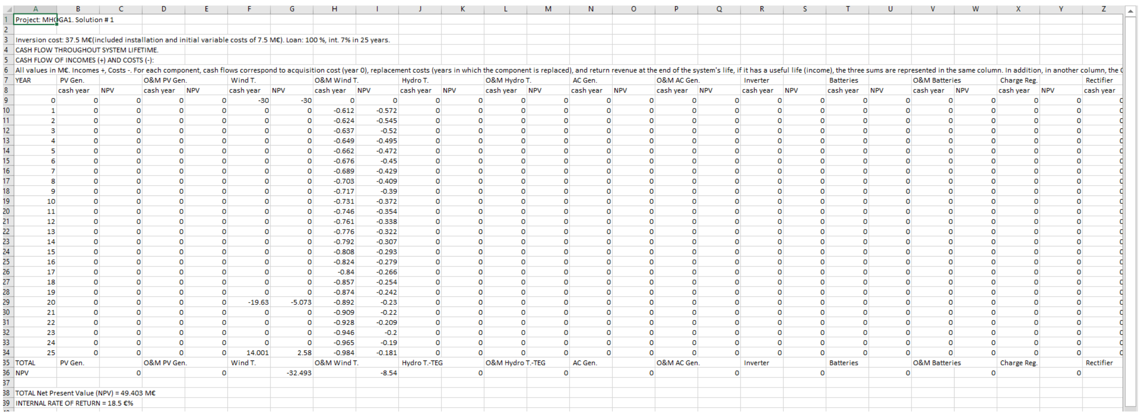


We save the file. Open the saved file with Microsoft Excel (or equivalent software). When opening it we will see a warning:



We answer "Yes" and the Excel file opens perfectly, showing the table of costs.

- Keep in mind that the decimal separation appears as a point. If the decimal separation defined in Windows is comma (usual in Spain and other countries), for Excel to treat the data as numbers we have to:
  - Select the entire Excel sheet and change points by commas
  - Or, in the properties of the Excel sheet, indicate that the decimal separation is the point for this file.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	Project: MHOGA1. Solution # 1																									
2																										
3	Inversion cost: 37.5 M€(included installation and initial variable costs of 7.5 M€). Loan: 100 %, int. 7% in 25 years.																									
4	CASH FLOW THROUGHOUT SYSTEM LIFETIME.																									
5	CASH FLOW OF INCOMES (+) AND COSTS (-):																									
6	All values in M€. Incomes +, Costs -. For each component, cash flows correspond to acquisition cost (year 0), replacement costs (years in which the component is replaced), and return revenue at the end of the system's life, if it has a useful life (income), the three sums are represented in the same column. In addition, in another column, the (																									
7	YEAR	PV Gen.		O&M PV Gen.		Wind T.		O&M Wind T.		Hydro T.		O&M Hydro T.		AC Gen.		O&M AC Gen.		Inverter		Batteries		O&M Batteries		Charge Reg.		Rectifier
8		cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year	NPV	cash year
9	0	0	0	0	0	-30	-30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	-0.612	-0.572	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	2	0	0	0	0	0	0	-0.624	-0.545	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	3	0	0	0	0	0	0	-0.637	-0.52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	4	0	0	0	0	0	0	-0.649	-0.495	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	5	0	0	0	0	0	0	-0.662	-0.472	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	6	0	0	0	0	0	0	-0.676	-0.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	7	0	0	0	0	0	0	-0.689	-0.429	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	8	0	0	0	0	0	0	-0.703	-0.409	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	9	0	0	0	0	0	0	-0.717	-0.39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	10	0	0	0	0	0	0	-0.731	-0.372	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	11	0	0	0	0	0	0	-0.746	-0.354	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	12	0	0	0	0	0	0	-0.761	-0.338	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	13	0	0	0	0	0	0	-0.776	-0.322	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	14	0	0	0	0	0	0	-0.792	-0.307	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	15	0	0	0	0	0	0	-0.808	-0.293	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	16	0	0	0	0	0	0	-0.824	-0.279	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	17	0	0	0	0	0	0	-0.84	-0.266	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	18	0	0	0	0	0	0	-0.857	-0.254	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	19	0	0	0	0	0	0	-0.874	-0.242	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	20	0	0	0	0	-19.63	-5.073	-0.892	-0.23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	21	0	0	0	0	0	0	-0.909	-0.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	22	0	0	0	0	0	0	-0.928	-0.209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	23	0	0	0	0	0	0	-0.946	-0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	24	0	0	0	0	0	0	-0.965	-0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	25	0	0	0	0	14.001	2.58	-0.984	-0.181	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	TOTAL	PV Gen.		O&M PV Gen.		Wind T.		O&M Wind T.		Hydro T.-TEG		O&M Hydro T.-TEG		AC Gen.		O&M AC Gen.		Inverter		Batteries		O&M Batteries		Charge Reg.		Rectifier
36	NPV		0		0		-32.493		-8.54		0		0		0		0		0		0		0		0	
37																										
38	TOTAL Net Present Value (NPV) = 49.403 M€																									
39	INTERNAL RATE OF RETURN = 18.5 €%																									

We can save this Excel file by the "Save As" option of Microsoft Excel in Excel format (*.xlsx) and the next time we open it, the previous warning will no longer appear.

24. First solution found which includes battery and inverter/charger.

If we move right through the table with the bottom bar, and focus on the columns “Cn Bat (kAh)” and “P.inv (MW)”, we move down until we se the first case with battery and inverter both different from 0. In our case, it is row # 20. It is the first solution that includes both battery and inverter/charger.

Report	Costs	P. PV (MWp_dc)	Slope#1(º)	Cn Bat. (kAh)	P. Gen (MW)	P. Inv (MW)	P. Wind T. (MW)	F. Turb (m3/s)	P. FC (MW)	P. Elyz. (MW
REPORT...	COSTS...	3x1	27	1x0x5	1x0	5	15x2	0	0	
REPORT...	COSTS...	5x1	27	1x0x5	1x0	0	15x2	0	0	
REPORT...	COSTS...	0x1	27	1x1x5	1x0	0	15x2	0	0	
REPORT...	COSTS...	1x1	27	1x0x5	1x0	0	14x2	0	0	
REPORT...	COSTS...	2x1	27	1x0x5	1x0	10	15x2	0	0	
REPORT...	COSTS...	4x1	27	1x0x5	1x0	5	15x2	0	0	
REPORT...	COSTS...	2x1	27	1x0x5	1x0	0	14x2	0	0	
REPORT...	COSTS...	1x1	27	1x1x5	1x0	0	15x2	0	0	
REPORT...	COSTS...	0x1	27	1x1x5	1x0	5	15x2	0	0	

Focusing on row 20 (solution 20th), we can see that this row has 15 wind turbines, a battery bank of 5 MWh (5 kAh x 1 kV) and an inverter/charger of 5 MW.

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
12	**47.766**	**1.22**	**0**	16.91	549	42.625	40.98	0.0322	SIMULATE..	REPOR
13	**47.503**	**1.28**	**0**	16.37	555	45	39.43	0.0331	SIMULATE..	REPOR
14	**47.494**	**1.14**	**0**	17.62	540.05	39.375	43.59	0.0313	SIMULATE..	REPOR
15	**47.49**	**1.08**	**0**	18.34	507	36.5	43.22	0.0301	SIMULATE..	REPOR
16	**47.432**	**1.19**	**0**	17.05	546	41.75	41.81	0.0321	SIMULATE..	REPOR
17	**47.246**	**1.25**	**0**	16.5	552	44.125	40.18	0.0329	SIMULATE..	REPOR
18	**47.138**	**1.11**	**0**	17.85	510	38	42.31	0.0307	SIMULATE..	REPOR
19	**47.08**	**1.18**	**0**	17.18	543.05	40.875	42.68	0.0319	SIMULATE..	REPOR
20	**47.025**	**1.14**	**0**	17.39	540.05	40	43.64	0.0317	SIMULATE..	REPOR

We can see many results. In blue we can see the results of the annual energy. The energy generated by the wind turbines, Ew (GWh) is the same as the optimal solution, however the export energy, Eexport (energy that is not used in the system) is higher. During some hours, when the wind generation is higher than the maximum power allowed to be injected to the grid (23 MW), the batteries are charged using energy from the wind turbines that in the optimal solution was lost; later the batteries inject that energy to the grid, that's why E export is higher than in the optimal solution.

Epv(GWh)	Ew(GWh)	Et(GWh)	E export(GWh)	E Sell(GWh)	E Buy(GWh)	E ch. bat(GWh)	E disch. bat (GWh)	E elyzer.
4.652	117.661	0	122.313	118.457	0	0	0	
7.752	117.661	0	125.414	120.884	0	0	0	
0	117.661	0	117.661	114.555	0	0	0	
1.551	109.817	0	111.368	109.788	0	0	0	
3.101	117.661	0	120.762	117.193	0	0	0	
6.202	117.661	0	123.863	119.687	0	0	0	
3.101	109.817	0	112.918	111.182	0	0	0	
1.551	117.661	0	119.212	115.89	0	0	0	
0	117.661	0	117.829	114.683	0	0.166	0.157	

Energy injected in the AC grid, E sell, in this case is a bit higher than in the optimal solution.

Energy charged by the battery bank (energy that enters into the battery) is 0.166 GWh/yr while the discharged energy (energy that effectivelly supplies the battery, considering efficiency) is 0.157 GWh/yr (we must take into account that in the simulation we can see that at the beginning of the simulation, January 1st, battery is fully charged; at the end of the year is fully discharged).

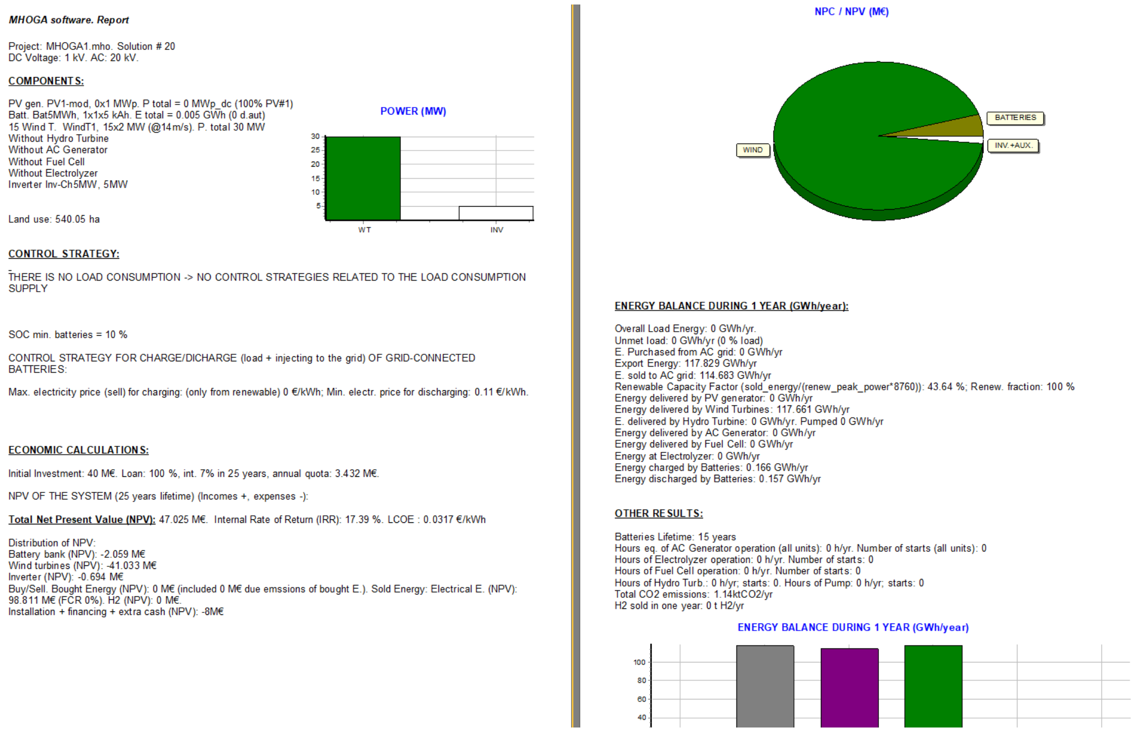
We can see the incomes due to energy sold the first year are 6.942 M€.

E Sell (M€/yr)	Sell H2 (M€/yr)	NPV PV (M€)	NPV Bat. (M€)	NPV Aux. (M€)	NPV Inv. (M€)	NPV Gen. (M€)	NPV WindT (M€)	C. Hydro (NPC) (M
7.175	0	-4.112	0	0	-0.694	0	-41.033	0
7.334	0	-6.854	0	0	0	0	-41.033	0
6.918	0	0	-2.059	0	0	0	-41.033	0
6.636	0	-1.371	0	0	0	0	-38.298	0
7.092	0	-2.742	0	0	-1.387	0	-41.033	0
7.256	0	-5.483	0	0	-0.694	0	-41.033	0
6.729	0	-2.742	0	0	0	0	-38.298	0
7.006	0	-1.371	-2.059	0	0	0	-41.033	0
6.942	0	0	-2.059	0	-0.694	0	-41.033	0

Also the total incomes due to energy sold, in present value (NPV), 98.811 M€.

NPV WindT (M€)	C. Hydro (NPC) (M	NPV FC (M€)	NPV Elyz. (M€)	NPV Fuel Gen (M€)	NPV Fuel FC (M€)	NPV Buy (M€)	NPV Sell (M€)	NPV
-41.033	0	0	0	0	0	0	102.13	
-41.033	0	0	0	0	0	0	104.391	
-41.033	0	0	0	0	0	0	98.462	
-38.298	0	0	0	0	0	0	94.459	
-41.033	0	0	0	0	0	0	100.944	
-41.033	0	0	0	0	0	0	103.281	
-38.298	0	0	0	0	0	0	95.777	
-41.033	0	0	0	0	0	0	99.718	
-41.033	0	0	0	0	0	0	98.811	

Many of these results can be seen in the report (in the 20th row or the table, click in REPORT):



MHOGA software. Report

Project: MHOGA1.mho. Solution # 20
DC Voltage: 1 kV. AC: 20 kV.

COMPONENTS:

PV gen. PV1-mod, 0x1 MWp. P total = 0 MWp_dc (100% PV#1)
Batt. Bat5MWh, 1x1x5 kAh. E total = 0.005 GWh (0 d.aut)
15 Wind T. WindT1, 15x2 MW (@14m/s). P. total 30 MW
Without Hydro Turbine
Without AC Generator
Without Fuel Cell
Without Electrolyzer
Inverter Inv-Ch5MW, 5MW

Land use: 540.05 ha

CONTROL STRATEGY:

THERE IS NO LOAD CONSUMPTION -> NO CONTROL STRATEGIES RELATED TO THE LOAD CONSUMPTION SUPPLY

SOC min. batteries = 10 %

CONTROL STRATEGY FOR CHARGE/DICHARGE (load + injecting to the grid) OF GRID-CONNECTED BATTERIES:

Max. electricity price (sell) for charging: (only from renewable) 0 €/kWh; Min. electr. price for discharging: 0.11 €/kWh.

ECONOMIC CALCULATIONS:

Initial Investment: 40 M€. Loan: 100 %, int. 7% in 25 years, annual quota: 3.432 M€.

NPV OF THE SYSTEM (25 years lifetime) (Incomes +, expenses -):

Total Net Present Value (NPV): 47.025 M€. Internal Rate of Return (IRR): 17.39 %. LCOE : 0.0317 €/kWh

Distribution of NPV:
Battery bank (NPV): -2.059 M€
Wind turbines (NPV): -41.033 M€
Inverter (NPV): -0.694 M€
Buy/Sell. Bought Energy (NPV): 0 M€ (included 0 M€ due emssions of bought E.). Sold Energy: Electrical E. (NPV): 98.811 M€ (FCR 0%). H2 (NPV): 0 M€.
Installation + financing + extra cash (NPV): -8M€

ENERGY BALANCE DURING 1 YEAR (GWh/year):

Overall Load Energy: 0 GWh/yr.
Unmet load: 0 GWh/yr (0 % load)
E. Purchased from AC grid: 0 GWh/yr
Export Energy: 117.829 GWh/yr
E. sold to AC grid: 114.683 GWh/yr
Renewable Capacity Factor (sold_energy/(renew_peak_power*8760)): 43.64 %; Renew. fraction: 100 %
Energy delivered by PV generator: 0 GWh/yr
Energy delivered by Wind Turbines: 117.661 GWh/yr
E. delivered by Hydro Turbine: 0 GWh/yr. Pumped 0 GWh/yr
Energy delivered by AC Generator: 0 GWh/yr
Energy delivered by Fuel Cell: 0 GWh/yr
Energy at Electrolyzer: 0 GWh/yr
Energy charged by Batteries: 0.166 GWh/yr
Energy discharged by Batteries: 0.157 GWh/yr

OTHER RESULTS:

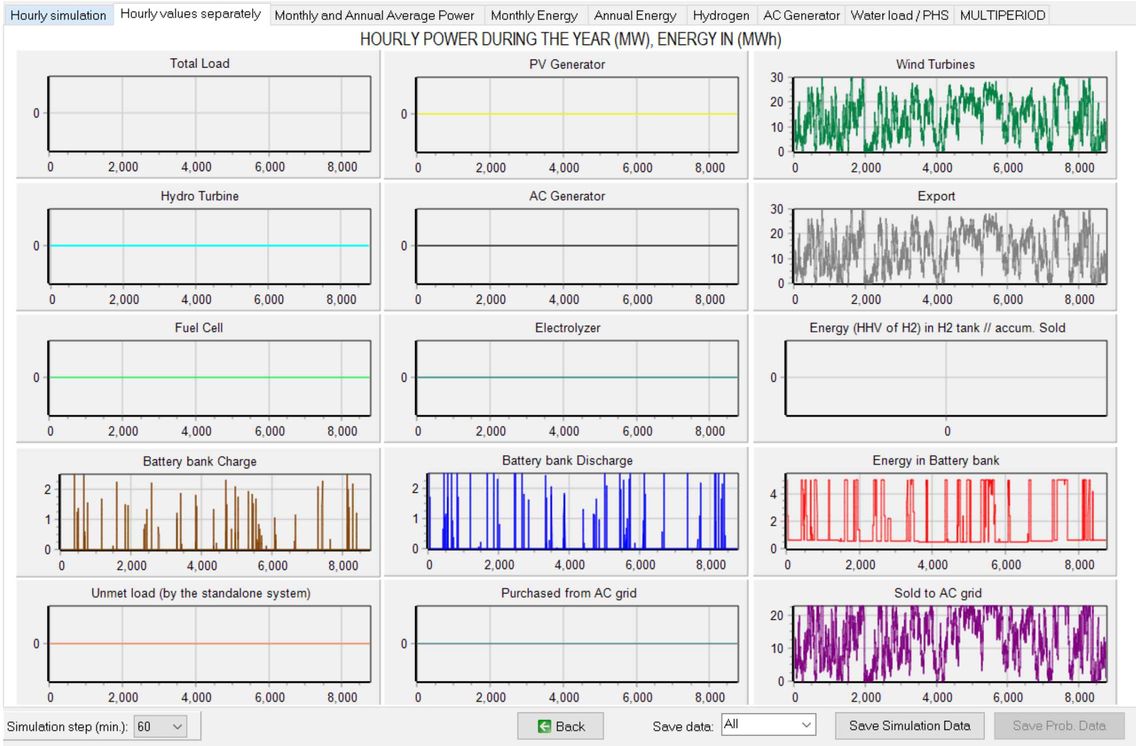
Batteries Lifetime: 15 years
Hours eq. of AC Generator operation (all units): 0 h/yr. Number of starts (all units): 0
Hours of Electrolyzer operation: 0 h/yr. Number of starts: 0
Hours of Fuel Cell operation: 0 h/yr. Number of starts: 0
Hours of Hydro Turb.: 0 h/yr; starts: 0. Hours of Pump: 0 h/yr; starts: 0
Total CO2 emissions: 1.14ktCO2/yr
H2 sold in one year: 0 t H2/yr

In the main screen again, we can see the simulation of the operation of this solution by clicking on the 20th row of the table, in "**SIMULATE**":

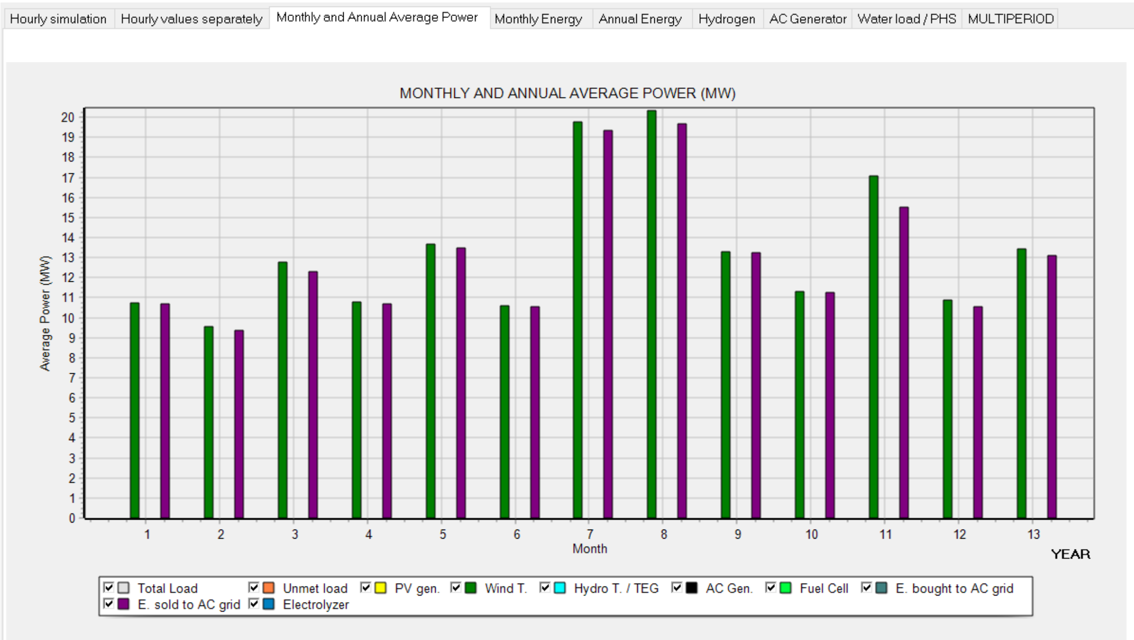
In the first tab (Hourly simulation), we can see the energy price and the limits to charge/discharge the batteries by clicking “**Energy price**” button. But we can see this over the power graph by checking “**See over**” checkbox (with the “**Legend**” checked we see the legend of both graphs).

In the screenshot above 5 consecutive days are shown. We can see that batteries are only charged when wind generation is higher than 23 MW (maximum power allowed to be injected into the grid), the rest from that value is used to charge the batteries until they are fully charged (SOC=100% is the red line of 5 MWh). When the sell electricity price is higher than 0.11 €/kWh and wind generation is lower than 23 MW, batteries are discharged at the maximum rate but not exceeding 23 MW together with the wind generation.

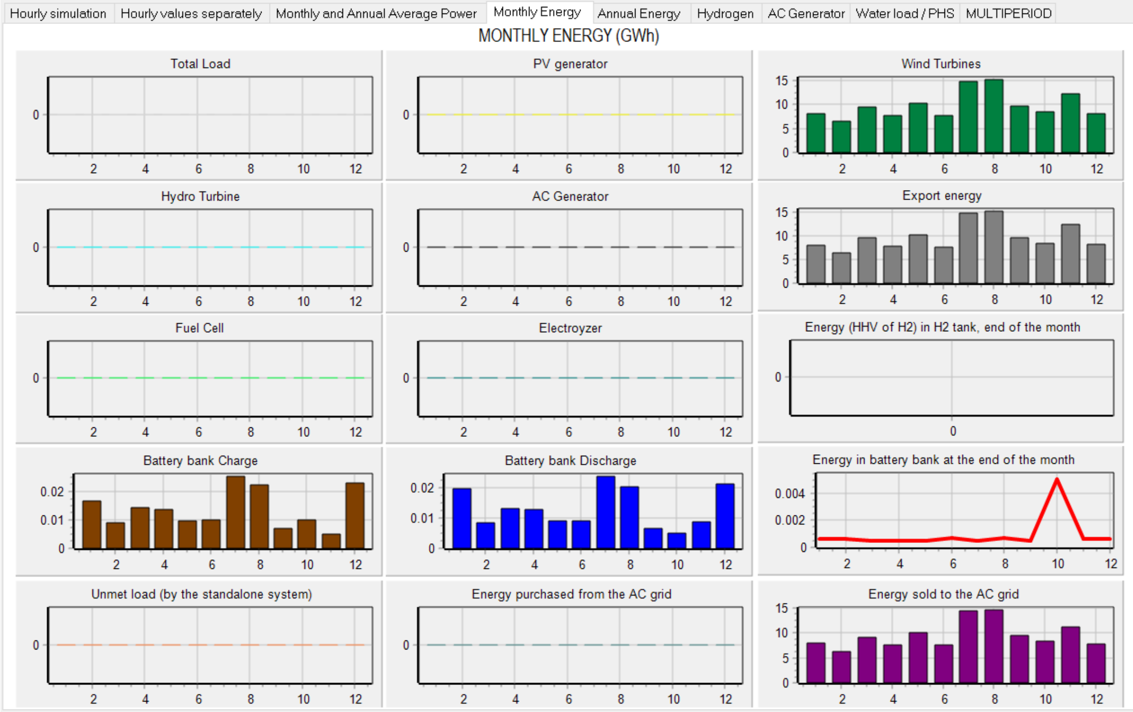
In the second tab of the simulation screen we can see the whole year:

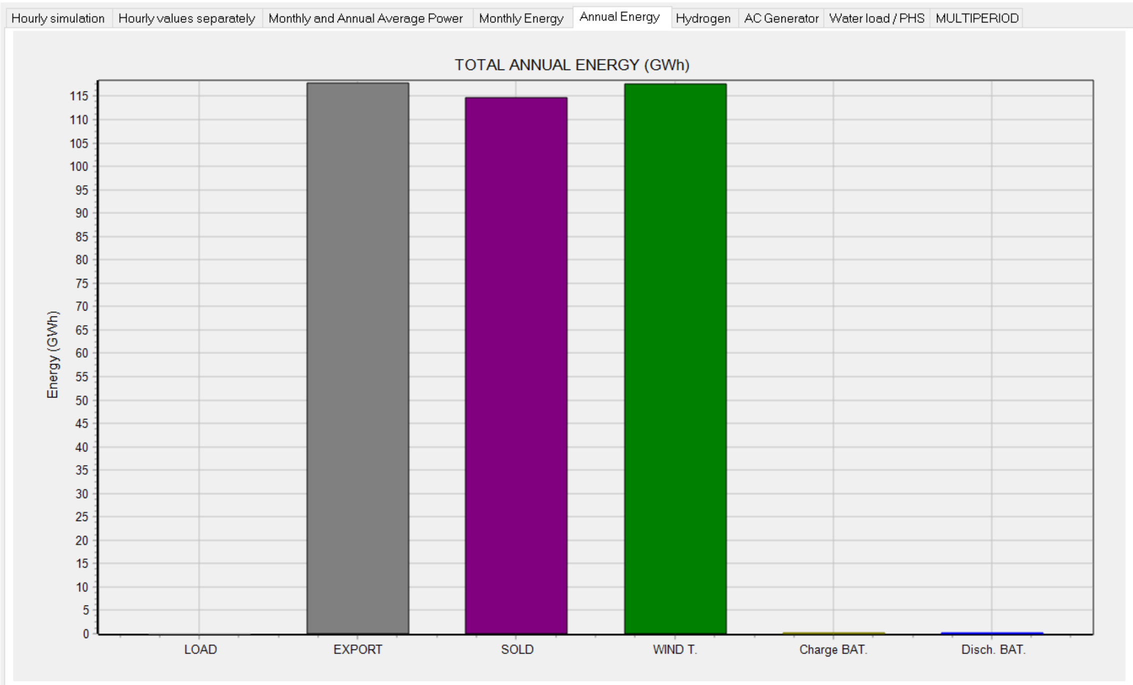


Third tab:



Other tabs:

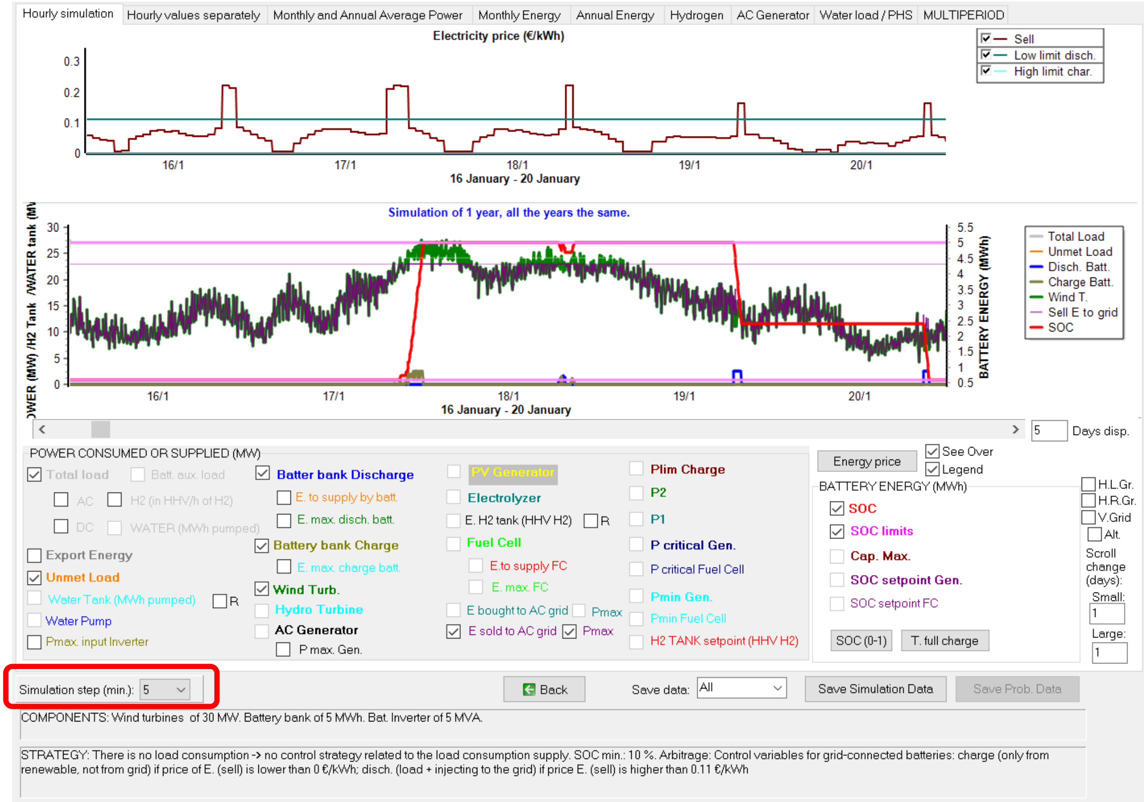




25. Simulation in steps lower than 1 h.

In the simulation screen, we can change the simulation time step, under the checkboxes, in the left area, and the simulation will be updated to the new time steps.

For example, change to 5 minutes. After several seconds (please, be patient) the simulation results are updated, seeing now the simulation in 5 minutes time steps. We can see the variability of the wind generation due to the variability of the wind speed.

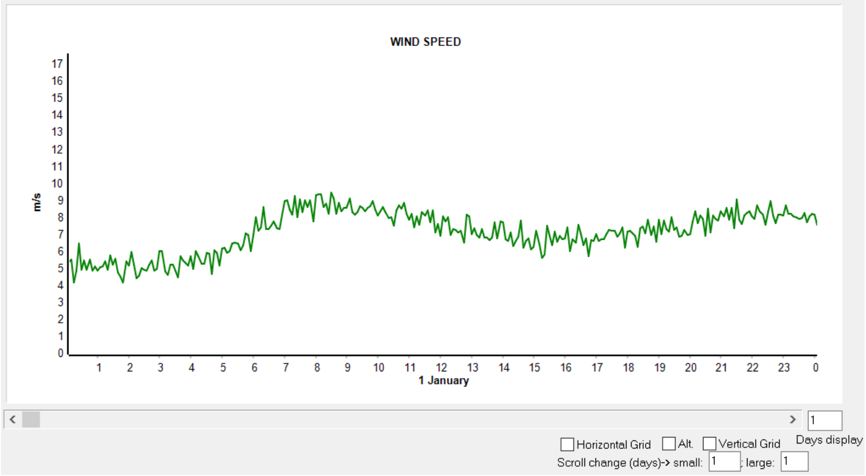


By clicking on the simulation screen in "**Back**" button we return to the main screen.

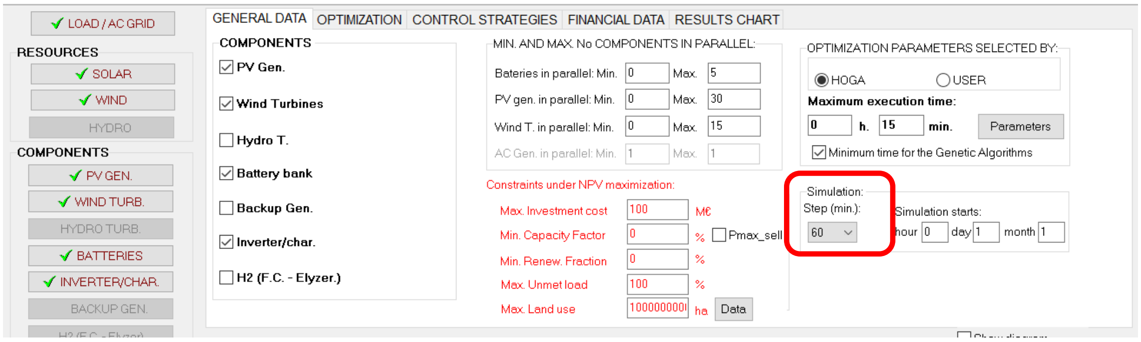
In the main screen, the results of the solution 29th has been updated to the simulation step of 5 min: the NPV has been slightly increased.

We could optimize the system with this time step (even with lower time step, until 1 min.), however the optimization would take a lot of time and we will not do it in this guide.

In the WIND screen, we can see the simulation of the wind speed in steps of 5 min (**Graph in setps** of 5 min. button).



In the main screen again, GENERAL DATA tab, we can return to the 60 min time step by selecting it in the Simulation section:



Then, if we click in the 20th row, we can see how it returns to the results of the 60 min time step simulation:

20	47.025	1.14	0	17.39	540.05	40	43.64	0.0317	SIMULATE..	REPOR

26. Save results table.

In the main screen, we can save the results table by clicking on the button "**Save Excel table**"

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	49.929	1.12	0	18.59	540	37.5	43.59	0.0298	SIMULATE..	REPOR
2	49.514	1.16	0	18.09	543	39	42.68	0.0304	SIMULATE..	REPOR
3	49.11	1.12	0	18.26	540	38.125	43.59	0.0303	SIMULATE..	REPOR
4	49.069	1.19	0	17.63	546	40.5	41.81	0.0311	SIMULATE..	REPOR
5	48.696	1.16	0	17.78	543	39.625	42.68	0.0309	SIMULATE..	REPOR
6	48.584	1.22	0	17.19	549	42	40.98	0.0318	SIMULATE..	REPOR
7	48.292	1.12	0	17.94	540	38.75	43.59	0.0308	SIMULATE..	REPOR
8	48.25	1.19	0	17.33	546	41.125	41.81	0.0316	SIMULATE..	REPOR
9	48.065	1.25	0	16.77	552	43.5	40.18	0.0324	SIMULATE..	REPOR

COMPONENTS: 15 Wind Turb. WindT1 (2 MW at 15 m/s) // Unmet load = 0 % // Total Net Present Value (NPV) = 49.929 M€, IRR = 18.6%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. Control variables for grid-connected batteries: charge (only from renewable, not from grid) if price of E. (sell) is lower than 0 €/kWh; disch. (load + injecting to the grid) if price E. (sell) higher than 0.11 €/kWh

Save Excel table

The table is saved where we choose. When we open the file with Microsoft Excel, after accepting the warning, the table appears.

Project: D:\PROYECTOS MHOGA 3.4-202403XX\MHOGA1.mho

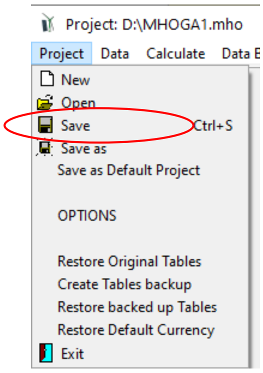
No.	NPV(M€)	Em.CO2(kt/yr)	Unmet(GWh/yr)	Unmet(%)	IRR(%)	Land use(ha)	Investment(M€)	Capacity Factor (%)	LCOE (€/kWh)
1	49.929	1.125	0	0	18.59	540	37.5	43.59	0.0298
2	49.514	1.157	0	0	18.09	543	39	42.68	0.0304
3	49.11	1.125	0	0	18.26	540	38.125	43.59	0.0303
4	49.069	1.189	0	0	17.63	546	40.5	41.81	0.0311
5	48.696	1.157	0	0	17.78	543	39.625	42.68	0.0309
6	48.584	1.221	0	0	17.19	549	42	40.98	0.0318
7	48.292	1.125	0	0	17.94	540	38.75	43.59	0.0308
8	48.25	1.189	0	0	17.33	546	41.125	41.81	0.0316
9	48.065	1.253	0	0	16.77	552	43.5	40.18	0.0324
10	47.877	1.157	0	0	17.48	543	40.25	42.68	0.0314
11	47.82	1.05	0	0	18.86	504	35	44.18	0.0294
12	47.766	1.221	0	0	16.91	549	42.625	40.98	0.0322
13	47.503	1.285	0	0	16.37	555	45	39.43	0.0331
14	47.494	1.143	0	0	17.62	540.05	39.375	43.59	0.0313
15	47.49	1.082	0	0	18.34	507	36.5	43.22	0.0301
16	47.432	1.189	0	0	17.05	546	41.75	41.81	0.0321
17	47.246	1.253	0	0	16.5	552	44.125	40.18	0.0329
18	47.138	1.114	0	0	17.85	510	38	42.31	0.0307
19	47.08	1.175	0	0	17.18	543.05	40.875	42.68	0.0319
20	47.025	1.143	0	0	17.39	540.05	40	43.64	0.0317
21	47.001	1.05	0	0	18.5	504	35.625	44.18	0.0299
22	46.947	1.221	0	0	16.64	549	43.25	40.98	0.0327
23	46.897	1.317	0	0	15.98	558	46.5	38.7	0.0337
24	46.751	1.146	0	0	17.4	513	39.5	41.44	0.0314
25	46.685	1.285	0	0	16.11	555	45.625	39.43	0.0335
26	46.672	1.082	0	0	18.01	507	37.125	43.22	0.0306
27	46.655	1.125	0	0	17.33	540	40	43.59	0.0318
28	46.634	1.207	0	0	16.76	546.05	42.375	41.81	0.0326
29	46.612	1.175	0	0	16.96	543.05	41.5	42.72	0.0324

table

We can save this Excel file by the "Save As" option of Microsoft Excel in Excel format (*.xlsx) and the next time we open it, the previous warning will no longer appear.

27. Save the project.

In the top menu of the main screen, click **Project-> Save**, the project will be saved. It should have been done periodically.



28. Save as default project.

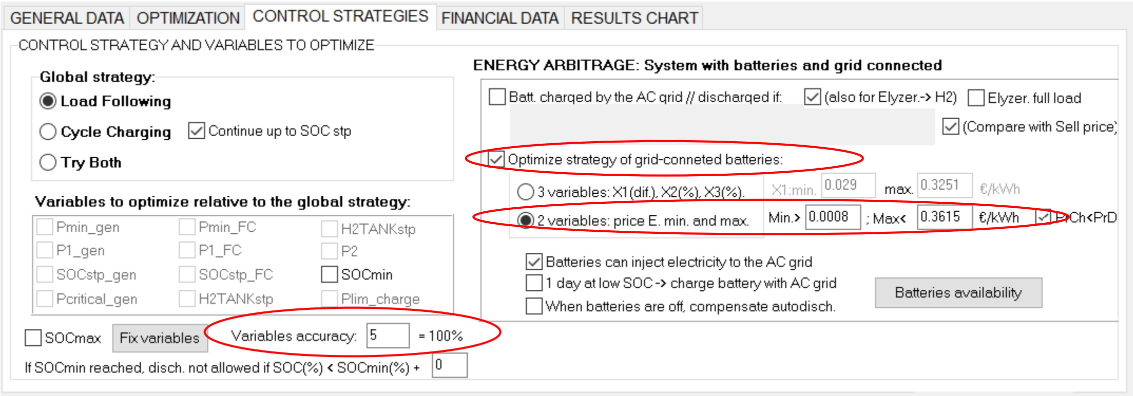
You don't have to do it in this case, however, in the top menu of the main screen, clicking **Project-> Save as Default Project** we can save the present project to be the default project when we create new projects. Later we can change the default project to another one that interests us more.

29. Optimize grid-connected battery management.

Save the project (**Project->Save**) and then save it with another name (**Project->Save as**) and give the name "MHOGA-optCont.mho".

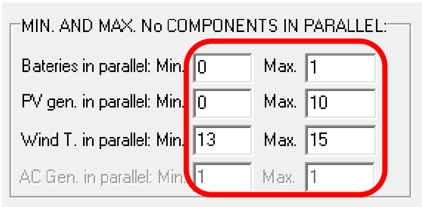
Maybe the battery management that we set is not optimal for this case. Now we will optimize the control strategy for the battery.

In the main screen, CONTROL STRATEGIES tab, check “Optimize strategy of grid-connected batteries”. We could optimize 3 or 2 variables (see the user manual), in this case, as we don’t want to take a lot of time in the optimization, we select “2 variables: price E min. and max.”. At its right the limits are automatically set (considering max. and min. prices of the electricity sold to the AC grid), we don’t change them.

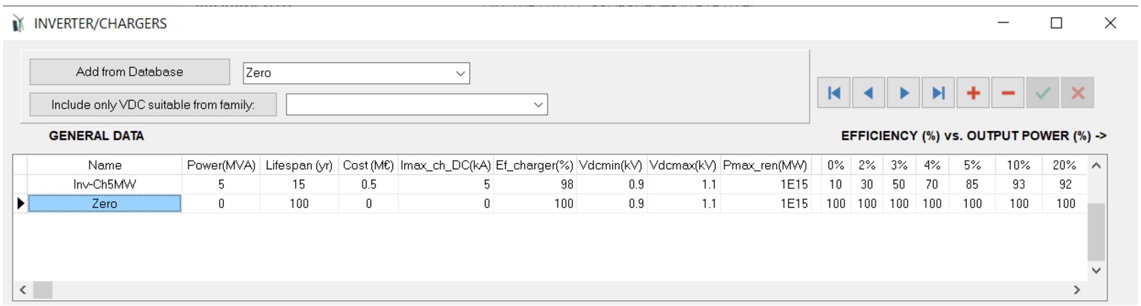


Now for each combination of components, there will be 36 possible solutions of control strategy (we have 2 control variables, and each one can take 6 values, as in variables accuracy 5=100%, therefore each variable con take the values of 0%, 20%, 40%, 60%, 80% and 100%, where 100% is the maximum value of each variable; therefore 6*6=36 possible combinations of control variables).

In the main screen, GENERAL DATA tab, we reduce the search space in order to do the optimization quickly (in a real project we would leave the original values).



Also, in the INVERTER/CHARGERS screen, we delete the ones of 10 and 20 MW (select the row of the table and click “-“ button at the top right), leaving only the ones of 0 and 5 MW:



In the main screen, save the project and then click CALCULATE.

After several minutes, the optimization finishes. The optimal (first row) is the same as before (section 24), as it is just a wind park of 15 wind turbines, without batteries nor inverter/charger (and in this case the control strategies have no meaning as there is no battery bank).

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	49.929	1.12	0	18.59	540	37.5	43.59	0.0298	SIMULATE..	REPOR
2	49.514	1.16	0	18.09	543	39	42.68	0.0304	SIMULATE..	REPOR
3	49.11	1.12	0	18.26	540	38.125	43.59	0.0303	SIMULATE..	REPOR
4	49.069	1.19	0	17.63	546	40.5	41.81	0.0311	SIMULATE..	REPOR
5	48.696	1.16	0	17.78	543	39.625	42.68	0.0309	SIMULATE..	REPOR
6	48.584	1.22	0	17.19	549	42	40.98	0.0318	SIMULATE..	REPOR
7	48.25	1.19	0	17.33	546	41.125	41.81	0.0316	SIMULATE..	REPOR
8	48.067	1.15	0	17.6	540.05	40	43.49	0.0321	SIMULATE..	REPOR
9	48.065	1.25	0	16.77	552	43.5	40.18	0.0324	SIMULATE..	REPOR

COMPONENTS: 15 Wind Turb. WindT1 (2 MW at 15 m/s) // Unmet load = 0 % // Total Net Present Value (NPV) = 49.929 M€, IRR = 18.6%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. ARB.: Control variables for grid-connected batteries: charge (only from renewable, not from grid) if price of E. (sell) is lower than 0.3615 €/kWh; disch. (load + injecting to the grid) if price E. higher than 0.3615 €/kWh

If we search in the table, we can see that now the best solution which includes battery and inverter/charger is the number 8 (same solution as before the 20th one of section 24, but with different control strategy). We can see it has the same components as the previous # 20 (section 24), that is, 15 wind turbines, battery bank of 5 MWh and inverter of 5 MW:

P. PV (MWp_dc)	Slope#1(º)	Cn Bat. (kAh)	P. Gen (MW)	P. Inv (MW)	P. Wind T. (MW)	F. Turb (m3/s)	P. FC (MW)	P. Elyz. (MW)	H2 tank (t)	NF
0x1	27	1x0x5	1x0	0	15x2	0	0	0		0
1x1	27	1x0x5	1x0	0	15x2	0	0	0		0
0x1	27	1x0x5	1x0	5	15x2	0	0	0		0
2x1	27	1x0x5	1x0	0	15x2	0	0	0		0
1x1	27	1x0x5	1x0	5	15x2	0	0	0		0
3x1	27	1x0x5	1x0	0	15x2	0	0	0		0
2x1	27	1x0x5	1x0	5	15x2	0	0	0		0
0x1	27	1x1x5	1x0	5	15x2	0	0	0		0
4x1	27	1x0x5	1x0	0	15x2	0	0	0		0

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	49.929	1.12	0	18.59	540	37.5	43.59	0.0298	SIMULATE..	REPOR
2	49.514	1.16	0	18.09	543	39	42.68	0.0304	SIMULATE..	REPOR
3	49.11	1.12	0	18.26	540	38.125	43.59	0.0303	SIMULATE..	REPOR
4	49.069	1.19	0	17.63	546	40.5	41.81	0.0311	SIMULATE..	REPOR
5	48.696	1.16	0	17.78	543	39.625	42.68	0.0309	SIMULATE..	REPOR
6	48.584	1.22	0	17.19	549	42	40.98	0.0318	SIMULATE..	REPOR
7	48.25	1.19	0	17.33	546	41.125	41.81	0.0316	SIMULATE..	REPOR
8	48.067	1.15	0	17.6	540.05	40	43.49	0.0321	SIMULATE..	REPOR
9	48.065	1.25	0	16.77	552	43.5	40.18	0.0324	SIMULATE..	REPOR

Moving right in the table (row 8th) we can also see the min. (0.07294 €/kWh) and max. (0.14508 €/kWh) price of sell electricity to charge / discharge:

Pr.max.C(€/k'	Pr.min.D(€/kV	Etotal(GWh)	Eren(GWh)	Epv(GWh)	Ew(GWh)	Et(GWh)	E export(GWh)	E Sell(GWh)	E Buy(GWh)
0.3615	0.3615	0	117.661	0	117.661	0	117.661	114.555	
0.3615	0.3615	0	119.212	1.55	117.661	0	119.212	115.89	
0.3615	0.3615	0	117.661	0	117.661	0	117.661	114.555	
0.3615	0.3615	0	120.762	3.101	117.661	0	120.762	117.193	
0.3615	0.3615	0	119.212	1.55	117.661	0	119.212	115.89	
0.3615	0.3615	0	122.313	4.652	117.661	0	122.313	118.457	
0.3615	0.3615	0	120.762	3.101	117.661	0	120.762	117.193	
0.07294	0.14508	0	117.661	0	117.661	0	117.561	114.3	
0.3615	0.3615	0	123.863	6.202	117.661	0	123.863	119.687	

And now E sell is 114.3 kWh, a bit lower than in the previous case solution #20 (section 24), however part of this energy is paid at a higher price, therefore the incomes are higher.

E ch. bat(GWh)	E disch. bat (GWh)	E elyzer. (GWh)	E gen (GWh)	E FC (GWh)	Hours eq. Gen	Bat. life (yr)	Hours Ch. Bat.	Hours Disch. E
0	0	0	0	0	0	100	0	
0	0	0	0	0	0	100	0	
0	0	0	0	0	0	100	0	
0	0	0	0	0	0	100	0	
0	0	0	0	0	0	100	0	
0	0	0	0	0	0	100	0	
0	0	0	0	0	0	100	0	
1.29	1.187	0	0	0	0	10.07	0	
0	0	0	0	0	0	100	0	

Now energy charged by the battery bank (energy that enters into the battery) is 1.29 GWh/yr while the discharged energy (energy that effectively supplies the battery, considering efficiency) is 1.187 GWh/yr, these values are around 10 times higher than values of section 24.

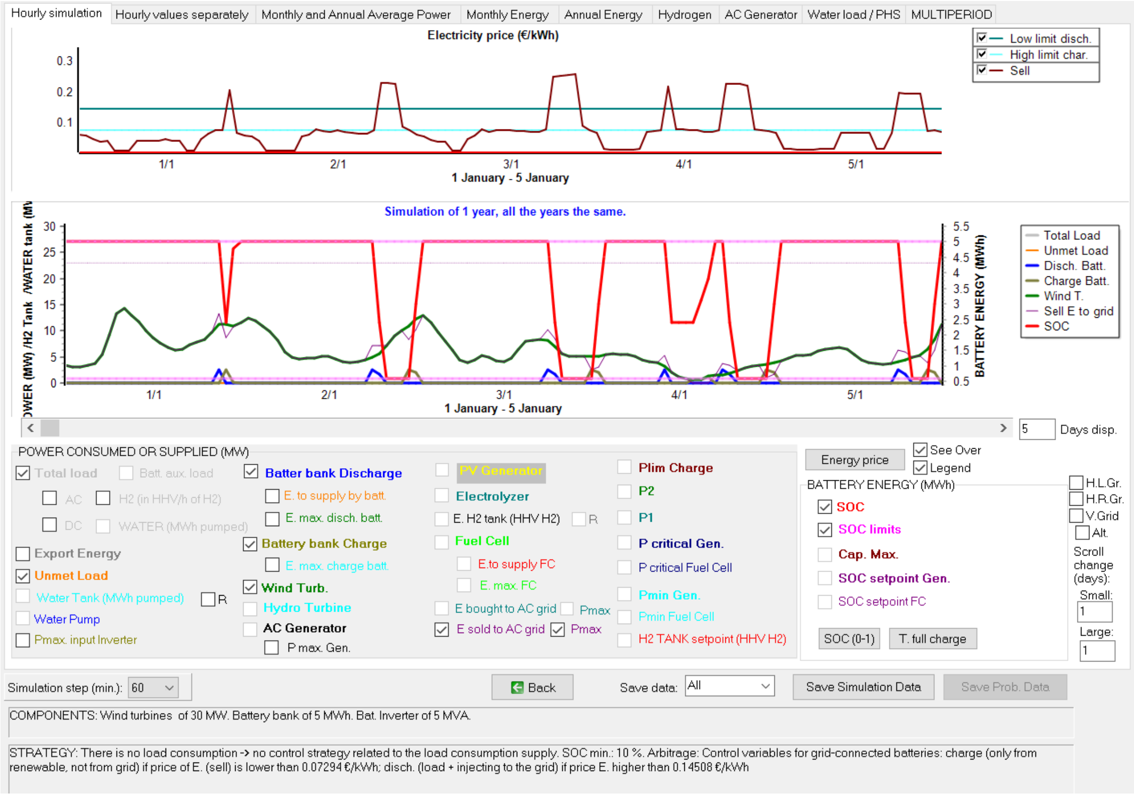
We can see the incomes due to energy sold the first year are higher than in section 24.

E Sell (M€/yr)	Sell H2 (M€/yr)	NPV PV (M€)	NPV Bat. (M€)	NPV Aux. (M€)	NPV Inv. (M€)	NPV Gen. (M€)	NPV WindT (M€)	C. Hydro (NPC) (M
6.918	0	0	0	0	0	0	-41.033	0
7.006	0	-1.371	0	0	0	0	-41.033	0
6.918	0	0	0	0	-0.694	0	-41.033	0
7.092	0	-2.742	0	0	0	0	-41.033	0
7.006	0	-1.371	0	0	-0.694	0	-41.033	0
7.175	0	-4.112	0	0	0	0	-41.033	0
7.092	0	-2.742	0	0	-0.694	0	-41.033	0
7.047	0	0	-2.509	0	-0.694	0	-41.033	0
7.256	0	-5.483	0	0	0	0	-41.033	0

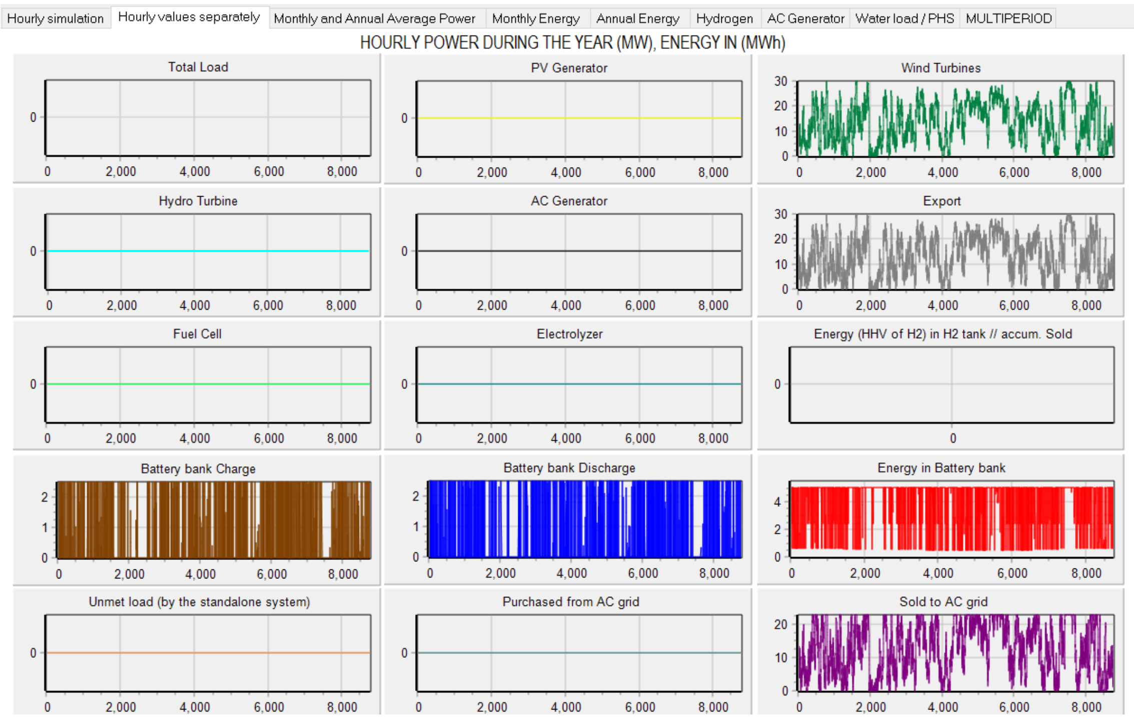
Also the total incomes due to energy sold in present value (NPV) are higher than in section 24.

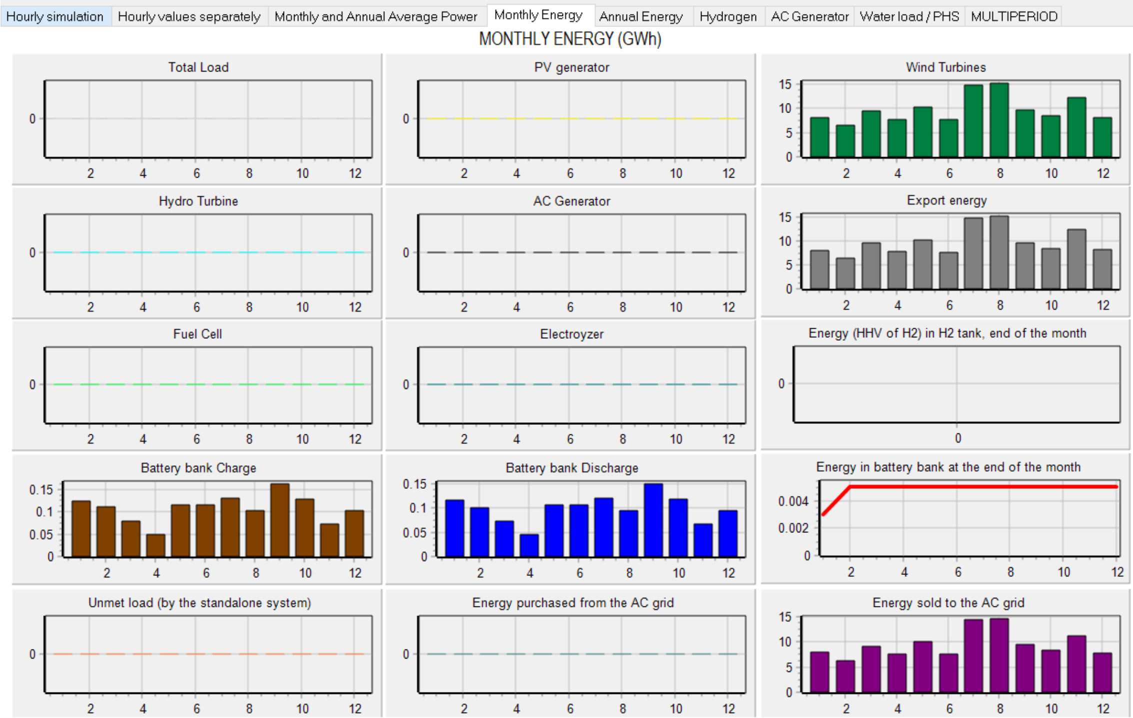
C. Hydro (NPC) (M	NPV FC (M€)	NPV Elyz. (M€)	NPV Fuel Gen (M€)	NPV Fuel FC (M€)	NPV Buy (M€)	NPV Sell (M€)	NPV H2 Sell (M€)
0	0	0	0	0	0	98.462	0
0	0	0	0	0	0	99.718	0
0	0	0	0	0	0	98.462	0
0	0	0	0	0	0	100.944	0
0	0	0	0	0	0	99.718	0
0	0	0	0	0	0	102.13	0
0	0	0	0	0	0	100.944	0
0	0	0	0	0	0	100.303	0
0	0	0	0	0	0	103.281	0

We can see the simulation (row 8th, click **SIMULATE**):



Almost all the days batteries perform 1 full cycle (some days more than 1), compared to the one of section 24, where many days batteries were not used.





30. Batteries with low price.

Save the project (**Project->Save**) and then save it with another name (**Project->Save as**) and give the name “MHOGA-optCont-Bat-cheap.mho” (or another name with less characters if the path from the root is too long, depending on the folder where you save the project).

Let’s suppose that our batteries cost (CAPEX) were much lower, for example 1/3 of the original cost. To change its cost, in the batteries screen, select the row of the name of the battery and change it (for example, add “-“ at the end). Then, after changing the name, we can modify any parameter (if we didn’t change the name, the changes would not be updated). So after changing the name, we change the cost to 0.5 M€:

Name	Cnom.(kAh)	Volt.(kV)	Cost(M€)	C.O&M(%/yr)	SOCmin(%)	Self_d(%/mon.)	Imax(kA)	Eff(%)	Float(yr)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	TYPE
Bat5MWh-	5	1	0.5	1	10	1	2.5	92	15	48000	24000	16000	12000	9600	8000	6857	6000	5333	4000	Li

The same for the inverter charger, let’s suppose that the cost now is 0.15 M€ instead the original cost of 0.5 M€, change the name and then change the cost:

GENERAL DATA — EFFICIENCY (%) vs. OUTPUT POWER (%) ->

Name	Power(MVA)	Lifespan (yr)	Cost (M€)	Imax_ch_DC(kA)	Ef_charger(%)	Vdcmin(kV)	Vdcmax(kV)	Pmax_ren(MW)	0%	2%	3%	4%	5%	10%	20%
Inv-Ch5MW-	5	15	0.15	5	98	0.9	1.1	1E15	10	30	50	70	85	93	92
Zero	0	100	0	0	100	0.9	1.1	1E15	100	100	100	100	100	100	100

Now we optimize again. Now the optimal system is of 15 wind turbines but it includes battery of 5 MWh and inverter/charger of 5 MW:

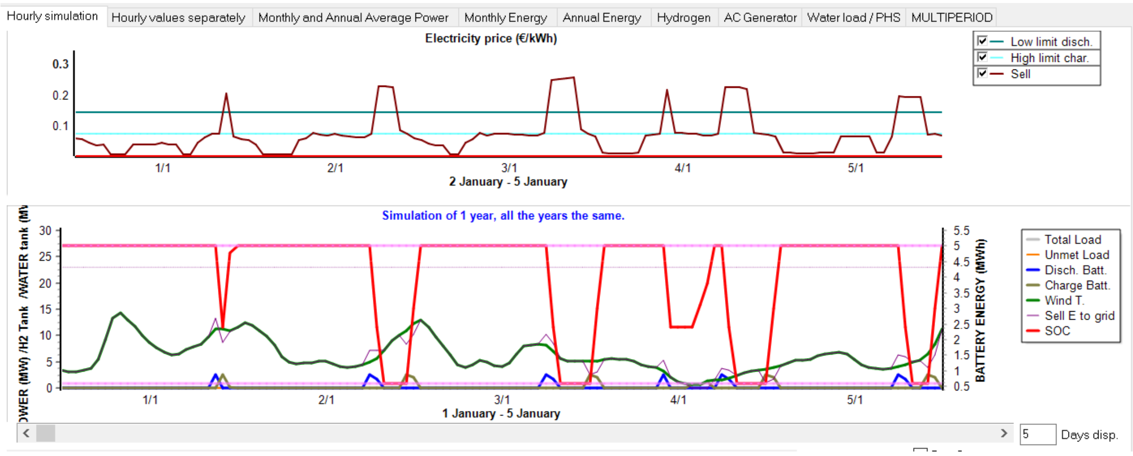
#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	50.563	1.15	0	18.51	540.05	38.313	43.49	0.0306	SIMULATE..	REPOR
2	50.139	1.18	0	18.02	543.05	39.813	42.58	0.0312	SIMULATE..	REPOR
3	49.929	1.12	0	18.59	540	37.5	43.59	0.0298	SIMULATE..	REPOR
4	49.692	1.22	0	17.57	546.05	41.313	41.72	0.0319	SIMULATE..	REPOR
5	49.683	1.12	0	18.49	540	37.688	43.59	0.0299	SIMULATE..	REPOR
6	49.514	1.16	0	18.09	543	39	42.68	0.0304	SIMULATE..	REPOR
7	49.269	1.16	0	18	543	39.188	42.68	0.0306	SIMULATE..	REPOR
8	49.205	1.25	0	17.13	549.05	42.813	40.89	0.0325	SIMULATE..	REPOR
9	49.117	1.14	0	18.26	540.05	38.125	43.59	0.0303	SIMULATE..	REPOR

COMPONENTS: Batteries Bat5MWh- (5 kAh): 1s. x 1p. // 15 Wind Turb. WindT1 (2 MW at 15 m/s) // Bat. Inverter Inv-Ch5MW- of 5 MVA // Unmet load = 0 % // Total Net Present Value (NPV) = 50.563 M€, IRR = 18.5%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. SOC min.: 10 %. ARB.: Control variables for grid-connected batteries: charge (only from renewable, not from grid) if price of E. (sell) is lower than 0.0729 €/kWh; disch. (load + injecting to the grid) if price E. higher than 0.1451 €/kWh

The previous optimal solution (just 15 wind turbines) is now the third best one (3rd row).

We can see the simulation of the best solution, it is the same simulation as the one shown in previous section, but the NPV is higher as battery and inverter costs are lower.



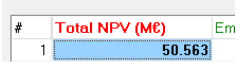
We could see the effect of changing the control strategy min. and max. prices of selling electricity. In the results table, you can change the values of the min. and or max. prices. For example, in the first row (optimal solution), we change the min. price for discharge to 0.18 €/kWh.

Pr.max.C(€/k	Pr.min.D(€/kV	E total(GWh)	Eren(GWh)	Epv(GWh)	Ew(GWh)	Et(GWh)	E export(GWh)	E Sell(GWh)	E Buy(GWh)
0.07294	0.18	0	117.661	0	117.661	0	117.611	114.422	
0.07294	0.14508	0	119.212	1.55	117.661	0	119.108	115.632	
0.3615	0.3615	0	117.661	0	117.661	0	117.661	114.555	
0.07294	0.14508	0	120.762	3.101	117.661	0	120.661	116.938	
0.3615	0.3615	0	117.661	0	117.661	0	117.661	114.555	
0.3615	0.3615	0	119.212	1.55	117.661	0	119.212	115.89	
0.3615	0.3615	0	119.212	1.55	117.661	0	119.212	115.89	
0.07294	0.14508	0	122.313	4.652	117.661	0	122.22	118.212	
0.0008	0.0008	0	117.661	0	117.661	0	117.661	114.555	

After clicking in the first row, the results are updated in that row. We can see the total NPV of the first solution is now reduced and now it would not be optimal:

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	50.075	1.15	0	18.41	540.05	38.313	43.54	0.0305	SIMULATE..	REPOR

We change the price of the table again to the original value and the result are updated to the original ones:



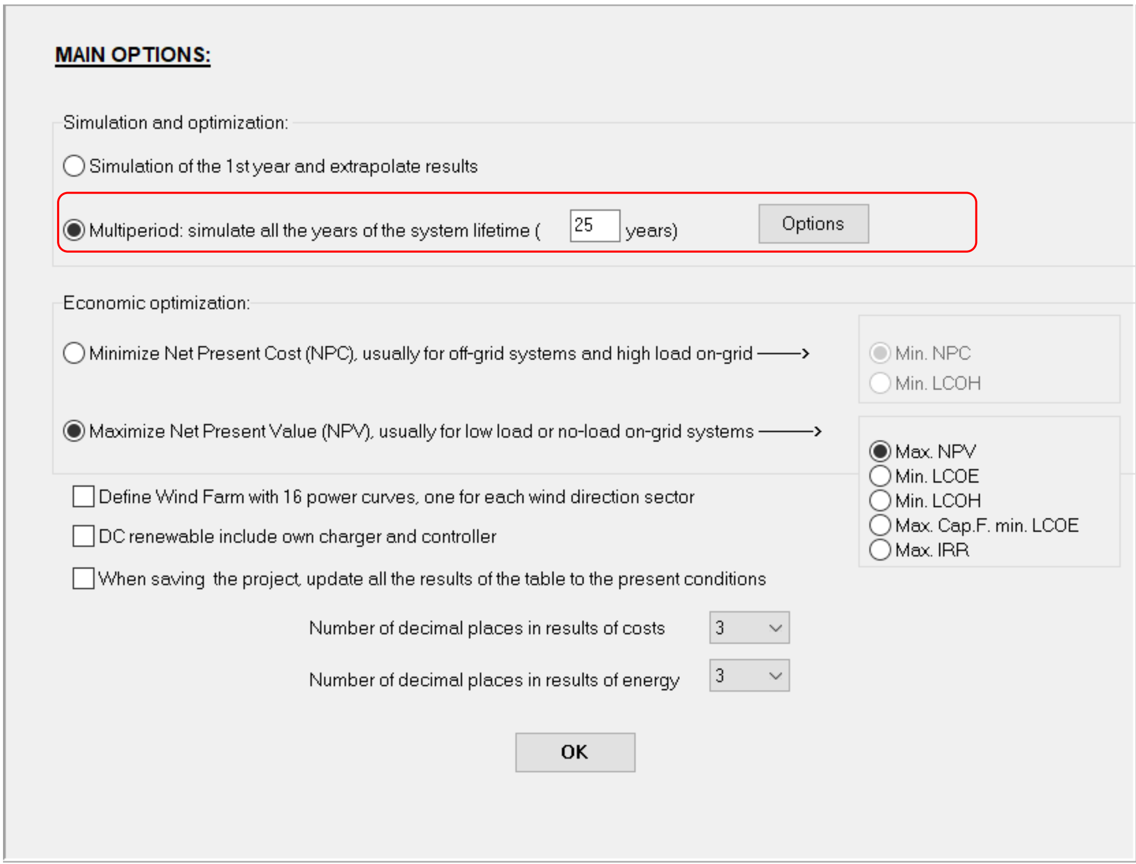
31. Multi-period optimization.

Save the project (**Project->Save**) and then save it with another name (**Project->Save as**) with the name “MHOGA-optCont-Bat-Cheap-M.mho”.

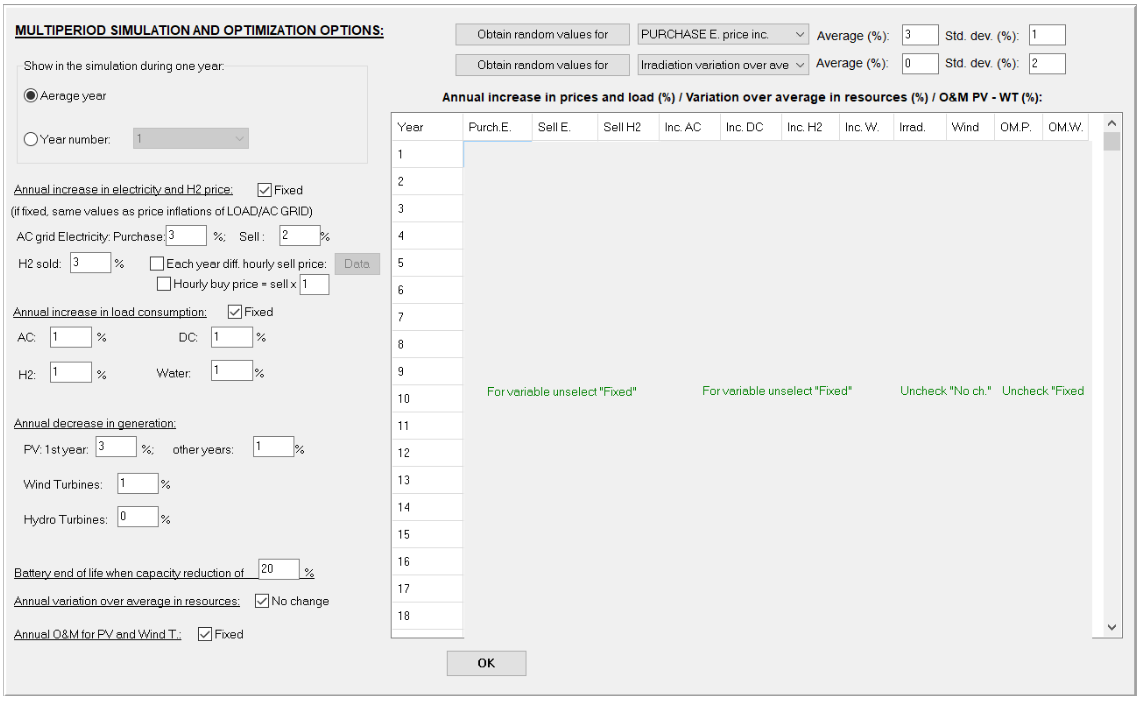
Now we will use multi-period simulation and optimization. Multi-period implies better simulation (it simulates all the system lifetime, not just the typical year) and it includes the reduction in the power of the renewable sources with time, the increase in load (in the case there is load consumption), different electricity price inflations for the different years, different resources, etc. However, it implies much higher computation time (usually more than 30 times compared to the simulation of a typical year). **In this guide, just in some examples multi-period is used, due to the higher computation time, however in real projects you are encouraged to use multi-period simulation and optimization.**

In the upper menu, **Project->OPTIONS**.

Select “**Mutiperiod: simulate all the years of the system lifetime…**”



Then click in **Options** button.



The annual increase in electricity and H2 price are connected to the values set in the LOAD/AC GRID screen, any change in them is changed in the other screen.

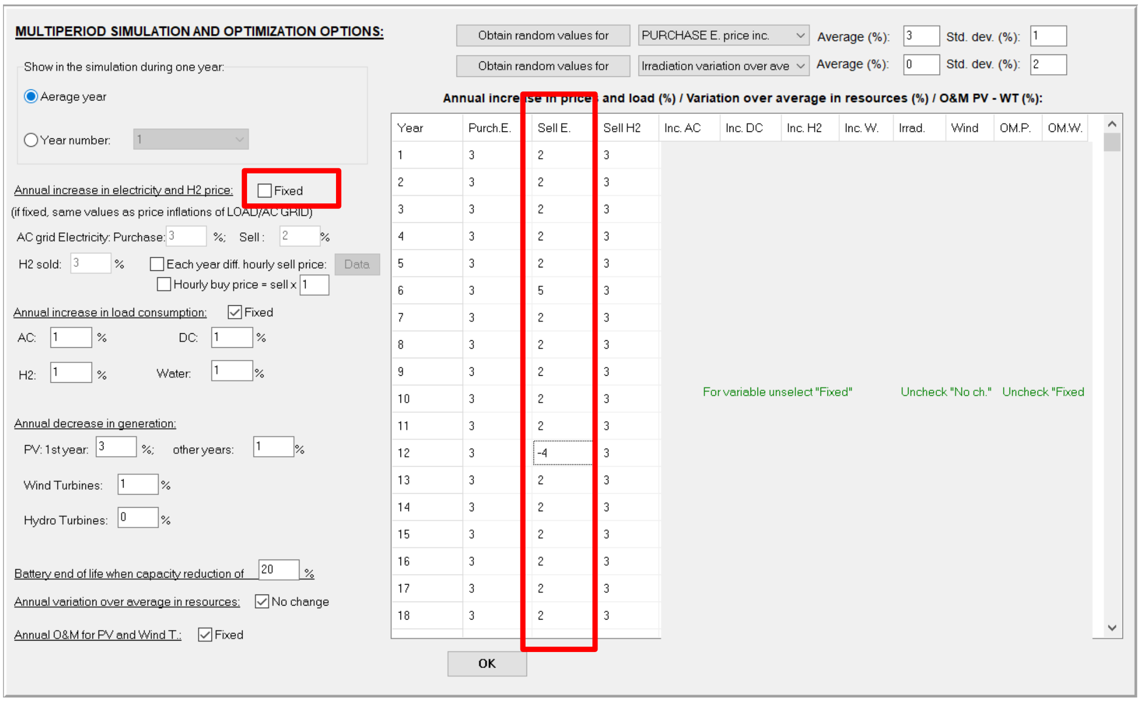
An annual increase in the load consumption of 1% is considered (each year the load is 1% higher than the previous year), however in this case it is not used (there is no load).

It is also considered by default that the PV modules generation is decreased 3% after 1 year, and the rest of the years it is reduced 1%, wind turbines generation is reduced 1% per year, and battery bank capacity reduction is 20% at the end of its lifetime.

We can define annual values for these data, different for each year, unchecking the corresponding “Fixed” checkbox. Then in the table at the right appears the columns where you can change the values.

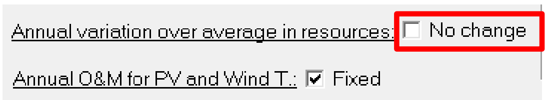
Also, you can define annual variation in resources, if you uncheck “No change”, and annual O&M for PV or for wind turbines if you uncheck the checkbox “Fixed” at the bottom.

For example, let’s suppose that the 6th year the inflation of the sell electricity price will be 5% and the 12th year it will be -4%, and the rest of the years 2%: uncheck the corresponding “Fixed” checkbox and change in the table.

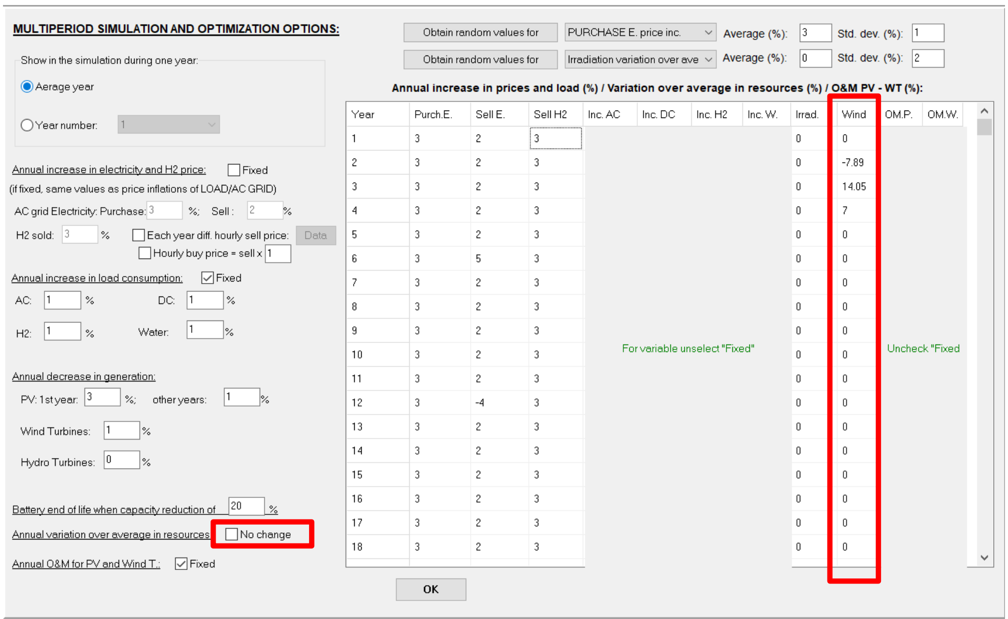


Also, let’s suppose that we want the annual wind speed to change over the average, for example decreasing 7,89% over the average in year 2, increasing 14.05% over the average in year 3 and increasing 7% over the average in year 4.

First, uncheck “No change” for annual variation over average in resources.



Then change the values:



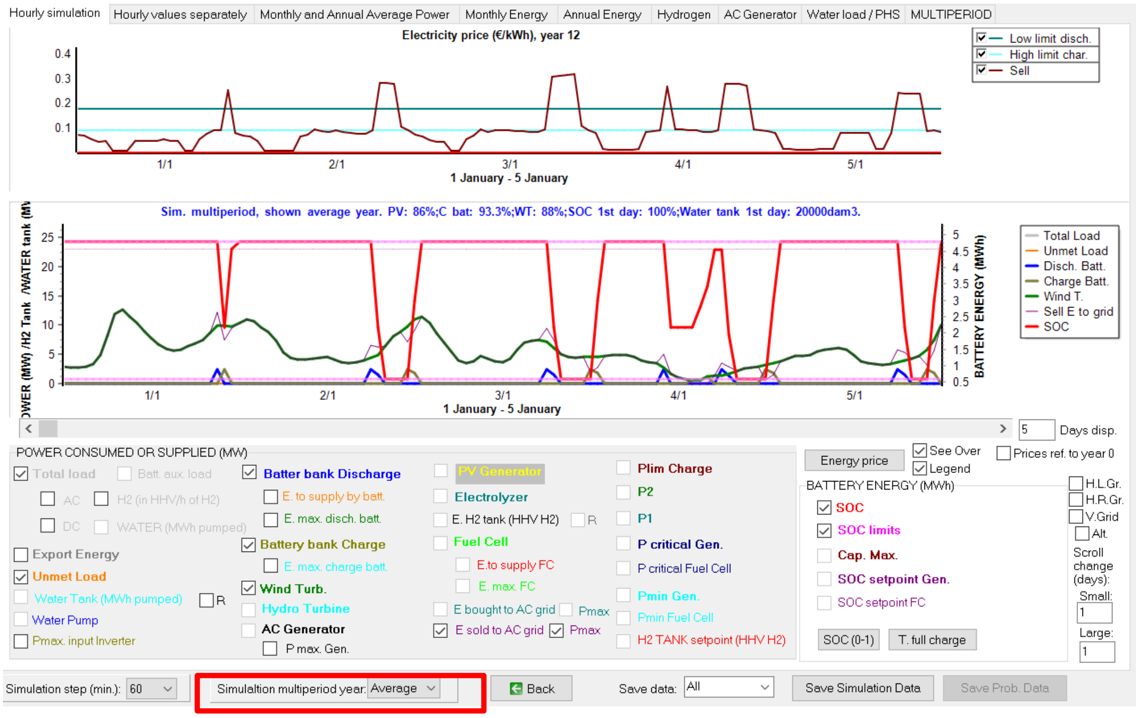
We leave the rest of the default values. Click OK, then OK.

Now, in the main screen, click in the first row of the results table. The optimal solution is simulated considering the multi-period, and all the columns are updated to the results of the multiperiod, showing in the energy columns the average values of the 25 years of its lifetime. Emissions (2nd column) is the average of all of the years (considering all the emissions during the system lifetime, including the emissions due to acquisition and replacement of the components).

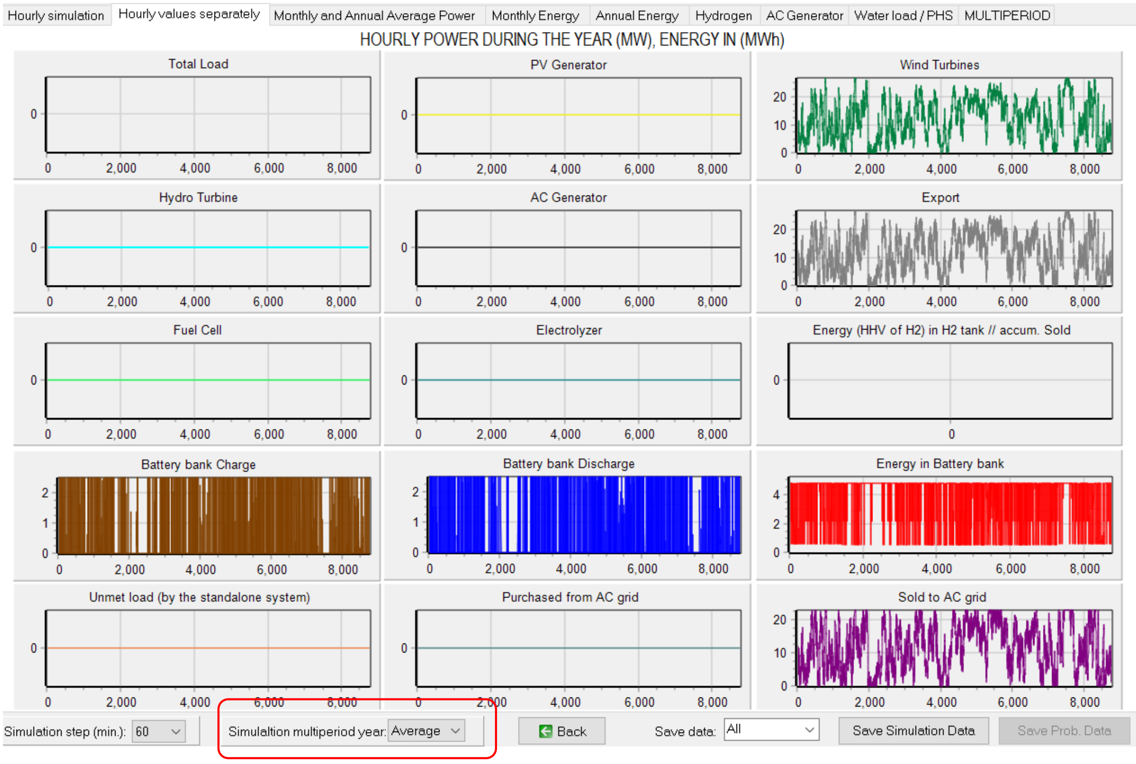
#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	45.66	1.83	0	17.82	540.05	38.313	40.85	0.0326	SIMULATE..	REPOR

The NPV has been decreased. Except for the data of the NPV and emissions, all the data of the table of costs and energies are referred to the average values of the years of the system lifetime, that is, annual average values.

Let's see the simulation of the best solution, clicking in **SIMULATE** in the first row. By default, the average year (year 12) is shown.



We can also see the other tabs:



We can change the year shown:

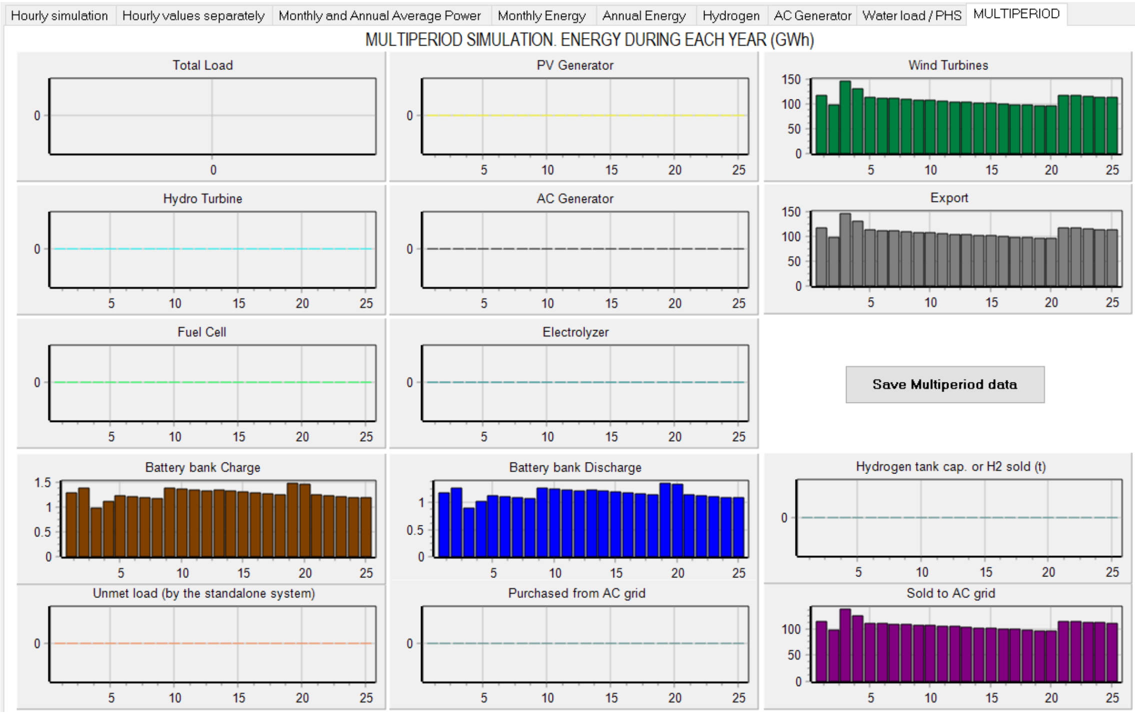
Year 1: same as without multi-period

Remember, in our case we saw wind in year 2 was 7.89% lower than the average, while in year 3 it was 14.05% higher and in year 4 it was 7% higher. Also, each year the wind generation is reduced 1% due to the degradation of the wind turbine.

Year 2: lower generation

Year 3: higher generation

We can see the summary of all the years in the last tab MULTIPERIOD:



In the middle right of this tab the button "**Save Multiperiod data**" can be used to save in Excel format the annual data of the input variables and of the reults. Once saved, you can open the Excel file, where the economic data are cash flow of each year (not present value), that is, money that the owner of the system will have to spend or will receive that year.

The final column (total emissions) include emissions of the backup generator (diesel or any other fuel), the emissions due to the energy bought to the AC grid, etc.; 1st year includes life cycle emissions (manufacturing, recycling, etc.) of the different components.

Project: MHOGA-optCont-BatCheap-M.mho. Solution # 1

RESULTS DURING THE YEARS OF THE SYSTEM LIFETIME, MULTIPERIOD SIMULATION.

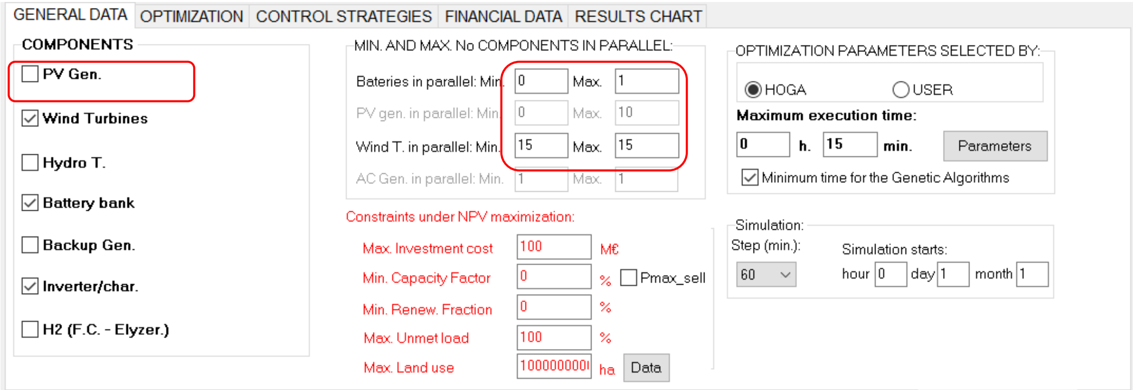
Costs and incomes are cash flow of each year (not present value)

Year	Cum. Inf. Purch. E(%)	Cum. Inf. Sell E(%)	Cum. Inf. Sell H2(%)	AC load(%)	DC load(%)	H2 load(%)	Water load(%)	Irrad.(%)	Wind(%)
1	3	2	3	100	100	100	100	0	0
2	6.09	4.04	6.09	101	101	101	101	0	-7.89
3	9.27	6.12	9.27	102.01	102.01	102.01	102.01	0	14.05
4	12.55	8.24	12.55	103.03	103.03	103.03	103.03	0	7
5	15.93	10.41	15.93	104.06	104.06	104.06	104.06	0	0
6	19.41	15.93	19.41	105.1	105.1	105.1	105.1	0	0
7	22.99	18.25	22.99	106.15	106.15	106.15	106.15	0	0
8	26.68	20.61	26.68	107.21	107.21	107.21	107.21	0	0
9	30.48	23.02	30.48	108.29	108.29	108.29	108.29	0	0
10	34.39	25.48	34.39	109.37	109.37	109.37	109.37	0	0
11	38.42	27.99	38.42	110.46	110.46	110.46	110.46	0	0
12	42.58	22.87	42.58	111.57	111.57	111.57	111.57	0	0
13	46.85	25.33	46.85	112.68	112.68	112.68	112.68	0	0
14	51.26	27.84	51.26	113.81	113.81	113.81	113.81	0	0
15	55.8	30.4	55.8	114.95	114.95	114.95	114.95	0	0
16	60.47	33	60.47	116.1	116.1	116.1	116.1	0	0
17	65.28	35.66	65.28	117.26	117.26	117.26	117.26	0	0
18	70.24	38.38	70.24	118.43	118.43	118.43	118.43	0	0
19	75.35	42.53	75.35	119.61	119.61	119.61	119.61	0	0
20	80.61	46.8	80.61	120.81	120.81	120.81	120.81	0	0
21	86.03	51.21	86.03	122.02	122.02	122.02	122.02	0	0
22	91.61	55.74	91.61	123.24	123.24	123.24	123.24	0	0
23	97.36	60.42	97.36	124.47	124.47	124.47	124.47	0	0
24	103.28	65.23	103.28	125.72	125.72	125.72	125.72	0	0
25	109.38	70.19	109.38	126.97	126.97	126.97	126.97	0	0

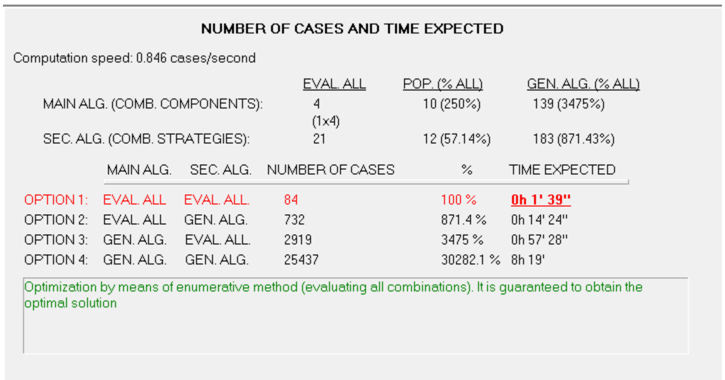
MULTI

We can optimize considering the multi-period.

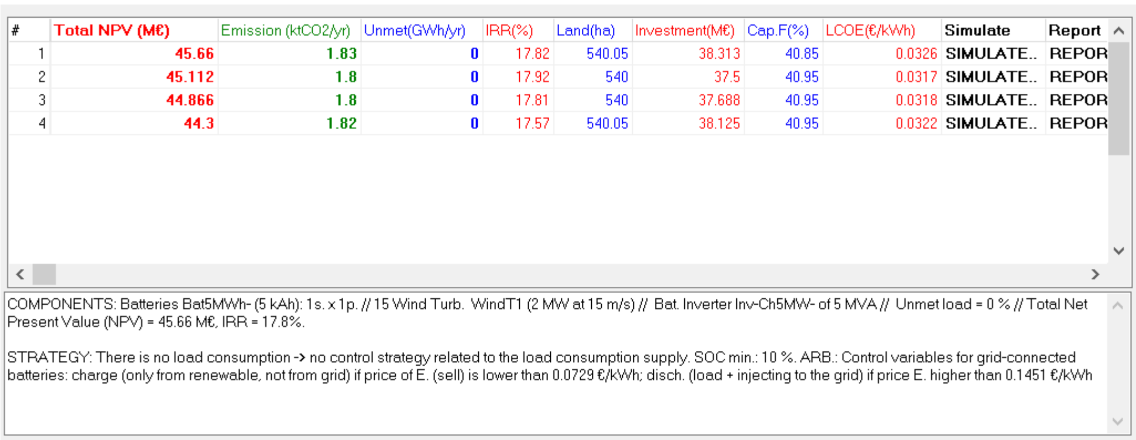
The optimization time could be a lot of time as it is much slower than without multi-period. In a real project, we would not reduce the possible components. However, in this guide, to reduce computation time, in the main screen, GENERAL DATA tab, we will uncheck PV Gen. and the min. and max. wind turbines in parallel will be 15.



Now we have just 4 combinations of components and, for each one, 36 combinations of control strategies, a total of 144 combinations, but the computation time is much lower than without multiperiod.



In the main screen, save the project and then **CALCULATE**. Each combination will be simulated during the 25 years of the lifetime, considering the decrease in generation, the variation of wind speed and the variation in inflation of sell electricity price. After several minutes, we obtain 4 solutions (corresponding to the 4 combinations of components, each one with the optimal control strategy). We have the same optimal solution as before.



We save the project.

32. Maximum injection power to the AC grid variable.

Open the previous project “MHOGA1-optCont-Bat-Cheap.mho” (**Project->Open**). Then save it with the name “MHOGA1-PmaxVar.mho” (**Project->Save as**).

We will modify the project supposing that the maximum power allowed to be injected in the AC grid is not a fixed value.

Let's suppose that the utility has set three hourly periods for the maximum power to be injected to the AC grid (P1, P2 and P3) with the following distribution:

SUMMER periods distribution:

0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h
P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2
12-13h	**13-14h**	**14-15h**	**15-16h**	**16-17h**	**17-18h**	**18-19h**	**19-20h**	**20-21h**	**21-22h**	**22-23h**	**23-24h**
P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2	P2

WINTER periods distribution:

0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h
P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2
12-13h	**13-14h**	**14-15h**	**15-16h**	**16-17h**	**17-18h**	**18-19h**	**19-20h**	**20-21h**	**21-22h**	**22-23h**	**23-24h**
P2	P2	P2	P3	P3	P3	P1	P1	P1	P1	P2	P2

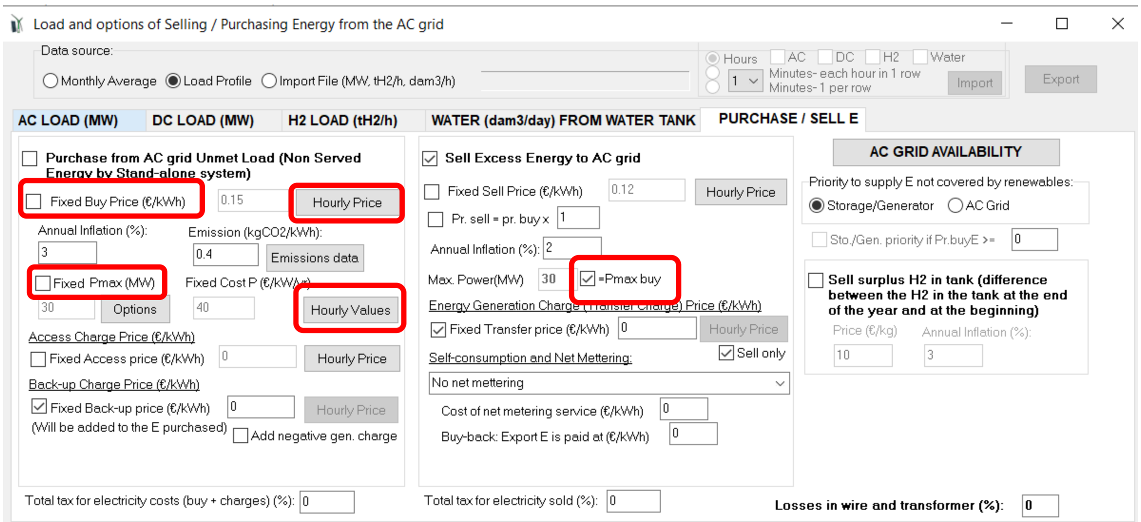
Where summer period in this example is considered to be from March 30th to October 26th.

Let's suppose that the maximum power allowed to be injected to the AC grid in P1 is 15 MW, in P2 is 18 MW and in P3 it is 23 MW.

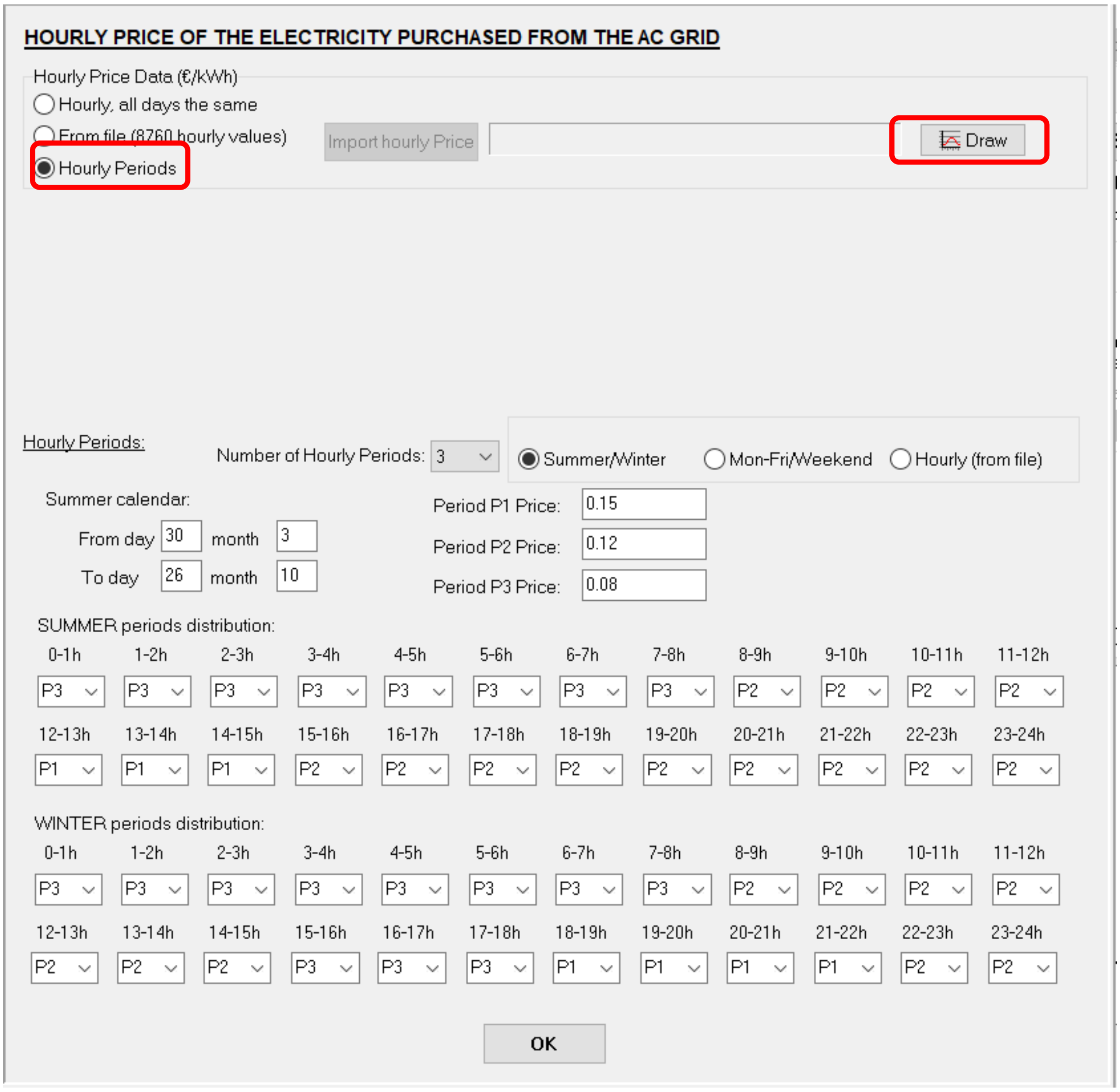
We cannot define different values for that power directly, but we can define for the maximum power allowed to be purchased to the AC grid and we can set the max. power injected to the AC grid is the same as the max. power purchased by the AC grid.

In **LOAD/AC GRID** window, **PURCHASE / SELL E** tab, uncheck "**Fixed Buy Price**" and "**Fixed Pmax**".

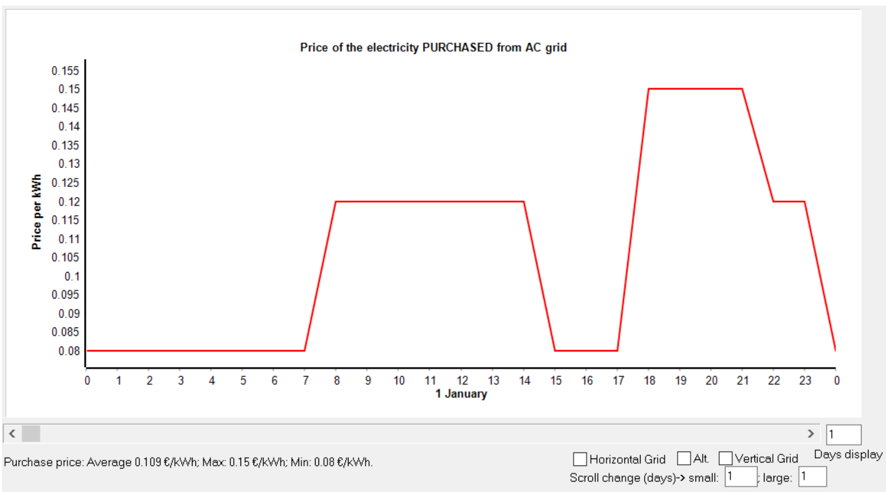
In the Sell excess energy to AC grid panel, select "**=Pmax buy**", this way the maximum power to be injected to the AC gris will be the same as the defined power to purchase from the AC grid.



Then click on "**Hourly Price**" button close to the buy price. Select **Hourly Periods** and accept all the default values (3 periods, summer/winter, distribution as shown):



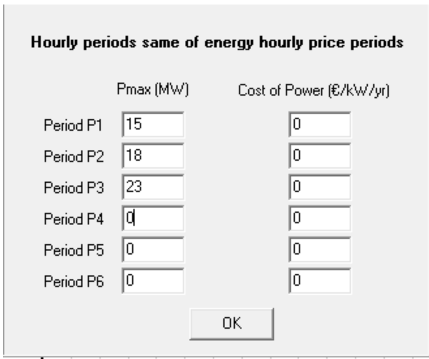
By clicking in the button “Draw” we can see the hourly distribution of the periods (P1 price of the electricity purchased to the AC grid 0.15 €/kWh, P2 price 0.12 €/kWh, P3 price 0.08 €/kWh). These prices will not be used by the software as there is no load and it is not allowed to buy electricity to the AC grid, but they can be used to see graphically the distribution of the periods.



Click Back and then OK.

In the **PURCHASE / SELL E** tab, click “**Hourly Values**” close to the options of the maximum power from the AC grid.

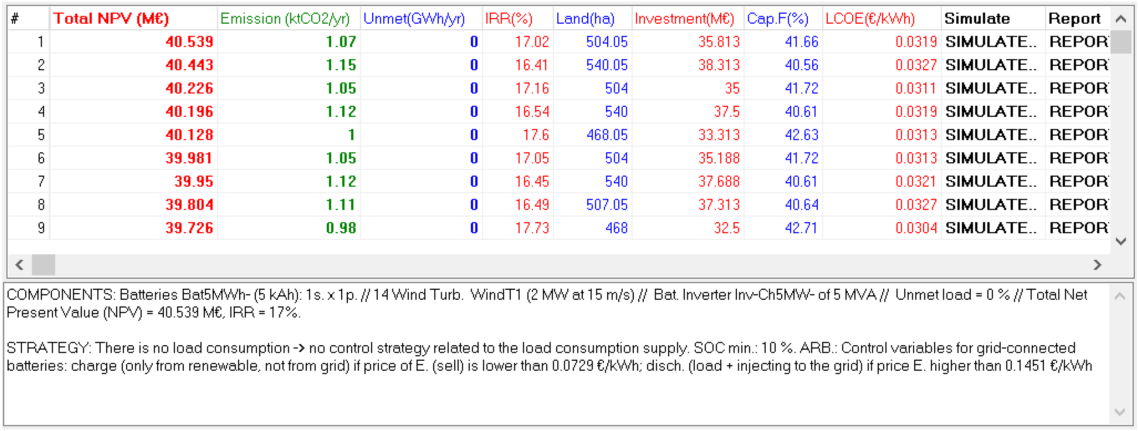
A small window appears. Change the values to the following Pmax and costs for the different peridos P1 to P3 (note that P4-P6 are not considered, anyway we write 0 in them):



Costs have been set to 0 because we will not purchase electricity to the AC grid. Anyway, this cost would not be considered.

OK and OK. Then, in the main screen, save the project and then CALCULATE.

After a pair of minutes, we see the results.



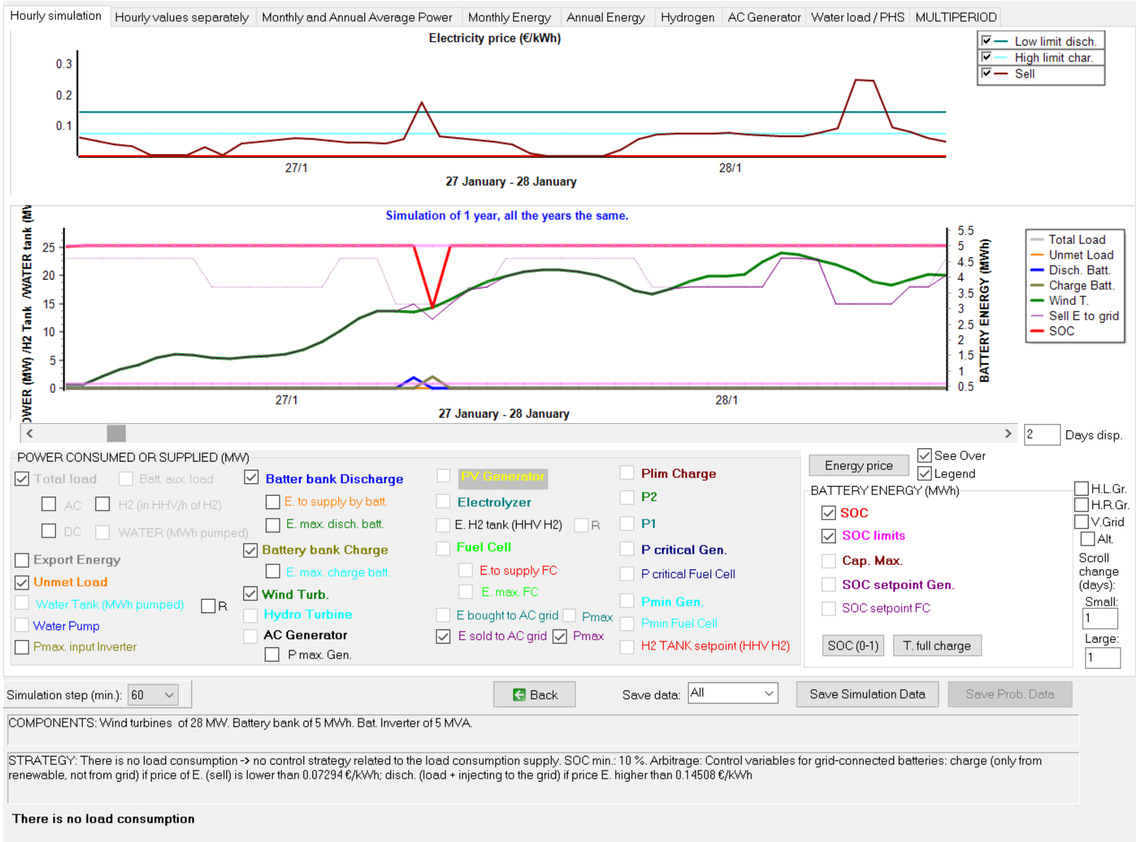
#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	40.539	1.07	0	17.02	504.05	35.813	41.66	0.0319	SIMULATE..	REPOR
2	40.443	1.15	0	16.41	540.05	38.313	40.56	0.0327	SIMULATE..	REPOR
3	40.226	1.05	0	17.16	504	35	41.72	0.0311	SIMULATE..	REPOR
4	40.196	1.12	0	16.54	540	37.5	40.61	0.0319	SIMULATE..	REPOR
5	40.128	1	0	17.6	468.05	33.313	42.63	0.0313	SIMULATE..	REPOR
6	39.981	1.05	0	17.05	504	35.188	41.72	0.0313	SIMULATE..	REPOR
7	39.95	1.12	0	16.45	540	37.688	40.61	0.0321	SIMULATE..	REPOR
8	39.804	1.11	0	16.49	507.05	37.313	40.64	0.0327	SIMULATE..	REPOR
9	39.726	0.98	0	17.73	468	32.5	42.71	0.0304	SIMULATE..	REPOR

COMPONENTS: Batteries Bat5MWh- (5 kAh): 1s. x 1p. // 14 Wind Turb. WindT1 (2 MW at 15 m/s) // Bat. Inverter Inv-Ch5MW- of 5 MVA // Unmet load = 0 % // Total Net Present Value (NPV) = 40.539 M€, IRR = 17%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. SOC min.: 10 %. ARB.: Control variables for grid-connected batteries: charge (only from renewable, not from grid) if price of E. (sell) is lower than 0.0729 €/kWh; disch. (load + injecting to the grid) if price E. higher than 0.1451 €/kWh

The optimal is composed of 14 wind turbines, battery of 5 MWh and inverter of 5 MW.

The simulation of the optimal system (January 27-28):



We can see the different hourly periods have different maximum output power to the energy sold to the AC grid.

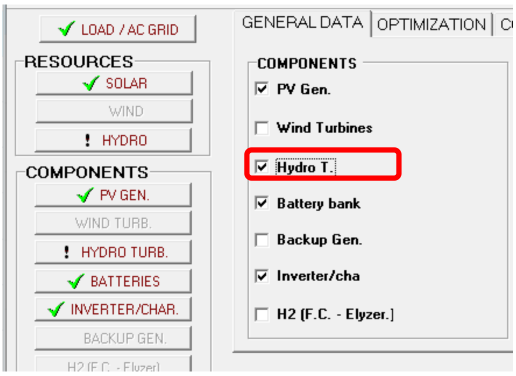
Back and save the project.

33. Pumped hydro storage (PHS).

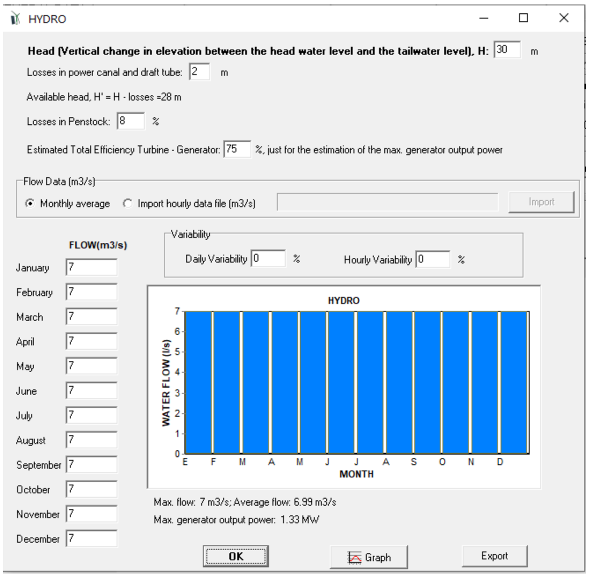
Open the previous project “MHOGA1-optCont-Bat-Cheap.mho” (**Project->Open**). Then save it with the name “MHOGA1-PHS.mho” (**Project->Save as**).

Now let’s suppose that we include pumped hydro storage (PHS). We build a water tank or reservoir so that water can be pumped to the water reservoir when the renewable power is higher than the maximum power to be injected to the AC grid and the turbine will run when the sell electricity price is high. Let’s suppose that the water reservoir maximum capacity is 800 dam^3 and the elevation head is 31 m.

In the main screen, click in the checkbox “**Hydro T.**”. Then, the buttons “HYDRO” and “HYDRO TURB” are enabled and “!” is added (it means that the data of these buttons should be introduced).

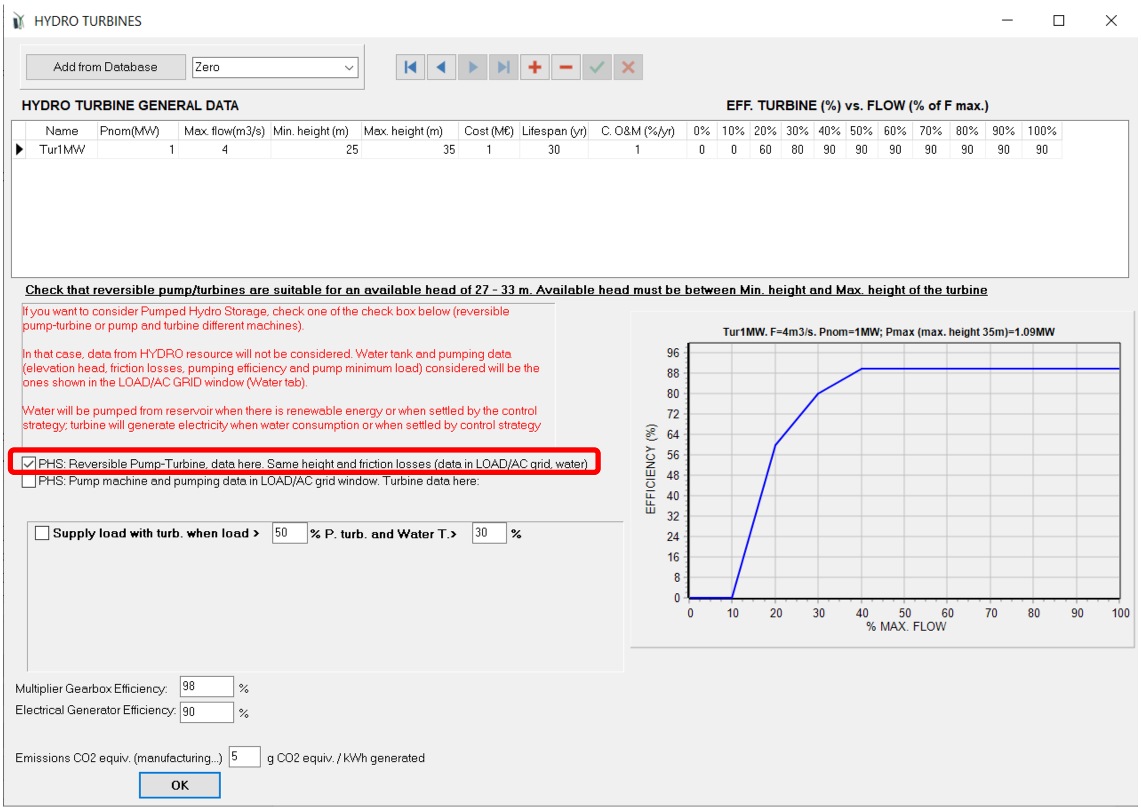


First click in "**! HYDRO**" button.



We accept all the default data with OK. In our case (PHS) the data of this window will not be considered (available head and water flow of this window would be considered if we had just a turbine that generates power with the available water flow, run-the-river hydro; this is not our case).

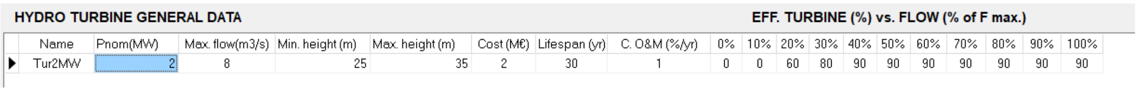
Now, in the main screen, click in "**! HYDRO TURB**" button.



For PHS, we can define a reversible pump-turbine or two different machines (pump and turbine).

Let's suppose that we will install a reversible pump-turbine, click in "**PHS: Reversible Pump-Turbine, data here….**"

The data of the reversible machine is in this window, that is, in the table. Let's suppose that in our case is the one of 2 MW (delete the default one and add from database the one of 2 MW).



We can see that this machine the maximum flow is 8 m^3/s, and the minimum and maximum height are 25 and 35 m. In our case the available head will be 31 m, which, + 10% losses implies a max. pumping head of 34.1 m, while when turbine runs the min. head is 31 m -10% losses, 27.9 m. As our turbine has 25 m for min. height and 35 for max. height, it is correct.

The efficiency vs. flow data of the table is for the turbine, the pump efficiency will be defined later (in the LOAD/AC GRID window, tab WATER…).

The maximum power of this machine is (including turbine efficiency for max. flow, multiplier gearbox and electrical generator efficiencies):

$$P = Water\_flow \cdot density \cdot g \cdot height\_max \cdot Total\_Efficiency =$$

$$= 8m^3/s \cdot 1000kg/m^3 \cdot 9{,}81m/s^2 \cdot 35m \cdot 0.9 \cdot 0.98 \cdot 0.9 \ = 2.18 \cdot 10^6 \text{ W} = 2.18 \text{ MW}$$

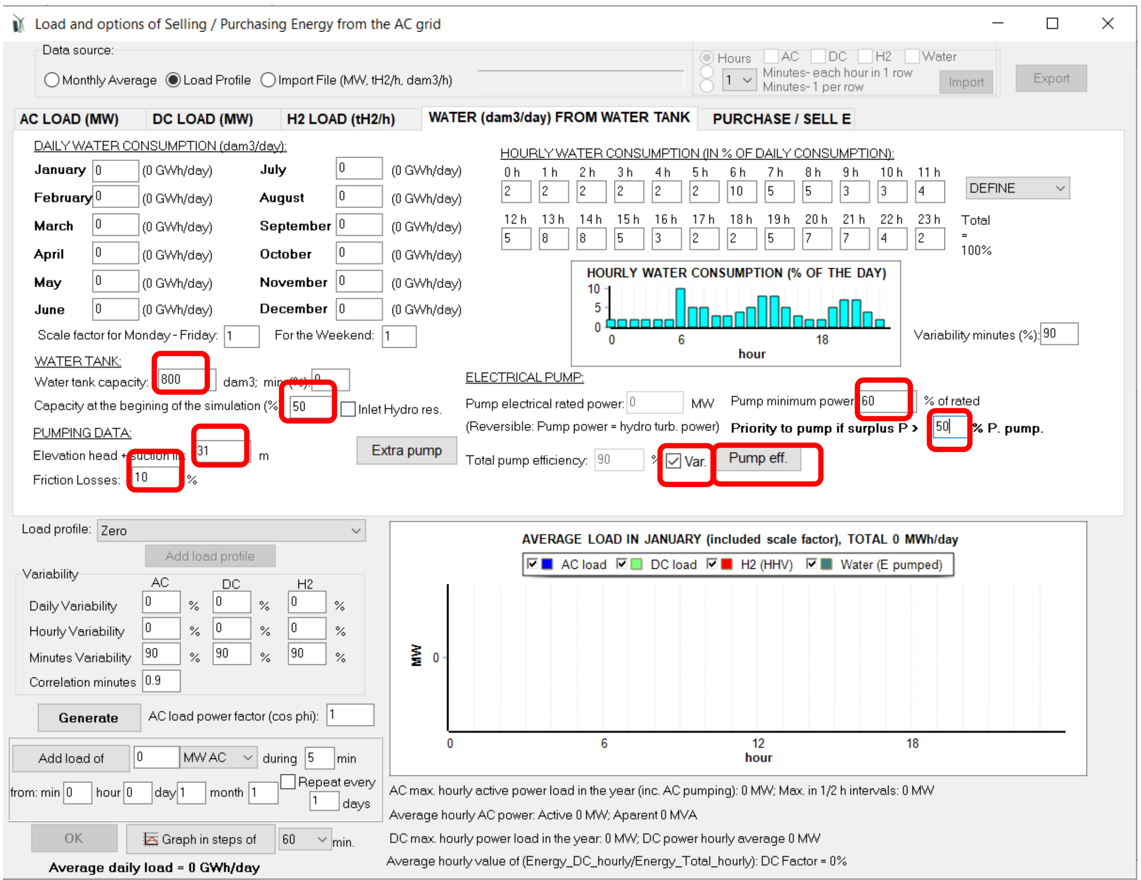
Click OK and return to the main screen.

The reservoir capacity, height, penstock losses and pumping efficiency must be defined in the "LOAD / AC GRID" window, WATER tab.

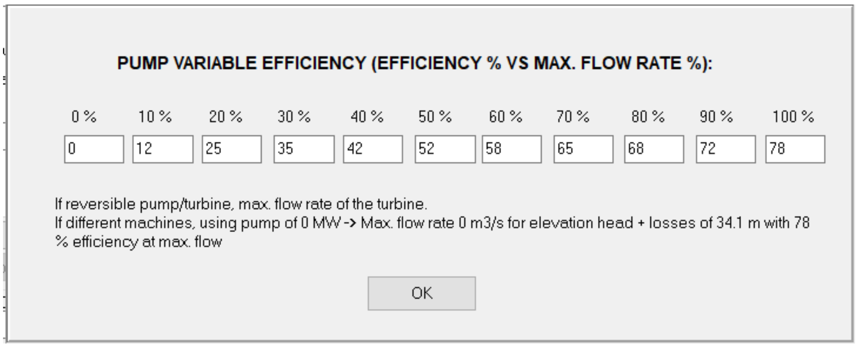
In the main screen, click "**LOAD / AC GRID**", and, in the **WATER** tab, we must define the reservoir maximum capacity (800 dam^3), the capacity at the beginning of the simulation (let's suppose it is at 50%, that is, 400 dam^3), the elevation head (31 m) and friction losses (let's suppose 10%).

The box of the Pump electrical rated power is disabled as this power is the same as the power of the turbine (it is the same machine), which was defined in the HYDRO T. window. However, the data of the pump efficiency must be defined here, because the pumping efficiency can be different than the turbine efficiency defined in the HYDRO T. window. We will suppose the total pump efficiency (including multiplier and electrical generator efficiencies) is variable. Also we will consider the minimum pump power is 60% of its rated power.

We want in this case that the surplus energy from the renewable power will be used priority to pump water if the surplus energy is higher than 50% of the pump rated power (otherwise the priority will be to charge the batteries).



We change the values shown in the figure. After selecting the checkbox "**Var**" (variable pump efficiency), we can click the "**Pump eff.**" Button, obtaining the following window:



The max. flow rate is the one of the turbine (8 m^3/s) and we must define the efficiency of the pump for each percentage of that maximum flow rate (from 0 to 100%), for a total elevation head of 34.1 m (including friction losses: 31 m + 10% = 34.1 m). Let's suppose the efficiency values are the default ones, therefore we accept it (click **OK**).

After changing any data of the reservoir or pumping data, the "OK" button of the LOAD/AC GRID data window is disabled, we must click in "**Generate**" to consider the new data, and later click in "**OK**".

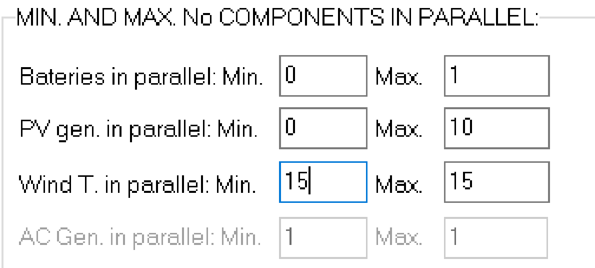
The maximum water pumped energy needed to get the reservoir full is (supposing pump efficiency 78%):

$$E = volume \cdot density \cdot g \cdot height \cdot (1+friction\_losses)/Efficiency =$$

$$=800000 m^3 \cdot 1000 kg/m^3 \cdot 9.81 m/s^2 \cdot 31 m \cdot (1+0.1)/0.78 = 3.43098 \cdot 10^{11}\ J = 95.305\ MWh$$

The cost of the water tank, pipelines, valves etc. should be added to the hydro turbine cost or it could be considered in the general costs (Main screen of the software -> Financial Data tab -> Installation Costs). In our case we will not consider these costs (we will suppose the water storage infrastructure previously exists).

In the main screen, we will just allow 15 wind turbines in parallel (to reduce the computation time), as it was the optimal previously. And we will allow between 0 and 1 battery banks in parallel (to allow the possibility of having or not having batteries in the system):



In the main screen, save the project and then click in **CALCULATE**. We obtain:

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	49.686	1.16	0	17.67	540.05	40.813	40.24	0.0326	SIMULATE..	REPORT.
2	49.458	1.14	0	17.81	540	40	40	0.0321	SIMULATE..	REPORT.
3	49.236	1.19	0	17.24	543.05	42.313	39.49	0.0333	SIMULATE..	REPORT.
4	49.212	1.14	0	17.72	540	40.188	40	0.0322	SIMULATE..	REPORT.
5	49.008	1.17	0	17.36	543	41.5	39.26	0.0327	SIMULATE..	REPORT.
6	48.762	1.17	0	17.28	543	41.688	39.26	0.0329	SIMULATE..	REPORT.
7	48.741	1.22	0	16.82	546.05	43.813	38.77	0.0339	SIMULATE..	REPORT.
8	48.647	1.16	0	17.51	540.05	40.625	40	0.0326	SIMULATE..	REPORT.
9	48.533	1.2	0	16.94	546	43	38.55	0.0334	SIMULATE..	REPORT.
10	48.287	1.2	0	16.86	546	43.188	38.55	0.0335	SIMULATE..	REPORT.

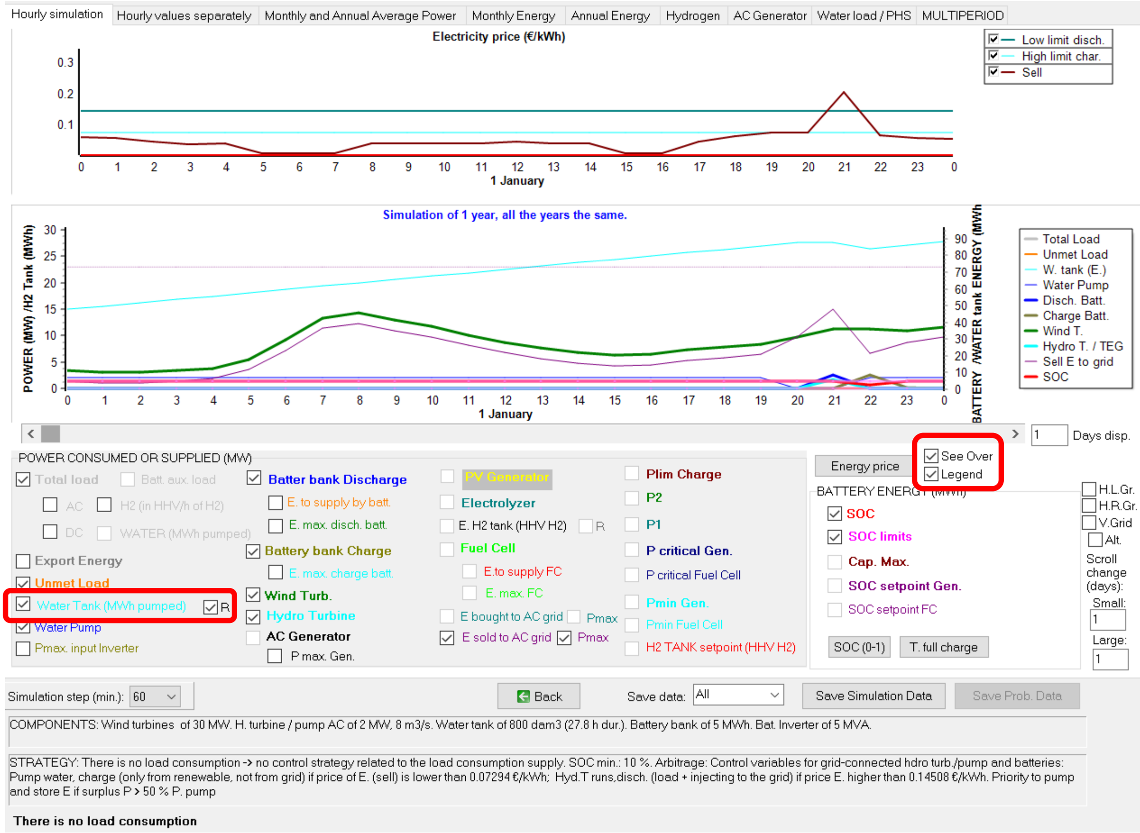
COMPONENTS: Batteries Bat5MWh- (5 kAh): 1s. x 1p. // 15 Wind Turb. WindT1 (2 MW at 15 m/s) // Hydro Turb. AC Tur2MW of 2 MW, 8 m3/s // Bat. Inverter Inv-Ch5MW- of 5 MVA // Unmet load = 0 % // Total Net Present Value (NPV) = 49.686 M€, IRR = 17.7%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. SOC min.: 10 %. ARB.: Control variables for grid-connected hdro turb./pump and batteries: Pump water, charge (only from renewable, not from grid) if price of E. (sell) is lower than 0.0729 €/kWh; Hyd.T runs, disch. (load + injecting to the grid) if price E. higher than 0.1451 €/kWh

The optimal system includes battery (it is better than not including battery). The NPV is a little lower than in the case without PHS (just with battery storage, section 30).

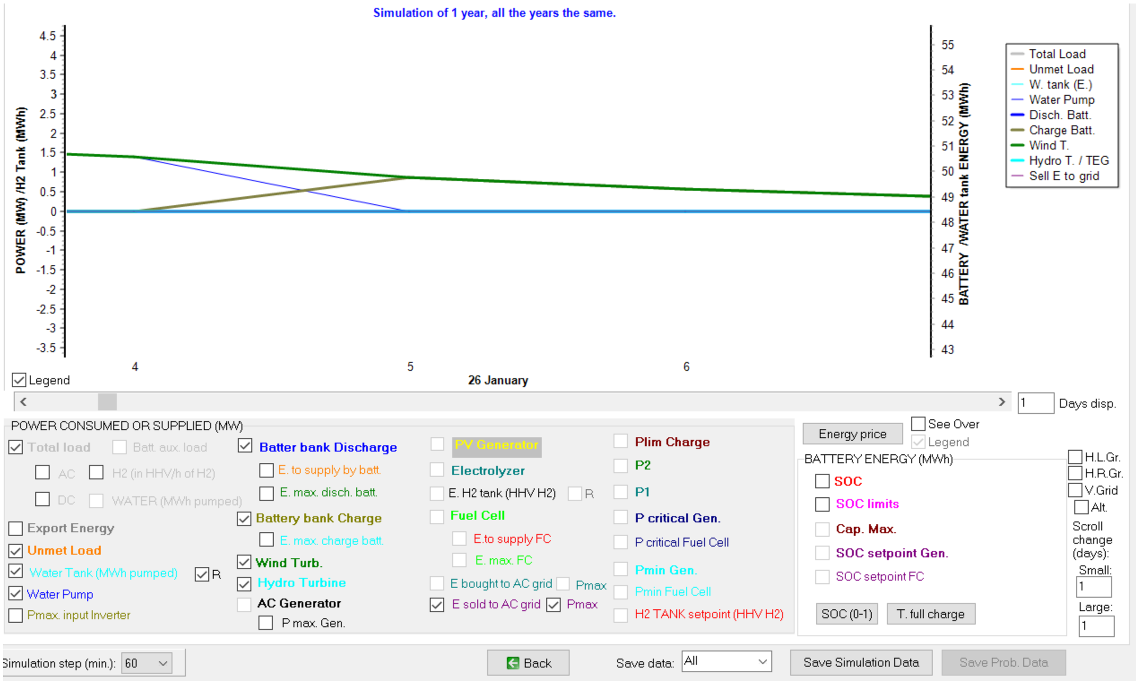
The limit for charge and discharge is the same value: if price is lower than 0.0729 €/kWh, charge with the renewables; if it is higher than 0.1451 €/kWh, discharge and inject to the grid.

We can see the simulation of the best system. Check the box "R" at the right of the "Water Tank (MWh pumped) to see the graphs correctly.

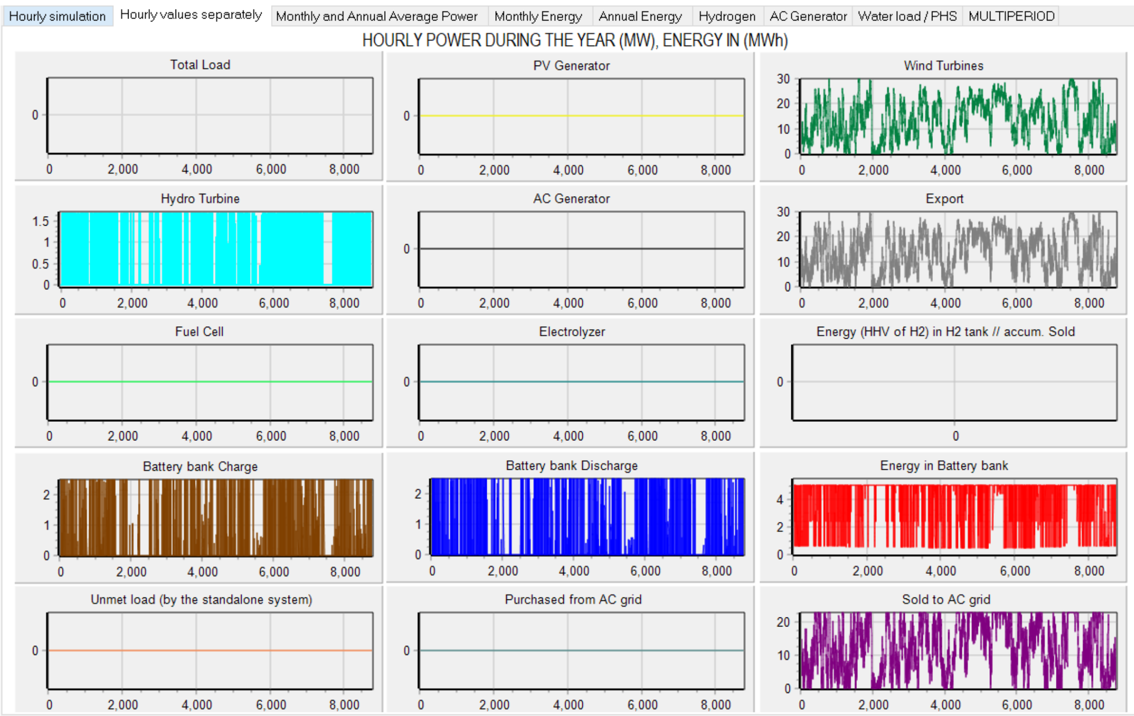


We can see that during the charge strategy, if electricity generated by renewable is higher than 50% of the pump rated power (50% of 2 MW = 1 MW), it is used priority in pumping water. When renewable power is lower than 1 MW, it is used priority to charge the battery. Of course, considering the maximum capacity of the water reservoir and of the battery.

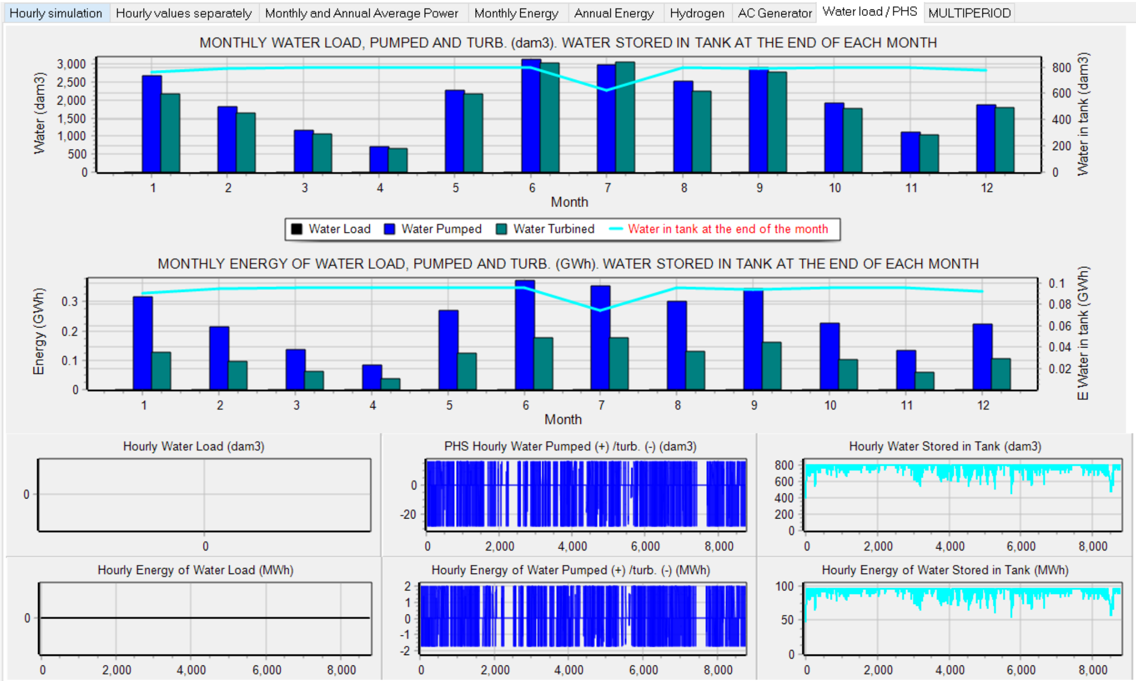
For example, January 26th, zooming in the graph from 4 to 6 a.m. we can see that if wind power is higher than 1 MW, it is used to pump water, but when it is lower than 1 MW, it is used to charge the battery (next figure).



Other tabs:



The "**Water load/PHS**" tab: we can see the water pumped and turbined and the water stored in the tank, in dam^3 and in GWh of equivalent store energy. In the lower graph of hourly water pumped/turb, positive is pumped and negative turbined.



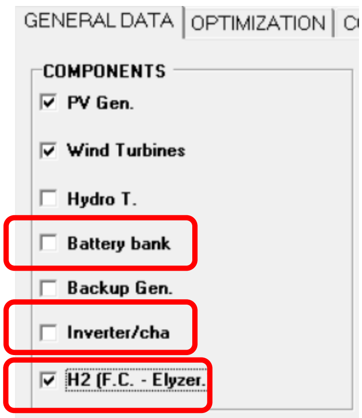
Save the project.

34. Green H2.

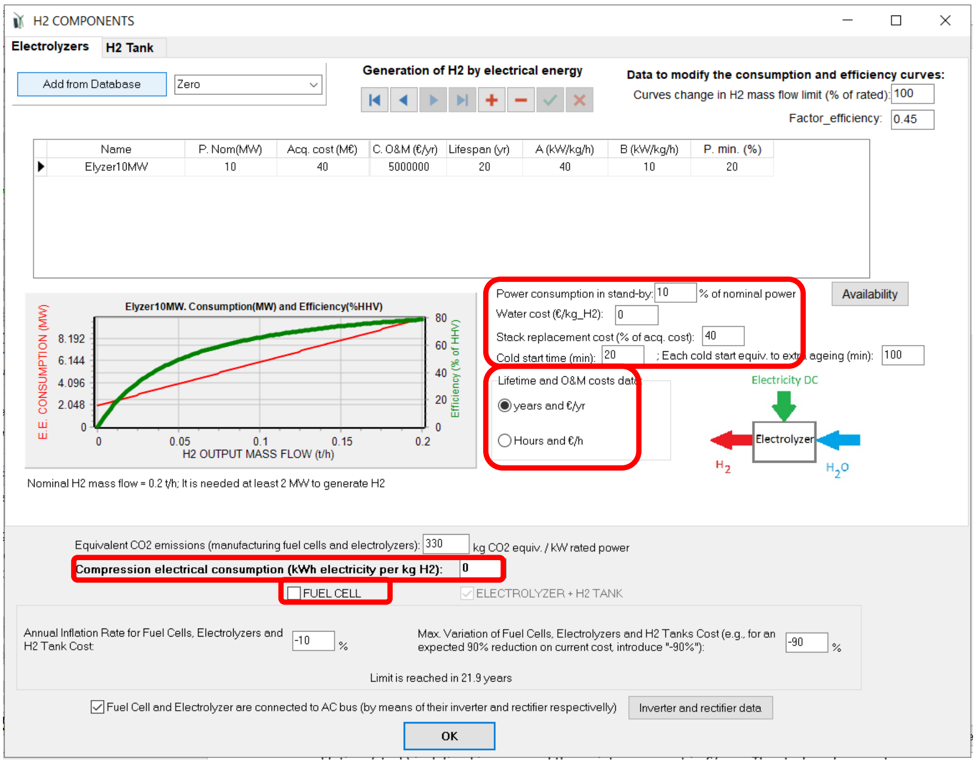
Open the previous project "MHOGA1-optCont.mho" (**Project->Open**). Then save it with the name "MHOGA1-H2.mho" (**Project->Save as**).

Now let's suppose that we want to generate hydrogen (by means of an electrolyzer) with the electricity that cannot be injected to the AC grid (because the renewable generation is higher than the maximum grid power during some hours) or during the hours when electricity sold to the grid is at low price. The hydrogen generated will be sold for external use.

In the main screen, select "**H2 (F.C. – Elyzer.)**" and uncheck "**Battery bank**" and "**Inverter/cha**", as we will not consider the batteries in our system (and the electrolyzer will have its own rectifier).



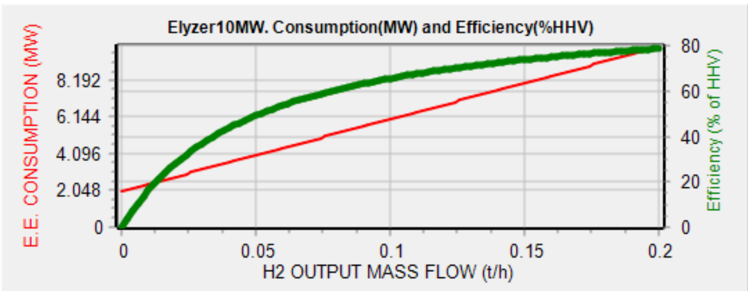
And then click in the button "**H2 (F.C. – Elyzer.)**":



In high power projects, by default there is no Fuel cell considered in the system ("FUEL CELL" checkbox is unchecked), just electrolyzer. Also by default no H2 tank is considered (all the hydrogen generated will be sold).

Let's leave the default electrolyzer (of 10 MW, with a high CAPEX of 40 M€ and 5 M€/year of OPEX, with an expected decrease of CAPEX of 10% annual with a limit of 90%, which will be reached in 21.9 years), without any change. You can see that, by default, a power consumption in stand-by of 10% of the nominal power of the electrolyzer is considered (all the hours when the electrolyzer is not generating hydrogen, it consumes 10·0.1= 1 MW). Also by default its lifetime (stack) is defined in years and the maintenance cost in €/year. The stack replacement cost, by default, is 40% of the CAPEX. Also, a cold start time and an extra ageing due to each start are defined.

A and B parameters (40 and 10 kW/kg/h, respectively) of the table are the consumption parameters, with them the electrical energy consumption (MW) vs. H2 generated mass flow (t/h) is shown in the graph (red line, left axis); the green line (right axis) is the efficiency in % of higher heating value (HHV) of the hydrogen.



Nominal H2 mass flow = 0.2 t/h; It is needed at least 2 MW to generate H2

These data (A and B parameters) together with the data of the top right area ("**Data to modify the consumption and efficiency curves**", see the user manual for more info) make the consumption and efficiency curves. You can change these data to fit the real consumption and efficiency curves of your electrolyzer. Suppose our electrolyzer curves fit with the following values and the A=31 and B=1.5 kW/kg/h:

Data to modify the consumption and efficiency curves:

Curves change in H2 mass flow limit (% of rated): 5

Factor_efficiency: 0.45

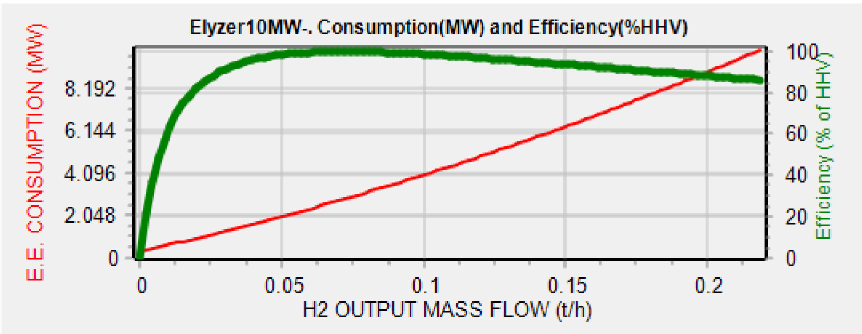
Name	P. Nom(MW)	Acq. cost (M€)	C. O&M (€/h)	Lifespan (h)	A (kW/kg/h)	B (kW/kg/h)	P. min. (%)
Elyzer10MW-	10	15	100	80000	31	1.5	5

Also we have changed the CAPEX to 15 M€, lifetime and O&M in hours and €/h will be 80,000 h and 100 €/h, and minimum power will be 5%.

Lifetime and O&M costs data:

- ○ years and €/yr
- ◉ Hours and €/h

Now the consumption and efficiency curves are (click in the table, in the row of the electrolyzer):



Nominal H2 mass flow = 0.219 t/h; It is needed at least 0.33 MW to generate H2

We will add the "Zero" electrolyzer to consider the possibility of not having electrolyzer (add the "Zero" electrolyzer from the database).

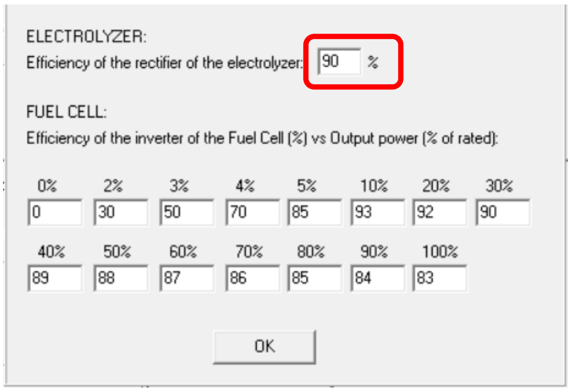
Name	P. Nom(MW)	Acq. cost (M€)	C. O&M (€/h)	Lifespan (h)	A (kW/kg/h)	B (kW/kg/h)	P. min. (%)
Elyzer10MW-	10	15	100	80000	31	1.5	5
Zero	0	0	0	1000000	40	10	20

By default, the electrolyzer is connected to the AC bus (defined in the checkbox at the bottom of the screeen), and has its own rectifier.

☑ Fuel Cell and Electrolyzer are connected to AC bus (by means of their inverter and rectifier respectivelly) | Inverter and rectifier data

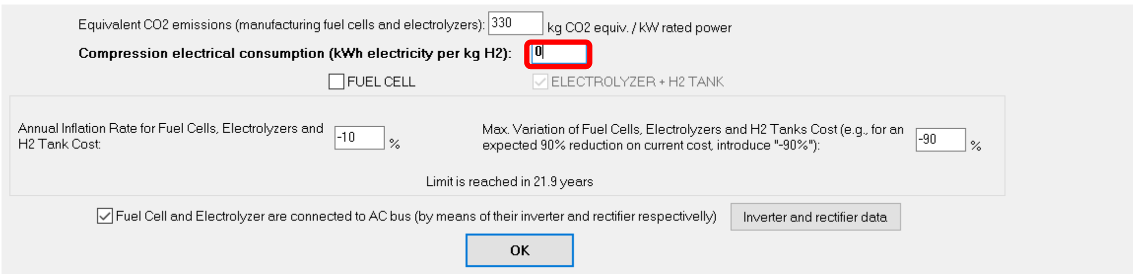
OK

If you click in the button "**Inverter and rectifier data**" (bottom of the screen)

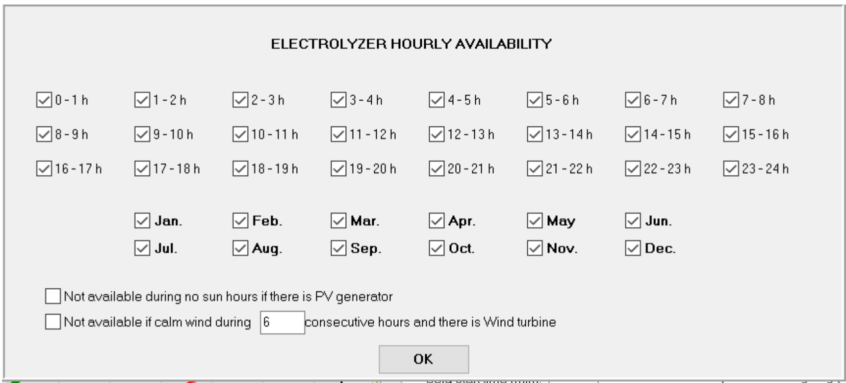


The electrolyzer rectifier efficiency is 90% by default, and its cost must be included in the electrolyzer cost. The maximum input to the electrolyzer will be 10/0.9= 11.11 MW, as the electrolyzer maximum power involved in the H2 generation is 10 MW (in the simulation screen of the results, the electrolyzer power is the internal power, that is, the real power involved in the H2 generation, with a maximum of 10 MW). We leave the data by default. The fuel cell efficiency is not considered as in our case there is no fuel cell. Click OK to close this little window.

The electricity consumption in compressing the H2 generated and other auxiliary processes must be set in "**Compression electrical consumption (kWh electricity per kg H2)**", by default it is 0 and we will leave the default value as we consider this consumption is included in the electrolyzer consumption curve.



If we click in the "**Availability**" button (right area), we can set the availability of the electrolyzer (if not available, it will not work and it will not consume stand-by power, it will be off). By default, it is available all the year. We could define that it is not available during no sun hours if there is PV generator in the system or not available if calm wind during a number of consecutive hours and there is wind turbine. We leave the default data:



OK to close this small window.

In the “**H2 tank**” tab (click on the top of the window in “H2 Tank”), leave the default checkbox checked. No H2 tank will be considered, that is, all the hydrogen generated will be sold for external use, it will not be stored to be used later by the fuel cell or by a hydrogen consumption of our facility. Therefore, no cost for the H2 tank will be considered (actually there will be a tank to store the hydrogen before being sold, but this cost must be included in the electrolyzer cost, we would only consider the hydrogen tank if we had an internal consumption of hydrogen). In the simulation screen of the results, the H2 generated will be shown as the H2 in the tank, that is, in the H2 tank we really will see the H2 generated that will be sold.

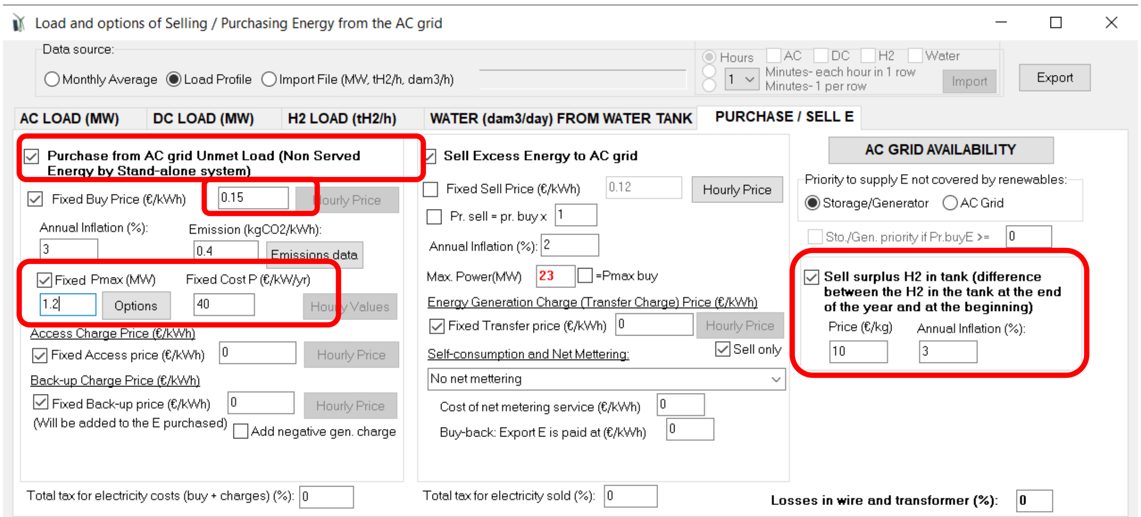
The costs of the real tank which will be in our facility to store the H2 before selling it, plus the cost of compressors, rectifier etc. must be included in the electrolyzer costs.

OK and return to the main screen.

As there is an AC load consumption due to the electrolyzer (when it is in stand-by), we will include the option to purchase electricity from the AC grid.

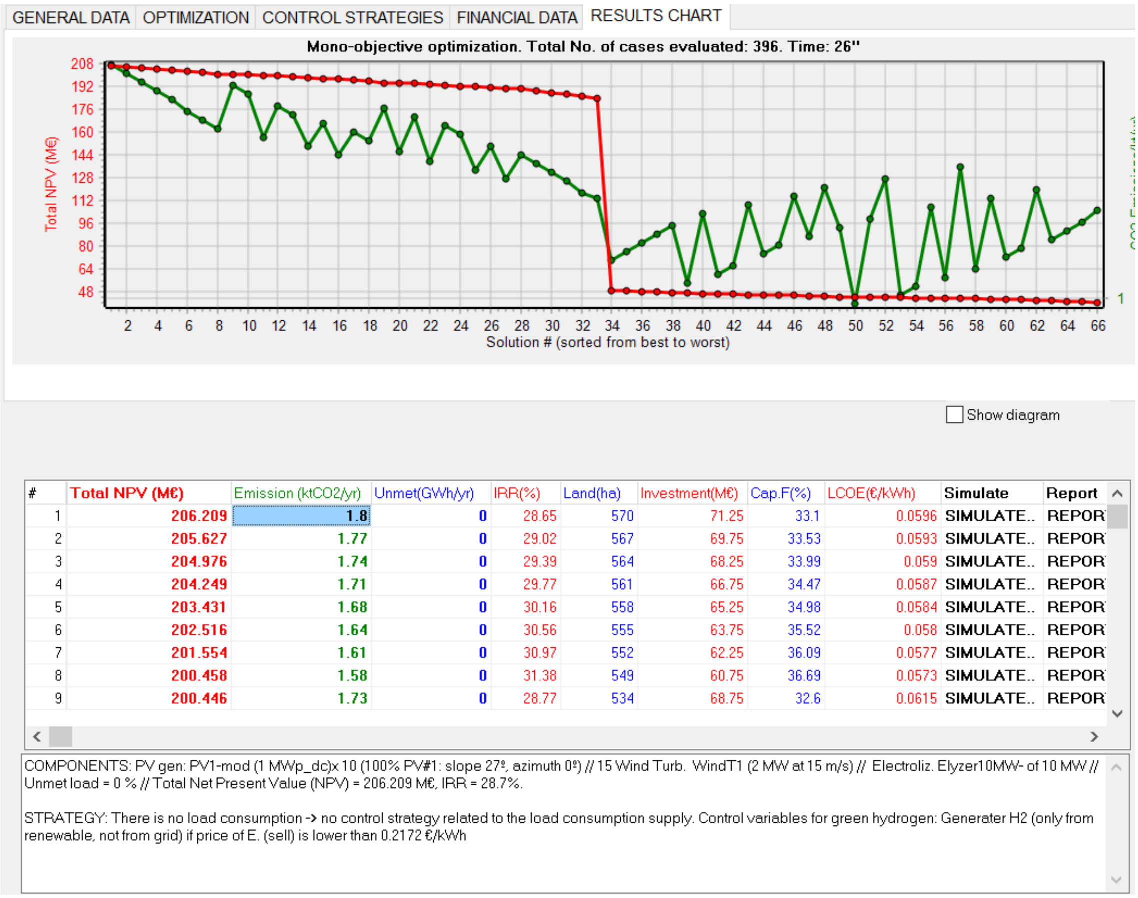
In the main screen, click “**LOAD / AC GRID**”, and, in the **PURCHASE / SELL E** tab, select “**Purchase from AC grid Unmet Load…**”, the purchase price will be the default value (0.15 €/kWh) and the sell price the hourly file we imported previously. We need to contract the power from the grid, which will be in this case for example 1.2 MW, with an annual cost of the power of 40 €/kW.

Also click on “**Sell surplus H2 in tank…**” to indicate we want to sell the H2 produced, and leave the default price of 10 €/kg and annual inflation of 3% for that price.



OK and, in the main screen, save the project and then CALCULATE.

There are 66 possible solutions of combinations of the components, each one has 6 possible combinations of control strategy. The optimal system includes 10 MW PV and 15 wind turbines, with the 10 MW electrolyzer. Remember, we had the constraint of maximum investment cost 100 M€, without that constraint the maximum allowed renewable capacity (10 MW PV and 15 wind turbines) would be the optimal combination to maximize NPV.

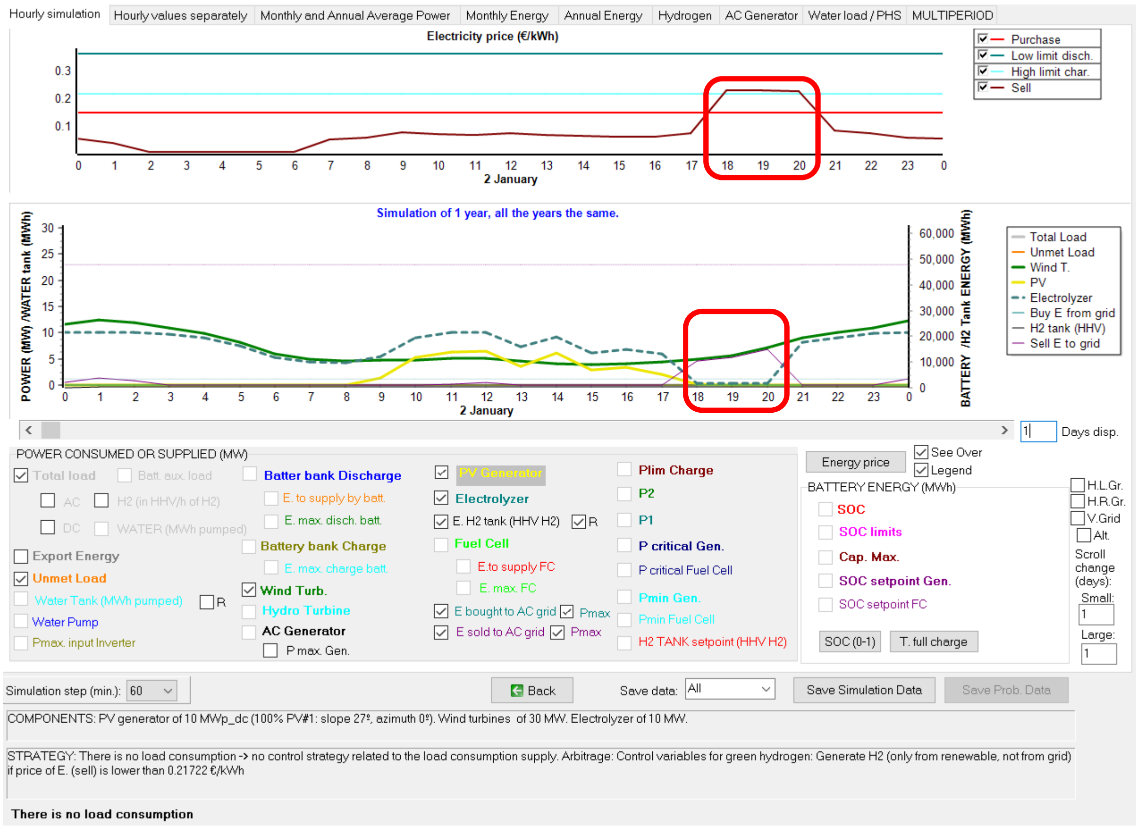


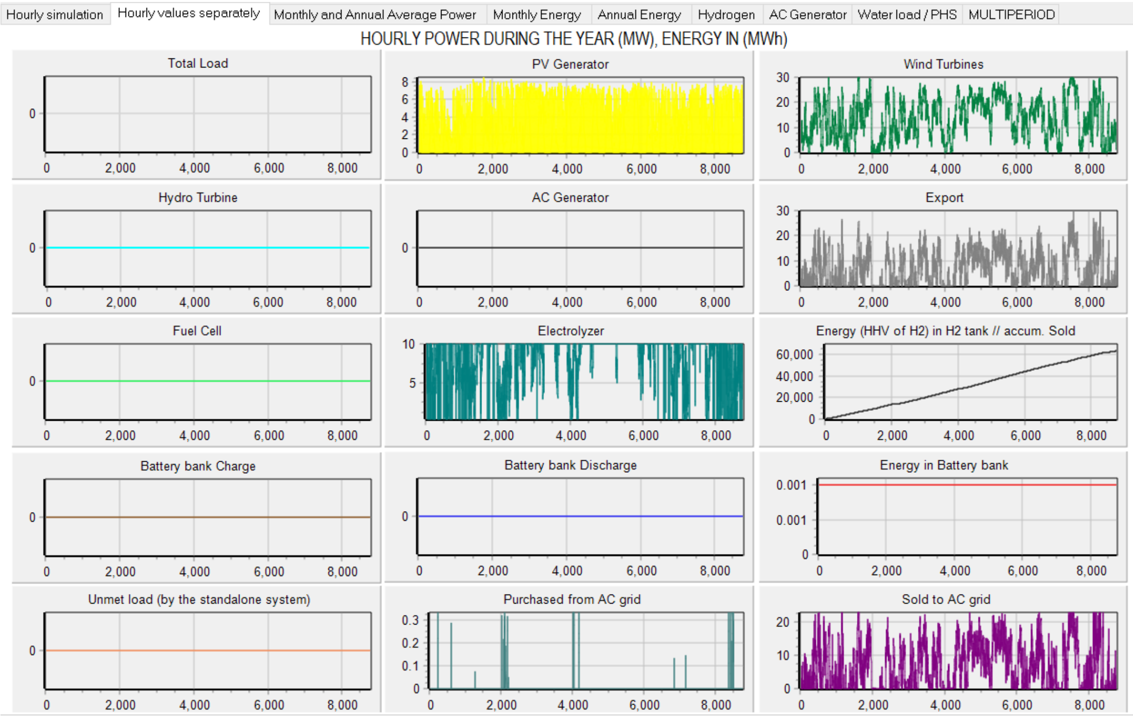
The strategy shows that hydrogen is produced from renewable sources when the sell price of electricity is lower than 0.2172 €/kWh (optimal limit), if the renewable power is higher than the nominal power of the electrolyzer (10 MW) the rest is injected to the grid. If price is higher than 0.2172 €/kWh, renewable power is injected to the grid.

We can see in the column “H2 tank (t)” the amount of hydrogen produced (and sold) during each year. In the optimal case (first row), 1604 tons of H2.

P. PV (MWp_dc)	Slope#1(º)	Cn Bat. (kAh)	P. Gen (MW)	P. Inv (MW)	P. Wind T. (MW)	F. Turb (m3/s)	P. FC (MW)	P. Elyz. (MW	H2 tank (t)	NP
10x1	27	0	1x0	0	15x2	0	0	10	1604.259	
9x1	27	0	1x0	0	15x2	0	0	10	[illegible]	
8x1	27	0	1x0	0	15x2	0	0	10	1589.1389	
7x1	27	0	1x0	0	15x2	0	0	10	1580.7052	
6x1	27	0	1x0	0	15x2	0	0	10	1571.4611	
5x1	27	0	1x0	0	15x2	0	0	10	1561.3929	
4x1	27	0	1x0	0	15x2	0	0	10	1550.5301	
3x1	27	0	1x0	0	15x2	0	0	10	1538.9487	
10x1	27	0	1x0	0	14x2	0	0	10	1583.6394	

For example, during several days in January there are several hours with the sell price higher than 0,2172 €/kWh, therefore renewable power is injected to the AC grid (except for the minimum power of the electrolyzer). See next figure, where this is marked, from 18 to 20 h. Note that, due to the differences in left and right axis of the two graphs, the graphs are not synchronized in the bottom axis view.





The **Hydrogen** tab: we can see in columns hydrogen generated during each month and the total sold (black line).

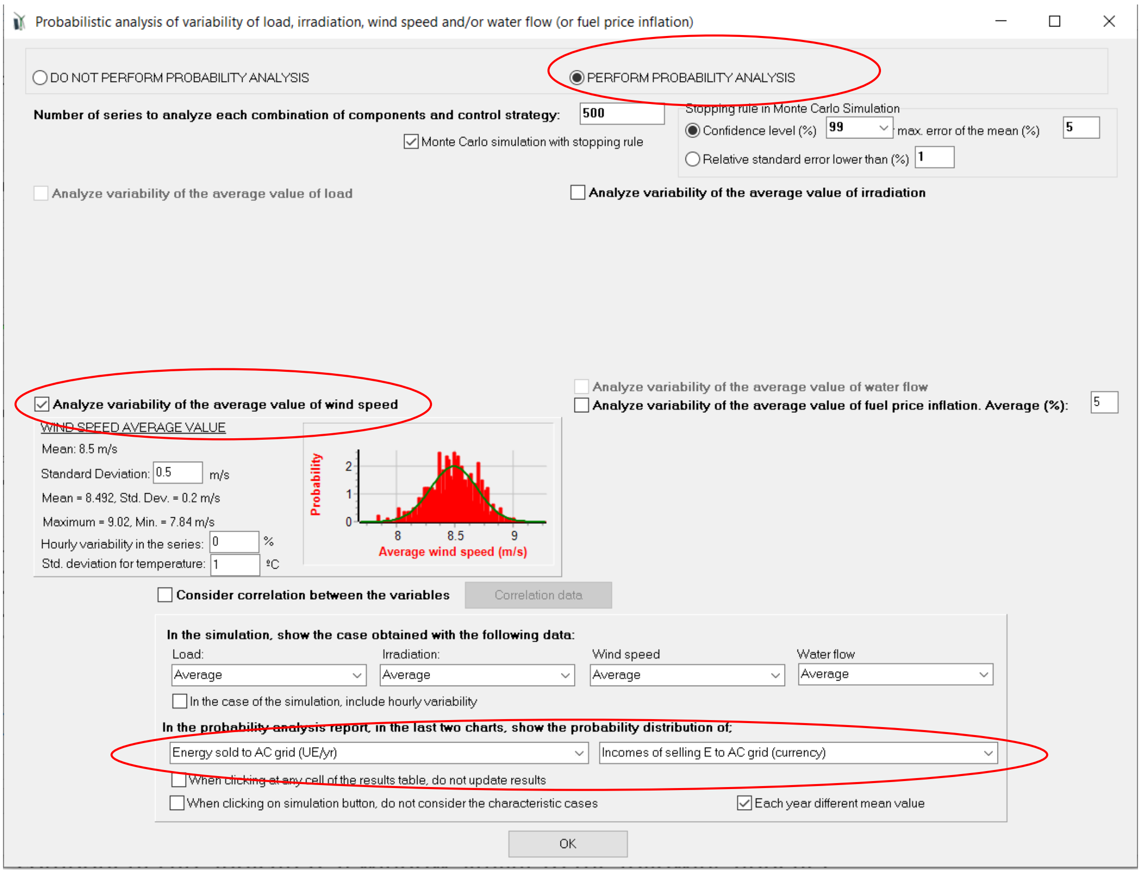
Save the project.

35. Probability analysis.

Next, we will perform, for a particular combination, the analysis of probability of variation of load, irradiation and inflation rate of the price of fuel (if we had diesel or other fuel generator). Thus we will see how the variations of these variables affect the system.

Open the previous project “MHOGA1.mho” (**Project->Open**). Then save it with the name “MHOGA1-Prob.mho” (**Project->Save as**).

In the main screen, click the "**Probability Analysis**" button (above the calculate button):



We select "**PERFORM PROBABILITY ANALYSIS**", and also "**Analyze the variability of the average value of wind speed**". We leave the number of series to be performed for each component combination and control strategy in 500 (default) and the stop rule according to the default value. We also leave the standard deviations that appear by default (for wind speed 0.5 m/s together with the temperature affecting the wind turbines 1°C).

In the two drop-downs menus at the bottom, select "**Energy sold to AC grid (UE/yr)**" and "**Incomes of selling E to AC grid (currency)**", respectively.

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

If we pass with the mouse over the area where the minimum and maximum number of parallel components are indicated, a window similar to the following appears:

NUMBER OF CASES AND TIME EXPECTED

Computation speed: 0.048 cases/second

	EVAL. ALL	POP. (% ALL)	GEN. ALG. (% ALL)
MAIN ALG. (COMB. COMPONENTS):	11904 (1x11904)	81 (0.68%)	1147 (9.64%)
SEC. ALG. (COMB. STRATEGIES):	1	3 (300%)	41 (4100%)

	MAIN ALG.	SEC. ALG.	NUMBER OF CASES	%	TIME EXPECTED
OPTION 1:	EVAL. ALL	EVAL. ALL	11904	100 %	2 days 19h
OPTION 2:	EVAL. ALL	GEN. ALG.	488064	4100 %	117 days 5h
OPTION 3:	GEN. ALG.	EVAL. ALL	1147	9.64 %	6h 35'
OPTION 4:	GEN. ALG.	GEN. ALG.	47027	395.1 %	11 days 7h

Waring!. Minimum computing time is 6h 35' so that the Main Genetic Algorithm can evaluate a minimum number of combinations.
With this minimum time it is not guaranteed to obtain the optimal combination of components, but this is probable to obtain the optimal or a solution near the optimal

Indicating that the calculation speed is now 0.048 cases/second (approximately 500 times lower than before, since each case is evaluated up to a maximum of 500 times with different wind speed series, obtained randomly from their probability curves, whose mean values follow a normal distribution as we have seen). MHOGA would need at least 2 days 19 h to perform the optimization considering all the combinations, and only 6 h 35’ if using genetic algorithms metaheuristic technique.

To avoid excessive time dedicated to follow this guide, in our case we will not perform the optimization including the probability analysis. What we are going to do is simply to see the effect of the variation of the wind speed in a concrete case. For example, if we want to see how the probability analysis affects the best solution found, **simply click on the first row of the table** (where the best solution is indicated).

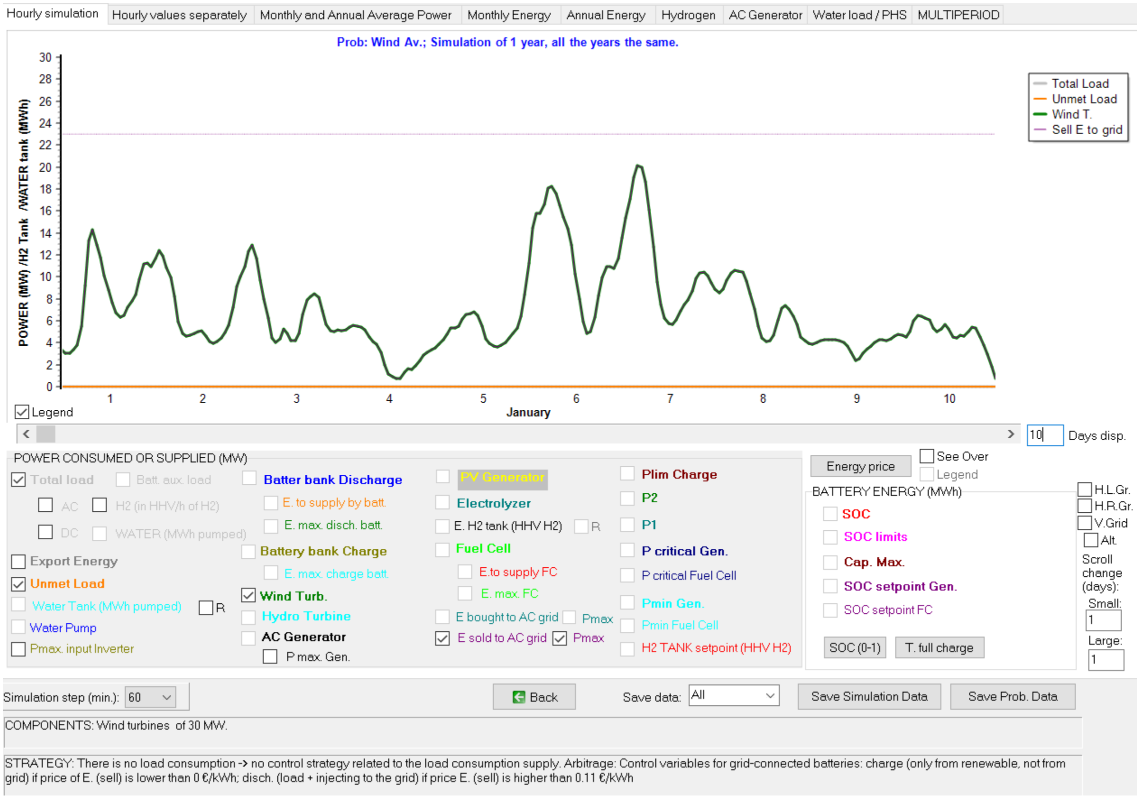
The following window appears, indicating that you are performing the 500 probability analysis combinations for the selected combination (although it will stop earlier if the stop criterion is reached before):

After a few seconds, that screen disappears and the results in the 1st row of the table are updated, but now the results we see in the 1st row are the average values of the combinations of probability analysis evaluated (500 or less if reached the stopping criterion). In our case, the average results are slightly different from the original result. Each time we click on the same row of the table, it will slightly change the result, because a new analysis of probability is performed.

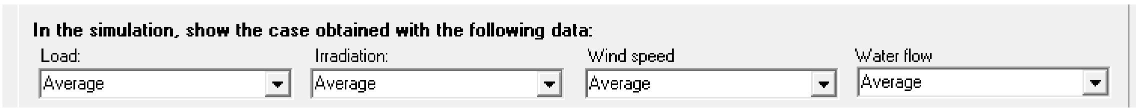
Gen	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	49.775	1.12	0	18.53	540	37.5	43.5	0.0301	SIMULATE..	REPOR

If we click again on the 1st row, but now in the "**SIMULATE**" cell, the following box appears, which indicates that you are doing the analysis of 500 probability combinations again (or less if the stop criterion is met), plus other 5 typical cases (combinations of mean, mean + standard deviation, mean-standard deviation, mean + 3 standard deviation, mean - 3 standard deviation), as there is only one variable in the probability analysis (wind speed), 5^1 = 5 typical cases of combinations are evaluated, in addition to the 500 (or less if the stop criterion is met) random combinations.

After some seconds the simulation screen appears:



The simulation of the case of average wind speed (Wind Av.) is visualized. By default, the average case is displayed, but we could have chosen to display another combination, for example, the worst extreme, which would be the case of average wind speed - 3·standard deviation, the case being displayed must be indicated before on the probability analysis screen as shown below:



In the simulation screen, clicking the "**Save Simulation Data**" button saves the time data of the simulation case being displayed (in our case, the average case).

By clicking the "**Save Prob. Data**" button, the results of the probability analysis are stored in an Excel file. If you open the saved Excel file, something similar to this is shown:

Project: MHOGA1-Prob Solution # 1
COMPONENTS: Wind turbines of 30 MW.
STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. Control variables for grid-connected batteries: charge batt. (only from renewable, not from grid) if price of E. (sell) is lower than 0 €/kWh; disch. batt. (load + injecting to the grid) if price E. (sell) is highe

RESULTS FOR THE DIFFERENT COMBINATIONS OF THE PROBABILITY ANALYSIS:
First 500 rows are the results corresponding to random data series. Next 5 rows correspond to characteristical cases. Next row correspond to the case shown in simulation. Finally MINIMUM, MAXIMUM, AVERAGE and STD.DEV. of the results of the 500 random series are shown:

Results corresponding to random data series:

Case prob. No.	Rad.(kWh/m2/day)	Tamb(ºC)	TambW(ºC)	Wind(m/s)	W.Flow(m3/s) or inf. fuel	Load(GWh/day)	Total NPV (M€)	LCOE(M€/kWh)	Emission(ktCO2/year)	Unmet(%)	Renew.(%)
0	5.44	18.62	18.62	8.5	0		49.6	0.03	1.1	0	100
1	5.44	18.62	19.94	8.52	0		49.7	0.03	1.1	0	100
2	5.44	18.62	16.29	8.87	0		57.4	0.028	1.1	0	100
3	5.44	18.62	20.17	8.64	0		52	0.029	1.1	0	100
4	5.44	18.62	17.69	8.27	0		45.1	0.031	1.1	0	100
5	5.44	18.62	18.19	9.42	0		66.3	0.025	1.1	0	100
6	5.44	18.62	18.94	8.35	0		46.6	0.031	1.1	0	100
7	5.44	18.62	18.28	8.82	0		56	0.028	1.1	0	100
8	5.44	18.62	17.88	7.14	0		19.1	0.043	1.1	0	100
9	5.44	18.62	18.81	8.95	0		58.2	0.027	1.1	0	100
10	5.44	18.62	18.4	8.83	0		56.2	0.028	1.1	0	100
11	5.44	18.62	16.79	8.21	0		44.1	0.032	1.1	0	100
12	5.44	18.62	18.46	9.08	0		60.7	0.027	1.1	0	100
13	5.44	18.62	19.77	8.58	0		51	0.029	1.1	0	100
14	5.44	18.62	18.21	8.08	0		40.8	0.033	1.1	0	100
15	5.44	18.62	18.49	8.12	0		41.8	0.032	1.1	0	100
16	5.44	18.62	19.6	8	0		38.7	0.034	1.1	0	100
17	5.44	18.62	20.4	8.96	0		57.9	0.028	1.1	0	100
18	5.44	18.62	18.84	8.37	0		46.9	0.031	1.1	0	100
19	5.44	18.62	18.7	9	0		59.2	0.027	1.1	0	100
20	5.44	18.62	18.46	8.2	0		43.4	0.032	1.1	0	100
21	5.44	18.62	17.8	8.55	0		50.9	0.029	1.1	0	100
22	5.44	18.62	19.93	9.32	0		64.3	0.026	1.1	0	100
23	5.44	18.62	18.41	8.05	0		40.1	0.033	1.1	0	100
24	5.44	18.62	18.19	8.24	0		44.4	0.032	1.1	0	100
25	5.44	18.62	18.18	9.34	0		65	0.026	1.1	0	100
26	5.44	18.62	15.78	8.78	0	0	56	0.028	1.1	0	100
27	5.44	18.62	19.59	8.36	0	0	46.4	0.031	1.1	0	100
28	5.44	18.62	19.26	8.68	0	0	53	0.029	1.1	0	100
29	5.44	18.62	19.11	7.74	0	0	33	0.036	1.1	0	100

prob

In this case we see the 500 rows corresponding to the random probability cases, one in each row of the table (cases 0 to 499, the stopping rule of the Monte Carlo Simulation was not met). In each case the average wind speed and temperature are random (following their probability curves defined in the probability analysis screen). In each case (each row of the table) the results of this case are shown: total NPV, LCOE, emissions, unmet load, renewable fraction, etc.

After the first 500 rows, the results for $5^1 = 5$ typical cases of combinations of wind speed, including the average case, the most optimistic (mean wind speed + 3DT) and More pessimistic (mean wind speed -3DT):

499	5.44	18.62	18.62	8.5	0	0	49.6	0.03	1.1	0	100
Results corresponding to characteristic cases (combinations of data: AVERAGE, AVERAGE+StdDv, AVERAGE+3StdDv, AVERAGE-StdDv, AVERAGE-3StdDv):											
Case prob. No.	Rad.(kWh/m2/day)	Tamb(ºC)	TambW(ºC)	Wind(m/s)	W.Flow(m3/s) or inf. fuel	Load(GWh/day)	Total NPV (M€)	LCOE(M€/kWh)	Emission(ktCO2/year)	Unmet(%)	Renew.(%)
500	5.44	18.62	18.62	8.5	0	0	49.6	0.03	1.1	0	100
501	5.44	18.62	18.62	9	0	0	59.1	0.027	1.1	0	100
502	5.44	18.62	18.62	10	0	0	74.5	0.024	1.1	0	100
503	5.44	18.62	18.62	8	0	0	38.9	0.034	1.1	0	100
504	5.44	18.62	18.62	7	0	0	15.6	0.046	1.1	0	100
Results corresponding to case shown in simulation:											
Case prob. No.	Rad.(kWh/m2/day)	Tamb(ºC)	TambW(ºC)	Wind(m/s)	W.Flow(m3/s) or inf. fuel	Load(GWh/day)	Total NPV (M€)	LCOE(M€/kWh)	Emission(ktCO2/year)	Unmet(%)	Renew.(%)
505	5.44	18.62	18.62	8.5	0	0	49.6	0.03	1.1	0	100
Values MINIMUM, MAXIMUM, AVERAGE and STD. DEV. of each result obtained in the 500 series:											
Case prob. No.	Rad.(kWh/m2/day)	Tamb(ºC)	TambW(ºC)	Wind(m/s)	W.Flow(m3/s) or inf. fuel	Load(GWh/day)	Total NPV(M€)	LCOE(M€/kWh)	Emission(ktCO2/year)	Unmet(%)	Renew.(%)
MINIMUM:	5.44	18.62	15.75	7.14	0	0	72.262	0.024	1.125	0	100
MAXIMUM:	5.44	18.62	21.21	9.81	0	0	19.116	0.043	1.125	0	100
MEAN:	5.44	18.62	18.6	8.47	0	0	48.65	0.03	1.12	0	100
STD.DEV.:	0	0	0.96	0.48	0	0	9.79	0.003	0	0	0

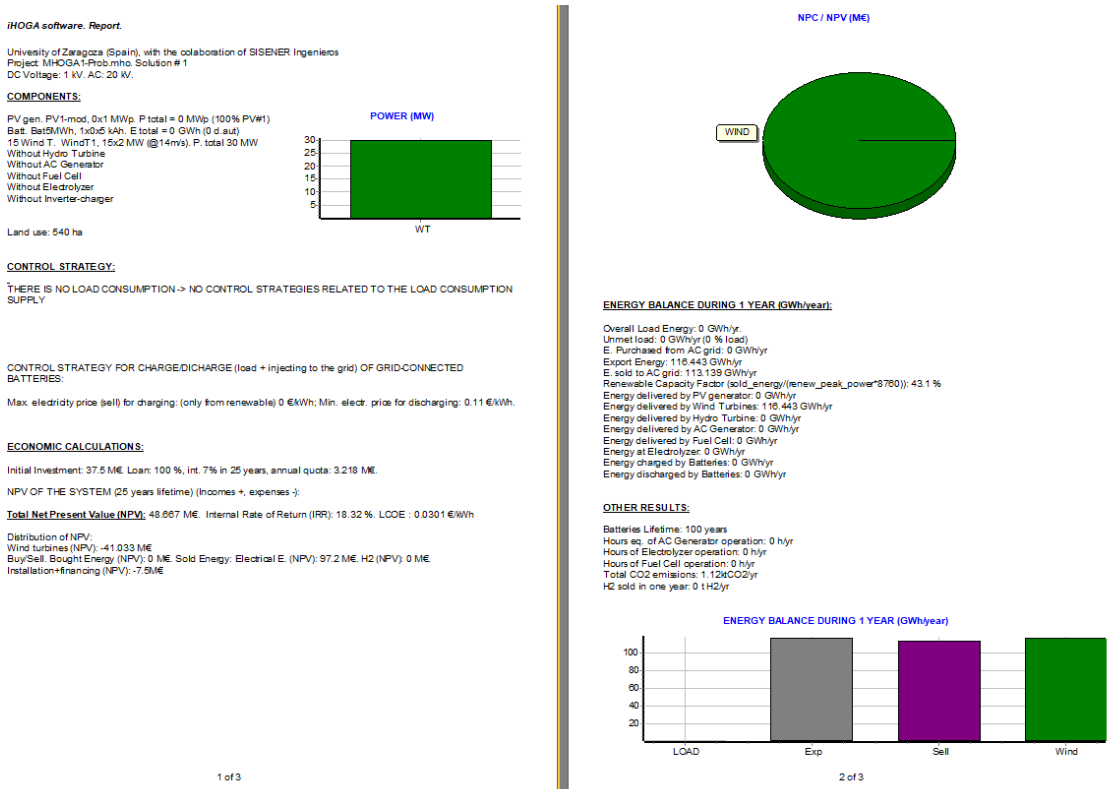
prob

It is observed that, in this case, the average case (mean wind speed, 8.5 m/s) has a NPV of 49.6 M€, the optimistic extreme case (mean wind speed + 3· std. dev = 8.5+3·0.5 = 10 m/s) has a NPV of 74.5 M€ and the pessimistic extreme case (mean wind speed - 3· std. dev = 8.5-3·0.5 = 7 m/s) has a NPV of 19.6 M€

The next line (case 505) shows the case that is represented graphically in the simulation (average case).

The following lines show the minimum, maximum, mean, and standard deviation values for each column (from the 0 to 499 cases, i.e., the random cases).

If we return to the main screen of MHOGA and click on the first row of the table, in the cell "**REPORT**", after a few seconds the report appears, which shows the average results of the analysis of probability of that combination of components and strategy:



iHOGA software. Report.

University of Zaragoza (Spain), with the colaboration of SISENER Ingenieros
Project: MHOGA1-Prob.mho. Solution # 1
DC Voltage: 1 kV. AC: 20 kV.

COMPONENTS:

PV gen. PV1-mod, 0x1 MWp. P total = 0 MWp (100% PV#1)
Batt. Bat5MWh, 1x0x5 kAh. E total = 0 GWh (0 d.aut)
15 Wind T. WindT1, 15x2 MW (@14m/s). P. total 30 MW
Without Hydro Turbine
Without AC Generator
Without Fuel Cell
Without Electrolyzer
Without Inverter-charger

Land use: 540 ha

CONTROL STRATEGY:

THERE IS NO LOAD CONSUMPTION -> NO CONTROL STRATEGIES RELATED TO THE LOAD CONSUMPTION SUPPLY

CONTROL STRATEGY FOR CHARGE/DICHARGE (load + injecting to the grid) OF GRID-CONNECTED BATTERIES:

Max. electricity price (sell) for charging: (only from renewable) 0 €/kWh; Min. electr. price for discharging: 0.11 €/kWh.

ECONOMIC CALCULATIONS:

Initial Investment: 37.5 M€. Loan: 100 %, int. 7% in 25 years, annual quota: 3.218 M€.

NPV OF THE SYSTEM (25 years lifetime) (Incomes +, expenses -):

Total Net Present Value (NPV): 48.667 M€. Internal Rate of Return (IRR): 18.32 %. LCOE : 0.0301 €/kWh

Distribution of NPV:
Wind turbines (NPV): -41.033 M€
Buy/Sell. Bought Energy (NPV): 0 M€. Sold Energy: Electrical E. (NPV): 97.2 M€. H2 (NPV): 0 M€
Installation+financing (NPV): -7.5M€

1 of 3

ENERGY BALANCE DURING 1 YEAR (GWh/year):

Overall Load Energy: 0 GWh/yr.
Unmet load: 0 GWh/yr (0 % load)
E. Purchased from AC grid: 0 GWh/yr
Export Energy: 116.443 GWh/yr
E. sold to AC grid: 113.139 GWh/yr
Renewable Capacity Factor (sold_energy/(renew_peak_power*8760)): 43.1 %
Energy delivered by PV generator: 0 GWh/yr
Energy delivered by Wind Turbines: 116.443 GWh/yr
Energy delivered by Hydro Turbine: 0 GWh/yr
Energy delivered by AC Generator: 0 GWh/yr
Energy delivered by Fuel Cell: 0 GWh/yr
Energy at Electrolyzer: 0 GWh/yr
Energy charged by Batteries: 0 GWh/yr
Energy discharged by Batteries: 0 GWh/yr

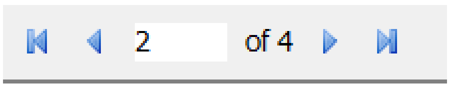
OTHER RESULTS:

Batteries Lifetime: 100 years
Hours eq. of AC Generator operation: 0 h/yr
Hours of Electrolyzer operation: 0 h/yr
Hours of Fuel Cell operation: 0 h/yr
Total CO2 emissions: 1.12ktCO2/yr
H2 sold in one year: 0 t H2/yr

2 of 3

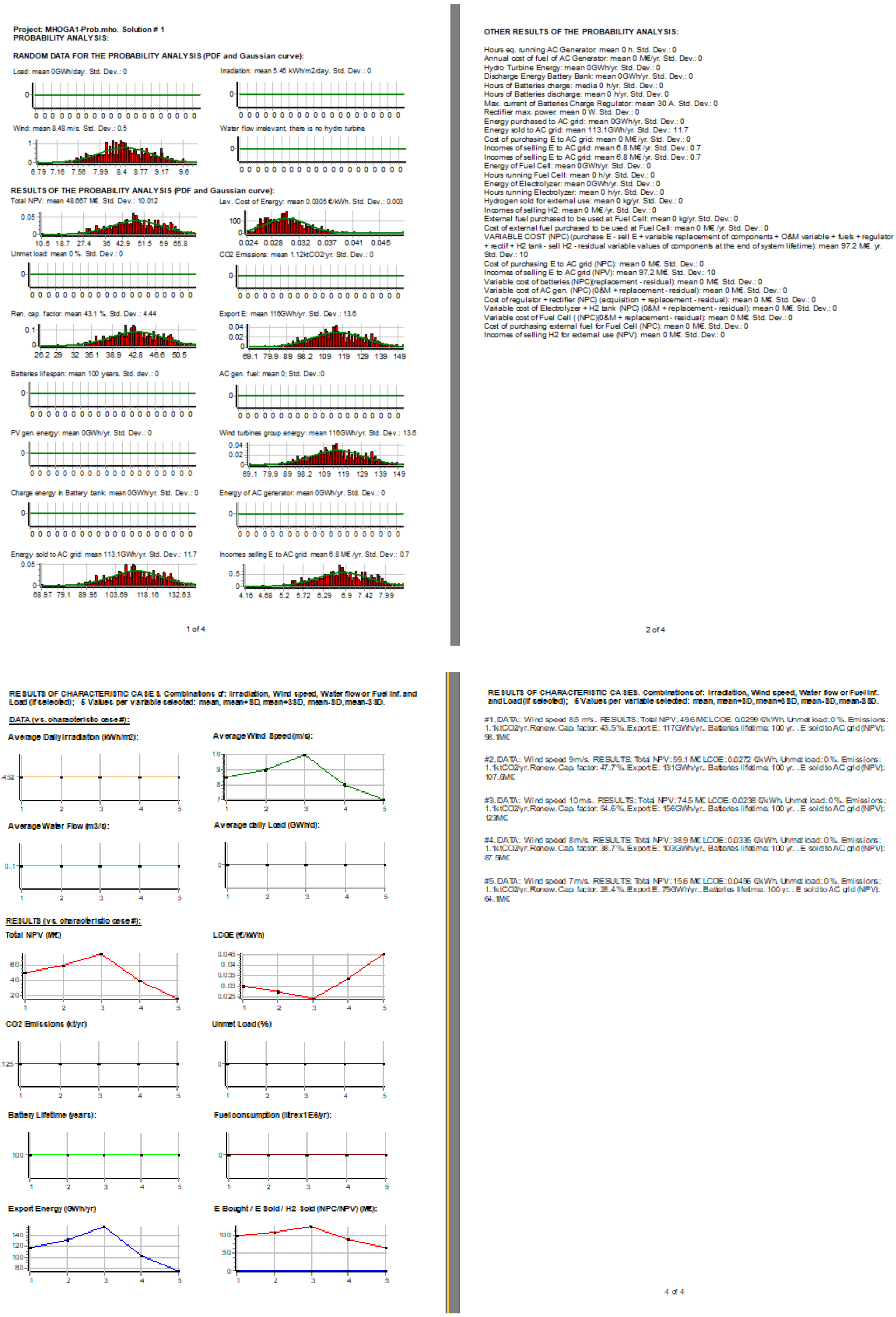
Click on "**Close**" (upper area of the report) and after selecting or not to save the .rtf file, after few seconds the report of the probability analysis of this case appears.

This report includes 4 pages, you move from one to the other with the arrow buttons at the top.

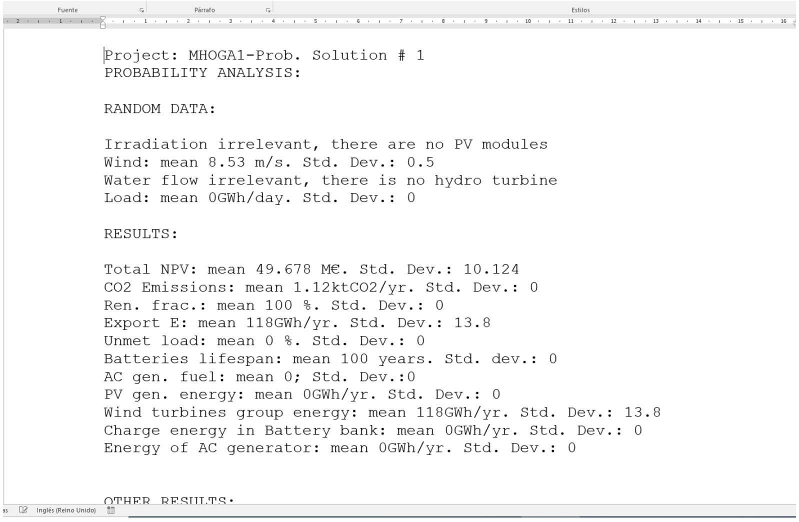


You can print or create a PDF file with the button , you select the printer (physical or pdf creator) and then you can print or create the PDF.

The first page shows the probability representation of the most representative results, marked in red the columns of the probability distribution obtained and the green curve is the one that best fits that distribution. The second page shows the results of other less important variables (only the mean and standard deviation) and then the results of the characteristic cases are shown (the 5 representative cases mentioned above, which include the mean and the optimistic and pessimistic extremes).



To close the report we click "**Close**" and we are asked if we want to save the results of the analysis of probability in a .doc or .rtf file (which can be open by Microsoft Word). We agree, save the file and open it with Microsoft Word:



```
Project: MHOGA1-Prob. Solution # 1
PROBABILITY ANALYSIS:

RANDOM DATA:

Irradiation irrelevant, there are no PV modules
Wind: mean 8.53 m/s. Std. Dev.: 0.5
Water flow irrelevant, there is no hydro turbine
Load: mean 0GWh/day. Std. Dev.: 0

RESULTS:

Total NPV: mean 49.678 M€. Std. Dev.: 10.124
CO2 Emissions: mean 1.12ktCO2/yr. Std. Dev.: 0
Ren. frac.: mean 100 %. Std. Dev.: 0
Export E: mean 118GWh/yr. Std. Dev.: 13.8
Unmet load: mean 0 %. Std. Dev.: 0
Batteries lifespan: mean 100 years. Std. dev.: 0
AC gen. fuel: mean 0; Std. Dev.:0
PV gen. energy: mean 0GWh/yr. Std. Dev.: 0
Wind turbines group energy: mean 118GWh/yr. Std. Dev.: 13.8
Charge energy in Battery bank: mean 0GWh/yr. Std. Dev.: 0
Energy of AC generator: mean 0GWh/yr. Std. Dev.: 0

OTHER RESULTS:
```

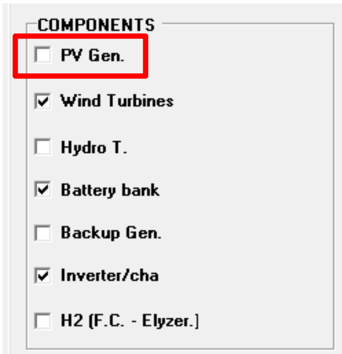
Finally, we save the project.

36. Sensitivity analysis.

Now we will perform the sensitivity analysis in the MHOGA1.mho original project.

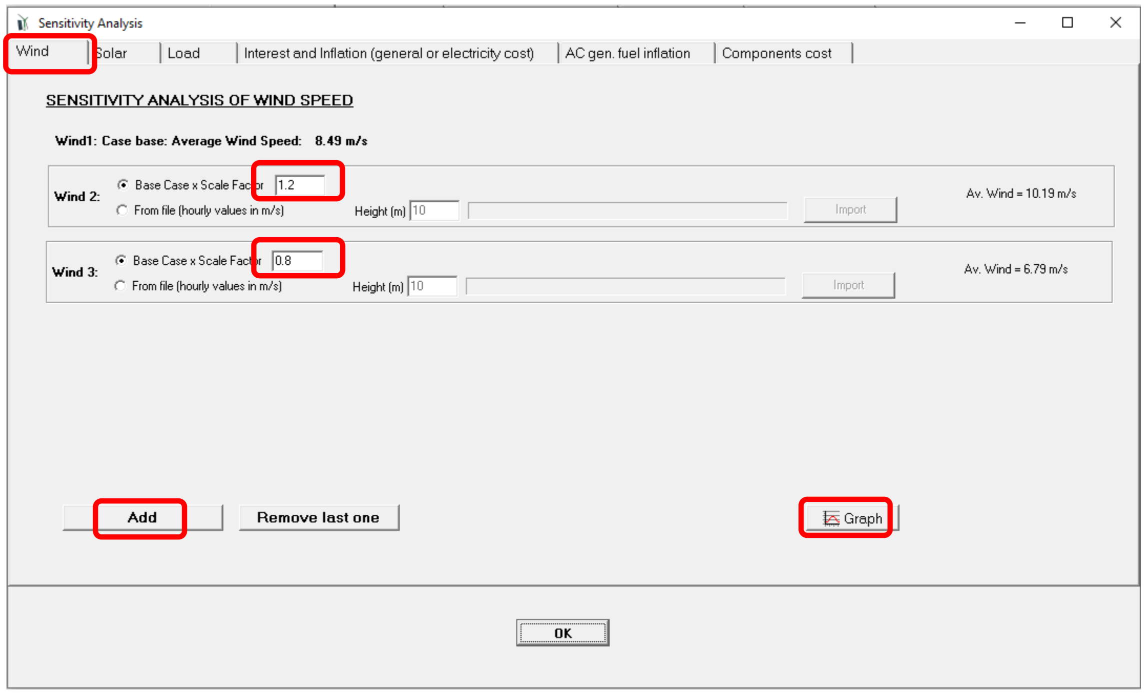
We open the MHOGA1.mho project and save it as "**MHOGA1-Sens.hoga**".

To reduce the search space and the computation speed, we unselect PV generators:

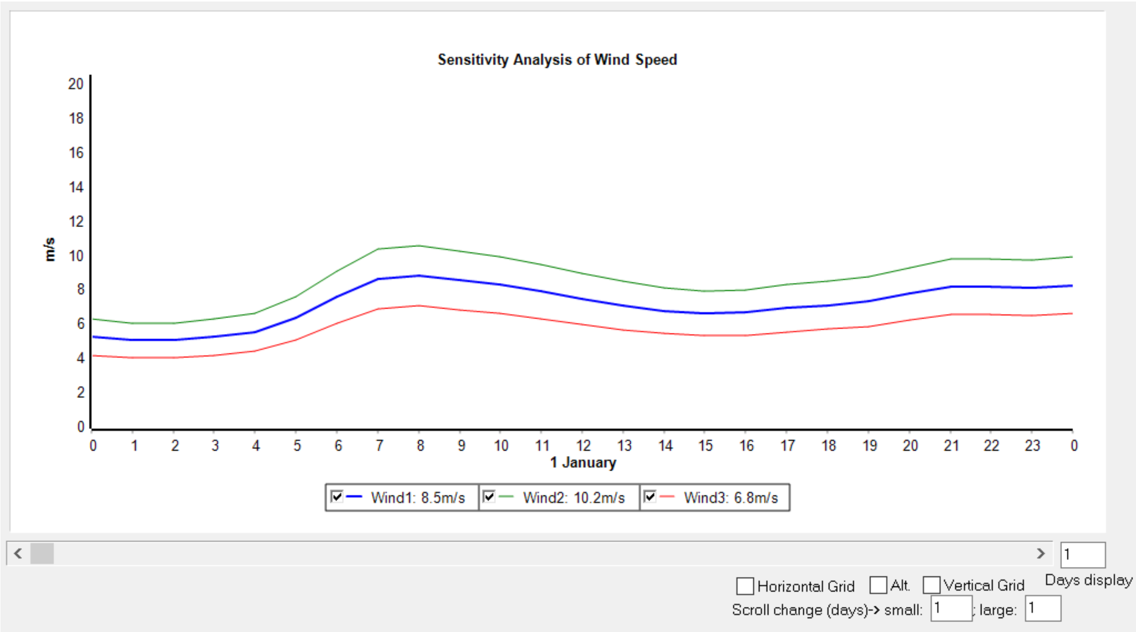


Click the "**Sensitivity Analysis**" button on the main screen (lower left area, above "Probability Analysis").

A screen appears with different tabs. We select the left tab, **Wind**. We click in “**Add**” two times, two cases of the sensitivity analysis appear, cases Wind2 and Wind3 (Wind1 is the base case defined in the wind speed window). We set 1.2 for the scale factor of wind speed for Wind2 case and 0.8 for Wind3 case.



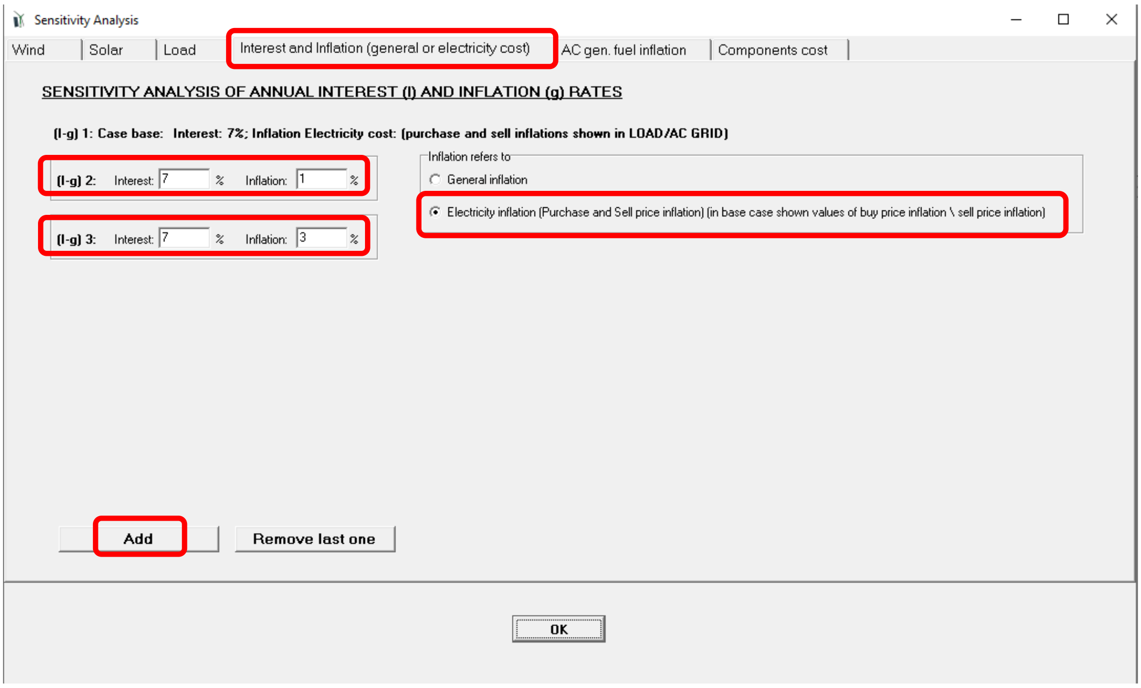
With the "**Graph**" button we can see the three wind speed series:



Back and then click in "**Interest and Inflation (general or electricity cost)**" tab.

We choose "**Electricity inflation (….**" as we will consider the sensitivity analysis of the electricity sell price inflation.

We click in "**Add**" two times, two cases of the sensitivity analysis appear, cases (I-g)2 and (I-g)3. We set 7% for interest rate (nominal discount rate) and 1% for electricity price inflation for case (I-g) 2 and 7% and 3% for case (I-g) 3.

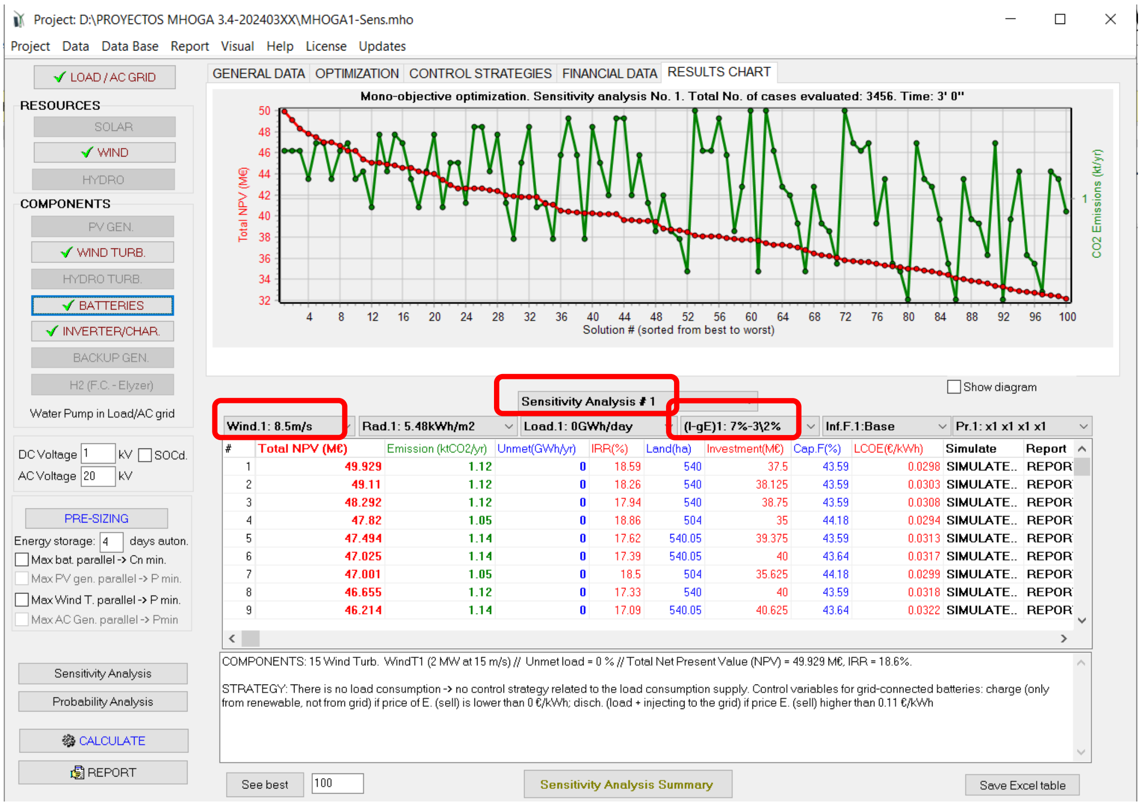


We could also define sensitivity analysis of components cost, load (if there was load consumption), irradiation (if there was PV generation), and AC gen. fuel inflation (if there was a backup generator).

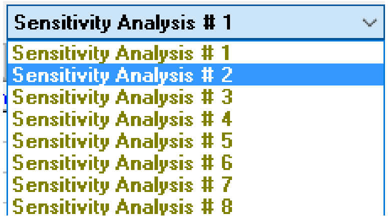
Click on "**OK**" (it takes some seconds to close the window) and, in the main screen, save the project and then "**CALCULATE**".

After a few minutes the sensitivity analysis ends. We have analyzed 3 cases of wind speed x 3 cases of interest and electricity price inflation = 9 projects.

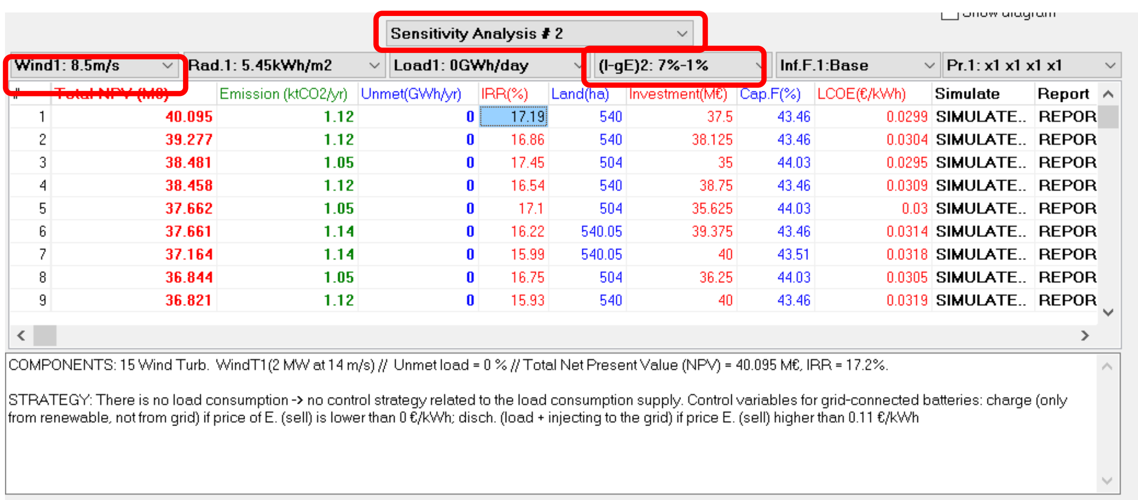
By default, the sensitivity analysis #1 is shown, corresponding to the base case (same result as in the MHOGA1.hoga Project).



We can select another project by clicking on the drop-down box "Sensitivity analysis #" (above the results table):

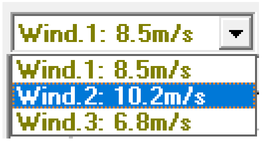


For example, if we choose # 2, the results of sensitivity analysis #2 appear:



We see that it corresponds to the base wind, Wind1 (8.5 m/s average wind speed) and the case of interest and inflation of electricity price (I-gE)2: 7% and 1%. As the inflation of electricity sell price is lower than the base case, the optimum has a lower NPV than in the base case.

We can also modify directly the drop-down box of each variable. For example, if we change the wind drop-down box and select Wind2:



We see that analysis number 5 appears, with higher NPV as wind speed is 20% higher than in the base case

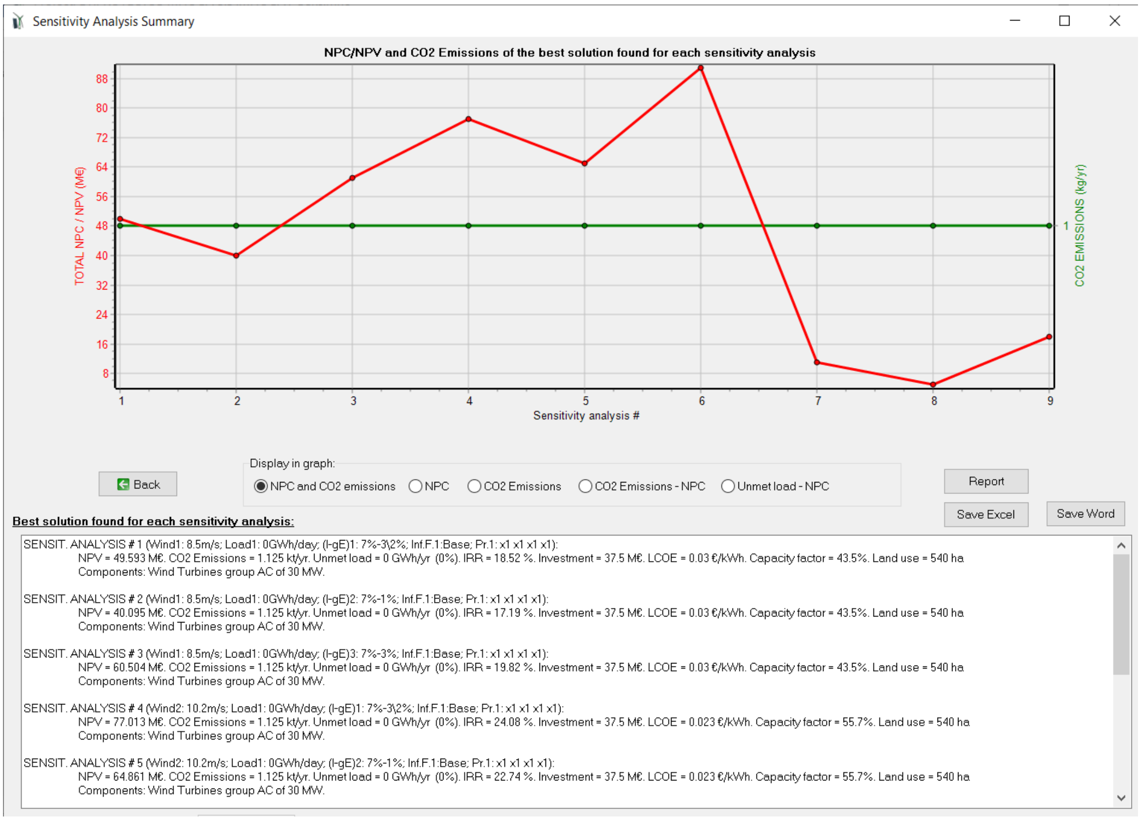
Show diagram

Sensitivity Analysis # 5

Wind2: 10.2m/s | Rad.1: 5.45kWh/m2 | Load1: 0GWh/day | (I-gE)2: 7%-1% | Inf.F.1:Base | Pr.1: x1 x1 x1 x1

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	64.861	1.12	0	22.74	540	37.5	55.75	0.0233	SIMULATE..	REPOR
2	64.233	1.05	0	23.61	504	35	57.68	0.0225	SIMULATE..	REPOR
3	64.043	1.12	0	22.35	540	38.125	55.75	0.0237	SIMULATE..	REPOR
4	63.415	1.05	0	23.17	504	35.625	57.68	0.0229	SIMULATE..	REPOR
5	63.224	1.12	0	21.96	540	38.75	55.75	0.0241	SIMULATE..	REPOR
6	62.694	0.98	0	24.37	468	32.5	59.39	0.0218	SIMULATE..	REPOR
7	62.596	1.05	0	22.75	504	36.25	57.68	0.0233	SIMULATE..	REPOR
8	62.427	1.14	0	21.57	540.05	39.375	55.75	0.0244	SIMULATE..	REPOR
9	62.097	1.14	0	21.31	540.05	40	55.82	0.0248	SIMULATE..	REPOR

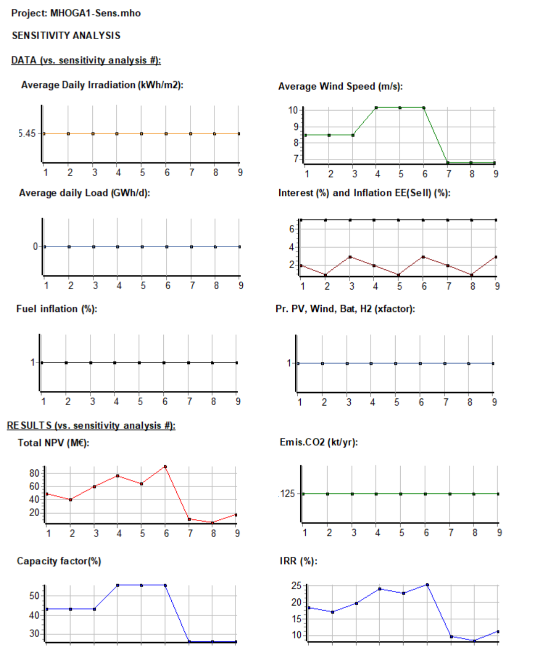
If we click on "**Sensitivity Analysis Summary**" (below the table) a comparative chart of the 9 analyzes projects appears, indicating below the optimal solution of each one:



Clicking the "**Save Excel**" button it saves an Excel file where the optimal solution for each of the sensitivity analysis projects appears:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Project: MHOGA1-Sens.mho. Best system found for each case of the sensitivity analysis																	
2	Sens.#		Wind (m/s)		Rad(kWh/m2/d)		Load(GWh/d)		Interest(%)		Inflation EE(Purch/Sell)(%)		Infla.Fuel(%)		Pr.PV(x)		Pr.W.T.(x)	
3	1		8.5		5.45		0		7		3\2		1		1		1	
4	2		8.5		5.45		0		7		1		1		1		1	
5	3		8.5		5.45		0		7		3		1		1		1	
6	4		10.2		5.45		0		7		3\2		1		1		1	
7	5		10.2		5.45		0		7		1		1		1		1	
8	6		10.2		5.45		0		7		3		1		1		1	
9	7		6.8		5.45		0		7		3\2		1		1		1	
10	8		6.8		5.45		0		7		1		1		1		1	
11	9		6.8		5.45		0		7		3		1		1		1	
12																		

If we click on the "**Report**" button a report of the sensitivity analysis appears, that can be printed or saved in PDF.



Optimal solution found for each case of the sensitivity analysis:

SENSIT. ANALYSIS # 1 (Wind1: 8.5m/s; Load1: 0GWh/day; (I-gE)1: 7%-3\2%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 49.593 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 18.52 %. Land use = 540 ha.
Capacity factor = 43.5%. Investment = 37.5 M€. LCOE = 0.03 €/kWh. E. sold to AC grid (NPC) = 98.126 M€.

SENSIT. ANALYSIS # 2 (Wind1: 8.5m/s; Load1: 0GWh/day; (I-gE)2: 7%-1%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 40.095 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 17.19 %. Land use = 540 ha.
Capacity factor = 43.5%. Investment = 37.5 M€. LCOE = 0.03 €/kWh. E. sold to AC grid (NPC) = 88.629 M€.

SENSIT. ANALYSIS # 3 (Wind1: 8.5m/s; Load1: 0GWh/day; (I-gE)3: 7%-3%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 60.504 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 19.82 %. Land use = 540 ha.
Capacity factor = 43.5%. Investment = 37.5 M€. LCOE = 0.03 €/kWh. E. sold to AC grid (NPC) = 109.038 M€.

SENSIT. ANALYSIS # 4 (Wind2: 10.2m/s; Load1: 0GWh/day; (I-gE)1: 7%-3\2%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 77.013 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 24.08 %. Land use = 540 ha.
Capacity factor = 55.7%. Investment = 37.5 M€. LCOE = 0.023 €/kWh. E. sold to AC grid (NPC) = 125.546 M€.

SENSIT. ANALYSIS # 5 (Wind2: 10.2m/s; Load1: 0GWh/day; (I-gE)2: 7%-1%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 64.861 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 22.74 %. Land use = 540 ha.
Capacity factor = 55.7%. Investment = 37.5 M€. LCOE = 0.023 €/kWh. E. sold to AC grid (NPC) = 113.395 M€.

SENSIT. ANALYSIS # 6 (Wind2: 10.2m/s; Load1: 0GWh/day; (I-gE)3: 7%-3%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 90.974 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 25.4 %. Land use = 540 ha.
Capacity factor = 55.7%. Investment = 37.5 M€. LCOE = 0.023 €/kWh. E. sold to AC grid (NPC) = 139.507 M€.

SENSIT. ANALYSIS # 7 (Wind3: 6.8m/s; Load1: 0GWh/day; (I-gE)1: 7%-3\2%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 10.955 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 9.87 %. Land use = 540 ha.
Capacity factor = 26.4%. Investment = 37.5 M€. LCOE = 0.049 €/kWh. E. sold to AC grid (NPC) = 59.488 M€.

SENSIT. ANALYSIS # 8 (Wind3: 6.8m/s; Load1: 0GWh/day; (I-gE)2: 7%-1%; Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
NPV = 5.197 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 8.49 %. Land use = 540 ha.
Capacity factor = 26.4%. Investment = 37.5 M€. LCOE = 0.049 €/kWh. E. sold to AC grid (NPC) = 53.73 M€.

If we click on the "**Save Word**" button a report in rtf format is saved, which can be open by Microsoft Word.

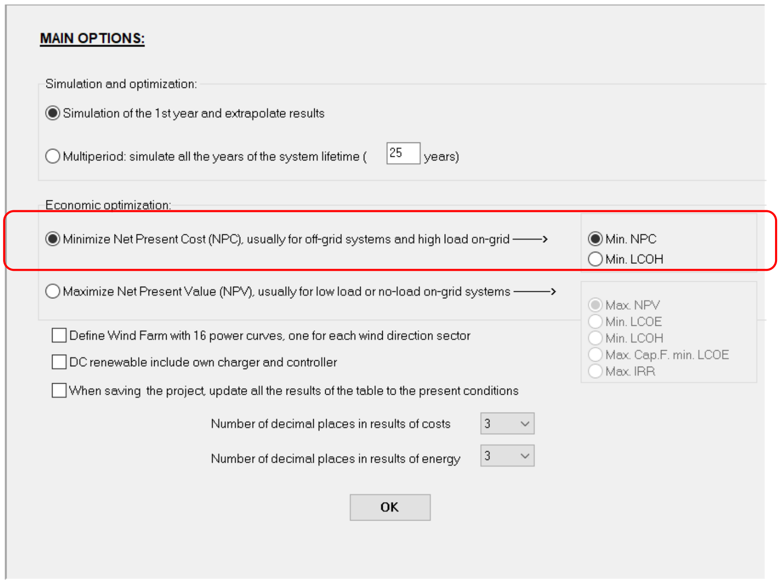
```
Project: MHOGA1-Sens.mho. Optimal solution found for each sensitivity
analysis:

SENSIT. ANALYSIS # 1 (Wind1: 8.5m/s; Load1: 0GWh/day; (I-gE)1: 7%-3\2%;
Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
      NPV = 49.593 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr
(0%). IRR = 18.52 %. Investment = 37.5 M€. LCOE = 0.03 €/kWh. Capacity
factor = 43.5%. Land use = 540 ha Components: Wind Turbines group AC of
30 MW.

SENSIT. ANALYSIS # 2 (Wind1: 8.5m/s; Load1: 0GWh/day; (I-gE)2: 7%-1%;
Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
      NPV = 40.095 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr
(0%). IRR = 17.19 %. Investment = 37.5 M€. LCOE = 0.03 €/kWh. Capacity
factor = 43.5%. Land use = 540 ha Components: Wind Turbines group AC of
30 MW.

SENSIT. ANALYSIS # 3 (Wind1: 8.5m/s; Load1: 0GWh/day; (I-gE)3: 7%-3%;
Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
      NPV = 60.504 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr
(0%). IRR = 19.82 %. Investment = 37.5 M€. LCOE = 0.03 €/kWh. Capacity
factor = 43.5%. Land use = 540 ha Components: Wind Turbines group AC of
30 MW.

SENSIT. ANALYSIS # 4 (Wind2: 10.2m/s; Load1: 0GWh/day; (I-gE)1: 7%-3\2%;
Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
      NPV = 77.013 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr
(0%). IRR = 24.08 %. Investment = 37.5 M€. LCOE = 0.023 €/kWh. Capacity
factor = 55.7%. Land use = 540 ha Components: Wind Turbines group AC of
30 MW.

SENSIT. ANALYSIS # 5 (Wind2: 10.2m/s; Load1: 0GWh/day; (I-gE)2: 7%-1%;
Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
      NPV = 64.861 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr
(0%). IRR = 22.74 %. Investment = 37.5 M€. LCOE = 0.023 €/kWh. Capacity
factor = 55.7%. Land use = 540 ha Components: Wind Turbines group AC of
30 MW.

SENSIT. ANALYSIS # 6 (Wind2: 10.2m/s; Load1: 0GWh/day; (I-gE)3: 7%-3%;
Inf.F.1:Base; Pr.1: x1 x1 x1 x1):
      NPV = 90.974 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr
(0%). IRR = 25.4 %. Investment = 37.5 M€. LCOE = 0.023 €/kWh. Capacity
```

Finally, we return to the main screen ("**Back**") and save the project.

37. Project with load, minimization of NPC.

Close the software and open it again to create a new project. **Project->New**, create a new project with the name “MHOGA2.mho”

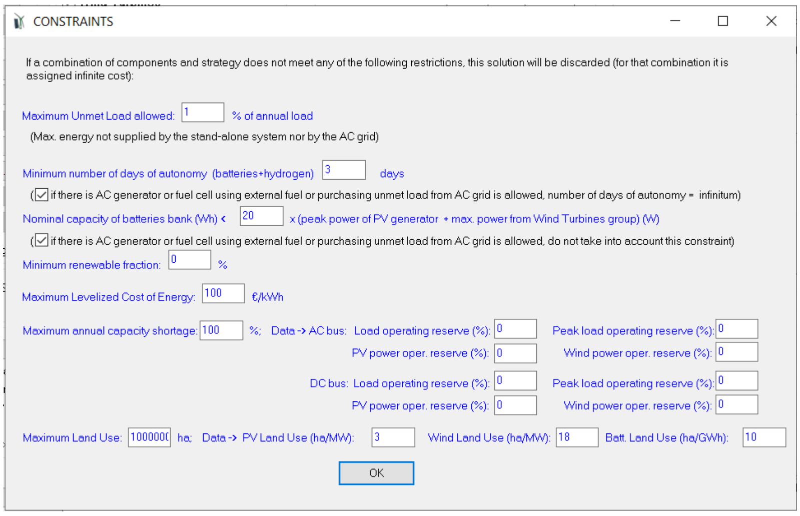
Project-> Options, select **Minimize Net Present Cost (NPC),…**



In the main screen, GENERAL DATA tab, we can see the constraint of the maximum unmet load allowed (by default, 1% annual). Click in “**More constraints**” button, to see all the constraints (we won’t change them, we will consider the default constraints):

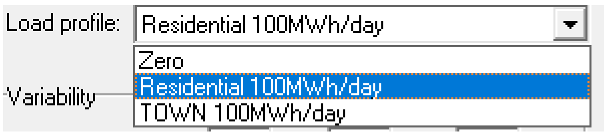
- Minimum number of autonomy days is 3 but it is not considered if there is AC grid as in our case.
- The third constraint related to the capacity of the battery compared to the peak power of the renewable sources is not considered as there is AC grid in our case.
- Default values of minimum renewable fraction and maximum LCOE are imply these constraints are not considered.
- Same for maximum capacity shortage (this should be consider to ensuring a minimum amount of operational reserve to face the sudden changes in load or in renewable generation, but we won’t consider it in this example; more info in the user manual).
- Same for maximum land use.

Therefore, only the maximum unmet load allowed is considered by default.

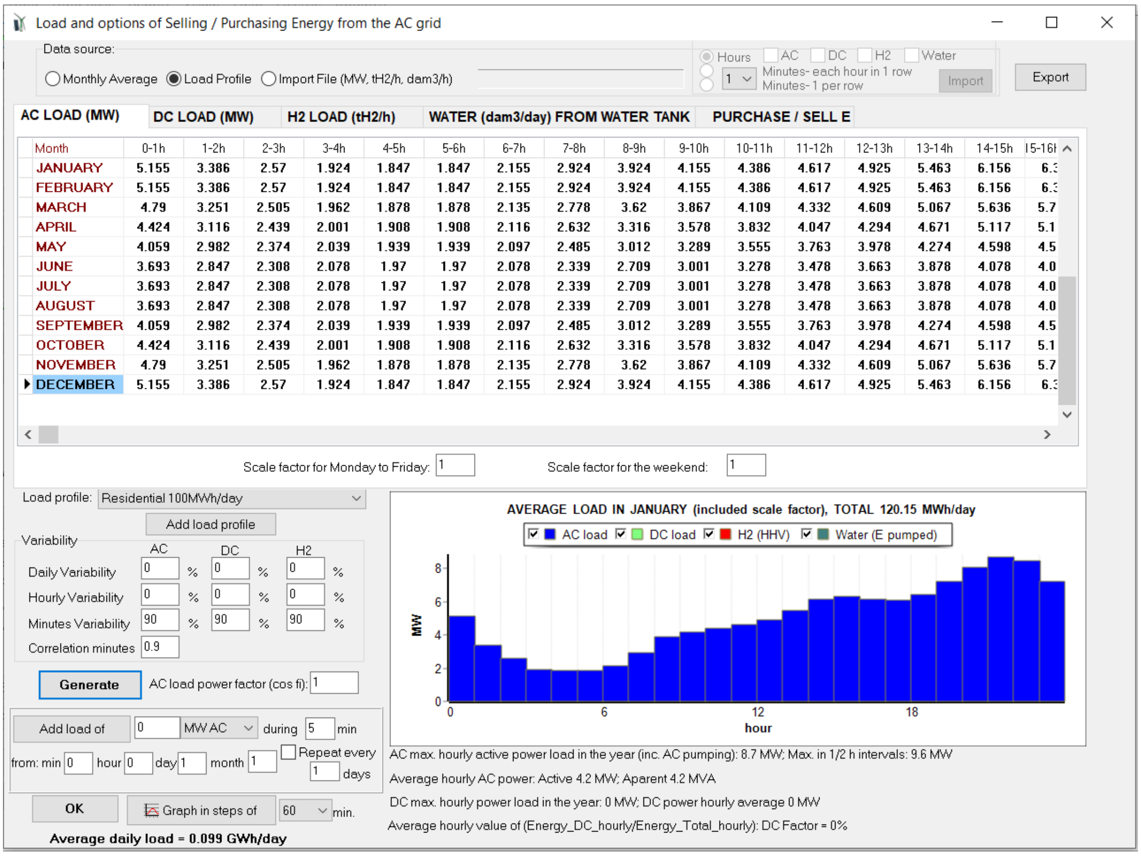


In the **LOAD/ AC GRID** screen, click in AC LOAD (MW) tab.

Add AC load, residential load of 100 MWh/day, by selecting it in the Load Profile (below the table):

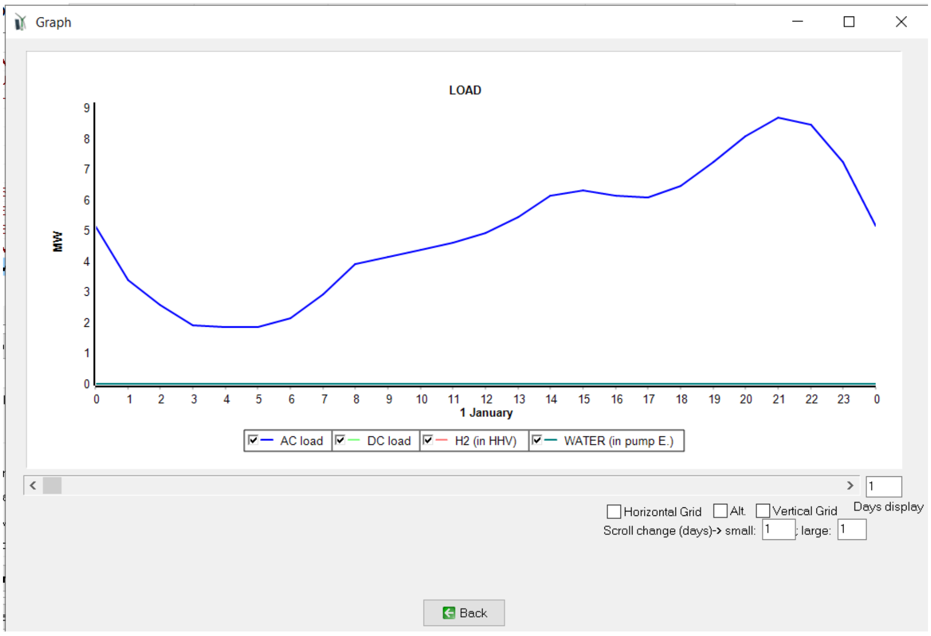


We click on **Generate** and approx. 0.1 GWh/day is obtained.



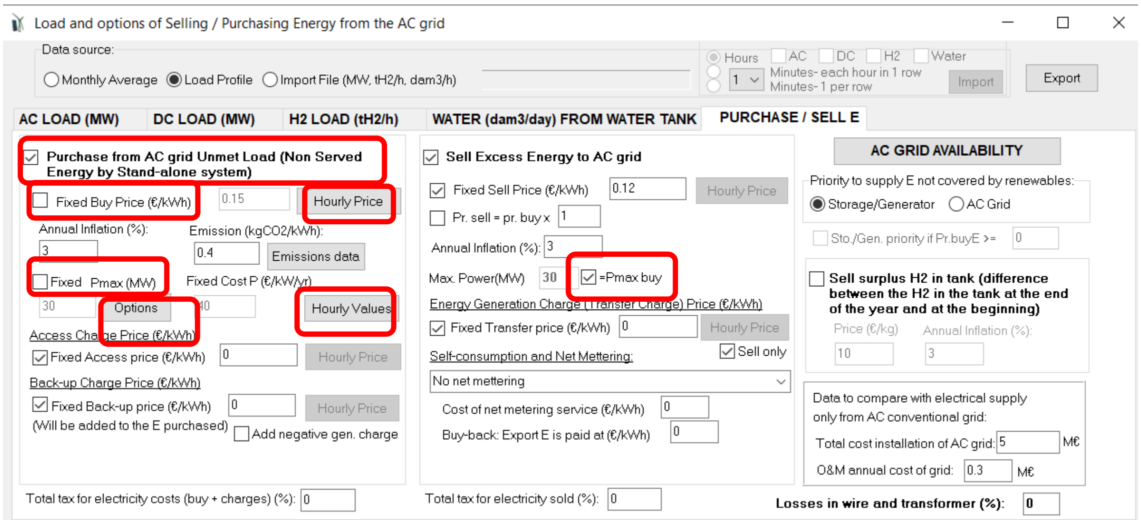
Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16h
JANUARY	5.155	3.386	2.57	1.924	1.847	1.847	2.155	2.924	3.924	4.155	4.386	4.617	4.925	5.463	6.156	6.3
FEBRUARY	5.155	3.386	2.57	1.924	1.847	1.847	2.155	2.924	3.924	4.155	4.386	4.617	4.925	5.463	6.156	6.3
MARCH	4.79	3.251	2.505	1.962	1.878	1.878	2.135	2.778	3.62	3.867	4.109	4.332	4.609	5.067	5.636	5.7
APRIL	4.424	3.116	2.439	2.001	1.908	1.908	2.116	2.632	3.316	3.578	3.832	4.047	4.294	4.671	5.117	5.1
MAY	4.059	2.982	2.374	2.039	1.939	1.939	2.097	2.485	3.012	3.289	3.555	3.763	3.978	4.274	4.598	4.5
JUNE	3.693	2.847	2.308	2.078	1.97	1.97	2.078	2.339	2.709	3.001	3.278	3.478	3.663	3.878	4.078	4.0
JULY	3.693	2.847	2.308	2.078	1.97	1.97	2.078	2.339	2.709	3.001	3.278	3.478	3.663	3.878	4.078	4.0
AUGUST	3.693	2.847	2.308	2.078	1.97	1.97	2.078	2.339	2.709	3.001	3.278	3.478	3.663	3.878	4.078	4.0
SEPTEMBER	4.059	2.982	2.374	2.039	1.939	1.939	2.097	2.485	3.012	3.289	3.555	3.763	3.978	4.274	4.598	4.5
OCTOBER	4.424	3.116	2.439	2.001	1.908	1.908	2.116	2.632	3.316	3.578	3.832	4.047	4.294	4.671	5.117	5.1
NOVEMBER	4.79	3.251	2.505	1.962	1.878	1.878	2.135	2.778	3.62	3.867	4.109	4.332	4.609	5.067	5.636	5.7
DECEMBER	5.155	3.386	2.57	1.924	1.847	1.847	2.155	2.924	3.924	4.155	4.386	4.617	4.925	5.463	6.156	6.3

With the “**Graph**” button we can see the load:

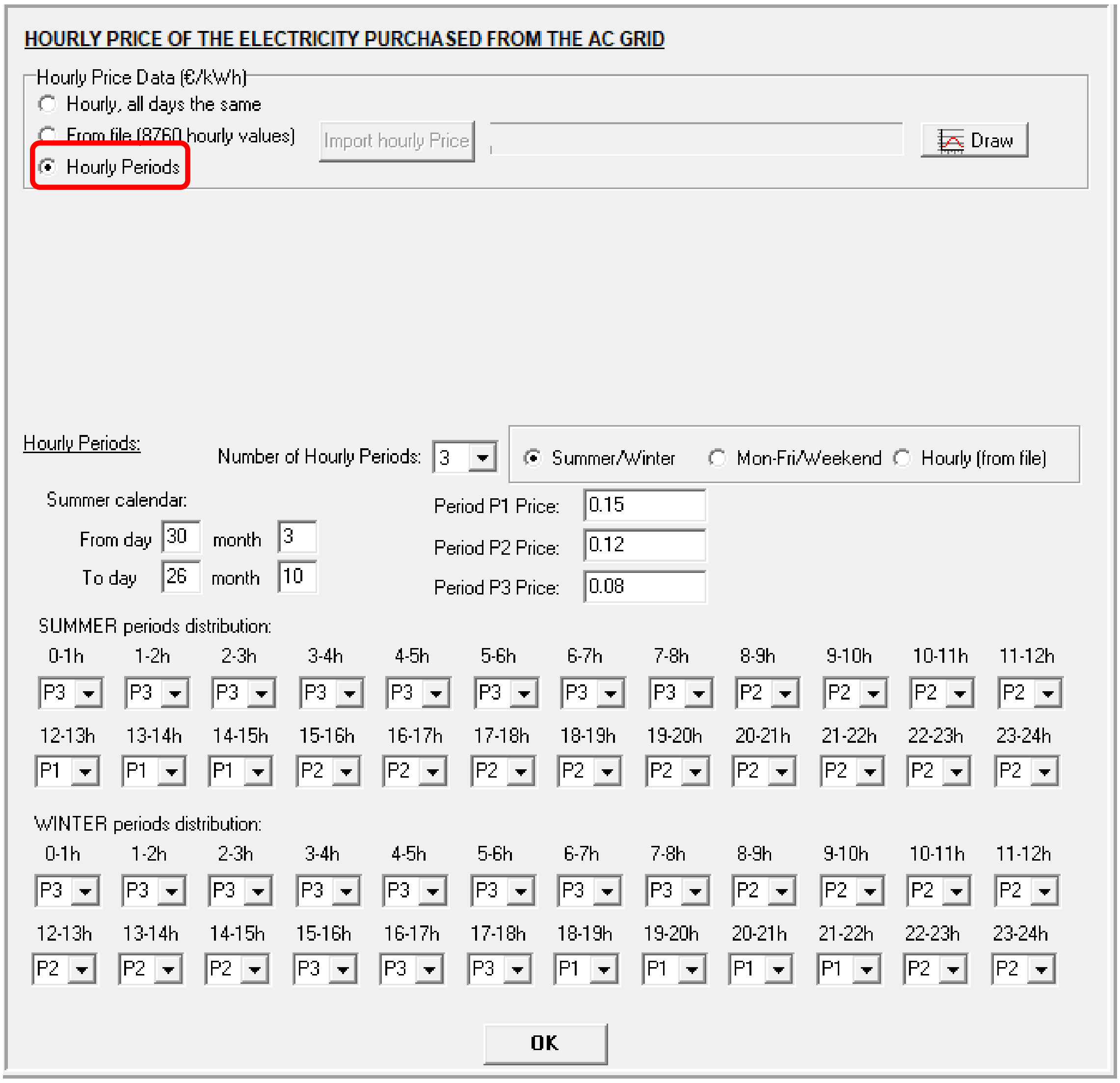


In **PURCHASE / SELL E** tab, let's suppose that the electricity price will be hourly, by periods, and the contracted power also by periods. Select "**Purchase from AC grid Unmet load ….**" and Uncheck "**Fixed Buy Price**" and "**Fixed Pmax**".

In the Sell excess energy to AC grid panel, select "**=Pmax buy**", this way the maximum power to be injected to the AC grid will be the same as the defined power to purchase from the AC grid.

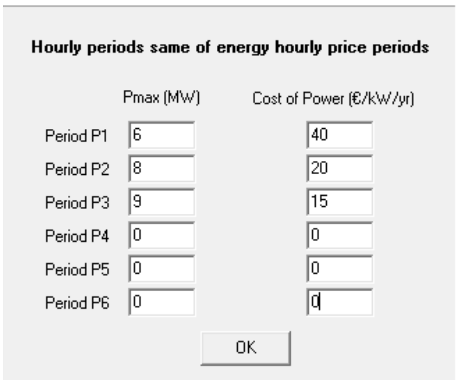


Then click on "**Hourly Price**" button close to the buy price. Select **Hourly Periods** and accept all the default values (3 periods, P1 price of the electricity purchased to the AC grid 0.15 €/kWh, P2 price 0.12 €/kWh, P3 price 0.08 €/kWh, distributed in summer/winter):



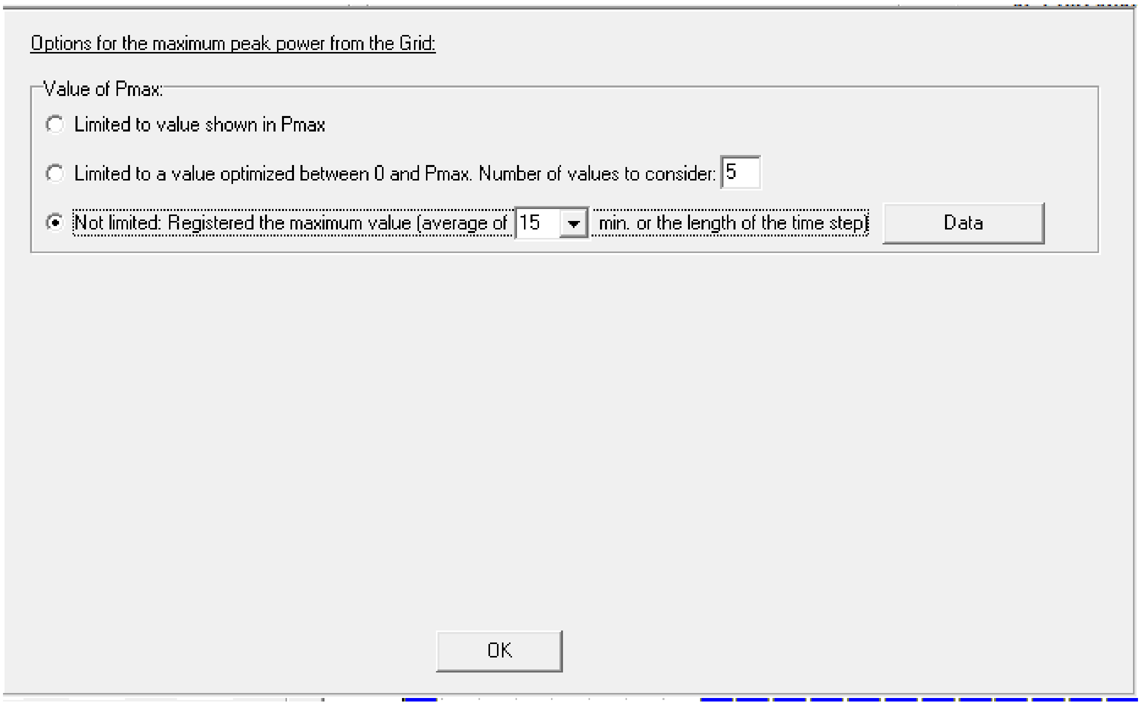
OK and, in the **PURCHASE / SELL E** tab, click "**Hourly Values**" close to the options of the contracted power Pmax.

A small window appears. Change the values to the following Pmax and costs for the different peridos P1 to P3 (note that P4-P6 are not considered, anyway we write 0 in them):



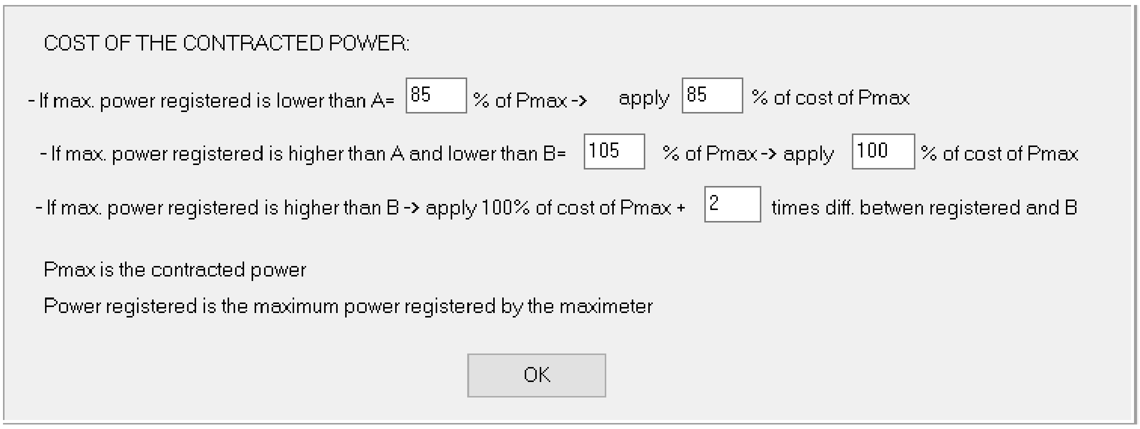
OK and, in the **PURCHASE / SELL E** tab, click "**Options**" close to the options of the contracted power Pmax.

A window appears. We can choose among: Power limited to the value shown in Pmax; Limited to an optimized value (it will be optimized during the opitmization, only valid for period P1), or the third option, which will be the one selected "**Not limited: Registered the maximum value (average of….**"



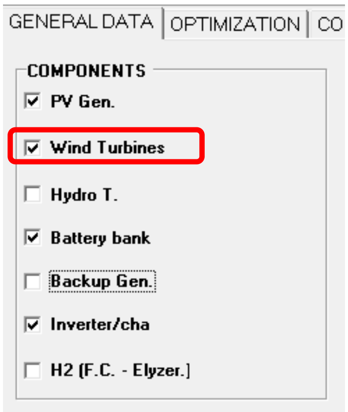
By using this option, the contracted power to buy electricity from the grid will not be the power defined, it will be the maximum power registered during the simulation for each period. However, the maximum power for selling electricity to the AC grid will be the values defined for each period.

And click in the button **Data**, leaving the default values (the way in Spain the cost of power is applied in the electrical bill for high power consumers, when we have the option of registering the maximum value of the power in the maximeter):



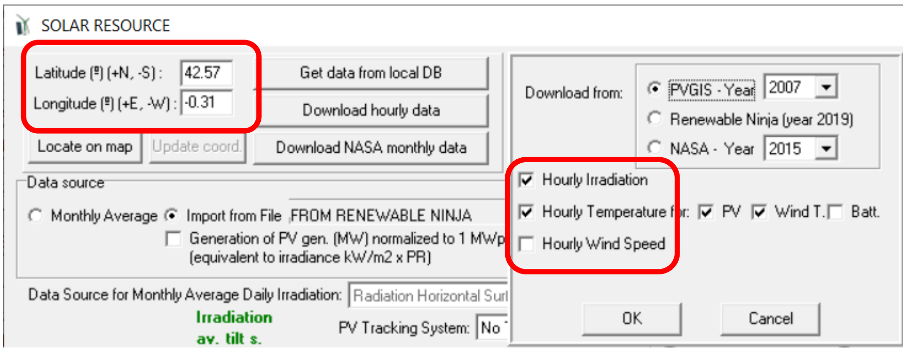
Click OK, OK and OK to return to the main screen of the software.

In the main window, check **Wind Turbines** so that we consider also them.

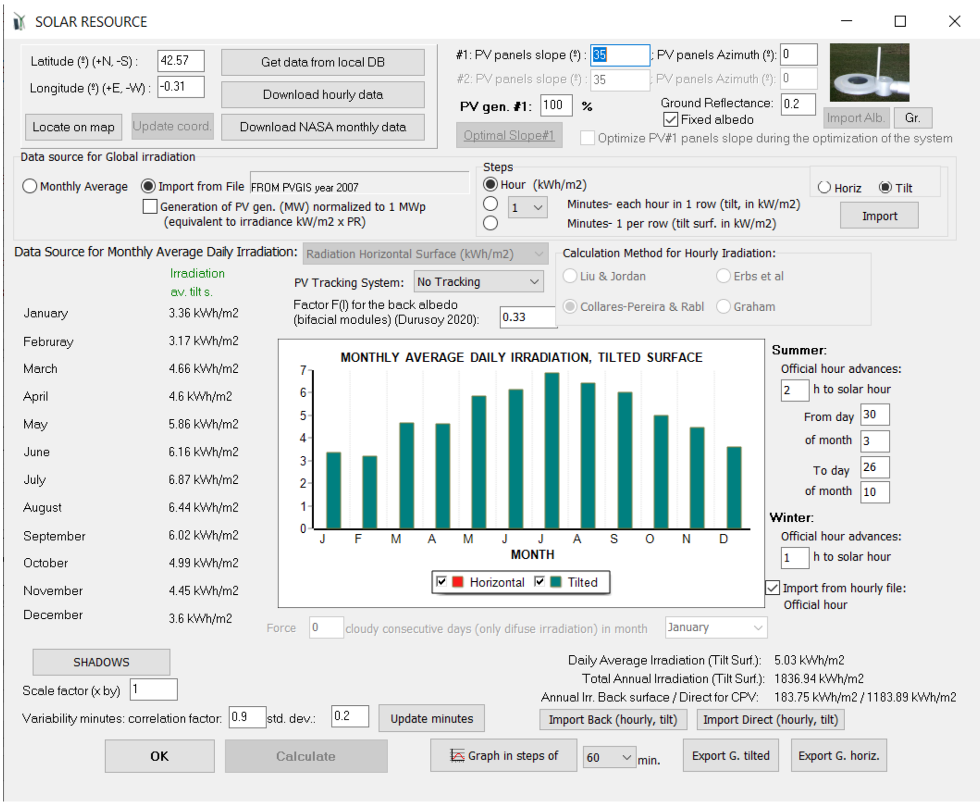


In **SOLAR**, set latitude to 42.57º and longitude -0.31º (Pyrenees in Huesca province, Spain).

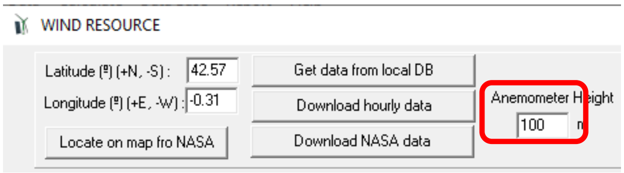
Then download hourly irradiation and temperature from PVGIS year 2007.

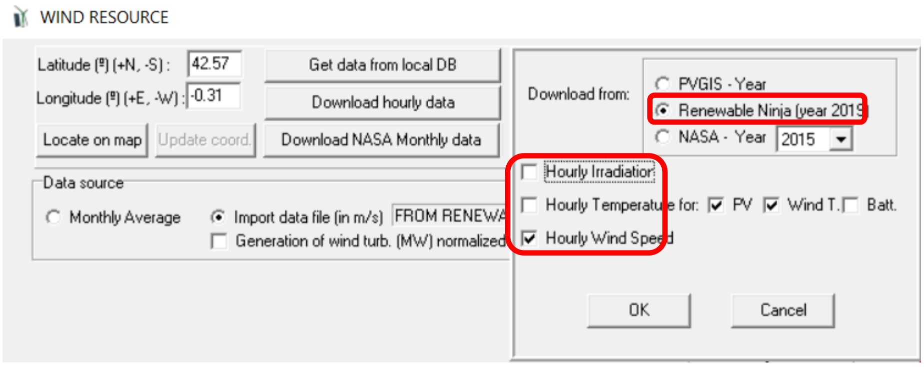


We obtain:

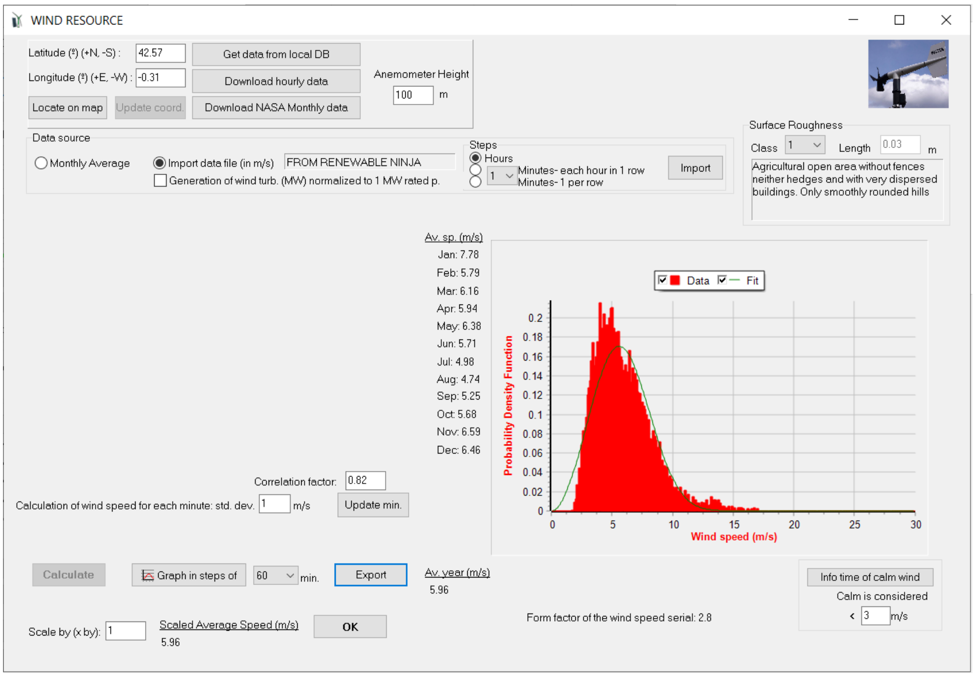


In the **WIND** screen, make sure the anemometer height is 100 m and download just wind speed from Renewable Ninja (not irradiation neither temperature).

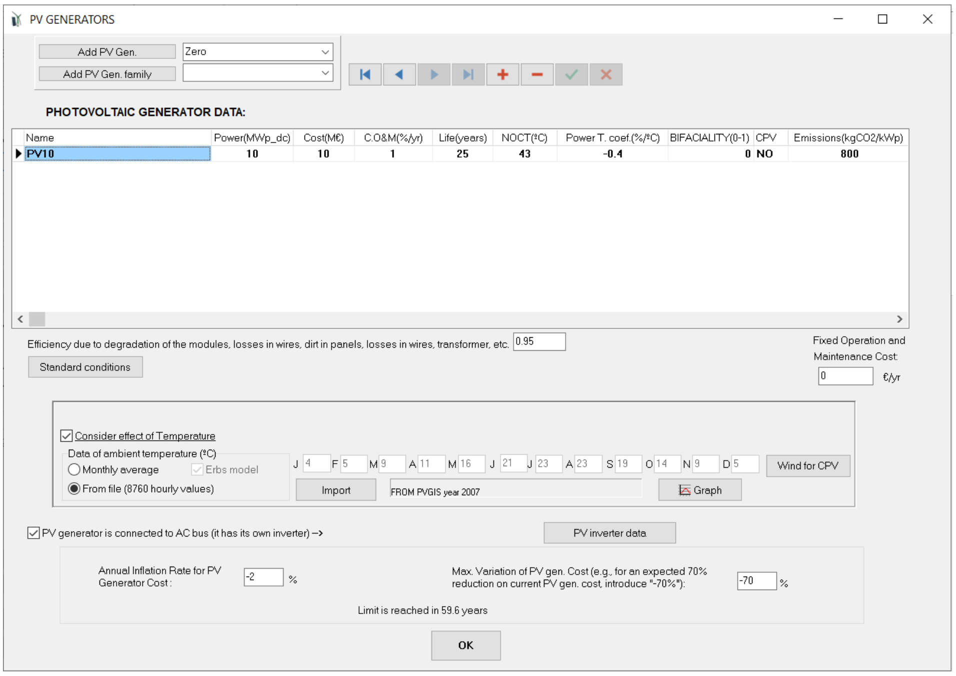




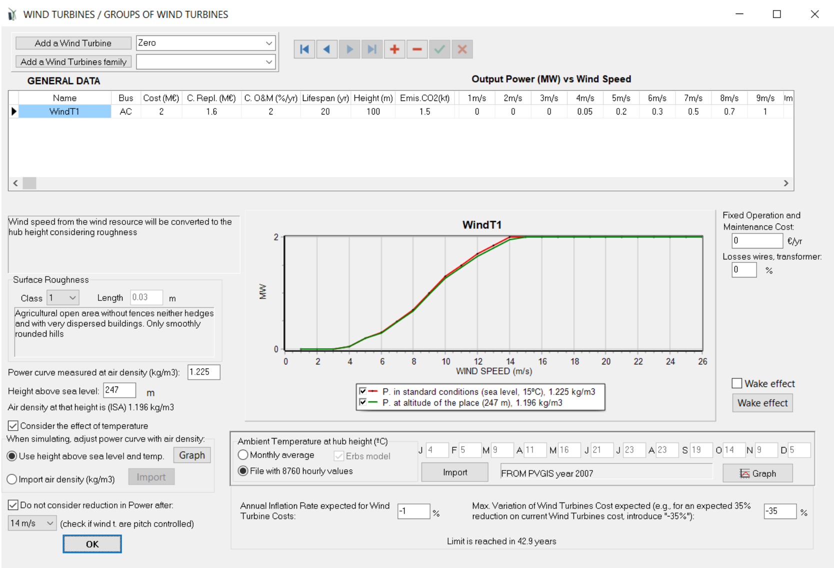
We obtain:



In **PV GEN.** accept the default PV data:

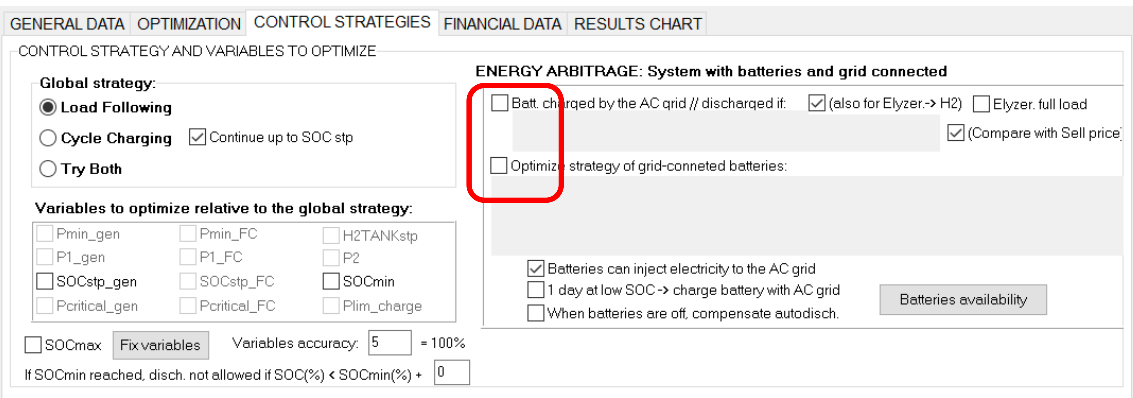


In **WIND TURB.**, also accept the default wind turbines data:

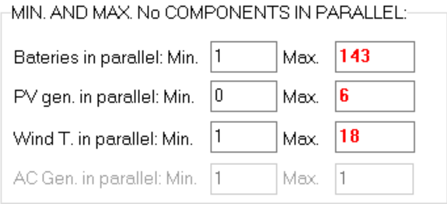


Same for **batteries** and **inverters**, default values.

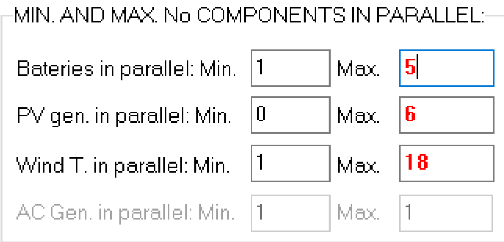
In the main screen, **CONTROL STATEGIES** tab, we uncheck the energy arbitrage (management of grid-connected batteries).



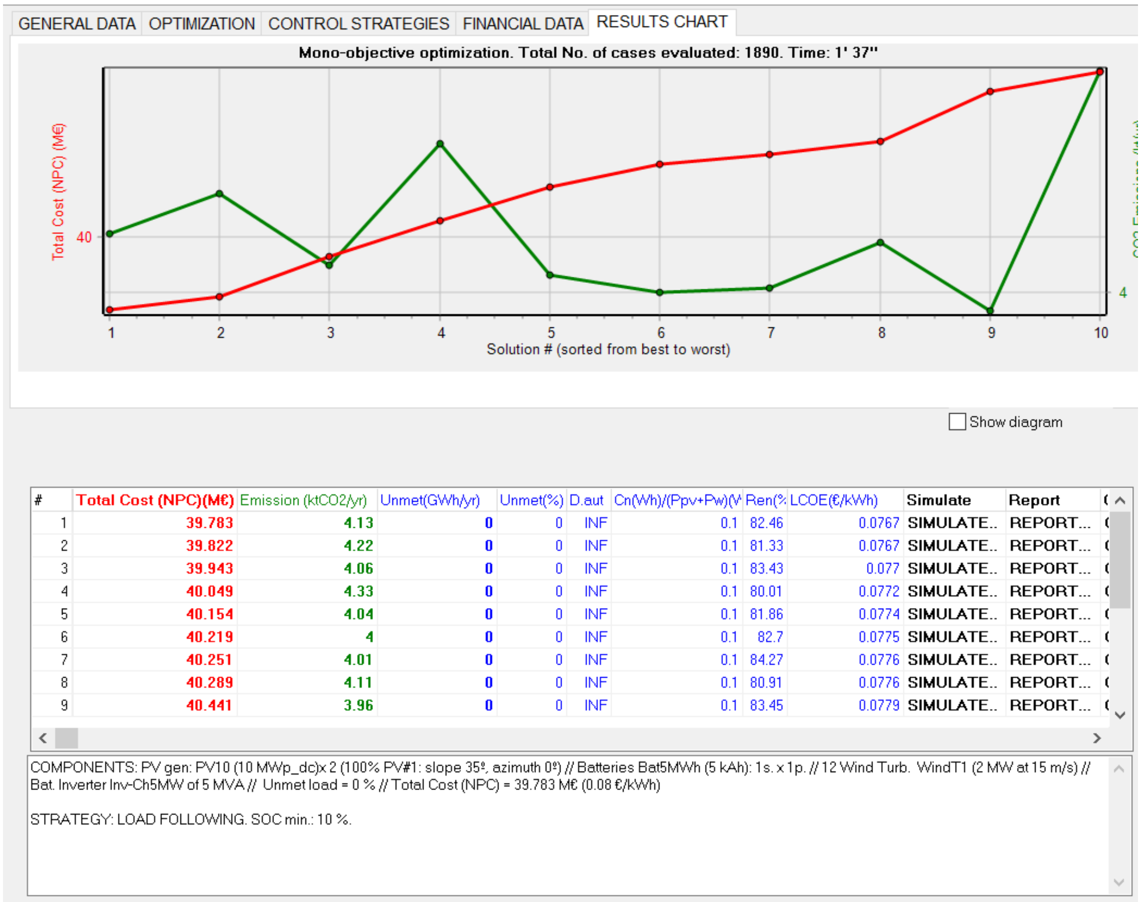
We click **PRE-SIZING** and obtain:



143 batteries in parallel is no sense, but this is the number of the default battery (5 MWh) in parallel needed to have 4 autonomy days. As there is AC grid, it has no sense, we change it to 5.

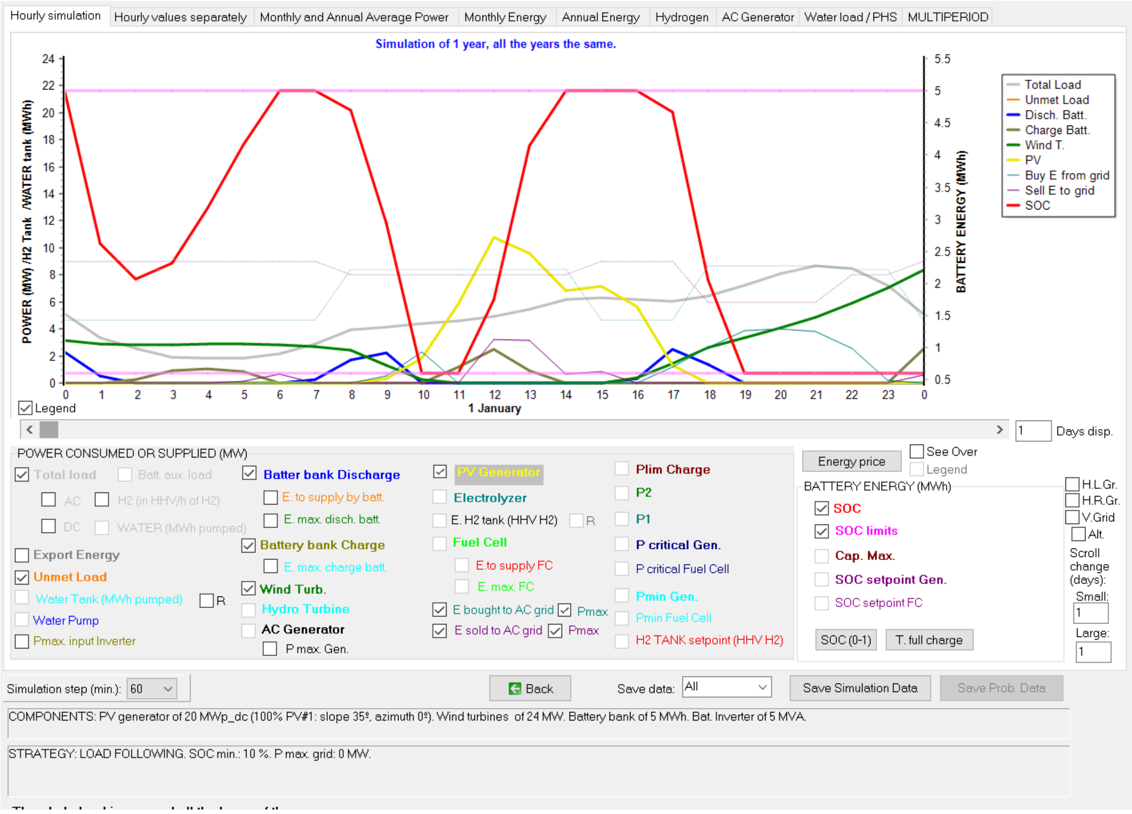


Save the project and then calculate:



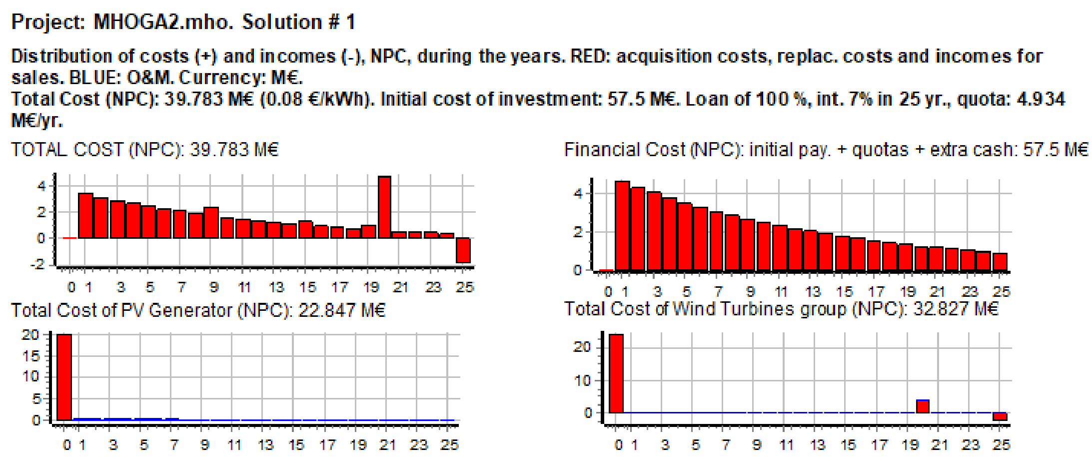
The optimal system is a PV generator of 20 MW (2x10) + 12 wind turbines of 2 MW + battery of 5 MWh + inverter-charger of 5 MVA.

The simulation of the optimal system:



We can see in purple dotted line the contracted power for the different periods (6, 8 and 9 MW), which is the same for purchasing or for selling electricity. In turquoise dotted line we can see the maximum consumed power from the grid, registered for each period and for each month. During the year we can see these values are not very different from the contract power values, so probably the contract power values are not far from the optimal.

In the main screen, in the first row of the results, if we click **COSTS**, we see the report of the costs of the optimal solution.



After closing, it asks for saving the cash flow. We say yes, and then we open it with Microsoft Excel. At the bottom we can see the results of the power registered and the power costs, for the different periods and months. We see the maximum power registered, the power to calculate the cost of the bill and the cost of the bill, for the different periods and months.

At the end it shows us the optimal contracted power so that the power cost in the bill would be minimized, in this case 6 MW for P1, 6.74 MW for P2 and 4.22 MW for P3 (if no request of increasing contracted power; if this request exists, 6 MW for all)

	A	B	C	D	E	F	G	H	I	J
43	RESULTS OF THE POWER REGISTERED AND THE POWER COSTS:									
44										
45	*RESULTS OF THE MAXIMUM POWER (MW) FROM THE GRID REGISTERED, 1st YEAR:									
46	MONTH	Period P1	Period P2	Period P3						
47	1	8.695	8.43	4.644						
48	2	8.695	8.464	5.155						
49	3	7.66	7.653	4.79						
50	4	0.663	6.641	4.424						
51	5	2.031	5.425	3.475						
52	6	2.006	4.113	3.173						
53	7	0	4.621	3.404						
54	8	0	4.498	3.565						
55	9	1.601	5.729	4.02						
56	10	6.252	6.625	4.424						
57	11	7.66	7.552	4.79						
58	12	8.695	8.464	5.155						
59	*Actual contract power is, for the different peridos: 6 MW; 8 MW; 9 MW;									
60	*RESULTS OF THE VALUE OF THE POWER (MW) TO CALCULATE THE COST OF THE POWER IN THE BILL, AND COSTS (M€), 1st YEAR:									
61	MONTH	Period P1(M	Cost 1st yr.(M	Period P2(M	Cost 1st yr.(M	Period P3(M	Cost 1st yr.(M€)			
62	1	10.79	0.0367	8.06	0.0137	7.65	0.0097			
63	2	10.79	0.0367	8.13	0.0138	7.65	0.0097			
64	3	8.72	0.0296	8	0.0136	7.65	0.0097			
65	4	5.1	0.0173	6.8	0.0116	7.65	0.0097			
66	5	5.1	0.0173	6.8	0.0116	7.65	0.0097			
67	6	5.1	0.0173	6.8	0.0116	7.65	0.0097			
68	7	5.1	0.0173	6.8	0.0116	7.65	0.0097			
69	8	5.1	0.0173	6.8	0.0116	7.65	0.0097			
70	9	5.1	0.0173	6.8	0.0116	7.65	0.0097			
71	10	6	0.0204	6.8	0.0116	7.65	0.0097			
72	11	8.72	0.0296	8	0.0136	7.65	0.0097			
73	12	10.79	0.0367	8.13	0.0138	7.65	0.0097			
74	*Total cost of the power, 1st year: 0.56 M€									
75	*If not considering that contract power of period P1 <= power of P2 <= power of P3....									
76	Optimal contract power would be: 6 MW; 6.74 MW; 4.22 MW; With a total cost of the power, 1st year: 0.507 M€									
77	*If considering that contract power of period P1 <= power of P2 <= power of P3....									
78	Optimal contract power would be: 6 MW; 6 MW; 6 MW; With a total cost of the power, 1st year: 0.561 M€									

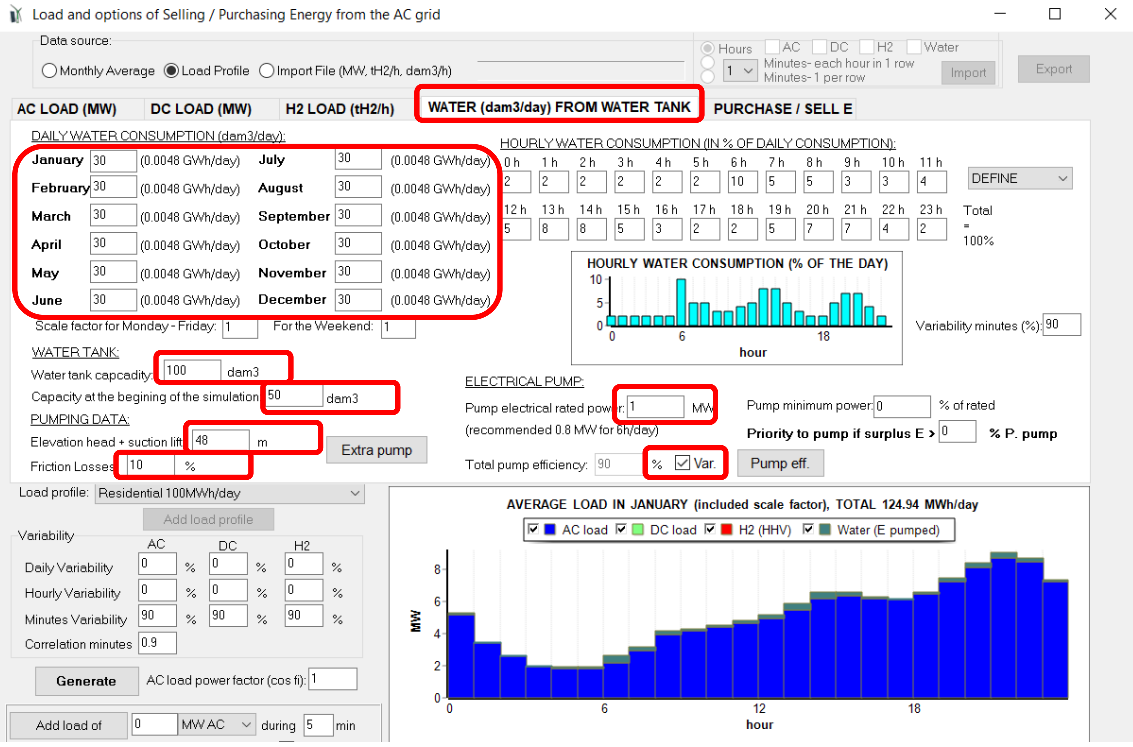
Save the project.

38. Add water load consumption.

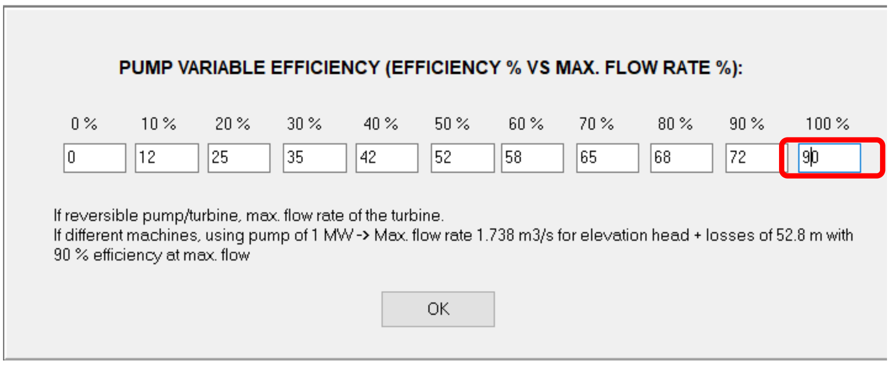
Save the previous project (“MHOGA2.mho”) with the name “MHOGA2-Water.mho” **(Project->Save as).**

We will add water consumption of 30 dam^3/day. Water comes from a tank or reservoir of 100 dam^3, which is previously pumped from a river with an elevation head + suction lift of 48 m, and friction losses in pumping are 10%. Let’s suppose that at the beginning of the simulation the tank is at 50% capacity (50 dam^3). The pump power is 1 MW and its efficiency is variable.

In LOAD/AC GRID screen, WATER tab, set these values:



Now let’s select the variable efficiency of the pump, by clicking the button “**Pump eff.**”. A small window appears where we can change the efficiency values (%) vs the % of maximum flow rate, where maximum flow rate is calculated considering the pump rated power, the total head with losses and the pump efficiency at maximum flow.

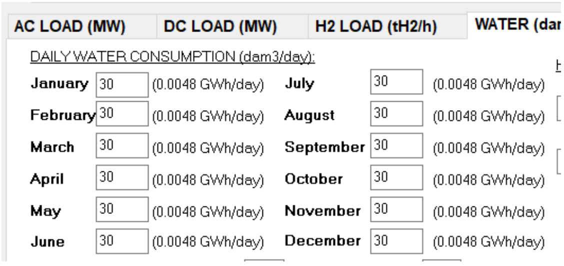


We change the value for 100% maximum flow, supposing efficiency is 90% and we leave the rest of the values by default. It shows that the maximum flow rate for 1 MW, 52.8 m head (inc. friction losses) and 90% pump efficiency is 1.738 m^3/s.

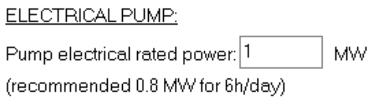
As for low % of max. flow rate the efficiency is low, the NPC of the results will be higher than if we would have chosen fixed efficiency.

We click in OK.

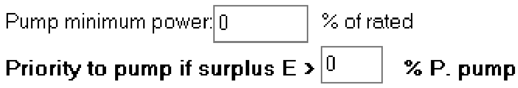
When we set the daily water consumption for each month, MHOGA calculates the pumped energy needed for pumping that water, considering the elevation head and losses, as we can see in GWh in brackets close to the values of the daily water consumption introduced previously:



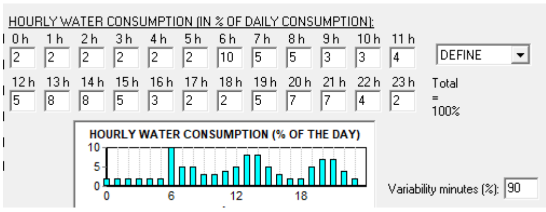
MHOGA recommends a 0.8 MW pump (below the pump power) to pump the load consumption in 6 h/day.



Minimum pump power (%) by default is 0% and also the priority to pump (when there is surplus power from the renewable sources) is when it is higher than 0% (that is, whenever there is surplus power from renewable, it will be used to pump first, and, if there is still surplus power, it will be used to charge the batteries):

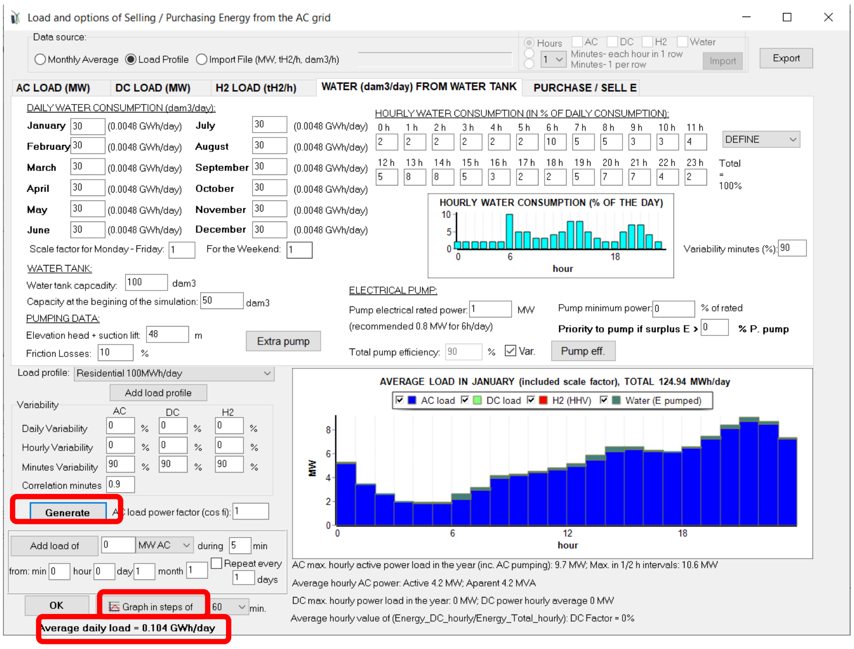


The water consumption distribution during the day (%, sum is 100%) is shown in a graph, we can change it but we will leave the default values.

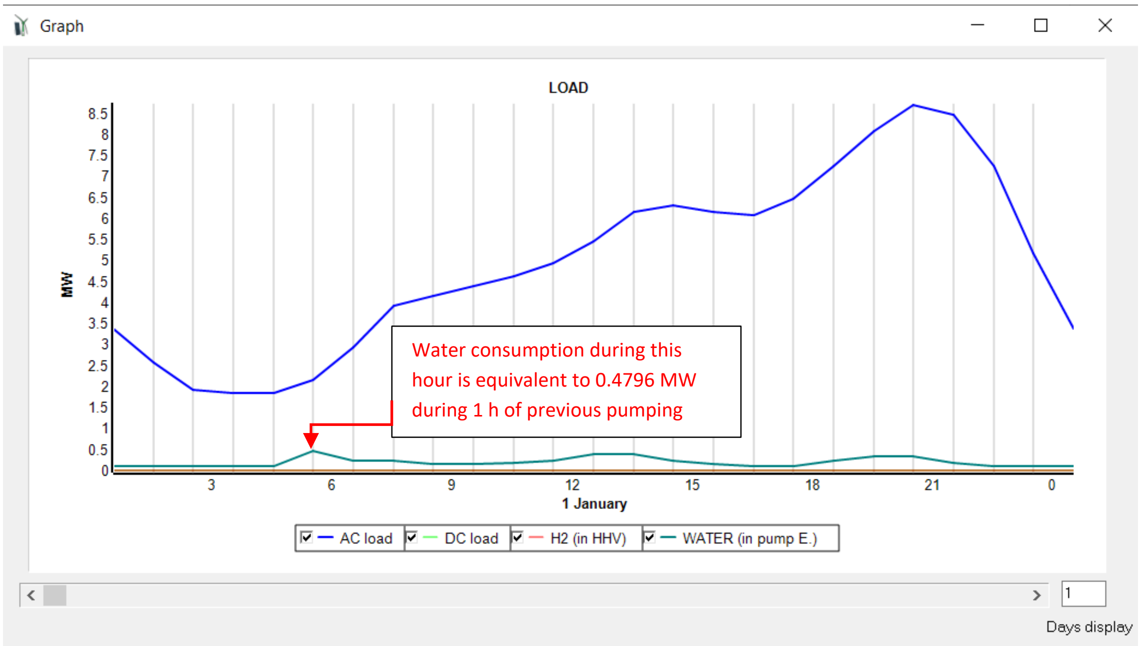


If you change it, all the values added must be 100%, obviously.

Now we click in "**Generate**" button and the total average daily load raises to 0.104 GWh/day. We can see graph of the average day load consumption for a specific month (depending on the last month that was clicked) in the right (if you click in the daily water consumption of other month, this graph shows its corresponding average daily load).



We can see the load consumption graph witt "**Graph in steps of**" button. If selected 60 min:



AC power consumption is shown in blue color and in turquoise color is water consumption (the 30 dam^3/day are converted to dam^3/h considering the distribution of the hourly water consumption and translated to MW previously pumped, taking into account the elevation head and losses). For example, in 1st January the water consumption in the hour that goes between 6 and 7 h a.m. is 10% of the day (10/100·30 = 3 dam^3), which will have been previously pumped a height of 48 m plus 10% friction losses (equivalent to a total height of 52.8 m) with a 90% max. flow efficiency pump. The energy needed to pre-pump that volume of water is:

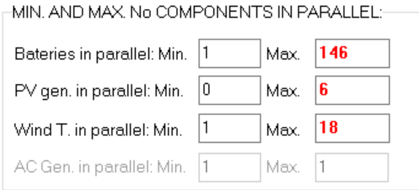
$$E = volume \cdot density \cdot g \cdot height \cdot (1+friction\_losses)/Efficiency =$$

$$=3000m^3 \cdot 1000kg/m^3 \cdot 9.81m/s^2 \cdot 48m \cdot (1+0.1)/0.9 = 1726560000\ \ J = 0.4796\ MWh.$$

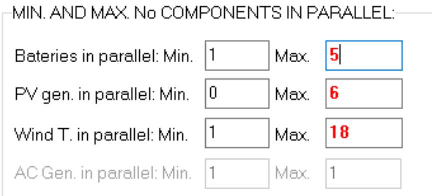
That is, equivalent to a consumption of 0.4796 MW during that hour, as shown in the graph.

We return to the main screen of the program.

We do pre-sizing (button “PRES-SIZING”), obtaining these maximum recommended values:

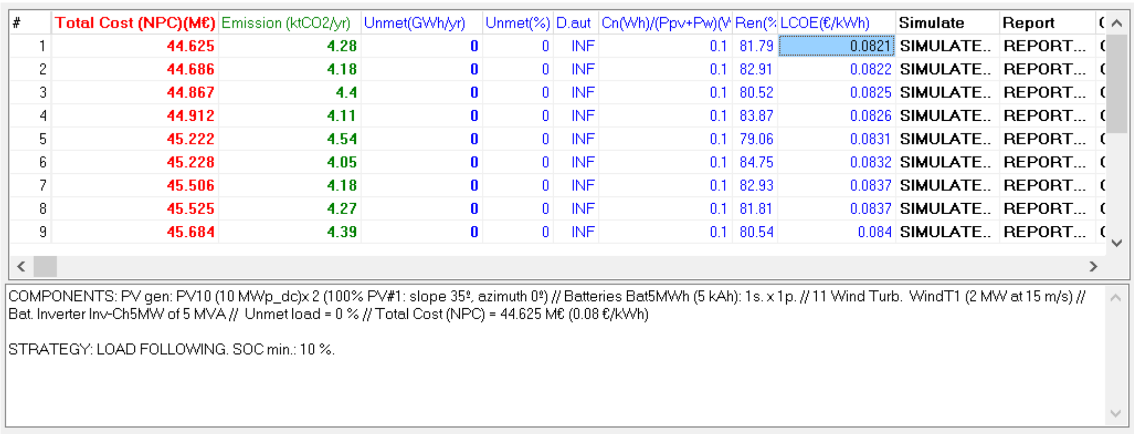


As we said before, the max. number of batteries in parallel has no sense as there is AC grid, therefore we will limit it to for example 5:



Now, save the project and then click in CALCULATE.

After 1 or 2 minutes we get:

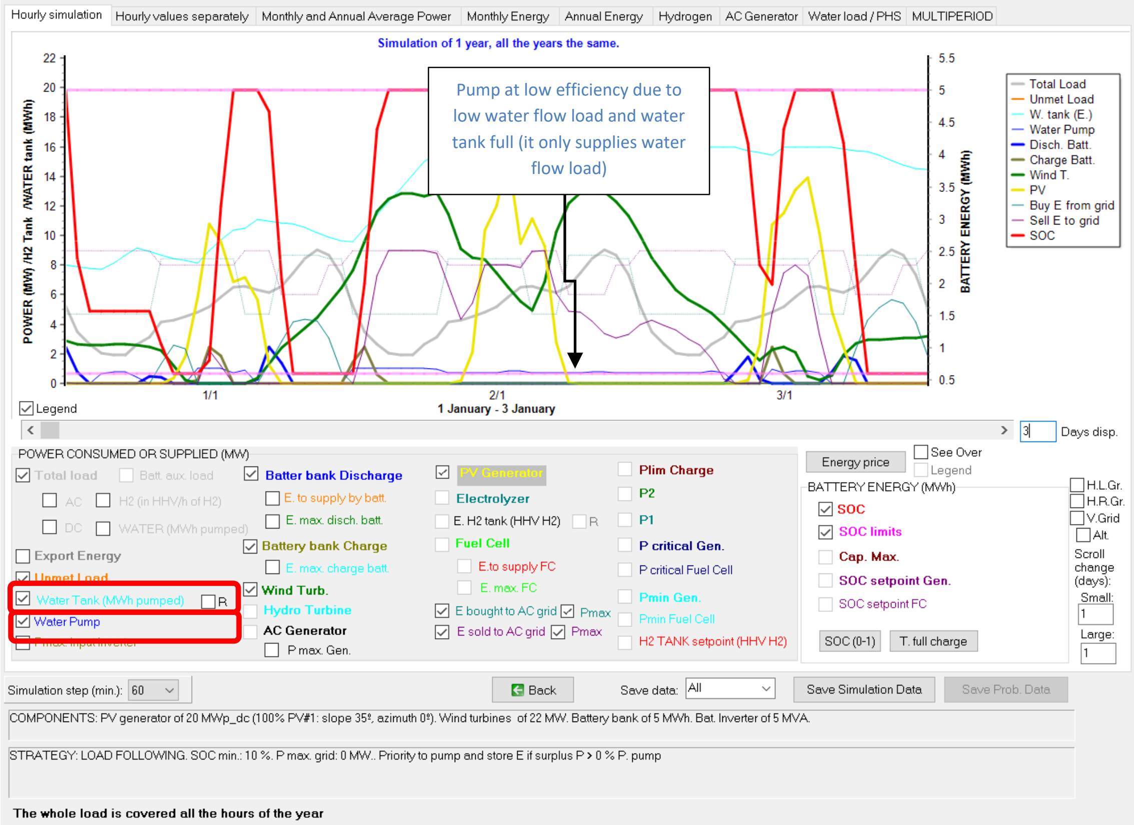


#	Total Cost (NPC)(M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(V	Ren(%	LCOE(€/kWh)	Simulate	Report	(
1	44.625	4.28	0	0	INF	0.1	81.79	0.0821	SIMULATE..	REPORT...	(
2	44.686	4.18	0	0	INF	0.1	82.91	0.0822	SIMULATE..	REPORT...	(
3	44.867	4.4	0	0	INF	0.1	80.52	0.0825	SIMULATE..	REPORT...	(
4	44.912	4.11	0	0	INF	0.1	83.87	0.0826	SIMULATE..	REPORT...	(
5	45.222	4.54	0	0	INF	0.1	79.06	0.0831	SIMULATE..	REPORT...	(
6	45.228	4.05	0	0	INF	0.1	84.75	0.0832	SIMULATE..	REPORT...	(
7	45.506	4.18	0	0	INF	0.1	82.93	0.0837	SIMULATE..	REPORT...	(
8	45.525	4.27	0	0	INF	0.1	81.81	0.0837	SIMULATE..	REPORT...	(
9	45.684	4.39	0	0	INF	0.1	80.54	0.084	SIMULATE..	REPORT...	(

COMPONENTS: PV gen: PV10 (10 MWp_dc)x 2 (100% PV#1: slope 35º, azimuth 0º) // Batteries Bat5MWh (5 kAh): 1s. x 1p. // 11 Wind Turb. WindT1 (2 MW at 15 m/s) // Bat. Inverter Inv-Ch5MW of 5 MVA // Unmet load = 0 % // Total Cost (NPC) = 44.625 M€ (0.08 €/kWh)

STRATEGY: LOAD FOLLOWING. SOC min.: 10 %.

The optimal includes 20 MW of PV, 11 wind turbines of 2 MW, battery of 5 MWh and inverter of 5 MVA. The simulation of the optimal (1st row) for 3 days:



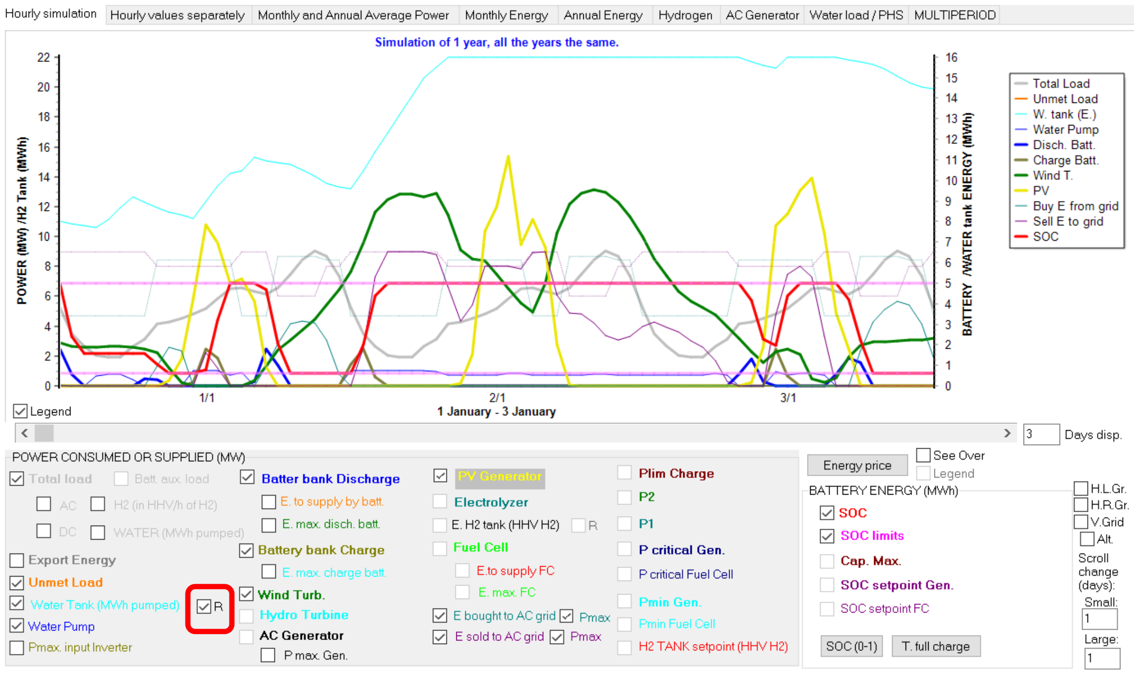
Simulation for the first 3 days of January. We can see the water tank energy in light blue, referred to the left axis ("**R**" is not checked") we can see the maximum energy in the water tank is around 16 MWh:

$$E = volume \cdot density \cdot g \cdot height \cdot (1+friction\_losses)/Efficiency =$$

$$=100000m^3 \cdot 1000kg/m^3 \cdot 9.81m/s^2 \cdot 48m \cdot (1+0.1)/0.9 = 5.755E10 \ \ J = 15.98 \ MWh.$$

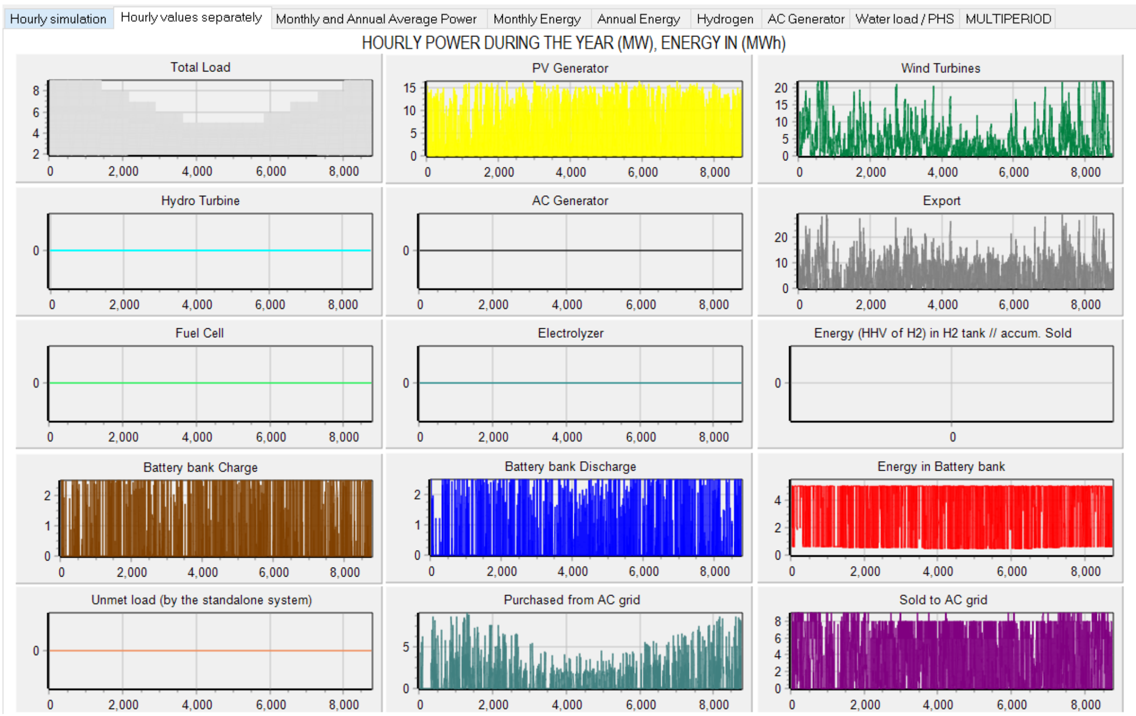
In dark blue, thin line, we can see the pump power. During the hours with low power from renewable sources, water is consumed from the tank (if tank has enough water) and the AC load not covered by the renewable sources is supplied by the battery bank (dark blue thick line, if it has enough energy; if not, it is covered by purchasing from the AC grid, turquoise thin line). During the hours when the renewable power is high, it supplies the AC load and with the surplus power the pump works to supply the water load and to store water in the tank; if the surplus power is higher than the rated power of the pump (1 MW) the batteries are charged (brown line). We can see during the hours when water load is low and water tank is full, the pump power is relatively high due to the low efficiency of the pump when it pumps low water flow.

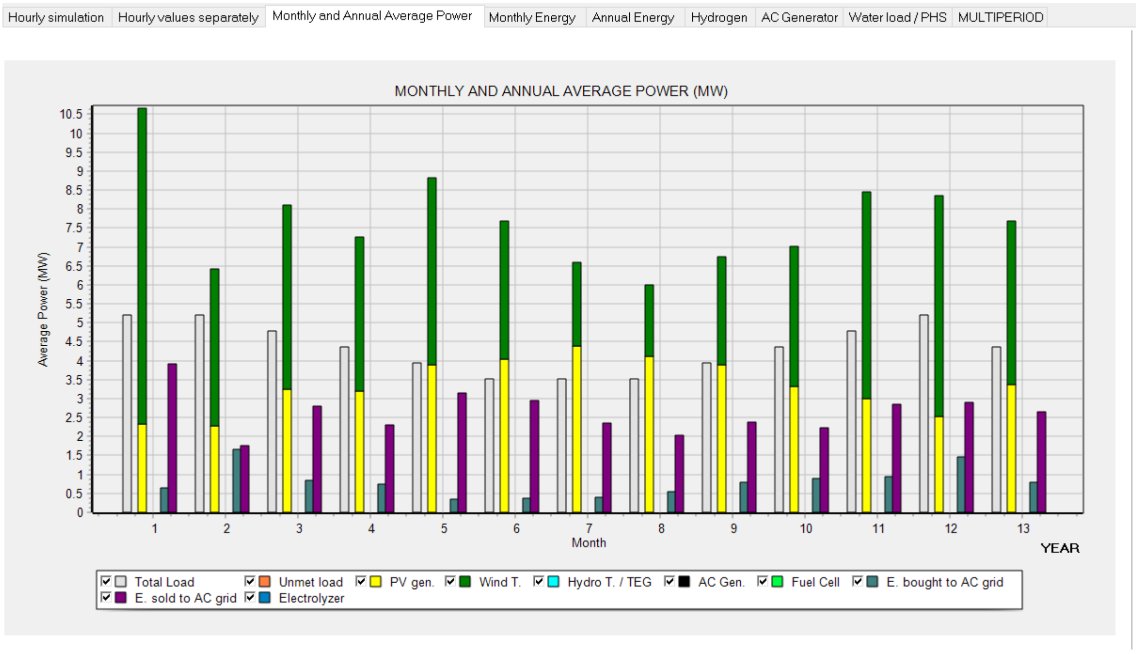
If we click in "**R**", it will be referred to the right axis:

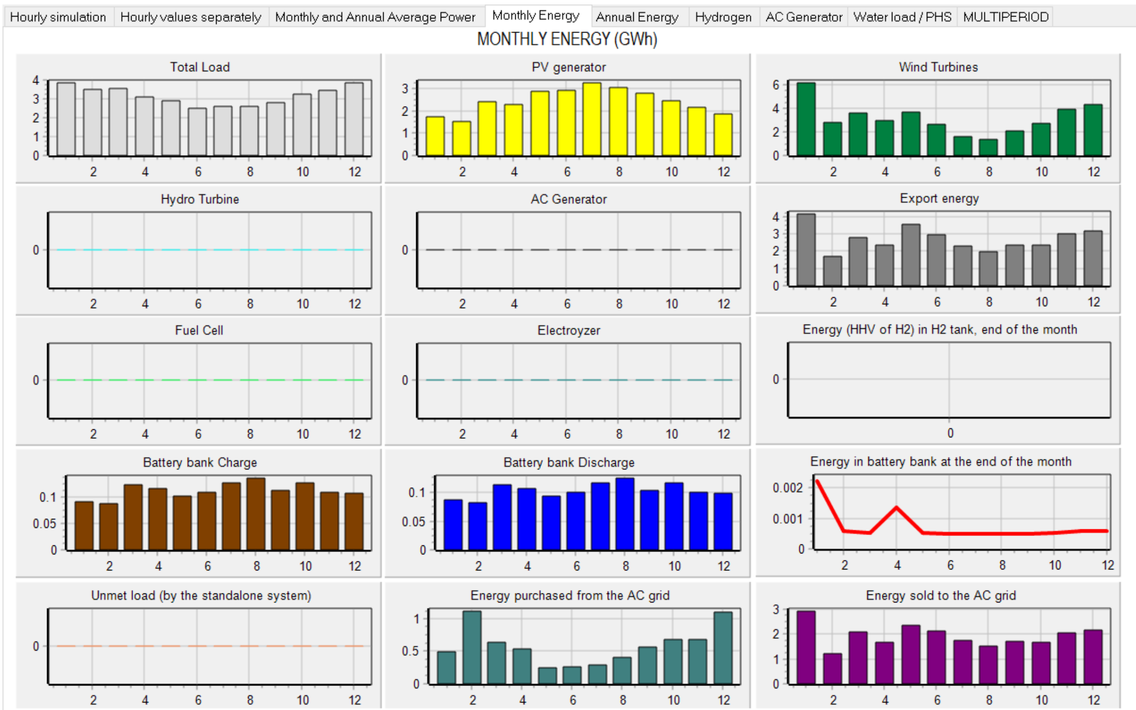


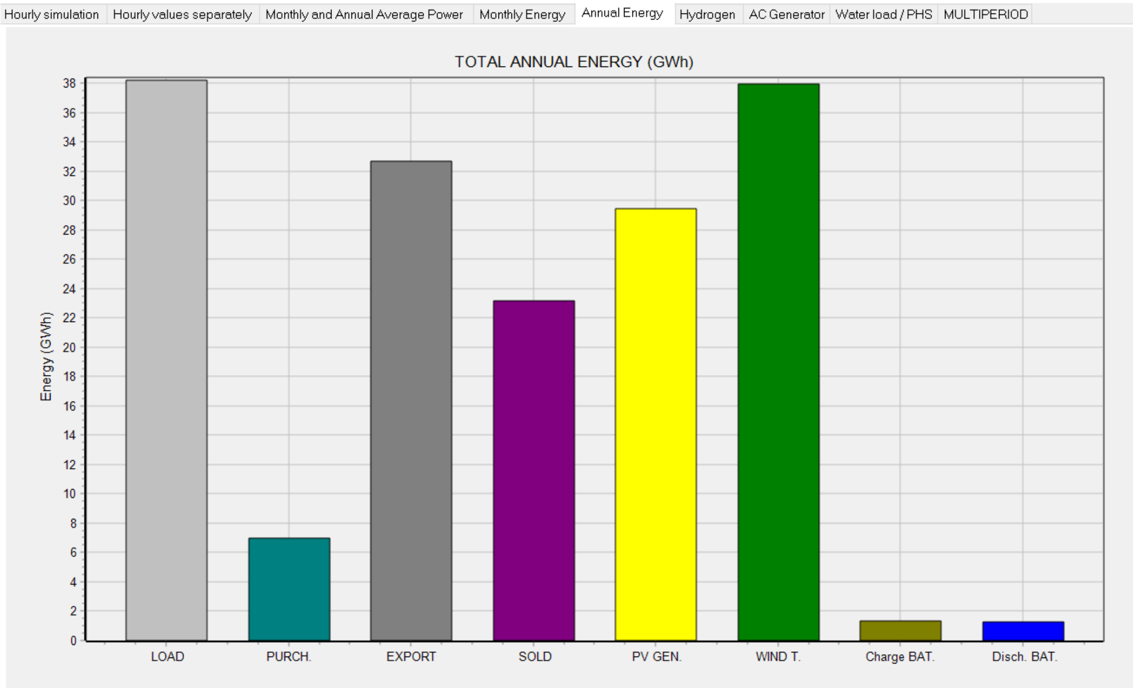
If there are many curves in the graph, we can uncheck some of them.

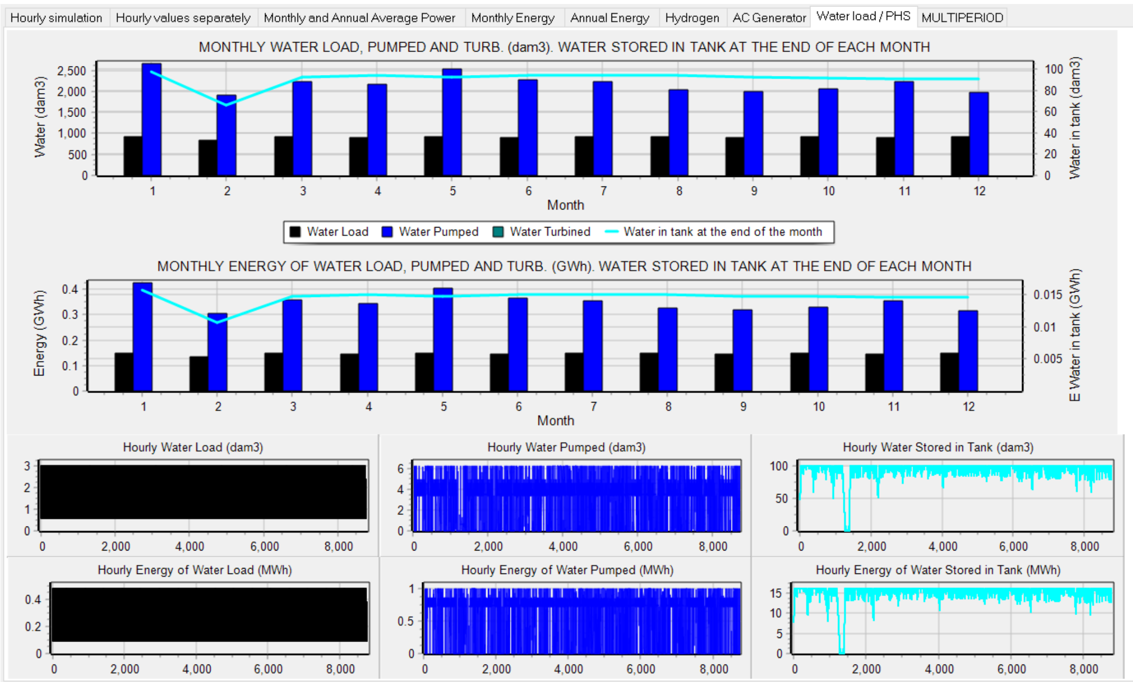
In the rest of the tabs:



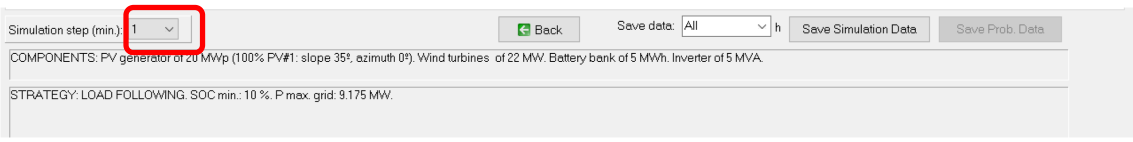

Hourly simulation
Hourly values separately
Monthly and Annual Average Power
Monthly Energy
Annual Energy
Hydrogen
AC Generator
Water load / PHS
MULTIPERIOD
MONTHLY AND ANNUAL AVERAGE POWER (MW)
Average Power (MW)
Month
YEAR
Total Load
Unmet load
PV gen.
Wind T.
Hydro T. / TEG
AC Gen.
Fuel Cell
E. bought to AC grid
E. sold to AC grid
Electrolyzer


Hourly simulation
Hourly values separately
Monthly and Annual Average Power
Monthly Energy
Annual Energy
Hydrogen
AC Generator
Water load / PHS
MULTIPERIOD
MONTHLY ENERGY (GWh)
Total Load
PV generator
Wind Turbines
Hydro Turbine
AC Generator
Export energy
Fuel Cell
Electroyzer
Energy (HHV of H2) in H2 tank, end of the month
Battery bank Charge
Battery bank Discharge
Energy in battery bank at the end of the month
Unmet load (by the standalone system)
Energy purchased from the AC grid
Energy sold to the AC grid

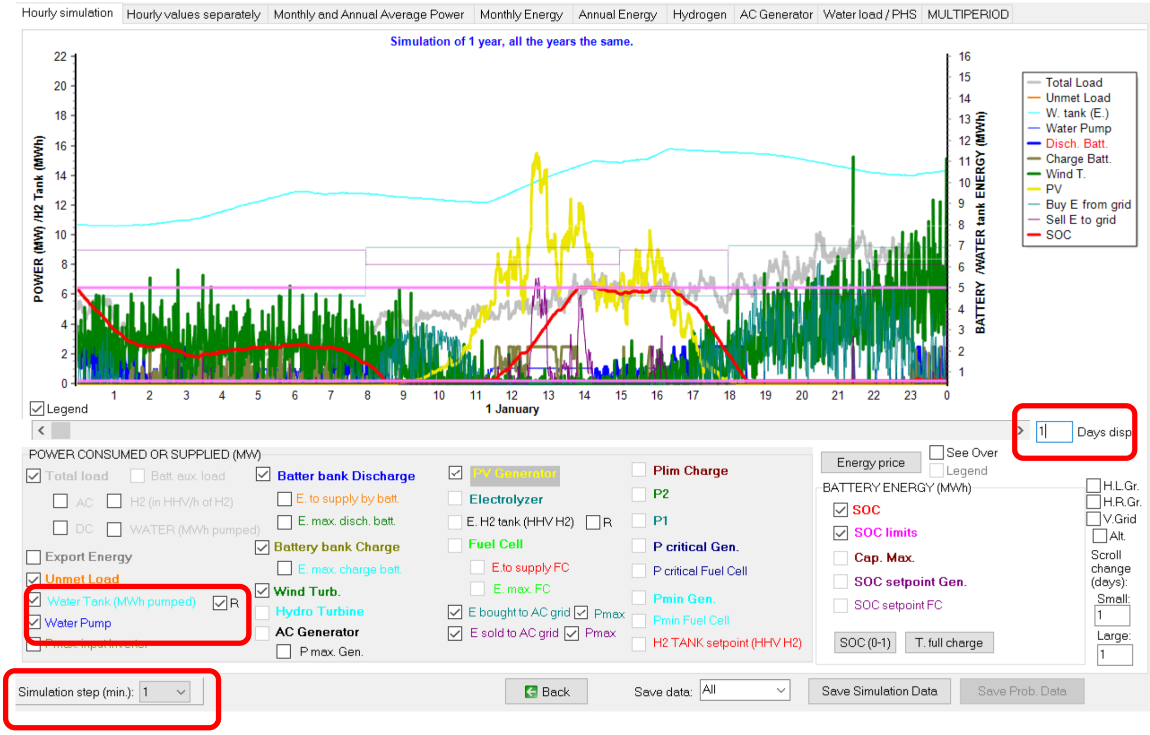




Save the project and then save it with the name “MHOGA2-Water-min.mho” **(Project->Save as)** because now we will change to 1 minute time step.



Go to the simulation screen of the optimal solution, tab “Hourly simulation” and change the time step to 1 minute (please, be patient, it can take even more than 1 minute depending on the computer speed as it has to simulate all the minutes of the year and all the variables must be shown), and, in the first tab we see (1 day display, january 1st):

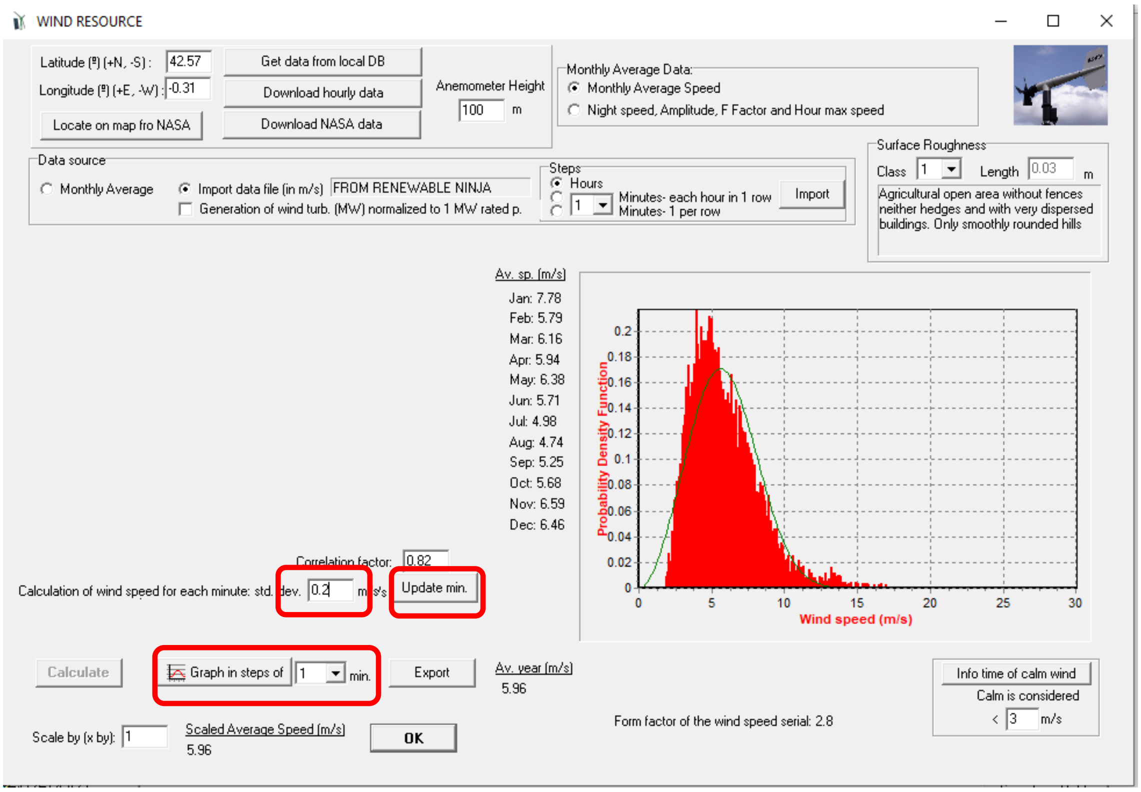


We can see the wind generation variability is very high. If we go back to the main screen, in the results table we can see the first row results has been updated to the simulation in 1 minute step:

Gen.	Total Cost (NPC)(M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(W	Ren(%	LCOE(€/kWh)	Simulate	Report	(
1	45.333	4.17	0	0	INF	0.1	82.57	0.0834	SIMULATE..	REPORT...	(

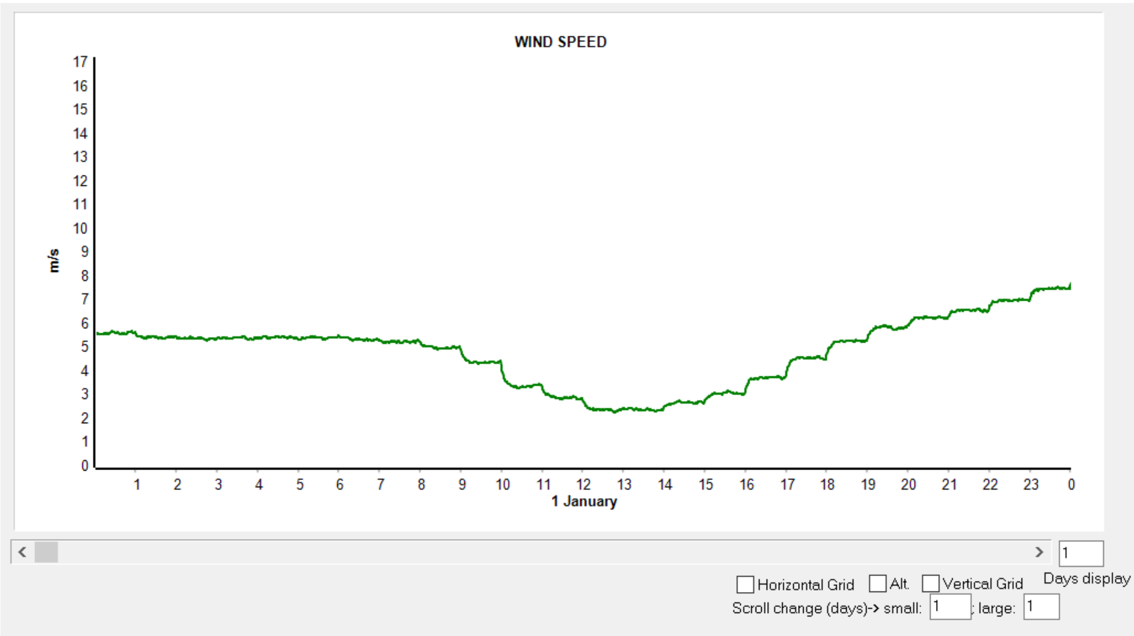
Remember that these results in minutes time steps can vary for each computer, as the wind speed in minutes steps are obtained with a certain randomness.

If we go to the **WIND** screen, we can change the standard deviation to calculate the wind speed in 1 minute time steps (from the hourly downloaded or calculated values), default is 1 m/s, but it implies high variability, we change to 0.2 m/s.



Then click in "**Update min.**", this way the calculation of the wind speed in minutes time step is redone.

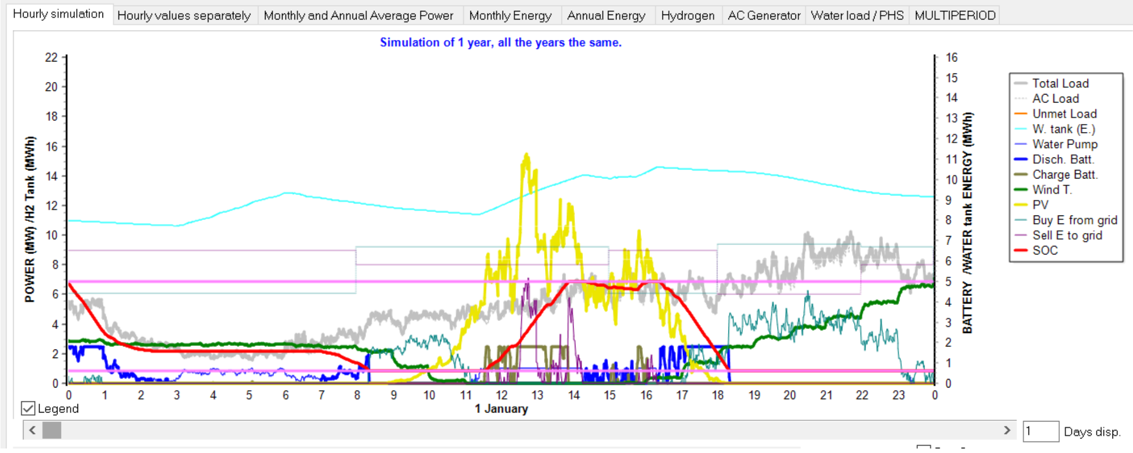
Then click in **Graph in steps of** 1 min:



Now variability is much lower.

Back and OK.

In the main screen of the software, if now we click in the first row of the results table in **SIMULATE**, we see the optimal solution simulated in steps of 1 min, now we can see the wind generation variation is much lower.



And results are updated:

Gen.	Total Cost (NPC)(M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(W	Ren(%	LCOE(€/kWh)	Simulate	Report
1	45.931	4.3	0	0	INF	0.1	81.65	0.0845	SIMULATE...	REPORT...

Save the project.

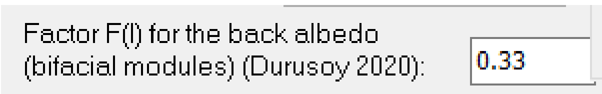
<u>39. Consider bifacial PV modules.</u>

Save the project and then open the previous project “MHOGA2-Water.mho”. Then, save it with the name “MHOGA2-Water-bifac.mho”.

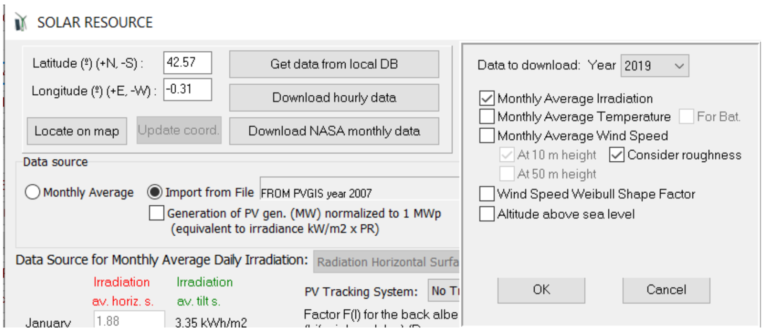
We want to consider bifacial PV modules. Let’s suppose that they are 10% more expensive than the normal PV modules, and the bifaciality factor is 0.7. We want to consider the previous PV generator of 10 MWp but also a new PV generator of bifacial PV modules, of 10 MWp nominal power (of the front surface) with a bifaciality of 0.7 and the cost of 11 M€ (10% higher).

To consider bifacial PV modules, you first need to calculate the irradiation over the back surface of the PV modules.

Go to the irradiation screen. We will consider the default value for the factor for the back albedo, F(l) = 0.33:

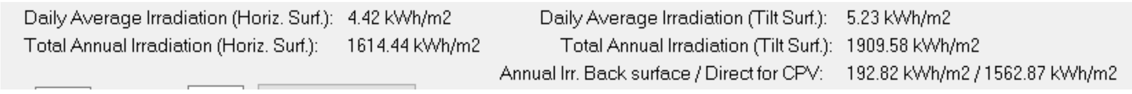


We need to use average monthly values for the irradiation so that we can calculate the back surface irradiation. Click in “**Download NASA monthly data**”, and **<u>deselect all the data except for the Monthly Average Irradiation</u>**.

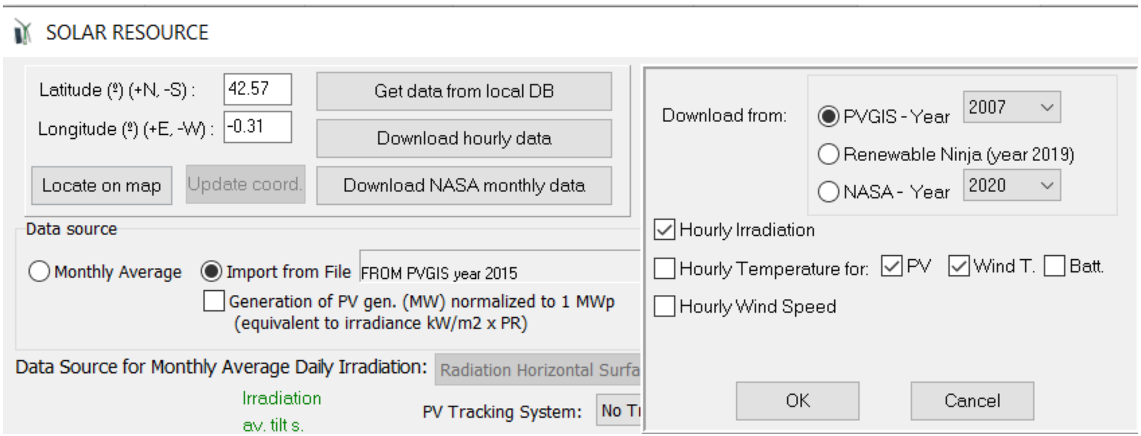


We download the average monthly irradiation. Then, save the project and click in button **Calculate**.

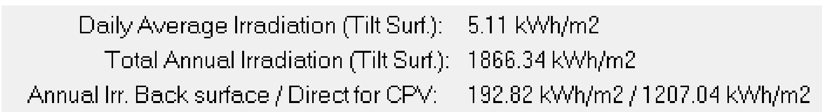
It calculates and we obtain similar irradiation as before for the front surface (see the text under the graph). For the back surface, 192.82 kWh/m^2 is the total irradiation of the year.



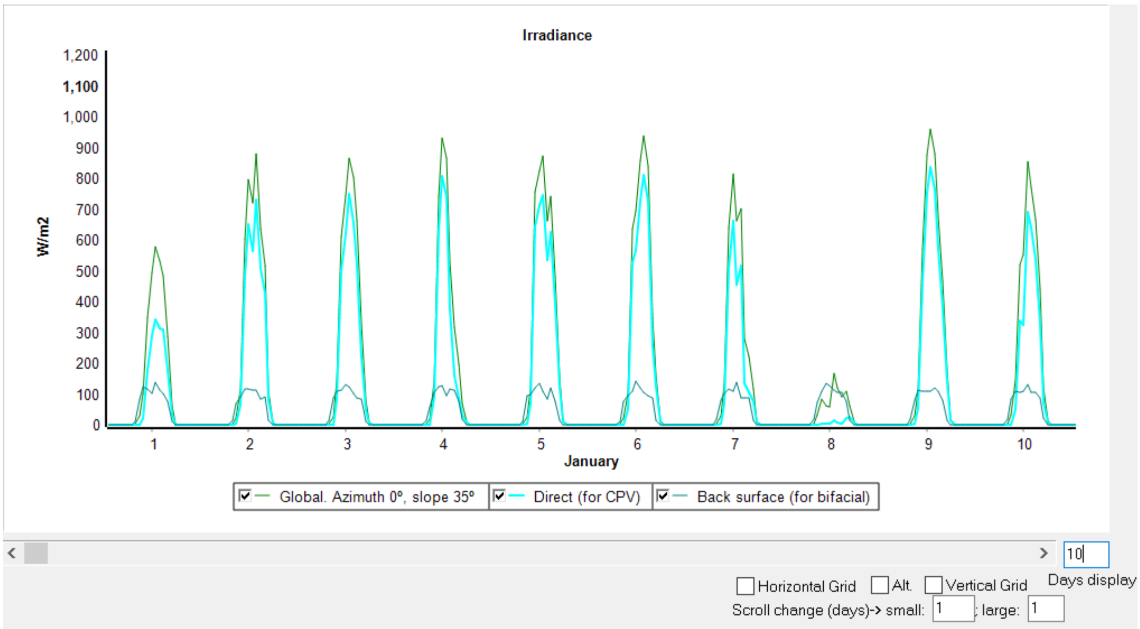
Now we will use the same values for the front surface as previously, so we will download hourly irradiation data from PVGIS, 2007 (**<u>just hourly irradiation, uncheck the other data</u>**):



After downloading, we can see the values of irradiation over the front surface, but also the irradiation over the back surface calculated before:



In the graph we see both data (front surface in green, back surface in light blue):



Accept and go to the PV generators screen. Add from the database the PV10-BIF, bifacial PV generator wit cost 11 M€ and bifaciality 0.7.

PHOTOVOLTAIC GENERATOR DATA:

Name	Power(MWp)	Cost(M€)	C.O&M(%/yr)	Life(years)	NOCT(ºC)	Power T. coef.(%/ºC)	BIFACIALITY(0-1)	CPV	missions(kgCO2/kWp
PV10	10	10	1	25	43	-0.4	0	NO	800
PV10-BIF	10	11	1	25	43	-0.4	0.7	NO	800

Therefore, we will consider two PV generators: the normal one and the bifacial one.

Accept and, in the main screen of the software, save the project and then CALCULATE.

The optimal system includes the normal PV generator, in this case, as its cost is lower than the bifacial PV generator, although the PV production is a little lower.

#	Total Cost (NPC)(M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(V	Ren(%	LCOE(€/kWh)	Simulate	Report	(
1	44.597	4.28	0	0	INF	0.1	81.77	0.082	SIMULATE..	REPORT...	(
2	44.676	4.18	0	0	INF	0.1	82.88	0.0821	SIMULATE..	REPORT...	(
3	44.824	4.4	0	0	INF	0.1	80.51	0.0824	SIMULATE..	REPORT...	(
4	44.909	4.11	0	0	INF	0.1	83.85	0.0826	SIMULATE..	REPORT...	(
5	45.167	4.55	0	0	INF	0.1	79.04	0.083	SIMULATE..	REPORT...	(
6	45.258	4.16	0	0	INF	0.1	82.55	0.0832	SIMULATE..	REPORT...	(
7	45.28	4.06	0	0	INF	0.1	84.67	0.0833	SIMULATE..	REPORT...	(
8	45.347	4.07	0	0	INF	0.1	83.64	0.0834	SIMULATE..	REPORT...	(
9	45.431	4.28	0	0	INF	0.1	81.3	0.0835	SIMULATE..	REPORT...	(

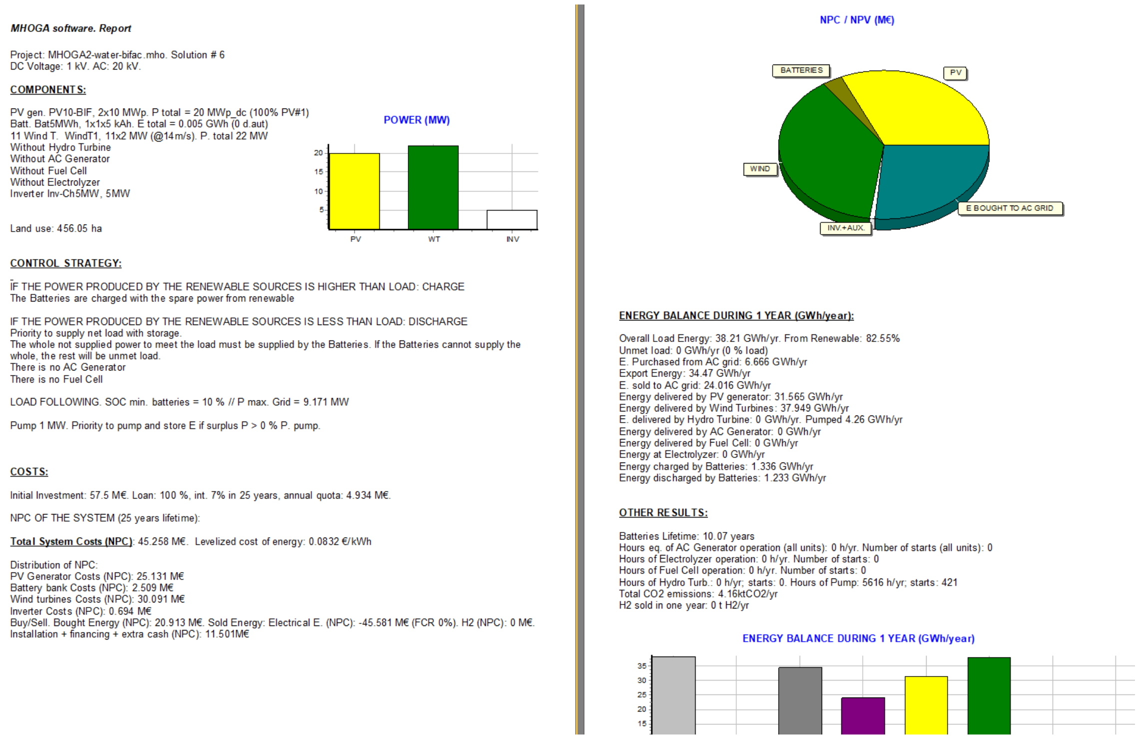
COMPONENTS: PV gen: PV10 (10 MWp_dc)x 2 (100% PV#1: slope 35º, azimuth 0º) // Batteries Bat5MWh (5 kAh): 1s. x 1p. // 11 Wind Turb. WindT1 (2 MW at 15 m/s) // Bat. Inverter Inv-Ch5MW of 5 MVA // Unmet load = 0 % // Total Cost (NPC) = 44.597 M€ (0.08 €/kWh)

STRATEGY: LOAD FOLLOWING. SOC min.: 10 %.

The 6th best solution includes bifacial PV generator (its PV generation is a bit higher than the first five solutions, due to bifaciality):

SOCmin (%)	Pmax Grid (MW)	Etotal(GWh)	Eren(GWh)	Epv(GWh)	Ew(GWh)	Et(GWh)	E export(GWh)	E Sell(GWh)	E Buy
10	0	38.21	67.369	29.42	37.949	0	32.709	23.185	
10	0	38.21	70.819	29.42	41.398	0	35.547	24.452	
10	0	38.21	63.919	29.42	34.499	0	29.941	21.861	
10	0	38.21	74.269	29.42	44.848	0	38.448	25.687	
10	0	38.21	60.469	29.42	31.049	0	27.263	20.498	
10	0	38.21	69.514	31.565	37.949	0	34.47	24.016	
10	0	38.21	77.719	29.42	48.298	0	41.414	26.896	
10	0	38.21	72.963	31.565	41.398	0	37.327	25.272	
10	0	38.21	66.064	31.565	34.499	0	31.686	22.711	

We can see the report of the sixth best solution, first one which includes bifacial:



MHOGA software. Report

Project: MHOGA2-water-bifac.mho. Solution # 6
DC Voltage: 1 kV. AC: 20 kV.

COMPONENTS:

PV gen. PV10-BIF, 2x10 MWp. P total = 20 MWp_dc (100% PV#1)
Batt. Bat5MWh, 1x1x5 kAh. E total = 0.005 GWh (0 d.aut)
11 Wind T. WindT1, 11x2 MW (@14m/s). P. total 22 MW
Without Hydro Turbine
Without AC Generator
Without Fuel Cell
Without Electrolyzer
Inverter Inv-Ch5MW, 5MW

Land use: 456.05 ha

CONTROL STRATEGY:

IF THE POWER PRODUCED BY THE RENEWABLE SOURCES IS HIGHER THAN LOAD: CHARGE
The Batteries are charged with the spare power from renewable

IF THE POWER PRODUCED BY THE RENEWABLE SOURCES IS LESS THAN LOAD: DISCHARGE
Priority to supply net load with storage.
The whole not supplied power to meet the load must be supplied by the Batteries. If the Batteries cannot supply the whole, the rest will be unmet load.
There is no AC Generator
There is no Fuel Cell

LOAD FOLLOWING. SOC min. batteries = 10 % // P max. Grid = 9.171 MW

Pump 1 MW. Priority to pump and store E if surplus P > 0 % P. pump.

COSTS:

Initial Investment: 57.5 M€. Loan: 100 %, int. 7% in 25 years, annual quota: 4.934 M€.

NPC OF THE SYSTEM (25 years lifetime):

Total System Costs (NPC): 45.258 M€. Levelized cost of energy: 0.0832 €/kWh

Distribution of NPC:
PV Generator Costs (NPC): 25.131 M€
Battery bank Costs (NPC): 2.509 M€
Wind turbines Costs (NPC): 30.091 M€
Inverter Costs (NPC): 0.694 M€
Buy/Sell. Bought Energy (NPC): 20.913 M€. Sold Energy: Electrical E. (NPC): -45.581 M€ (FCR 0%). H2 (NPC): 0 M€.
Installation + financing + extra cash (NPC): 11.501M€

ENERGY BALANCE DURING 1 YEAR (GWh/year):

Overall Load Energy: 38.21 GWh/yr. From Renewable: 82.55%
Unmet load: 0 GWh/yr (0 % load)
E. Purchased from AC grid: 6.666 GWh/yr
Export Energy: 34.47 GWh/yr
E. sold to AC grid: 24.016 GWh/yr
Energy delivered by PV generator: 31.565 GWh/yr
Energy delivered by Wind Turbines: 37.949 GWh/yr
E. delivered by Hydro Turbine: 0 GWh/yr. Pumped 4.26 GWh/yr
Energy delivered by AC Generator: 0 GWh/yr
Energy delivered by Fuel Cell: 0 GWh/yr
Energy at Electrolyzer: 0 GWh/yr
Energy charged by Batteries: 1.336 GWh/yr
Energy discharged by Batteries: 1.233 GWh/yr

OTHER RESULTS:

Batteries Lifetime: 10.07 years
Hours eq. of AC Generator operation (all units): 0 h/yr. Number of starts (all units): 0
Hours of Electrolyzer operation: 0 h/yr. Number of starts: 0
Hours of Fuel Cell operation: 0 h/yr. Number of starts: 0
Hours of Hydro Turb.: 0 h/yr; starts: 0. Hours of Pump: 5616 h/yr; starts: 421
Total CO2 emissions: 4.16ktCO2/yr
H2 sold in one year: 0 t H2/yr

40. Consider CPV

Save the previous project and then save as with the name “MHOGA2-Water-CPV.mho”.

Let’s consider a normal PV generator of 10 MWp and a Concentrating PV generator (CPV) of 10 MWp from de database. Both will be with sun tracking system in both axes.

In the irradiation screen, select for the PV tracking system: both axes:

PV Tracking System: Both Axis

Now download hourly data from PVGIS, 2007, only irradiation. The irradiation for the both axes tracking system will be downloaded:

Daily Average Irradiation (Tilt Surf.): 6.63 kWh/m2
Total Annual Irradiation (Tilt Surf.): 2420.63 kWh/m2
Annual Irr. Back surface / Direct for CPV: 192.82 kWh/m2 / 1677.09 kWh/m2

Global annual irradiation is 2420.63 kWh/m2 while direct is 167 (much higher values than previously with fixed tilt angle of 35º).

In the PV screen, change the bifacial PV for the CPV of the database (CPV10). Then, modify the names of the generator PV10 adding “-T2axes” to increase the costs to 13 M€ adding the cost of the tracking in two axes. We suppose the CPV10 already includes this cost.

PHOTOVOLTAIC GENERATOR DATA:

Name	Power(MWp_dc)	Cost(M€)	C.O&M(%/yr)	Life(years)	NOCT(ºC)	Power T. coef.(%/ºC)	BIFACIALITY(0-1)	CPV	Emissions(kgCO2/kWp
PV10-T2axes	10	13	1	25	43	-0.4	0	NO	800
CPV10	10	12	1	25	43	-0.14	0	OK	800

CPV will produce lower electrical generation as direct irradiation is lower than global. However, depending on the total cost of the PV and the CPV generator (including tracking system), the optimal solution can include PV or CPV.

Optimize the system. In this case, the normal PV is better than the CPV. The optimal system includes normal PV, 1 generator of PV10-T2axes.

#	Total Cost (NPC)(M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(W	Ren(%	LCOE(€/kWh)	Simulate	Report	(
1	44.831	4.02	0	0	INF	0.1	82.33	0.0824	SIMULATE..	REPORT...	(
2	44.855	3.96	0	0	INF	0.1	83.23	0.0825	SIMULATE..	REPORT...	(
3	44.971	4.1	0	0	INF	0.1	81.31	0.0827	SIMULATE..	REPORT...	(
4	45.053	3.91	0	0	INF	0.1	84.01	0.0828	SIMULATE..	REPORT...	(
5	45.342	4.29	0	0	INF	0.1	81.24	0.0834	SIMULATE..	REPORT...	(
6	45.348	4.21	0	0	INF	0.2	80.13	0.0834	SIMULATE..	REPORT...	(
7	45.398	4.43	0	0	INF	0.1	79.84	0.0835	SIMULATE..	REPORT...	(
8	45.41	3.88	0	0	INF	0.1	84.7	0.0835	SIMULATE..	REPORT...	(
9	45.482	4.18	0	0	INF	0.1	82.44	0.0836	SIMULATE..	REPORT...	(

COMPONENTS: PV gen: PV10-T2axes (10 MWp_dc)x 1 (Track. Both axis) // Batteries Bat5MWh (5 kAh): 1s. x 1p. // 13 Wind Turb. WindT1 (2 MW at 15 m/s) // Bat. Inverter Inv-Ch5MW of 5 MVA // Unmet load = 0 % // Total Cost (NPC) = 44.831 M€ (0.08 €/kWh)

STRATEGY: LOAD FOLLOWING. SOC min.: 10 %.

Let’s change the cost of the CPV to 8 M€, save the project and calculate again.

Name	Power(MWp_dc)	Cost(M€)	C.O&M(%/yr)	Life(years)	NOCT(ºC)	Power T. coef.(%/ºC)	BIFACIALITY(0-1)	CPV	Emissions(kgCO2/kWp
PV10-T2axes	10	13	1	25	43	-0.4	0	NO	800
CPV10-m	10	8	1	25	43	-0.14	0	OK	800

Now the optimal system includes CPV instead of the normal PV.

#	Total Cost (NPC)(M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(W	Ren(%	LCOE(€/kWh)	Simulate	Report	(
1	40.412	4.66	0	0	INF	0.1	79.25	0.0743	SIMULATE..	REPORT...	(
2	40.494	4.55	0	0	INF	0.1	80.48	0.0745	SIMULATE..	REPORT...	(
3	40.616	4.8	0	0	INF	0.1	77.88	0.0747	SIMULATE..	REPORT...	(
4	40.746	4.46	0	0	INF	0.1	81.55	0.0749	SIMULATE..	REPORT...	(
5	40.95	4.97	0	0	INF	0.1	76.25	0.0753	SIMULATE..	REPORT...	(
6	41.11	4.39	0	0	INF	0.1	82.48	0.0756	SIMULATE..	REPORT...	(
7	41.307	4.66	0	0	INF	0.1	79.29	0.076	SIMULATE..	REPORT...	(
8	41.307	4.55	0	0	INF	0.1	80.51	0.076	SIMULATE..	REPORT...	(
9	41.425	4.79	0	0	INF	0.1	77.92	0.0762	SIMULATE..	REPORT...	(

COMPONENTS: PV gen: CPV10-m (10 MWp_dc)x 2 (Track. Both axis) // Batteries Bat5MWh (5 kAh): 1s. x 1p. // 11 Wind Turb. WindT1 (2 MW at 15 m/s) // Bat. Inverter Inv-Ch5MW of 5 MVA // Unmet load = 0 % // Total Cost (NPC) = 40.412 M€ (0.07 €/kWh)

STRATEGY: LOAD FOLLOWING. SOC min.: 10 %.

41. Grid connected battery-only system

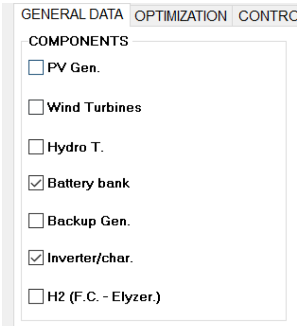
Now we will create a new project to simulate a battery system connected to the HV AC grid. There are no renewable sources, battery will be charged by the grid during specific hours and will be discharged during other hours.

The optimal battery size and management could be optimized by MHOGA, trying to maximize NPV or minimize LCOE. However, in this case we will suppose the size and operation are pre-defined by the designer, and we want to simulate the behavior of the system.

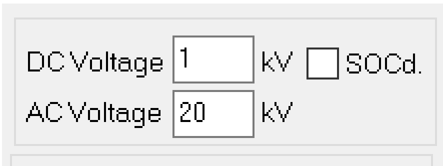
Suppose it is a 10 MWh / 10 MW battery bank and we want to charge from 0 to 5 h at 0.2 C-rate and we want to discharge from 18 to 21 h at 0.3 C-rate. Hourly electricity price (to be purchased for the charge), included taxes, is: from 0 to 8 h 0.04 €/kWh; from 8 to 18 h, 0.12 €/kWh; from 18 to 24 h: 0.15 €/kWh. The price of the electricity sold to the grid is 80% of the purchase price.

First, we open the software and create the project “Bat-only.mho”.

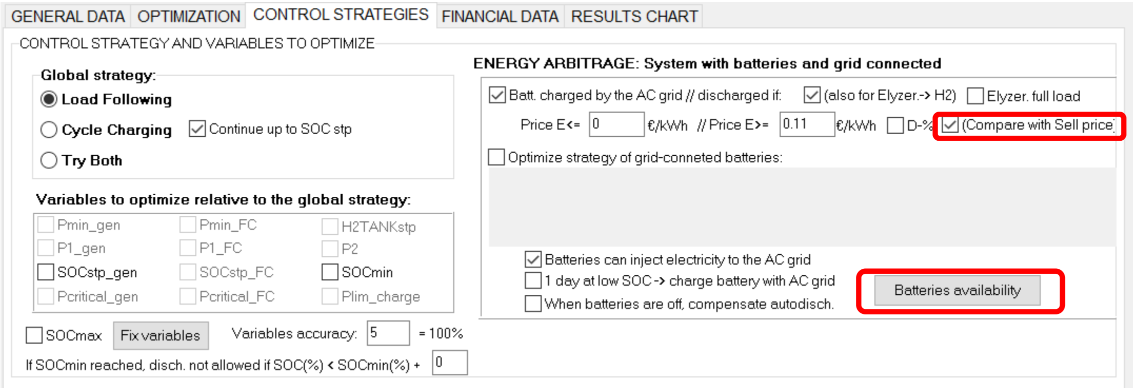
We only want battery and inverter-charger, therefore in the main screen we only allow these components:



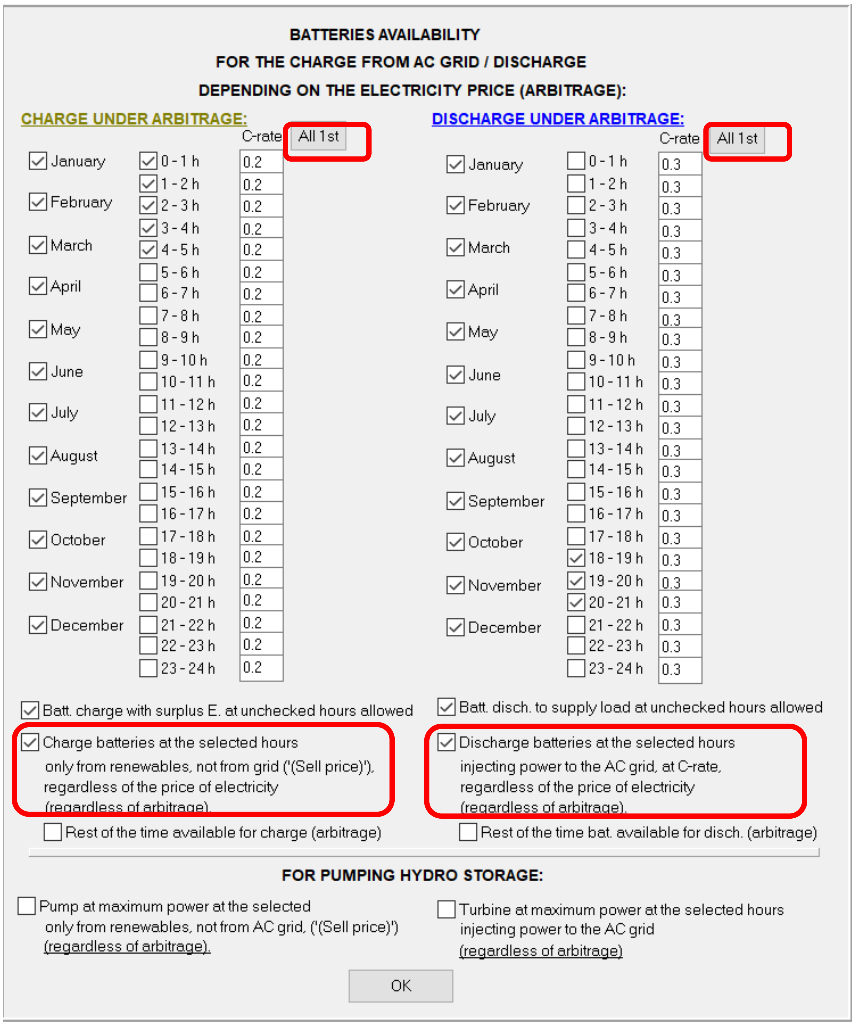
In the left zone of the main window, we can change the DC and AC voltage values. Let’s suppose our battery bank is connected to a DC bus voltage of 1 kV and the AC voltage bus is 20 kV (default data).



In the “**CONTROL STRATEGIES**” tab, unselect “**(Compare wit Sell price)**” checkbox, so that the battery can be charged from the AC grid (if checked, batteries only can be charged from our renewable sources). Price limits for charge / discharge will not be considered as we will later define in the batteries availability the hours when batteries will be charged/discharged compulsorily, regardless the price of electricity.

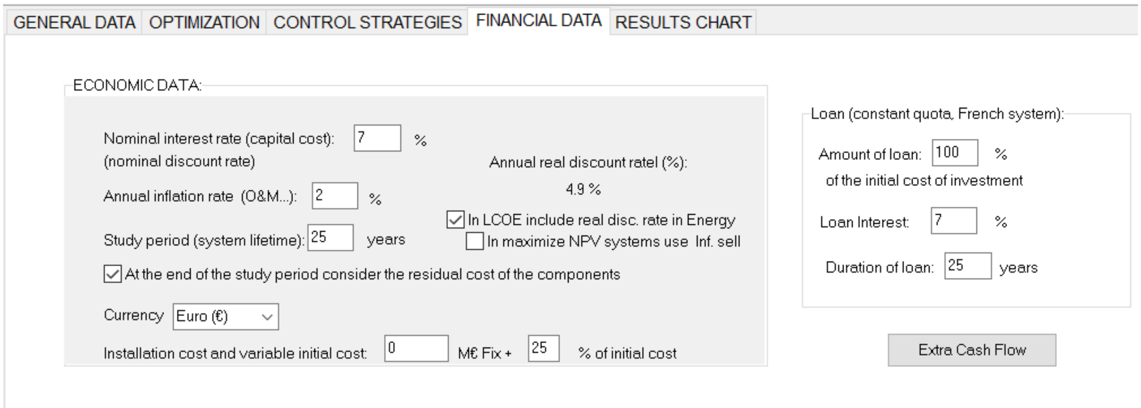


Then, click in "**Batteries availability**" button, select the hours for charge and for discharge, change the C-rate of the charge to 0.2 in the first hour and click in "**All 1st**" to change all the values, same for the discharge (with 0.3 C-rate), and check the below boxes "**Charge batteries at the selected hours…**" and "**Discharge batteries at the selected hours…**" so that batteries will be charged and discharged during the hours selected, regardless of the electricity price.



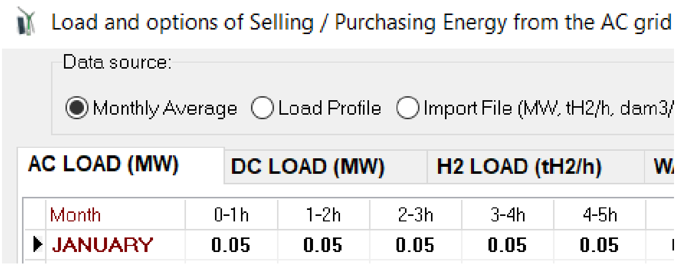
Click OK.

In the "**FINANCIAL DATA**" tab, let's suppose all the default data are correct. Nominal discount rate is 7%, system lifetime is 25 years, installation and variable initial cost is 25% of CAPEX, a loan of 100% is needed…

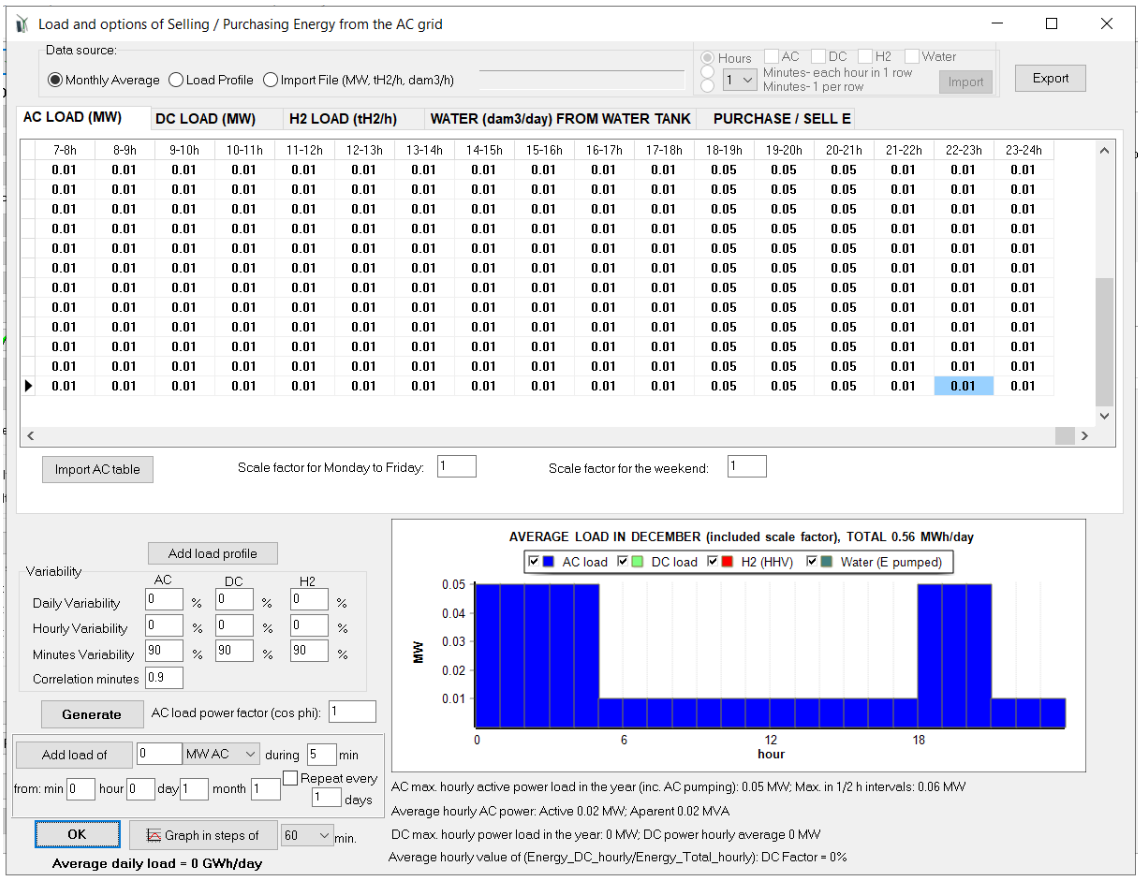


Let's suppose the battery bank auxiliary consumption (for air conditioning, etc.), in AC bus, is 50 kW from 0 to 5 h and from 18 to 21 h (when battery is charged/discharged), and it is reduced to 10 kW for the rest of the hours.

In the "**LOAD/AC GRID**" window, we click in "**AC LOAD (MW)**" tab and select "**Monthly Average**" for the Data source:

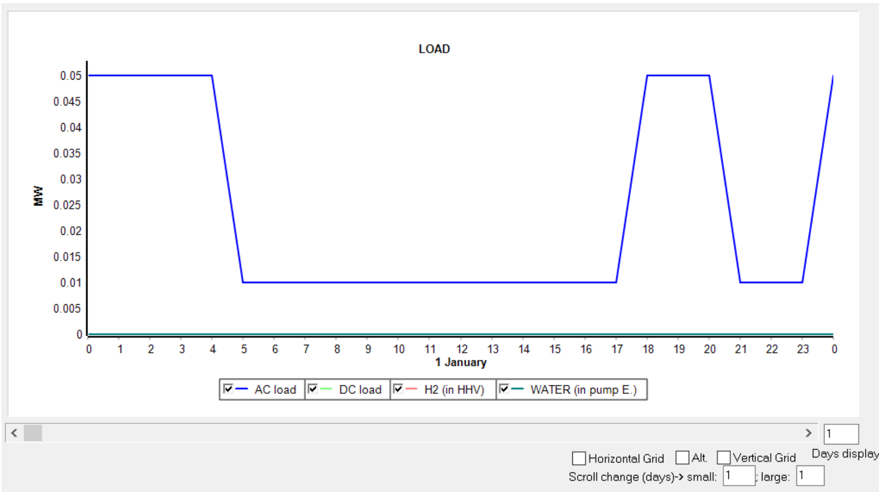


Then, in the table, we write 0.05 (MW, that is, equivalent to 50 kW) in the first row (JANUARY) in the cell of 0-1 h. Then we click in the next column (JANUARY, 1-2 h cell) and all the column of 0-1 h will be converted to 0.05 MW. We do the same for the hours from 0 to 5 h and from 18 to 22 h 0.05 MW, and for the rest of the hours 0.01 MW (that is, 10 kW).



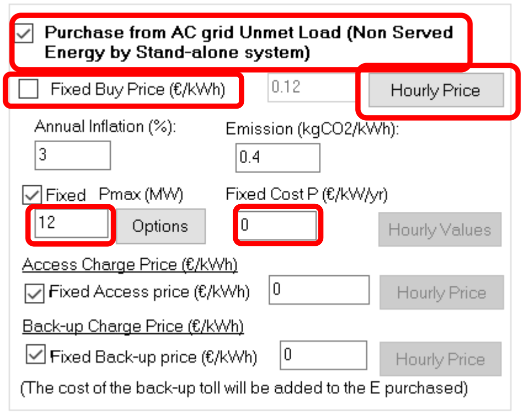
Then we click in “**Generate**” button to obtain the load consumption for all the time steps of the whole year.

Now we click in “**Graph in steps of**” button and we can see the hourly load consumption:

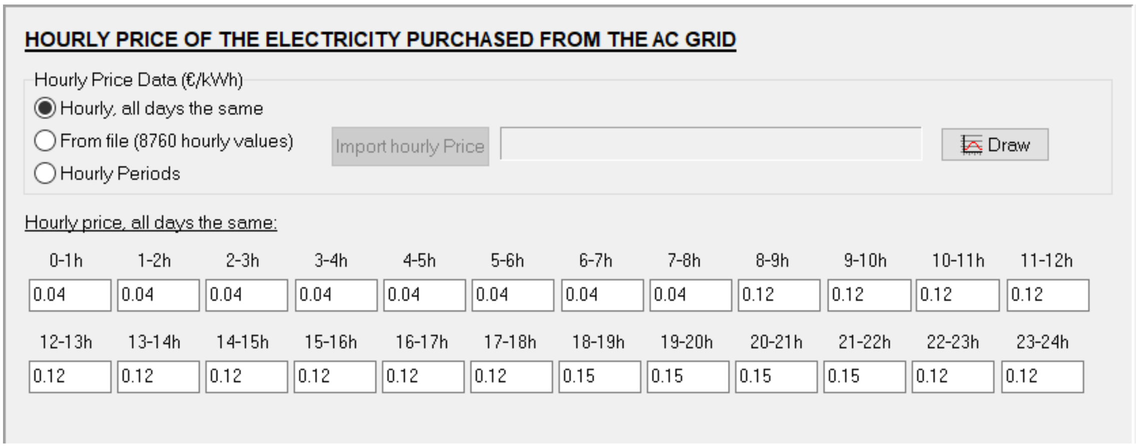


Now we go to the tab “**PURCHASE / SELL E**”.

Here, in the left, we check the box “**Purchase from AC grid…**” so that the energy consumption for the battery auxiliary components can be purchased from the grid, and also the energy to charge the batteries will come from the grid. Let’s suppose the maximum power from / to the grid is 12 MW, we set this value. Suppose that the cost of the contracted power is 0. Let’s suppose electricity annual inflation is expected to be 3% (as by default).

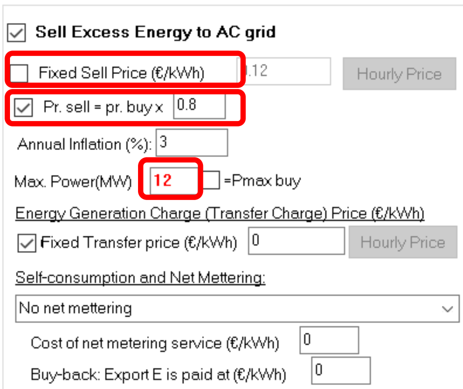


We uncheck the box "**Fixed Buy Price**" and then we click in "**Hourly Price**" button. In the window that appears, we set the hourly price values of the energy purchased to the AC grid (we could also import a file with the hourly price during the whole year or we could also set hourly periods):

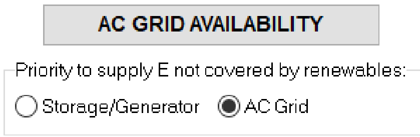


We click OK.

In the central zone of the "**PURCHASE / SELL E**" tab, we click in "**Pr. sell = pr. buy x** " and set the value to 0.8, so that the hourly sold energy price will be the 80% of the hourly purchased energy. Also we set max. power to 12 MW. Let's suppose electricity annual inflation is expected to be 3% (as by default).

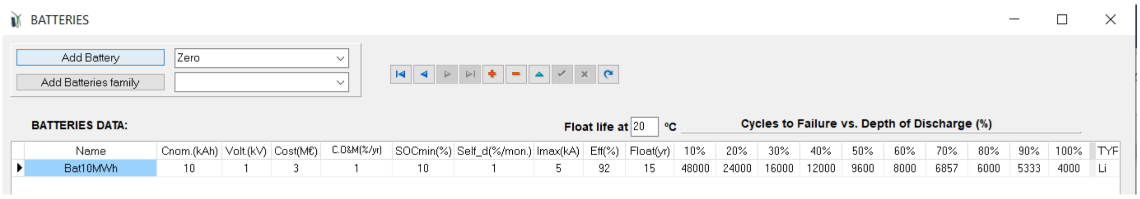


In the right zone of the "**PURCHASE / SELL E**" tab, we select the priority to supply the energy not covered by the renewable sources to the "**AC Grid**", this way the energy consumed by the auxiliary will be purchased from the grid instead of using the stored energy in the battery.



We click OK and return to the main window of the software.

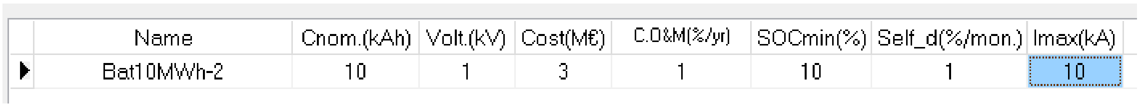
In the **BATTERIES** window, we delete the default battery and select the 10 MWh Li-ion battery of the database:



We can see that the nominal capacity is 10 kAh and the voltage is 1 kV, therefore the energy capacity is 10kAh·1kV= 10 MWh.

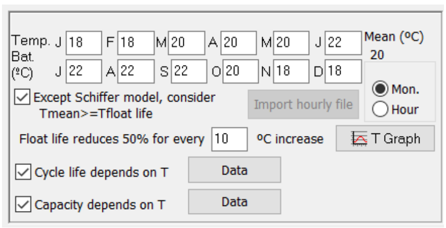
As our battery can supply 10 MW power, we will change the maximum current (Imax) from 5 kA to 10 kA (which, multiplied by 1 kV is 10 MW).

We can change the battery data in the database or here. If we want to change it here, we must change first the name, we click in the name and add “-2”. Then, we change the Imax to 10 kA:

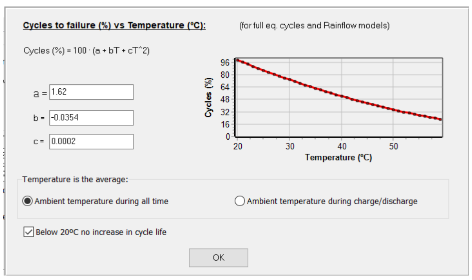


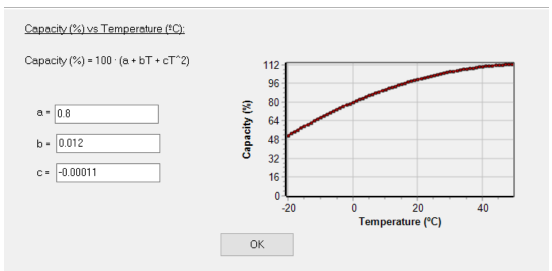
Let’s suppose the rest of the values are the default ones (CAPEX 3 M€, annual OPEX 1% of CAPEX, minimum allowed SOC 10%, roundtrip efficiency 92%, float life at 20ºC 15 years, cycle life vs. DOD as shown).

Let’s suppose the average temperature of the battery bank for the different months, considering the air conditioning, is the default:

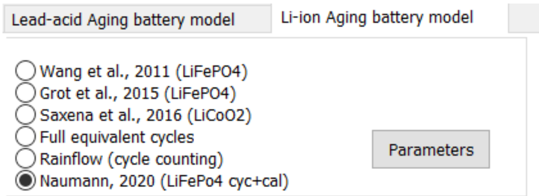


And the cycle life vs temperature and capacity vs temperature are the default ones (shown by the buttons “**Data**”):

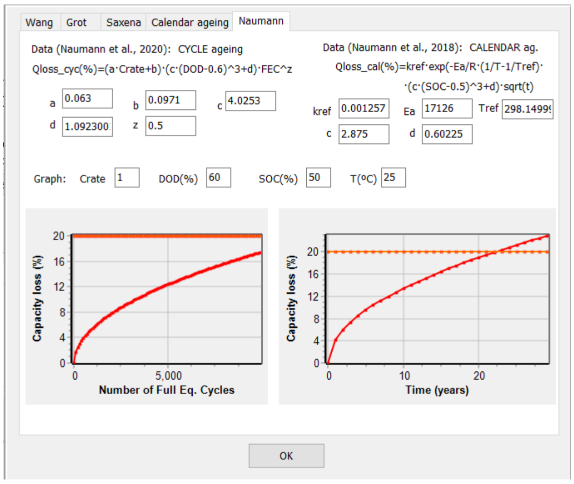




Let’s suppose the Li-ion battery is similar to the LiFePo4 / graphite batteries tested by the work of Naumann et al., 2020 (cycle ageing) and 2018 (calendar ageing) (in the user manual you can see the reference of the article). We select “**Naumann**” in the ageing model, which includes cycle degradation and calendar degradation:

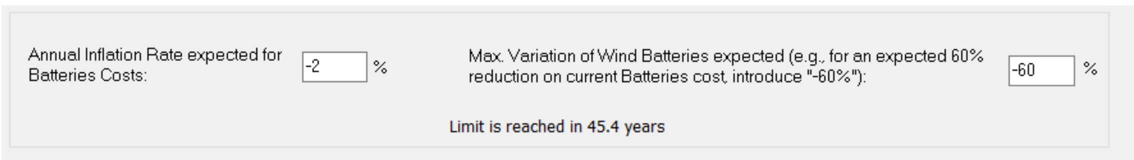


Click in “**Parameters**” button and we can see the values of the parameters used by the model, selecting the “**Naumann**” tab (we could change any of them):



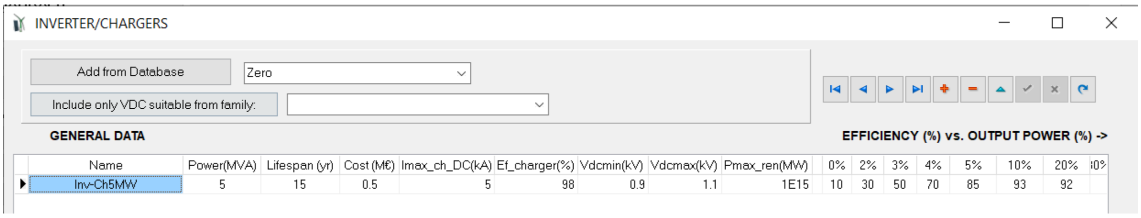
Click OK.

When battery bank remaining capacity is 80% of the nominal capacity, they will have to be replaced. We expect the CAPEX will be reduced 2% per year, until a 60% reduction is reached. For example, if the battery ageing model calculates the duration of battery is 9 years, in the year 9 and 18 they will be replaced.

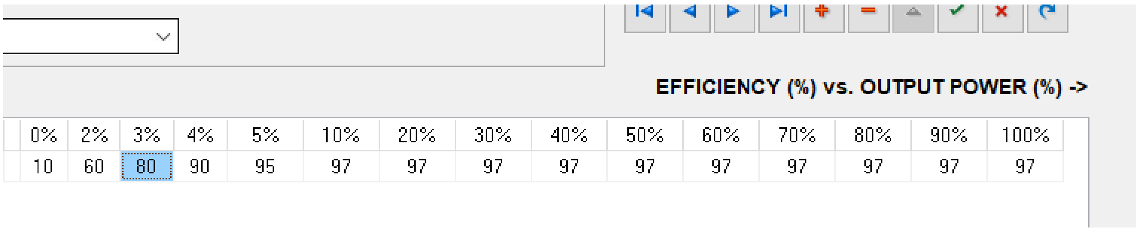


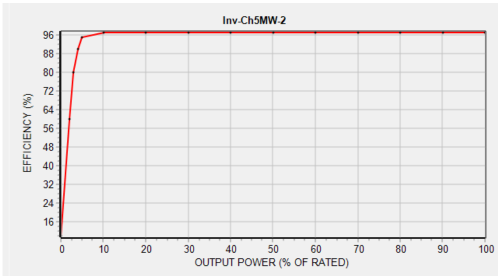
and OK to return to the main screen.

In the **INVERTER/CHAR**. Window, we delete the default inverter/chargers and leave only the one 5 MW. If we wanted to supply 10 MW, that is, C-rate = 1, we would need a 10 MW inverter/charger. However, we want lower C-rates, so we will use the 5 MW inverter. Even we could choose an inverter of lower power for this application, but we will use this one of 5 MW (maybe in the future we want to increment C-rate).

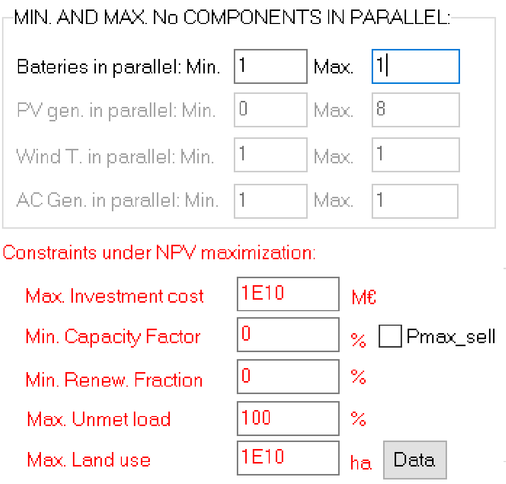


Let's suppose all the default values are correct: OPEX, CAPEX… Charger efficiency is 98%. However, the inverter efficiency vs. output power is very low and conservative values are shown. We change the name (add "-2" and then change the inverter efficiency as below):



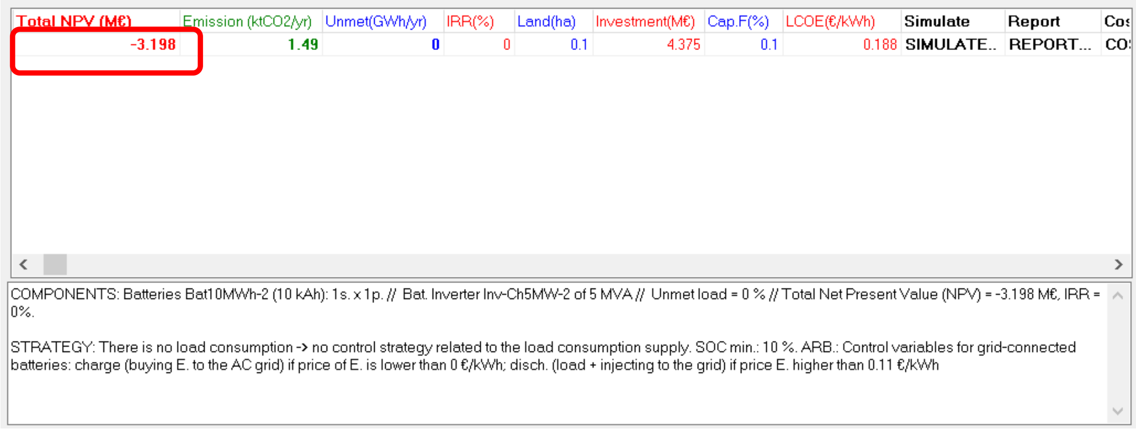


In the main screen of the software, make sure that there is one battery in parallel (min and max are 1), and constraints with their default values (so they are not considered):



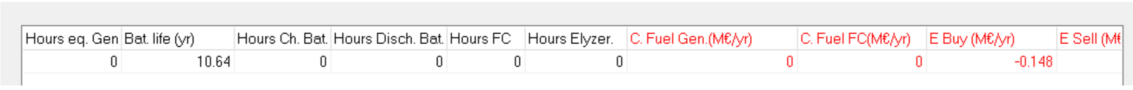
Then, click "**CALCULATE**" button to perform the simulation of the system.

We can see the results in the result table (just one combination has been studied).

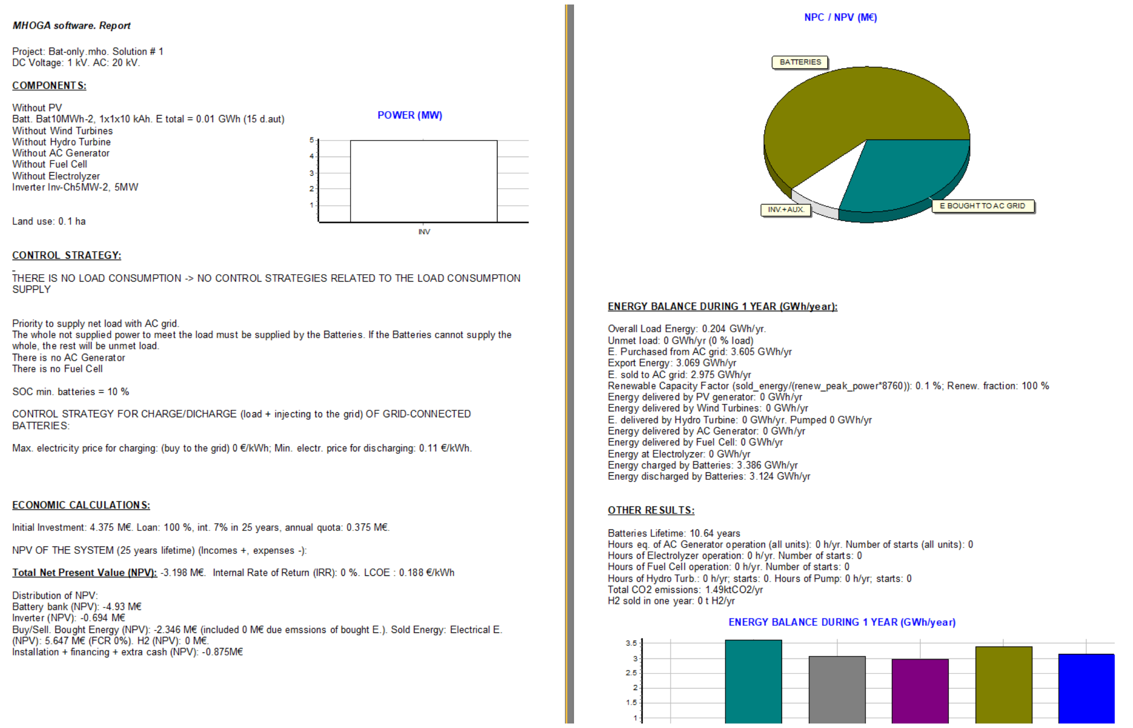


NPV is -3.198 M€, that is, <0, non-profitable system.

In the table we can see results of annual energy, costs, etc. We can also see the hours of battery charge/discharge, battery duration (10.64 years), etc.



If we click in "**REPORT**" we can see the main results.



MHOGA software. Report

Project: Bat-only.mho. Solution # 1
DC Voltage: 1 kV. AC: 20 kV.

COMPONENTS:

Without PV
Batt. Bat10MWh-2, 1x1x10 kAh. E total = 0.01 GWh (15 d.aut)
Without Wind Turbines
Without Hydro Turbine
Without AC Generator
Without Fuel Cell
Without Electrolyzer
Inverter Inv-Ch5MW-2, 5MW

Land use: 0.1 ha

CONTROL STRATEGY:

THERE IS NO LOAD CONSUMPTION -> NO CONTROL STRATEGIES RELATED TO THE LOAD CONSUMPTION SUPPLY

Priority to supply net load with AC grid.
The whole not supplied power to meet the load must be supplied by the Batteries. If the Batteries cannot supply the whole, the rest will be unmet load.
There is no AC Generator
There is no Fuel Cell

SOC min. batteries = 10 %

CONTROL STRATEGY FOR CHARGE/DICHARGE (load + injecting to the grid) OF GRID-CONNECTED BATTERIES:

Max. electricity price for charging: (buy to the grid) 0 €/kWh; Min. electr. price for discharging: 0.11 €/kWh.

ECONOMIC CALCULATIONS:

Initial Investment: 4.375 M€. Loan: 100 %, int. 7% in 25 years, annual quota: 0.375 M€.

NPV OF THE SYSTEM (25 years lifetime) (Incomes +, expenses -):

Total Net Present Value (NPV): -3.198 M€. Internal Rate of Return (IRR): 0 %. LCOE : 0.188 €/kWh

Distribution of NPV:
Battery bank (NPV): -4.93 M€
Inverter (NPV): -0.694 M€
Buy/Sell. Bought Energy (NPV): -2.346 M€ (included 0 M€ due emssions of bought E.). Sold Energy: Electrical E. (NPV): 5.647 M€ (FCR 0%). H2 (NPV): 0 M€.
Installation + financing + extra cash (NPV): -0.875M€

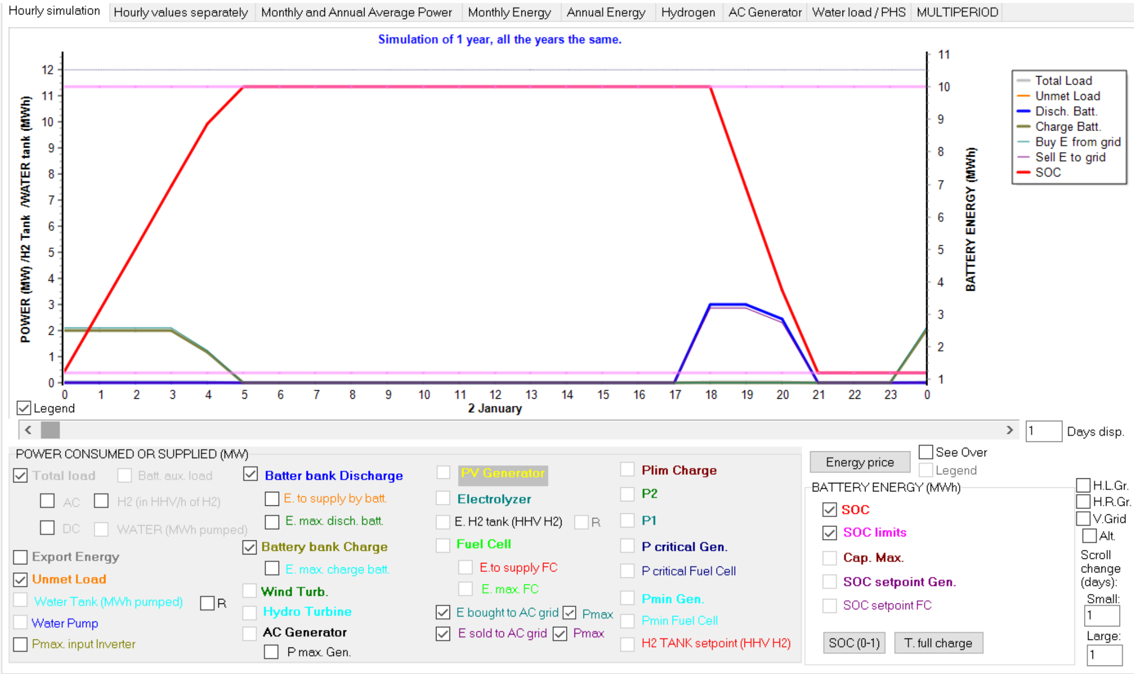
ENERGY BALANCE DURING 1 YEAR (GWh/year):

Overall Load Energy: 0.204 GWh/yr.
Unmet load: 0 GWh/yr (0 % load)
E. Purchased from AC grid: 3.605 GWh/yr
Export Energy: 3.069 GWh/yr
E. sold to AC grid: 2.975 GWh/yr
Renewable Capacity Factor (sold_energy/(renew_peak_power*8760)): 0.1 %; Renew. fraction: 100 %
Energy delivered by PV generator: 0 GWh/yr
Energy delivered by Wind Turbines: 0 GWh/yr
E. delivered by Hydro Turbine: 0 GWh/yr. Pumped 0 GWh/yr
Energy delivered by AC Generator: 0 GWh/yr
Energy delivered by Fuel Cell: 0 GWh/yr
Energy at Electrolyzer: 0 GWh/yr
Energy charged by Batteries: 3.386 GWh/yr
Energy discharged by Batteries: 3.124 GWh/yr

OTHER RESULTS:

Batteries Lifetime: 10.64 years
Hours eq. of AC Generator operation (all units): 0 h/yr. Number of starts (all units): 0
Hours of Electrolyzer operation: 0 h/yr. Number of starts: 0
Hours of Fuel Cell operation: 0 h/yr. Number of starts: 0
Hours of Hydro Turb.: 0 h/yr; starts: 0. Hours of Pump: 0 h/yr; starts: 0
Total CO2 emissions: 1.49ktCO2/yr
H2 sold in one year: 0 t H2/yr

If we click in "**SIMULATE**" we can see the simulation:



We can see charge is during the hours selected, at 0.2 rate (except at the end of the charge, which is not possible) and discharge at 0.3 rate (except at the end).

Click in "**Save simulation data**" button and save the Excel file.

Open the Excel file and save it as xlsx file. Open the xlsx file and we can see, for example, for January, the 2^{nd} (hiding selected rows and columns):

	A	B	D	AA	AB	AC	AD	AE	AF	AG	AJ	AL	AO	AQ	BA	BB	BC
6	HOURLY VALUES. All power values are expressed in MW (H2.load is in MW referring to the HHV of H2). The SOC data of the batteries in energy (MWh).																
7	Water tank (Water_tank) is energy needed to pump the water (MWh) while (Water_tank_volume) is the volume stored (dam3).																
8	No.Gen_on is the number of AC generators that are running during this time step. Hours_eq_Gen is the number of equivalent hours (including out-of-range penalty and start-up penalty) of AC generators. The fuel consumption of the Gen. AC (Fue																
9	Costs of purchasing energy to the grid, the fuel cost of the AC Gen. (Fuel.Cost), the cost of the external fuel used by the fuel cell (C.fuel.ext_FC) and incomes of selling E and costs of buying E to the AC grid (Inc.Sell and Cost.Buy) are expressed in M																
10	Load of Hydrogen (H2_load_mass) is expressed in t/h of H2. H2 in tank (H2_Tank_mass), H2 used by fuel cell, from H2 tank (Fuel.FC) or externally purchased (Fuel.ext_FC) and hydrogen generated by the electrolyzer (Prod_H2) are expressed in t o																
11	Hydrogen stored in H2 Tank (H2_Tank_HHV) is expressed in MWh HHV of H2																
12	Date	Hour	AC_load(MW)	C. bat(MW)	D. bat(MW)	Unmet_Load(	Export(MW)	Sell.grid(MW)	Sell.grid.Net(M	Purch.grid(MV	Pr.Sell.E(€/kW	Pr.Buy.E(€/kW	Inc.Sell(M€)	Cost.Buy(M€)	SOC(MWh)	SOCmin.(MW	SOCmax(MWh
37	02-January	0:00	0.05	2	0	0	0	0	0	2.09	0.032	0.04	0	0.00008	1.2	1.2	10
38	02-January	1:00	0.05	2	0	0	0	0	0	2.09	0.032	0.04	0	0.00008	3.11	1.2	10
39	02-January	2:00	0.05	2	0	0	0	0	0	2.09	0.032	0.04	0	0.00008	5.03	1.2	10
40	02-January	3:00	0.05	2	0	0	0	0	0	2.09	0.032	0.04	0	0.00008	6.95	1.2	10
41	02-January	4:00	0.05	1.18	0	0	0	0	0	1.25	0.032	0.04	0	0.00005	8.87	1.2	10
42	02-January	5:00	0.01	0	0	0	0	0	0	0.01	0.032	0.04	0	0	10	1.2	10
43	02-January	6:00	0.01	0	0	0	0	0	0	0.01	0.032	0.04	0	0	10	1.2	10
44	02-January	7:00	0.01	0	0	0	0	0	0	0.01	0.032	0.04	0	0	10	1.2	10
45	02-January	8:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
46	02-January	9:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
47	02-January	10:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
48	02-January	11:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
49	02-January	12:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
50	02-January	13:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
51	02-January	14:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
52	02-January	15:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
53	02-January	16:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
54	02-January	17:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	0	0	10	1.2	10
55	02-January	18:00	0.05	0	3	0	2.95	2.86	2.86	0	0.12	0.15	0.00034	0	10	1.2	10
56	02-January	19:00	0.05	0	3	0	2.95	2.86	2.86	0	0.12	0.15	0.00034	0	6.87	1.2	10
57	02-January	20:00	0.05	0	2.44	0	2.39	2.32	2.32	0	0.12	0.15	0.00028	0	3.74	1.2	10
58	02-January	21:00	0.01	0	0	0	0	0	0	0.01	0.12	0.15	0	0	1.2	1.2	10
59	02-January	22:00	0.01	0	0	0	0	0	0	0.01	0.12	0.15	0	0	1.2	1.2	10
60	02-January	23:00	0.01	0	0	0	0	0	0	0.01	0.12	0.15	0	0	1.2	1.2	10

We can see in column BA the SOC: January 2^{nd} at 0 h battery SOC is 1.2 MWh (SOC min. is 10% of 10MWh, that is, 1 MWh, which would be for 20ºC, however as temperature in January was set to 18ºC, the minimum SOC is increased as battery can supply lower energy, because capacity depends on temperature). During the first hour (row 37), battery is charged at C-rate=0.2, that is, 2 MW DC (column AA), and also auxiliary consumes 0.05 MW AC (column D), total 2.05 MW consumption from the grid during the first hour of the day. But battery is charged by means of the charger with 98% efficiency, therefore from the grid there comes 2/0.98 + 0.05 = 2.09 MW AC (Purch. Grid, column AG). Buy electricity price at this hour is 0.04 €/kWh (column AL), therefore the cost of buying electricity to the grid during first hour is 0.04€/kWh·2090kW·1h=83.6 € = 0.00008 M€ (column AQ).

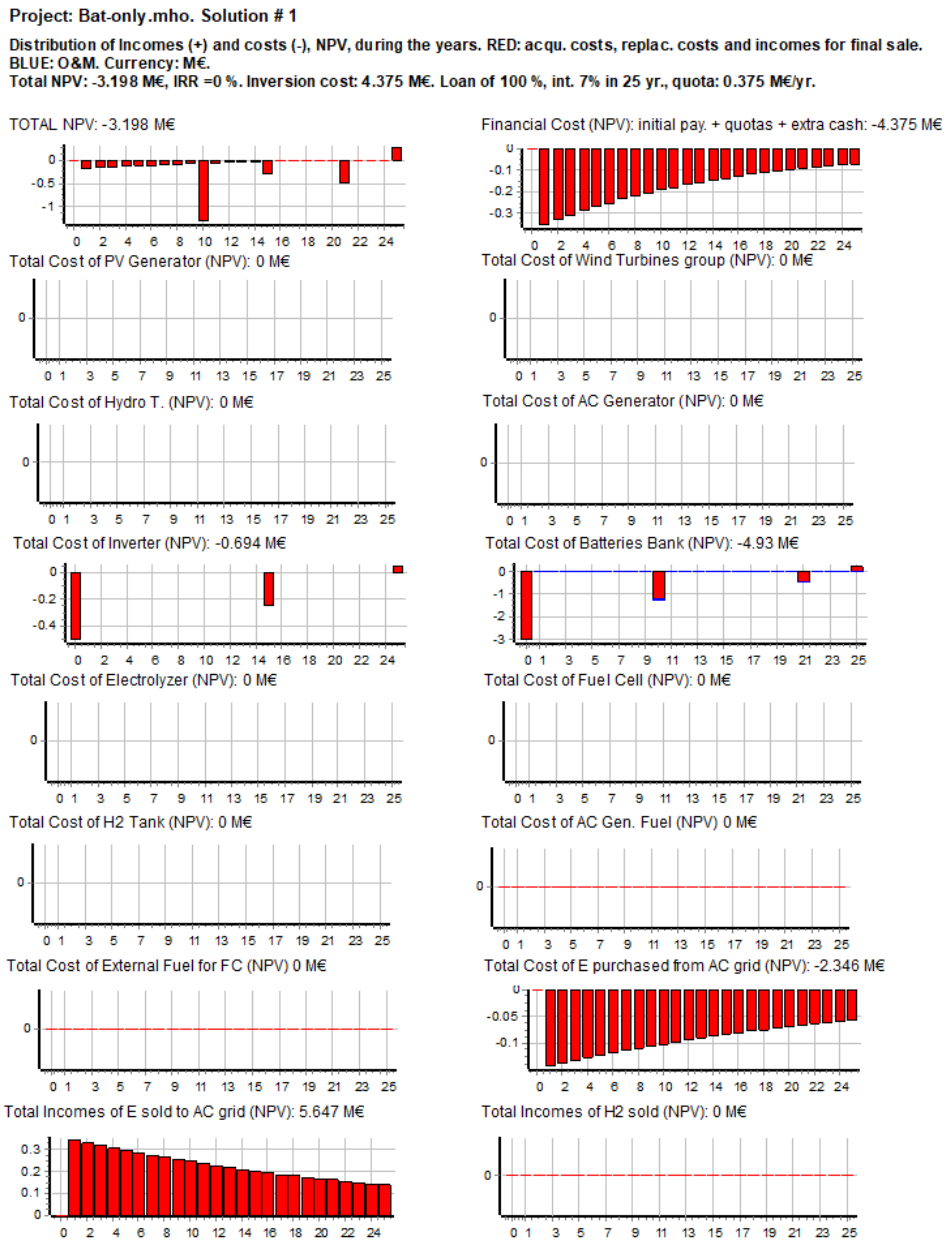
At the beginning of the second hour of January 2nd, row 38, battery SOC is 3.11 MWh (column BA). Previous hour it was 1.2 MWh, and we have added 2 MW during one hour, but roundtrip efficiency is 92% (considering charge efficiency = discharge efficiency = sqrt(0.92)=0.96), therefore we have really added to the battery 2MW·1h·0.96=1.91 MWh, which added to the 1.2 MWh we have now 3.11 MWh (column BA).

For the rest charge hours, the evaluation is similar.

At 18 h (row 55) SOC is 100% at the beginning of this hour (column BA 10 MWh). Battery discharge is 0.3 C-rate, that is, 3 MW DC (column AB). This DC power is converted by the inverter (efficiency for 30% output power 97%) in 3MW·0.97=2.91 MW. As we have 0.05 MW AC consumption for auxiliary, we have only 2.91-0.05 = 2.86 MW to be injected to the AC grid (columns AE and AF), which is valued at 0.12 €/kWh (0.15*80%), column AJ, with a value of incomes for this hour of 2860kW·1h·0.12€/kWh=343€=0.00034 M€ (column AO).

The SOC at the beginning of the next hour (row 56, column BA) is 10 MWh-3MW·1h/0.96= 6.87 MWh.

We go back to the software, we click in the results table in "**COSTS**", seeing the costs during the system lifetime:



We could do multi-period simulation (considering reduction of remaining capacity during the years): in the main screen of the software, menu Project -> Options, select "Multiperiod…".

<u>42. Green hydrogen production with electrolyzer at full load and battery</u>

Now we will create a new project to optimize a green hydrogen production system, powered by renewable sources. We can optimize it by maximizing the net present value (NPV) of the system, or by minimizing the LCOH or other options.

In this case, we want the electrolyzer to run at full load all the time: if the power from the renewable sources is not enough, the net electrolyzer load will be supplied from the electrical grid (purchased to the AC grid). If the grid electricity price is higher than a specific limit, the priority to supply the net electrolyzer load will be from the battery. If the power form the renewable sources is higher than the rated power of the electrolyzer, the surplus power will be sold to the AC grid.

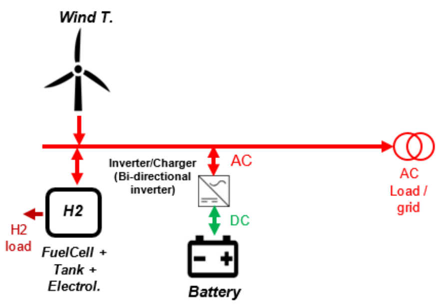
Therefore:

- Low electricity price: energy from the wind farm is used to feed the electrolyzer (which runs at full power) and charge the battery at the maximum charge rate allowed. If there is not enough power from the renewable sources, buy the rest to the grid.
- Medium electricity price: energy from the wind farm is used to feed the electrolyzer (which runs at full power). If not enough, buy the rest to the grid.
- High electricity price: if the power from the renewable sources is not enough to run the electrolyzer at full load, the rest will be supplied by the battery; if not enough, buy the rest to the grid.

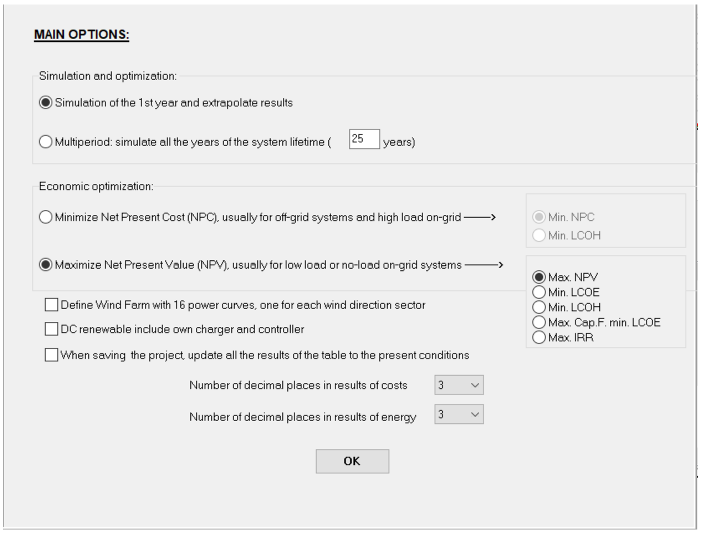
In any case, if there is surplus power, it will be sold to the AC grid.

First, we create a new project "**H2-prod-wind-bat.mho**" (Project -> New). Remember, the path from the root must not be too long, otherwise the software will show an error.

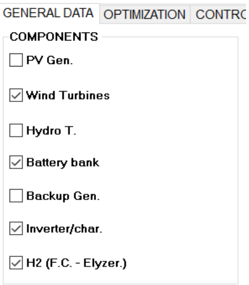
Let's suppose we just want to use wind turbines (no PV in this case). The system will also include electrolyzer, battery and inverter/charger.



In the main screen, **Project –> OPTIONS**, leave the default data (we will optimize by maximizing the NPV of the system):



In the main screen, **GENERAL DATA** tab, select the following:



First we will introduce the wind data. Let's suppose we don't want to use wind speed data; instead, we want to use as input data the output power of a wind farm normalized to 1 MW rated power.

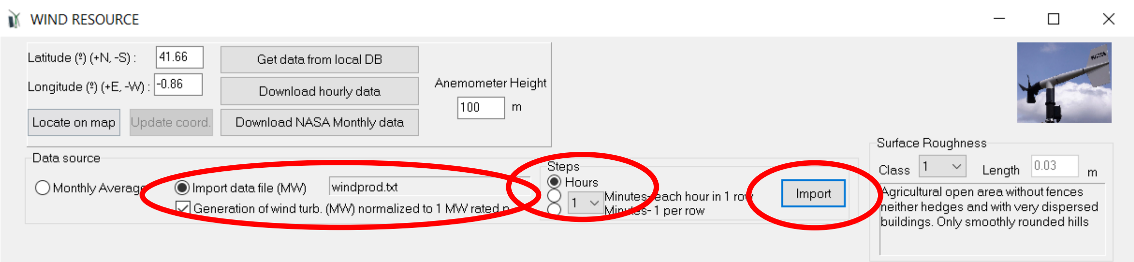
Click the **WIND** button.

This hourly wind farm output power (normalized to 1 MW) file can be downloaded here:

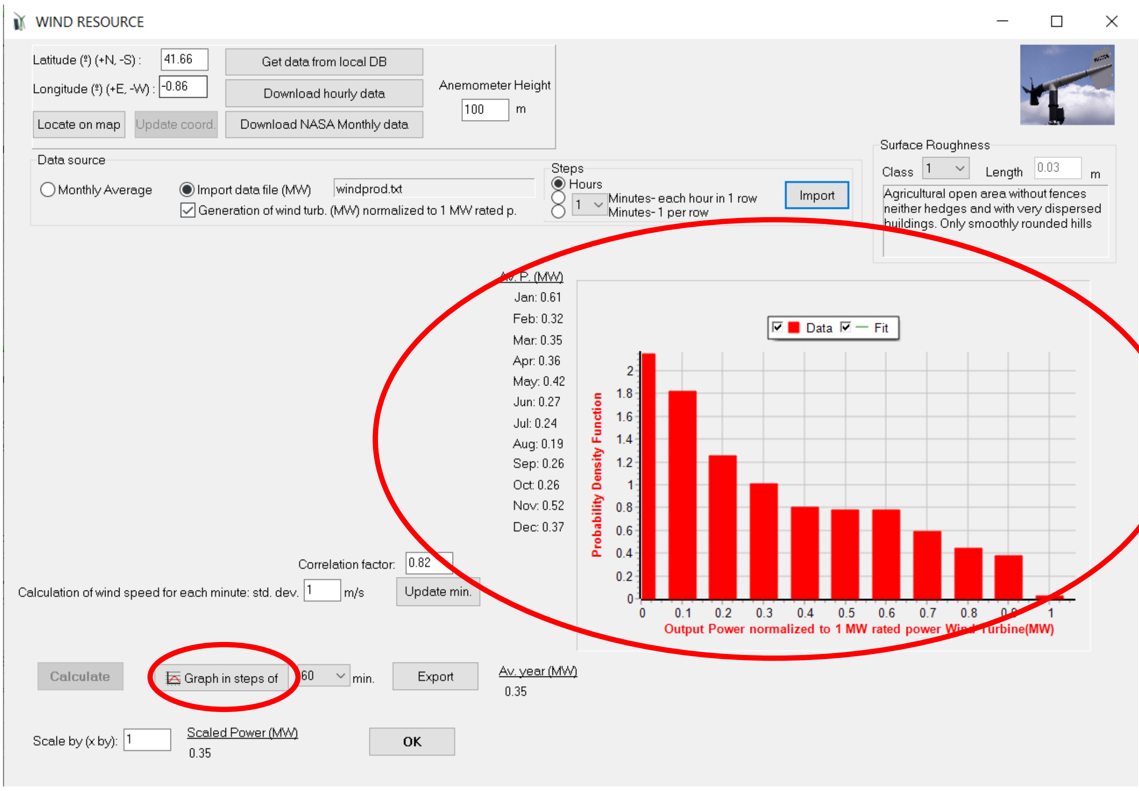
http://ihoga.unizar.es/Desc/windprod.zip

Download and unzip, you will get "windprod.txt" file, which has 8760 rows, one for each hour of the year, with the production of the wind farm (normalized to 1 MW rated power).

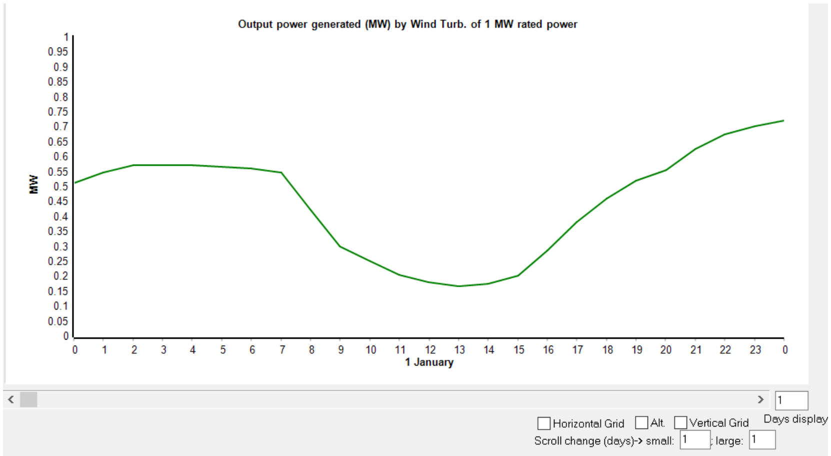
In the wind resource window, in "**Data source**" panel, select "**Import data file**" and "**Generation of wind turb. (MW) normalized to 1 MW rated p.**" In our case, steps must be in **Hours** (as by default) and then click the button "**Import**", then look for the "windprod.txt" file and import it.



Then, we can see the average values of the imported data for each month and the graph of the probability density function of the data imported.

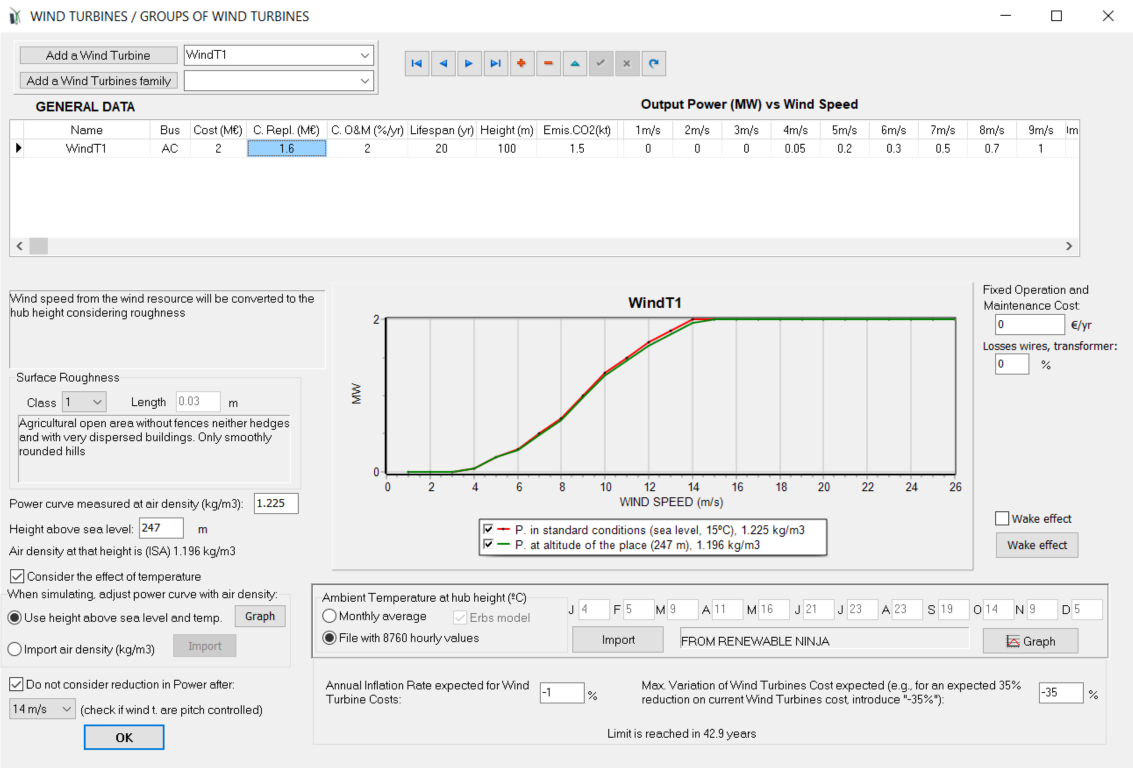


Clicking in the “Graph in steps of” button, we can see the data during the year (you can move with the position bar and you can change the number of days to display simultaneously):



Click Back, then OK and return to the main window.

In the main window of the software, click the **WIND TURB.** button, then the wind turbines screen appears:



By default, a wind turbine of 2 MW is considered. We could change it, add another one, etc. Let's suppose we want to consider just one type of wind turbine, of 4 MW, with a CAPEX of 4 M€, a replacement cost of 3.5 M€, and annual OPEX 2% of CAPEX (rest of the data same as the default one of 2 MW). We can define this wind turbine in the database of the software, or we simply could change the 2 MW one for the new one. We will do it. First, change the name to WindT4MW, and then change the rest of the data. It is mandatory to change the name, if not any other change will not be updated.

GENERAL DATA — Output Power (MW) vs Wind Speed

Name	Bus	Cost (M€)	C. Repl. (M€)	C. O&M (%/yr)	Lifespan (yr)	Height (m)	Emis.CO2(kt)	1m/s	2m/s	3m/s	4m/s	5m/s	6m/s	7m/s	8m/s	9m/s
WindT4MW	AC	4	3.5	2	20	100	1.5	0	0	0	0.1	0.4	0.6	1	1.4	2

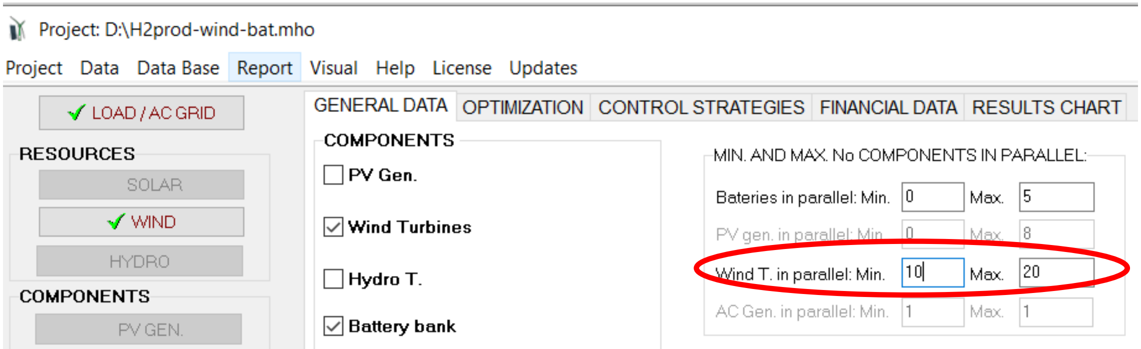
In this case, as we do not use wind speed data (we use the data of the wind production normalized to 1 MW rated power), the data of the output power vs wind speed is not necessary to be changed, except for the value of 14 m/s, as the rated power of the wind turbine is considered to be this value. Therefore, it is mandatory that we change the value for 14 m/s to 4 MW (the rest could be changed, if we want, as shown in the table, but it is not necessary, it would only be necessary if we were using wind speed as data and not wind production normalized to 1 MW):

Output Power (MW) vs Wind Speed

9m/s	10m/s	11m/s	12m/s	13m/s	14m/s	15m/s	16m/s	17m/s	18m/s	19m/s	20m/s	21m/s	22m/s	23m/s	24m/s	25m/s	26m/s
2	2.6	3	3.4	3.9	4	4	4	4	4	4	4	4	4	4	4	4	4

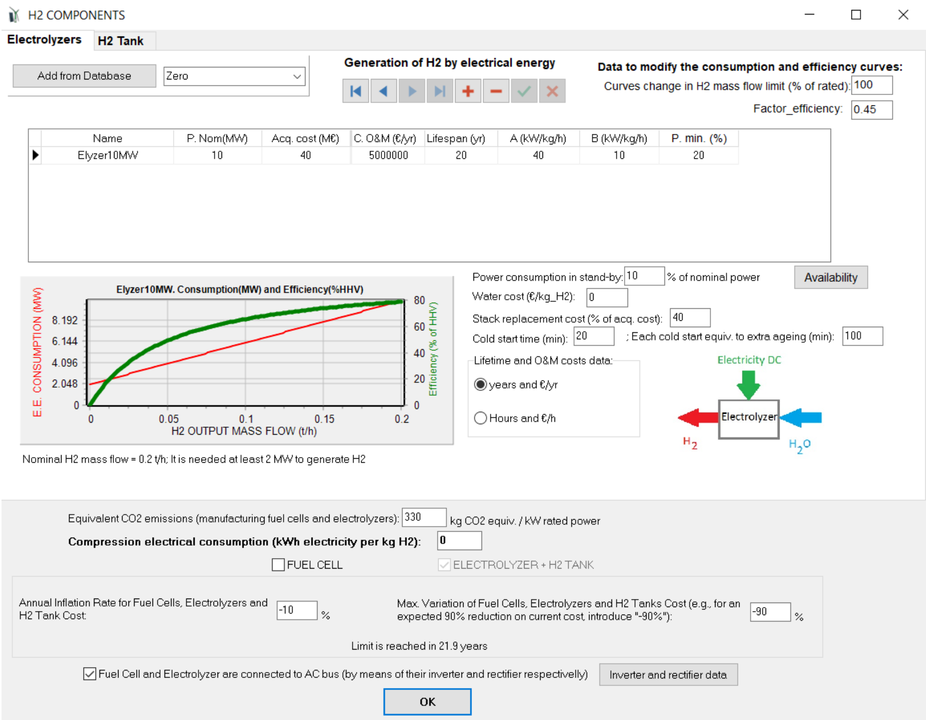
Then we click OK and we return to the main window of the software.

In the main window, **GENERAL DATA** tab, we can define the minimum and maximum number of wind turbines to be considered. Let's suppose we want to consider between 10 and 20 wind turbines (the software will take into account the different combinations: 10 wind turbines of 4 MW, 11 wind turbines of 4 MW, …. 20 wind turbines of 4 MW):



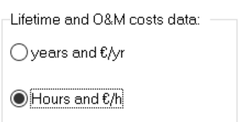
Now we will define the electrolyzers to be considered in the system.

In the main window, click in **H2 (F.C.-Elyzer)** button, and the next window appears:

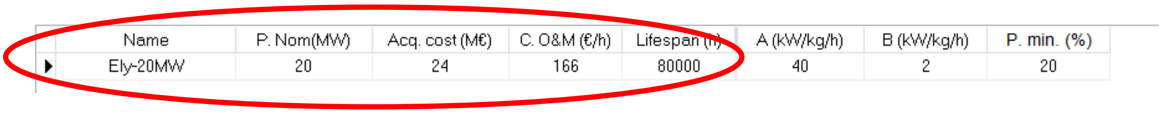


Let's suppose we want to consider just one type of electrolyzer, of 20 MW (we could consider more types, just adding more rows to the table).

In our case, we will consider the liftetime and O&M costs in hours and €/h, then select:

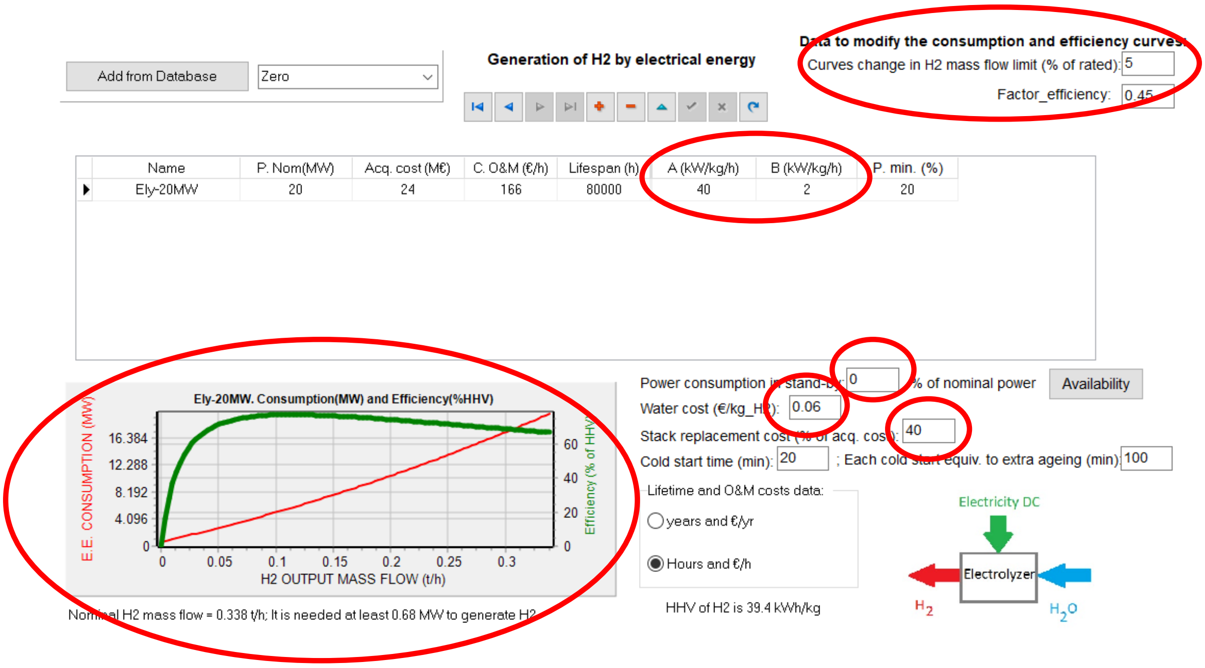


We could define a new electrolyzer in the database, but in this case we won't do it, we will just change the data of the one shown. Let's change the data of the one of 10 MW to another one of 20 MW. First, change the name of the electrolyzer of the table, for example to Ely-20MW (remember, you must change the name in order to change any parameters, if not, no change will be updated). Let's suppose the data of the one of 20 MW is: CAPEX 24 M€, OPEX 166 €/h, lifespan 80,000 h.



	Name	P. Nom(MW)	Acq. cost (M€)	C. O&M (€/h)	Lifespan (h)	A (kW/kg/h)	B (kW/kg/h)	P. min. (%)
▶	Ely-20MW	20	24	166	80000	40	2	20

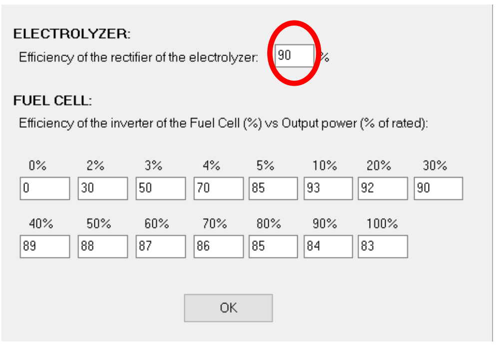
To consider the decay in the efficiency and fit with the efficiency vs hydrogen mass flow curve obtained from the electrolyzer manufacturer, we must modify the values of A, B, H2 mass flow limit and factor efficiency until we fit the curve (see the paper https://doi.org/10.1016/j.ijhydene.2023.08.273). Let's suppose that our curve fit with consumption parameters A = 40 kW/kg/h, B=2 kW/kg/h, H2 mass flow limit = 5% and factor efficiency 0,45. We obtain the following curves of consumption (red curve, left axis) and efficiency (green curve, right axis) vs. H2 mass flow:



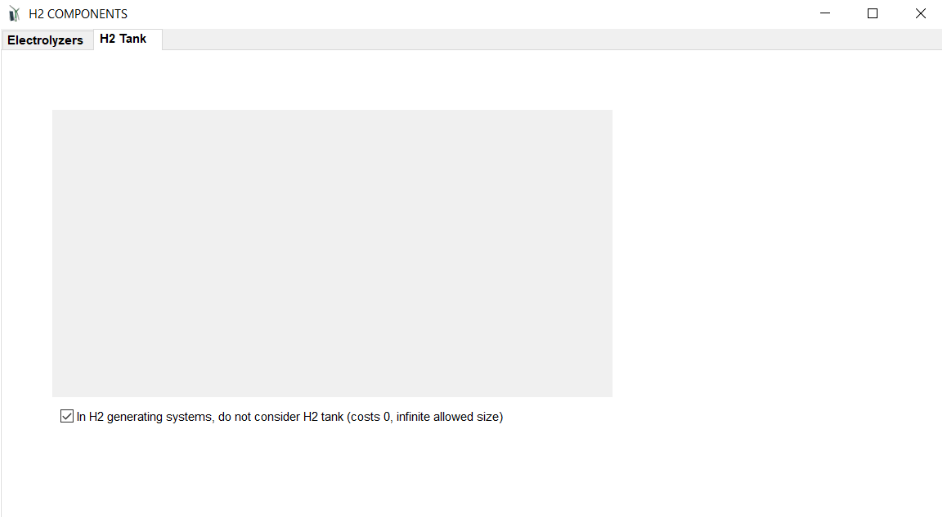
Also let's suppose the power consumption in stand-by is 0% of nominal power (it is not considered as all the time it will be at full load), the water cost is 0.06 € per kg of hydrogen produced, the stack replacement cost is 40% of CAPEX (see the previous figure).

We could define the compression electrical consumption, however in this case we suppose the electrolyzer consumption (defined previously) includes all the auxiliary consumptions.

As the electrolyzer is connected to the AC bus, it needs a rectifier. Click in the button "**Inverter and rectifier data**" (lower area of the window) to define the efficiency of the inverter of the fuel cell (not used in our case) and the rectifier of the electrolyzer. We can see the default rectifier efficiency is 90%, we leave this value.

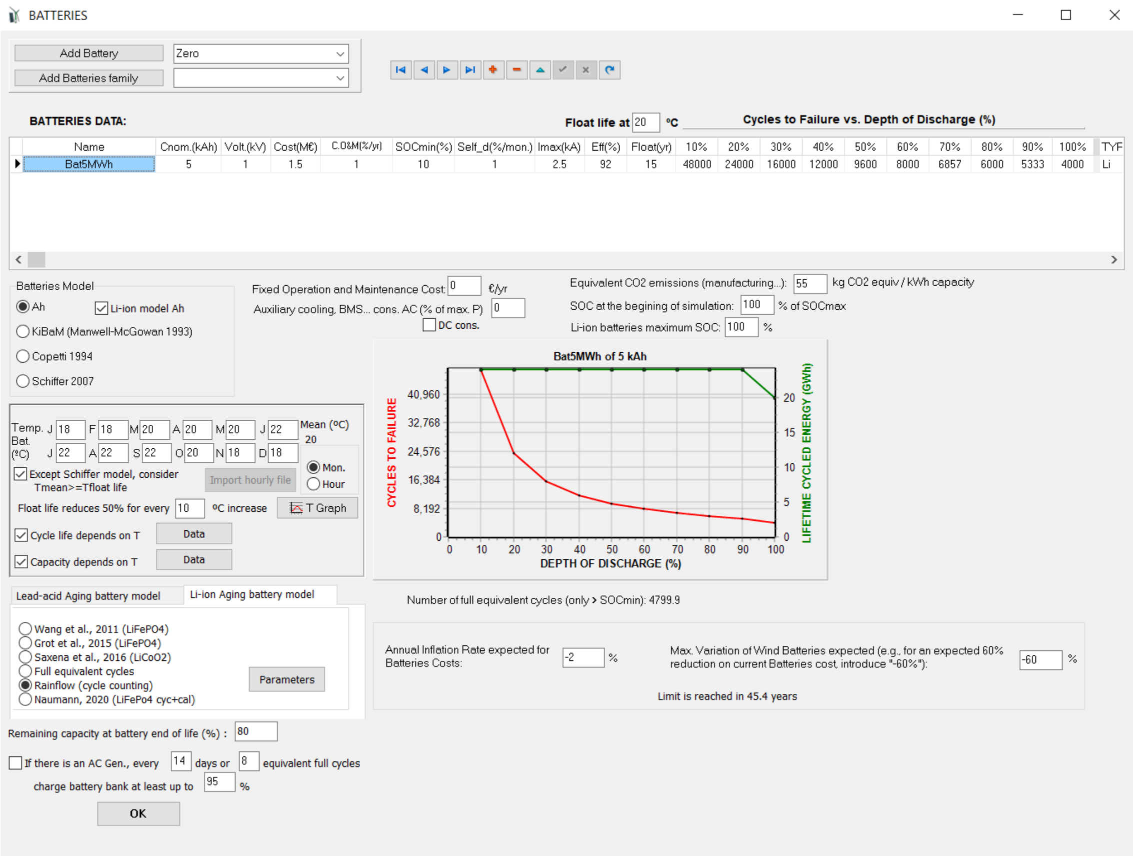


Click in the **H2 tank** tab (upper area of the window). We will not consider the hydrogen tank, because we want to sell all the hydrogen produced, we don't want to store H2 to use later in our system. The cost of the hydrogen tank, compressor, rectifier, and other auxiliary components is included in the electrolyzer CAPEX in our case.



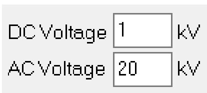
Then we click in OK and return to the main window.

In the main window, click in **BATTERIES**, and the battery window appears:

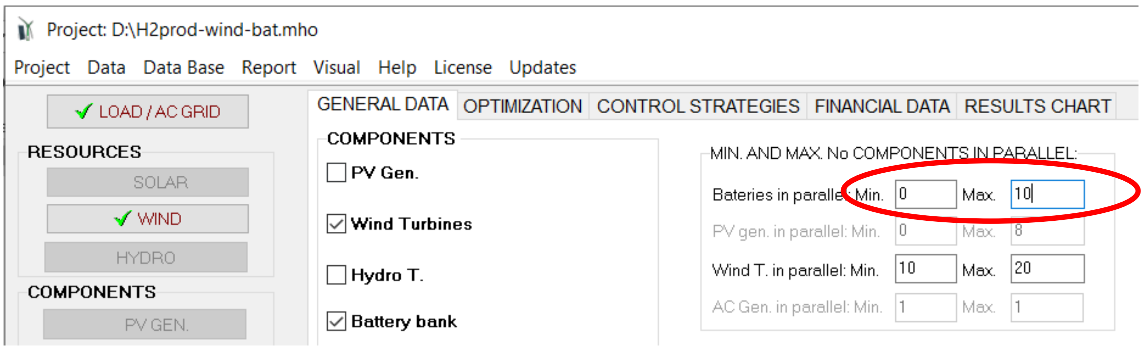


We could change any data, but let's suppose the default battery: Li-ion battery of 5 MWh (5 kAh, 1 kV), 4800 full equivalent cycles, 1.5 M€ CAPEX … is ok for us, so we leave all the default data. Also let's suppose the ambient temperature for the batteries and ageing model are ok. So we don't change anything and click OK.

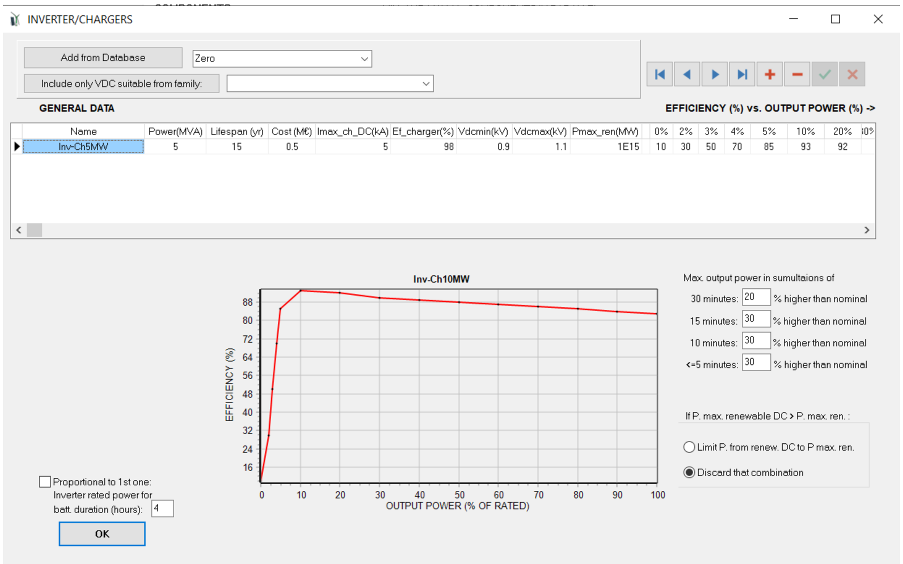
In the main window, in the left area, we can see the DC bus voltage (for the battery bank) is 1 kV, same as the battery voltage, therefore the software will always consider just 1 battery in serial (1 kV / 1 kV = 1 in serial). The number of parallel will depend on what we want to consider.



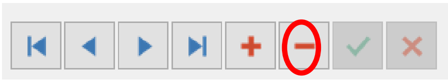
In the main window, **GENERAL DATA** tab, we can define the minimum and maximum number of batteries in parallel to be considered. Let's suppose we want to consider between 0 (that is, no battery bank) and 10 batteries of 5 MWh in parallel (the software will take into account the different combinations: battery bank of 0, battery bank of 5x1= 5 MWh, battery bank of 5x2 =10 MWh,…. battery bank of 5x10 = 50 MWh):



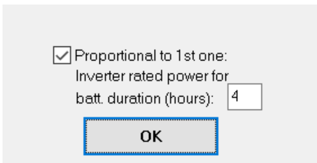
In the main window, click in **INVERTER/CHAR**. button to define the inverters/chargers (needed to connect the battery bank in DC bus to the AC bus).



We will consider only the inverter/charger of 5 MVA, therefore we delete the rest (we click in the rows we want to delete, and then click in "-")

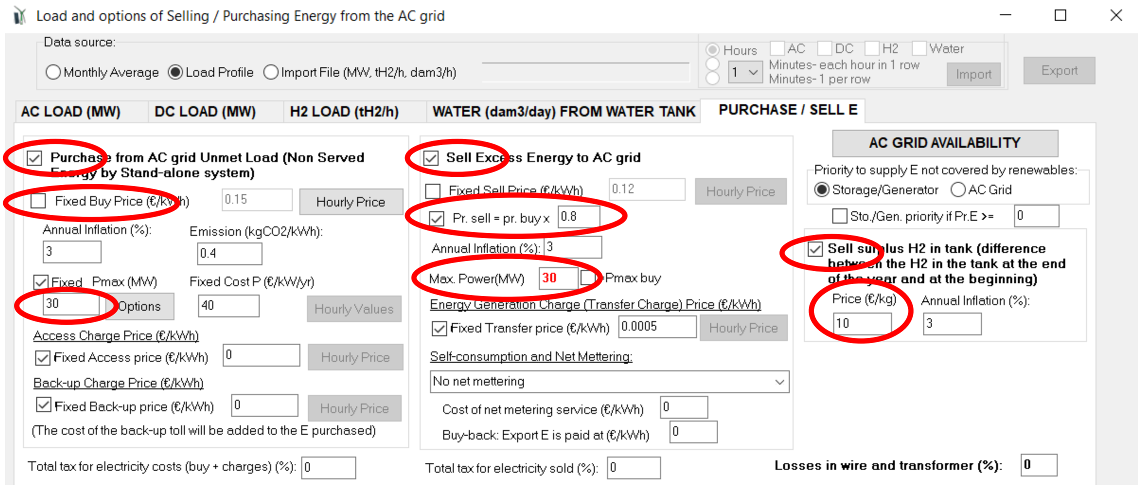


Let's suppose the data of the inverter/charger of 5 MVA is correct for us, but we want the inverter/charger to be considered in each combination of components to be proportional to this one, with battery duration of 4 h (for example, if in a combination the battery bank is of 10 MWh, the inverter/chager will be of 10 MWh/4h= 2 MW -> 2 MVA power, and the cost (CAPEX) will be proportional to the one of 5 MVA, that is 0.5·2/5= 0.2 M€, the maximum current for the charger, Imax_ch_DC will also be proportional). In the lower area of the window, we click this option.



Click OK and return to the main window. Then click in **LOAD / AC GRID**, by default there is no load. In the PURCHASE / SELL E tab, update the following (see next figure):

- Select the **Purchase energy** from AC grid and **Sell energy** to AC grid options.
- Uncheck the "**Fixed Buy Price**" box.
- Set to 30 MW the maximum power to buy from the grid and same value to the maximum power to sell to the grid (we suppose this value is the maximum grid power available).
- Click in "**Pr. Sell = pr. buy x**" and set 0.8 the factor. Therefore, we suppose sell electricity price is 80% of purchase electricity price.
- Select "**Sell surplus H2 in tank…**" and set to 10 €/kg the price of the hydrogen sold (all the hydrogen produced will be sold, at this price the first year and the next years considering the inflation, 3% annual by default).

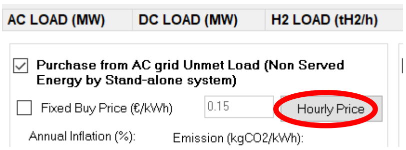


Now let's suppose that the electricity buy price is hourly (real time pricing tariff) and it has high differences between the minimum and maximum hourly price of each day. This hypothetical hourly price file can be downloaded here:

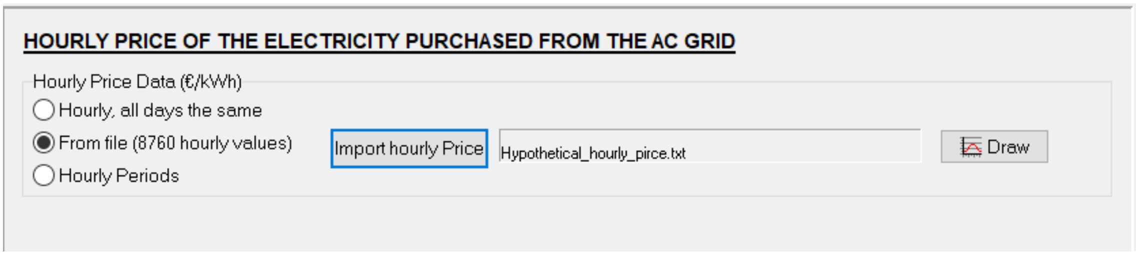
http://ihoga.unizar.es/Desc/Hypothetical_hourly_pirce.zip

Download and unzip, you will get "Hypothetical_hourly_pirce.txt" file.

Then, click in "**Hourly Price**" button below the option of "**Purchase from AC grid…**":

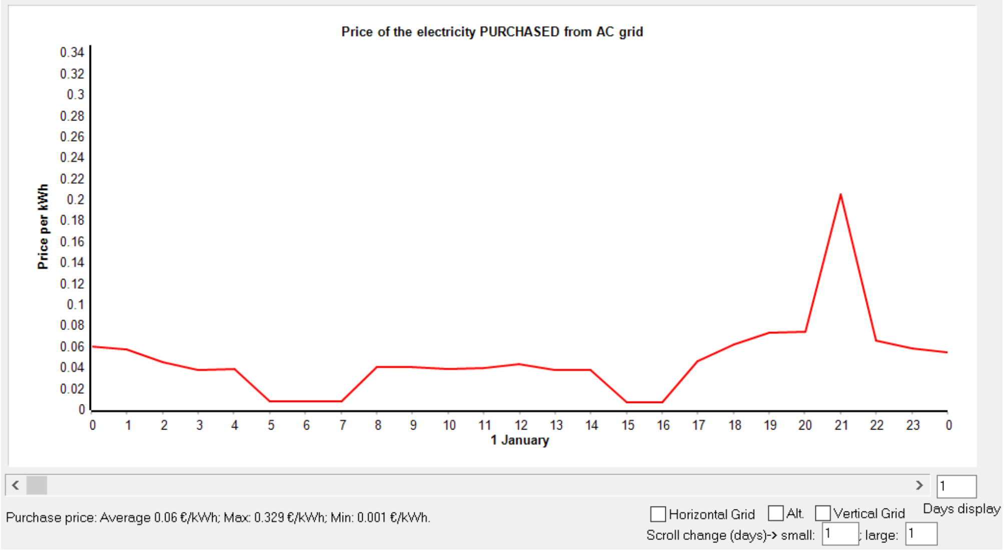


In the window that appears, select "From file (8760 values)" and import ("**Import hourly Price**" button) the "Hypothetical_hourly_pirce.txt" file.



This will be the hourly purchase price of the first year (hourly sell price will be 80%). For the next years of the system lifetime, we assume prices will be updated with an annual inflation of 3% (as default, we have not changed it).

Click in **Draw** to see the imported data.



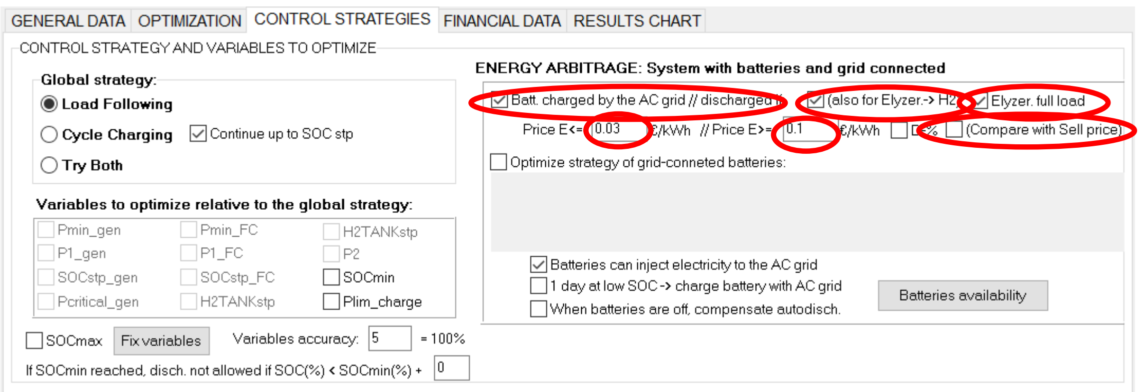
Click Back, OK and OK to return to the main screen.

In the main screen, **CONTROL STRATEGIES** tab, we can select the options of the control strategy.

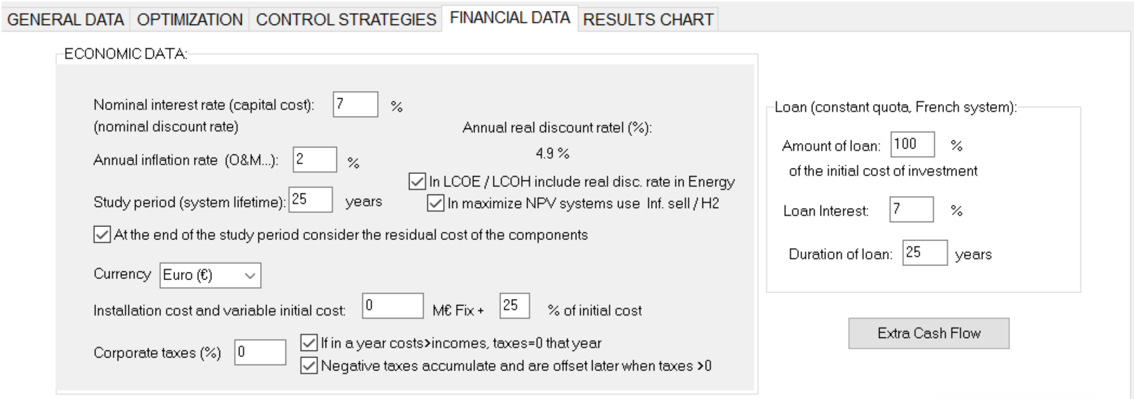
To consider control strategies in grid-connected systems related to the electrolyzer and/or the batteries, we must select the options of **ENERGY ARBITRAGE** (right area, next figure). We must check the box "**Batt. charged by the AC grid // discharged if**" to consider any option of energy arbitrage (including the option of using the electrolyzer to sell hydrogen). Also check the box "**(also for Elyzer -> H2)**" as we are also considering the electrolyzer, not only battery. And check the box "**Elyzer full load**" because we want the electrolyzer to be at full load all the time, consuming electricity from the grid if necessary.

We must also uncheck the box "**(Compare with Sell price)**", because, if this was checked the, the energy price to compare with would be the sell price, but also, if it was checked, the batteries and electrolyzer would only be charged by means of the renewable sources, not by the grid. As we want the batteries to be charged at low electricity price from the grid, and also during these time steps the electrolyzer must buy electricity to the grid to run at full power (if the renewable sources cannot fully feed it), we need to uncheck this checkbox.

Also, let's suppose we want the batteries to be charged only when the purchase electricity price is low (for example, lower than 0.03 €/kWh in the first year, the next years this price will be updated with the purchase electricity price inflation) and discharge the batteries to feed the electrolyzer (if renewables are not enough) when the purchase electricity price is high (for example, higher than 0.1 €/kWh in the first year):

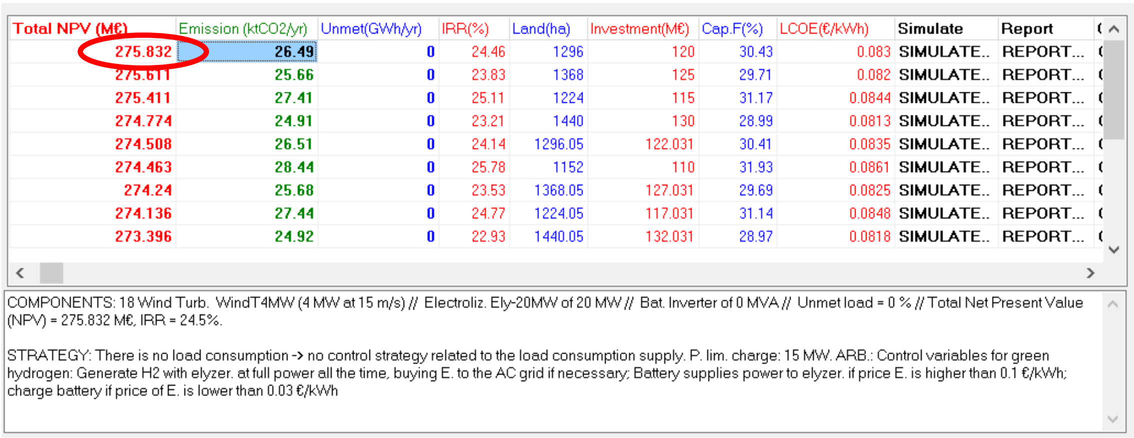


In the **FINANCIAL DATA** tab, we can see the general economic data, we leave them by default:



Now we have everything defined. We can calculate, the software will simulate all the combinations of components (11 combinations of wind turbines, between 10 and 20 in parallel; 11 combinations of batteries, between 0 and 10 in parallel; 1 combination of electrolyzer: total 11 x 11 x 1 = 121 combinations). The software will evaluate each combination, calculate all the results of each combination, and then sort them from best to worst considering the objective, which is in this case the maximization of the NPV.

Click in **CALCULATE.** After several seconds the system is optimized:

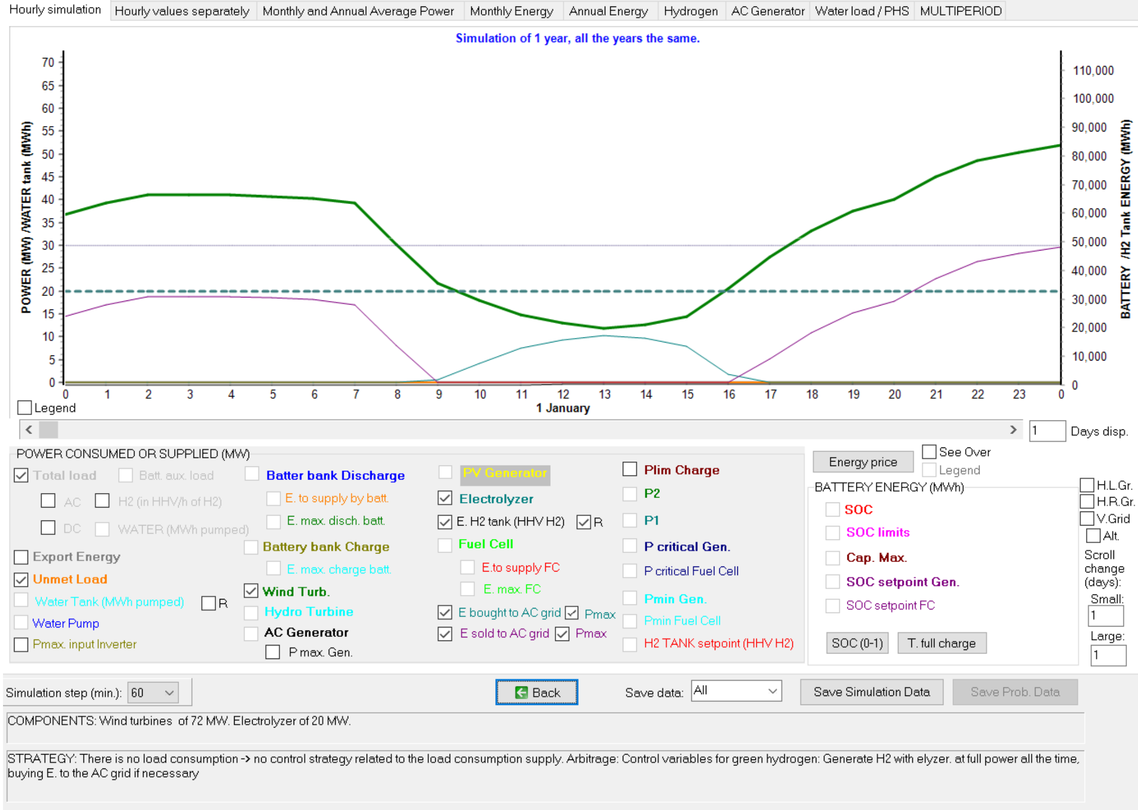


Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
275.832	26.49	0	24.46	1296	120	30.43	0.083	SIMULATE..	REPORT...
275.611	25.66	0	23.83	1368	125	29.71	0.082	SIMULATE..	REPORT...
275.411	27.41	0	25.11	1224	115	31.17	0.0844	SIMULATE..	REPORT...
274.774	24.91	0	23.21	1440	130	28.99	0.0813	SIMULATE..	REPORT...
274.508	26.51	0	24.14	1296.05	122.031	30.41	0.0835	SIMULATE..	REPORT...
274.463	28.44	0	25.78	1152	110	31.93	0.0861	SIMULATE..	REPORT...
274.24	25.68	0	23.53	1368.05	127.031	29.69	0.0825	SIMULATE..	REPORT...
274.136	27.44	0	24.77	1224.05	117.031	31.14	0.0848	SIMULATE..	REPORT...
273.396	24.92	0	22.93	1440.05	132.031	28.97	0.0818	SIMULATE..	REPORT...

The first row of the results is the optimal system (explained in the area below the results table): it consists of 18 wind turbines of 4 MW and electrolyzer of 20 MW. No battery nor inverter/charger are selected (that is, in this case the cost of the battery and inverter/charger is too high and it is better not to use them, it is not worth).

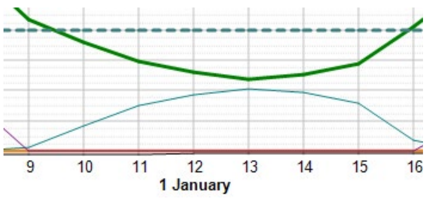
For each combination, we can see the NPV, emissions, unmet load (no meaning in this case as there is no load), IRR, land used, investment cost, capacity factor, LCOE (considering energy of the hydrogen produced as the HHV), the components used and many other results (use the displacement bar). We can see the simulation, the report and the cash flow detailed if we click the bold cells **SIMULATE**, **REPORT** or **COSTS**.

If we click in “**SIMULATE**” in the first row of the table, we will see the simulation of the optimal system:



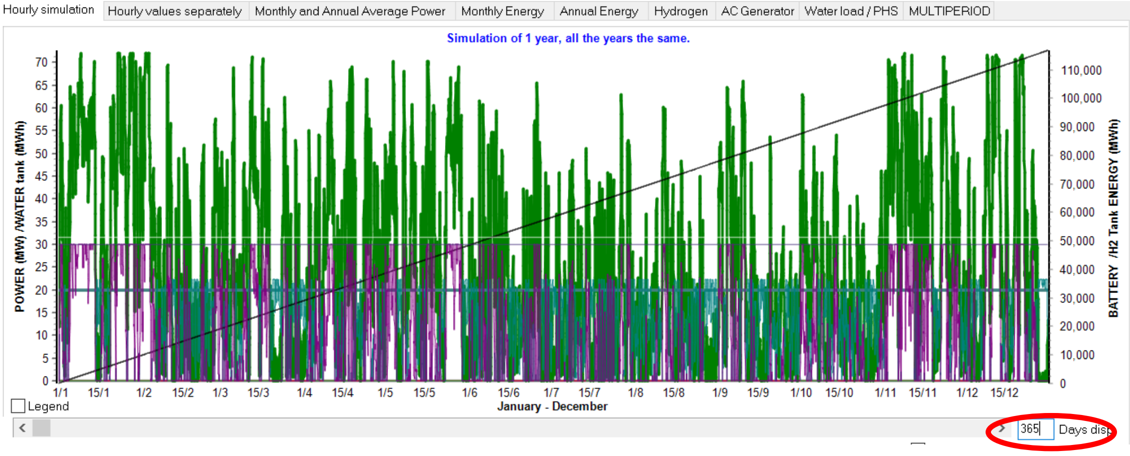
In the first hour of January 1st, we can see that the 18 wind turbines of 4 MW (total 72 MW rated power) generate roughly 37 MW, in green line (if we go to the wind resource window, and see the data imported from the wind farm normalized to 1 MW rated power, we can see for the first hour of the year it is roughly 0.5 MW -> multiplied by 72 MW rated power we obtain roughly 37 MW). In the graph we can see the electrolyzer runs at full power (20 MW, what we see in the graph, turquoise dot line, is the power consumed in DC by the electrolyzer), but it consumes in AC 20/0.9 = 22.2 MW (due to the rectifier efficiency of 90%). The rest AC power (37 MW – 22.2 MW), approx. 15 MW is sold to the AC grid.

For other hours, for example at 12 h, the wind farm generation (13 MW) is lower than what the electrolyzer needs in AC (22.2 MW), the rest (9.2 MW) are supplied by the AC grid (purchased to AC grid). Zoom in the graph:

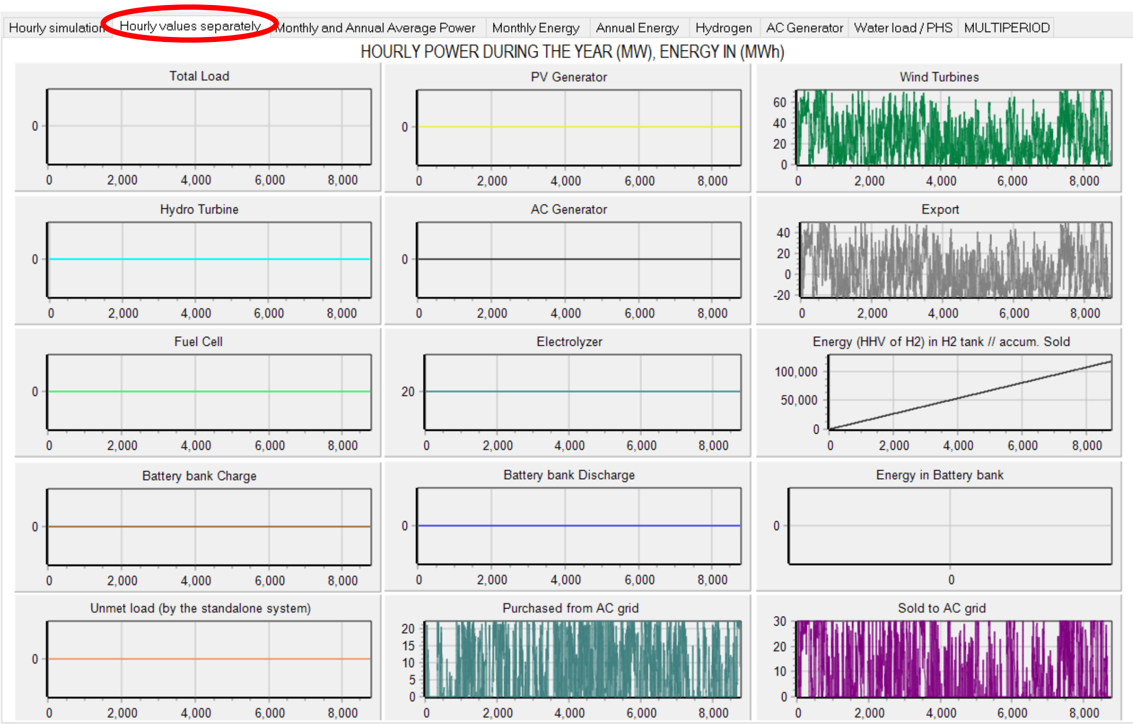


In the right axis there is the H2 production cumulated (in HHV, MWh) (in systems where hydrogen is later consumed, it shows the H2 in the tank).

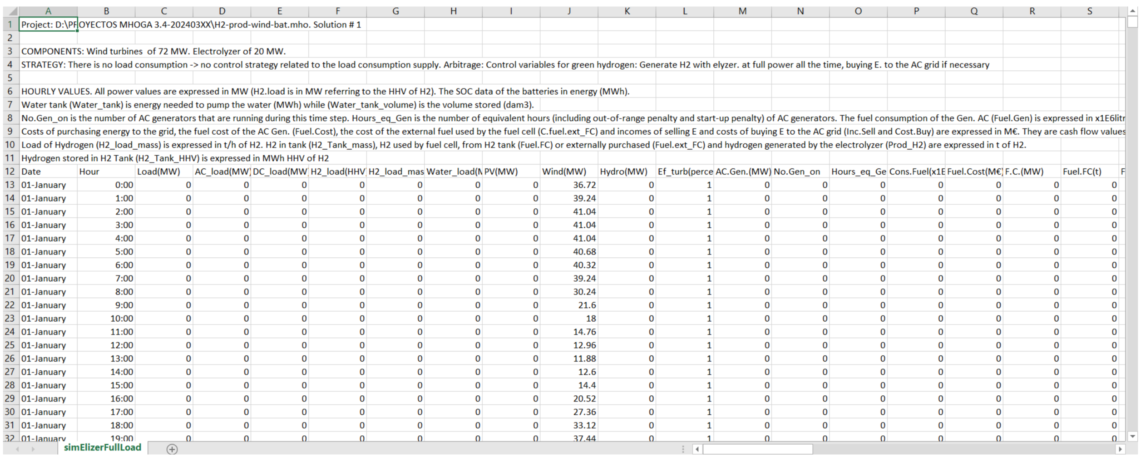
If we change the days to display to 365:



In the second tab of the screen, we can see the different components during the year:



If we click in "**Save Simulation Data**" button, we will save all the simulation results, which can be open by Excel.



Project: D:\PROYECTOS MHOGA 3.4-202403XX\H2-prod-wind-bat.mho. Solution # 1

COMPONENTS: Wind turbines of 72 MW. Electrolyzer of 20 MW.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. Arbitrage: Control variables for green hydrogen: Generate H2 with elyzer. at full power all the time, buying E. to the AC grid if necessary

HOURLY VALUES. All power values are expressed in MW (H2.load is in MW referring to the HHV of H2). The SOC data of the batteries in energy (MWh).

Water tank (Water_tank) is energy needed to pump the water (MWh) while (Water_tank_volume) is the volume stored (dam3).

No.Gen_on is the number of AC generators that are running during this time step. Hours_eq_Gen is the number of equivalent hours (including out-of-range penalty and start-up penalty) of AC generators. The fuel consumption of the Gen. AC (Fuel.Gen) is expressed in x1E6litr

Costs of purchasing energy to the grid, the fuel cost of the AC Gen. (Fuel.Cost), the cost of the external fuel used by the fuel cell (C.fuel.ext_FC) and incomes of selling E and costs of buying E to the AC grid (Inc.Sell and Cost.Buy) are expressed in M€. They are cash flow values

Load of Hydrogen (H2_load_mass) is expressed in t/h of H2. H2 in tank (H2_Tank_mass), H2 used by fuel cell, from H2 tank (Fuel.FC) or externally purchased (Fuel.ext_FC) and hydrogen generated by the electrolyzer (Prod_H2) are expressed in t of H2.

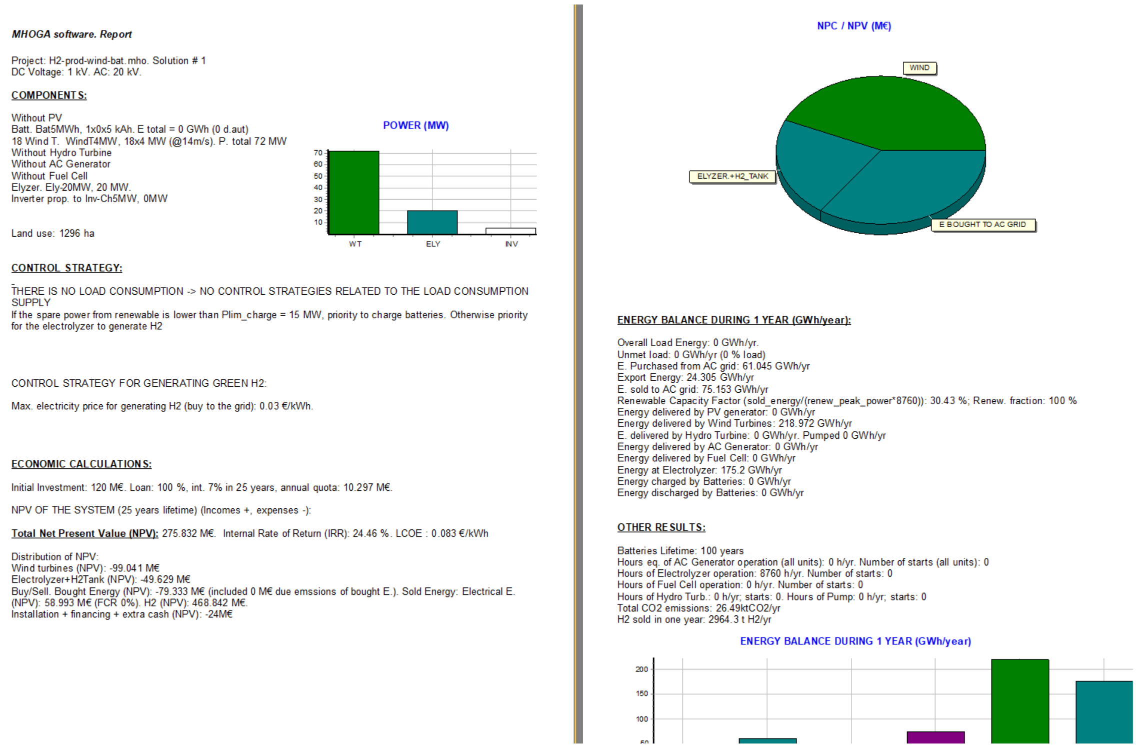
Hydrogen stored in H2 Tank (H2_Tank_HHV) is expressed in MWh HHV of H2

Date	Hour	Load(MW)	AC_load(MW	DC_load(MW	H2_load(HHV	H2_load_mas	Water_load(N	PV(MW)	Wind(MW)	Hydro(MW)	Ef_turb(perce	AC.Gen.(MW)	No.Gen_on	Hours_eq_Ge	Cons.Fuel(x1E	Fuel.Cost(M€	F.C.(MW)	Fuel.FC(t)
01-January	0:00	0	0	0	0	0	0	0	36.72	0	1	0	0	0	0	0	0	0
01-January	1:00	0	0	0	0	0	0	0	39.24	0	1	0	0	0	0	0	0	0
01-January	2:00	0	0	0	0	0	0	0	41.04	0	1	0	0	0	0	0	0	0
01-January	3:00	0	0	0	0	0	0	0	41.04	0	1	0	0	0	0	0	0	0
01-January	4:00	0	0	0	0	0	0	0	41.04	0	1	0	0	0	0	0	0	0
01-January	5:00	0	0	0	0	0	0	0	40.68	0	1	0	0	0	0	0	0	0
01-January	6:00	0	0	0	0	0	0	0	40.32	0	1	0	0	0	0	0	0	0
01-January	7:00	0	0	0	0	0	0	0	39.24	0	1	0	0	0	0	0	0	0
01-January	8:00	0	0	0	0	0	0	0	30.24	0	1	0	0	0	0	0	0	0
01-January	9:00	0	0	0	0	0	0	0	21.6	0	1	0	0	0	0	0	0	0
01-January	10:00	0	0	0	0	0	0	0	18	0	1	0	0	0	0	0	0	0
01-January	11:00	0	0	0	0	0	0	0	14.76	0	1	0	0	0	0	0	0	0
01-January	12:00	0	0	0	0	0	0	0	12.96	0	1	0	0	0	0	0	0	0
01-January	13:00	0	0	0	0	0	0	0	11.88	0	1	0	0	0	0	0	0	0
01-January	14:00	0	0	0	0	0	0	0	12.6	0	1	0	0	0	0	0	0	0
01-January	15:00	0	0	0	0	0	0	0	14.4	0	1	0	0	0	0	0	0	0
01-January	16:00	0	0	0	0	0	0	0	20.52	0	1	0	0	0	0	0	0	0
01-January	17:00	0	0	0	0	0	0	0	27.36	0	1	0	0	0	0	0	0	0
01-January	18:00	0	0	0	0	0	0	0	33.12	0	1	0	0	0	0	0	0	0
01-January	19:00	0	0	0	0	0	0	0	37.44	0	1	0	0	0	0	0	0	0

simElizerFullLoad

In the Hydrogen tab, hydrogen production and cumulated, by moths:

If we return to the main screen, and click in the first row of the results table, in **REPORT** cell, we obtain the report of the optimal system, where it is shown the components, control strategy, economic results, energy balance and other results (it can be printed, saved in PDF… and when we close, it asks if you want to save it in .doc or .rtf file which can be open by Microsoft Word):



MHOGA software. Report

Project: H2-prod-wind-bat.mho. Solution # 1
DC Voltage: 1 kV. AC: 20 kV.

COMPONENTS:

Without PV
Batt. Bat5MWh, 1x0x5 kAh. E total = 0 GWh (0 d.aut)
18 Wind T. WindT4MW, 18x4 MW (@14m/s). P. total 72 MW
Without Hydro Turbine
Without AC Generator
Without Fuel Cell
Elyzer. Ely-20MW, 20 MW.
Inverter prop. to Inv-Ch5MW, 0MW

Land use: 1296 ha

CONTROL STRATEGY:

THERE IS NO LOAD CONSUMPTION -> NO CONTROL STRATEGIES RELATED TO THE LOAD CONSUMPTION SUPPLY
If the spare power from renewable is lower than Plim_charge = 15 MW, priority to charge batteries. Otherwise priority for the electrolyzer to generate H2

CONTROL STRATEGY FOR GENERATING GREEN H2:

Max. electricity price for generating H2 (buy to the grid): 0.03 €/kWh.

ECONOMIC CALCULATIONS:

Initial Investment: 120 M€. Loan: 100 %, int. 7% in 25 years, annual quota: 10.297 M€.

NPV OF THE SYSTEM (25 years lifetime) (Incomes +, expenses -):

Total Net Present Value (NPV): 275.832 M€. Internal Rate of Return (IRR): 24.46 %. LCOE : 0.083 €/kWh

Distribution of NPV:
Wind turbines (NPV): -99.041 M€
Electrolyzer+H2Tank (NPV): -49.629 M€
Buy/Sell. Bought Energy (NPV): -79.333 M€ (included 0 M€ due emssions of bought E.). Sold Energy: Electrical E. (NPV): 58.993 M€ (FCR 0%). H2 (NPV): 468.842 M€.
Installation + financing + extra cash (NPV): -24M€

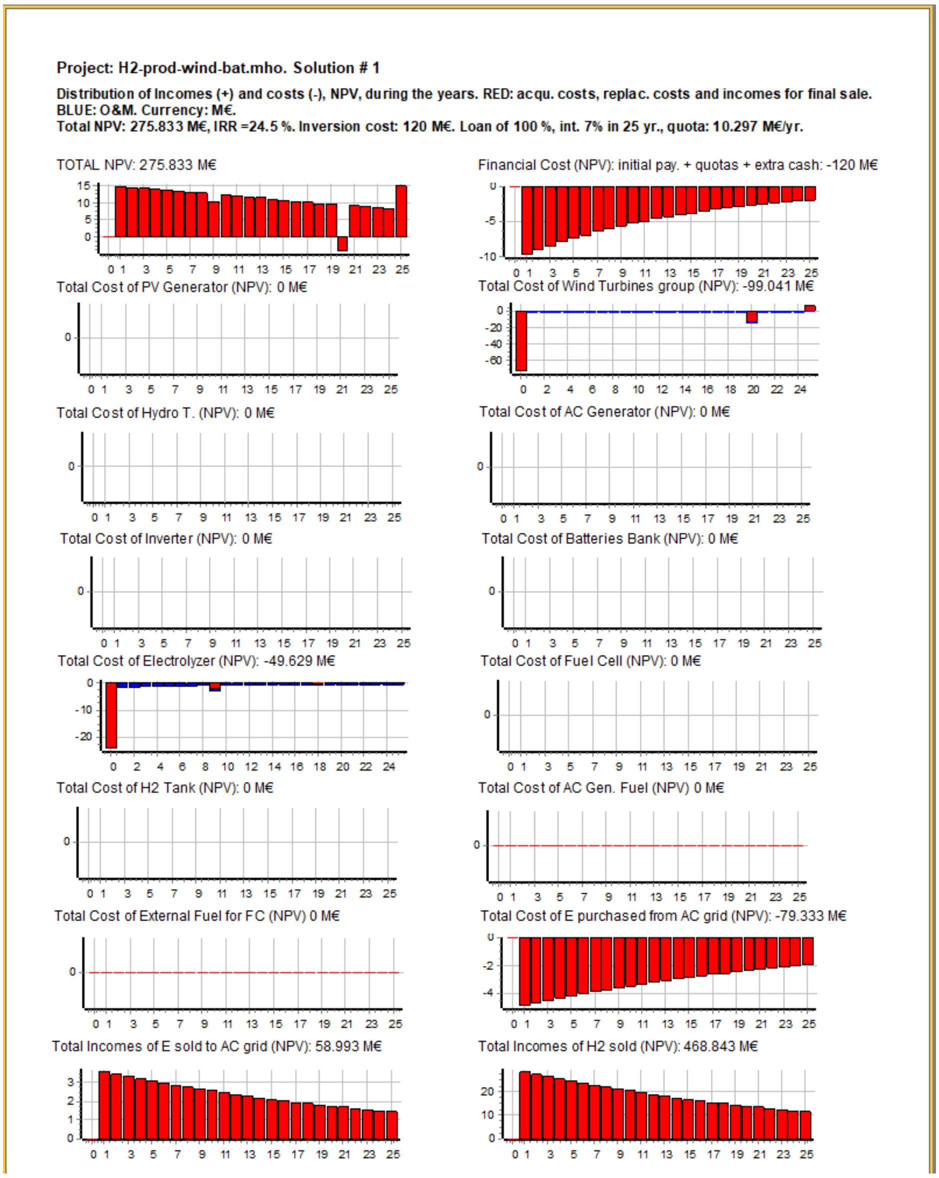
ENERGY BALANCE DURING 1 YEAR (GWh/year):

Overall Load Energy: 0 GWh/yr.
Unmet load: 0 GWh/yr (0 % load)
E. Purchased from AC grid: 61.045 GWh/yr
Export Energy: 24.305 GWh/yr
E. sold to AC grid: 75.153 GWh/yr
Renewable Capacity Factor (sold_energy/(renew_peak_power*8760)): 30.43 %; Renew. fraction: 100 %
Energy delivered by PV generator: 0 GWh/yr
Energy delivered by Wind Turbines: 218.972 GWh/yr
E. delivered by Hydro Turbine: 0 GWh/yr. Pumped 0 GWh/yr
Energy delivered by AC Generator: 0 GWh/yr
Energy delivered by Fuel Cell: 0 GWh/yr
Energy at Electrolyzer: 175.2 GWh/yr
Energy charged by Batteries: 0 GWh/yr
Energy discharged by Batteries: 0 GWh/yr

OTHER RESULTS:

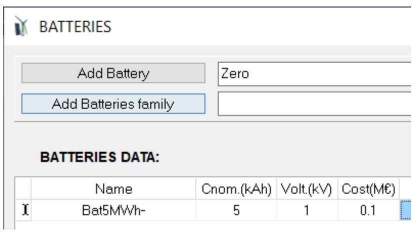
Batteries Lifetime: 100 years
Hours eq. of AC Generator operation (all units): 0 h/yr. Number of starts (all units): 0
Hours of Electrolyzer operation: 8760 h/yr. Number of starts: 0
Hours of Fuel Cell operation: 0 h/yr. Number of starts: 0
Hours of Hydro Turb.: 0 h/yr; starts: 0. Hours of Pump: 0 h/yr; starts: 0
Total CO2 emissions: 26.49ktCO2/yr
H2 sold in one year: 2964.3 t H2/yr

If we return to the main screen, and click in the first row of the results table, in **COSTS** cell, we obtain the report of the costs of the system, in detail (it can be printed, saved in PDF… and when we close, it asks if you want to save it in Excel file):



Now we return to the main screen.

Let’s see how the results change if we change the CAPEX of the batteries. Go to the batteries screen, change the name of the battery (for example, add “-“) and change the CAPEX to 0.1 M€ (a very high reduction from the 1.5 M€ original), this cost is not real, but we will use it to see if with low battery prices the batteries are included in the optimal system.



Now return to the main screen and **CALCULATE** again.

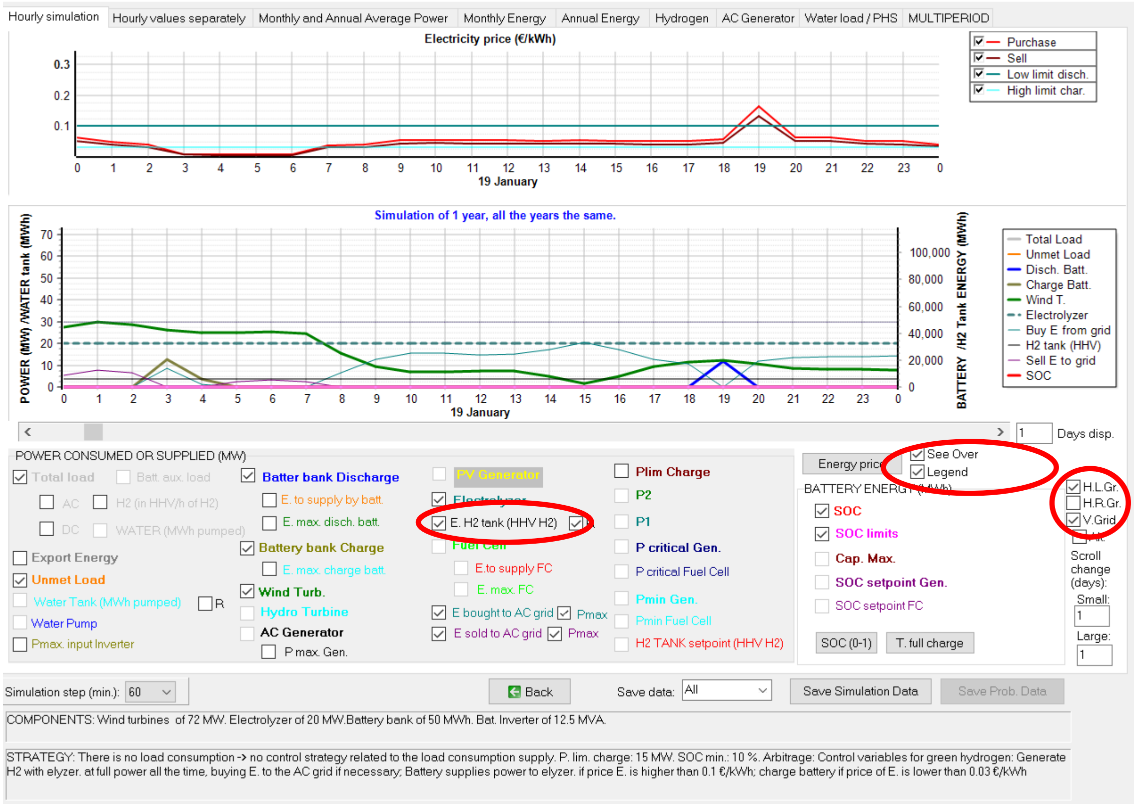
#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report
1	284.217	26.79	0	24.59	1296.5	122.813	30.3	0.0806	SIMULATE..	REPOR
2	284.191	27.76	0	25.25	1224.5	117.813	31.03	0.0817	SIMULATE..	REPOR
3	283.712	28.83	0	25.93	1152.5	112.813	31.79	0.0831	SIMULATE..	REPOR
4	283.648	25.92	0	23.95	1368.5	127.813	29.58	0.0797	SIMULATE..	REPOR
5	283.541	26.77	0	24.58	1296.45	122.531	30.3	0.0808	SIMULATE..	REPOR
6	283.477	27.74	0	25.24	1224.45	117.531	31.04	0.0819	SIMULATE..	REPOR
7	283.012	25.91	0	23.94	1368.45	127.531	29.59	0.0799	SIMULATE..	REPOR
8	282.973	28.81	0	25.93	1152.45	112.531	31.79	0.0834	SIMULATE..	REPOR
9	282.848	26.75	0	24.58	1296.4	122.25	30.31	0.081	SIMULATE..	REPOR

COMPONENTS: Batteries Bat5MWh- (5 kAh): 1s. x 10p. // 18 Wind Turb. WindT4MW (4 MW at 15 m/s) // Electroliz. Ely-20MW of 20 MW // Bat. Inverter of 12.5 MVA // Unmet load = 0 % // Total Net Present Value (NPV) = 284.217 M€, IRR = 24.6%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. P. lim. charge: 15 MW. SOC min.: 10 %. ARB.: Control variables for green hydrogen: Generate H2 with elyzer. at full power all the time, buying E. to the AC grid if necessary; Battery supplies power to elyzer. if price E. is higher than 0.1 €/kWh; charge battery if price of E. is lower than 0.03 €/kWh

Now the optimal system (first row of the results table) includes batteries. It is composed of 18 wind turbines of 4 MW (total 68 MW), electrolyzer of 20 MW, 10 batteries of 5 MWh (total 50 MWh) and inverter/charger of 12.5 MVA (for 4 h battery duration). NPV is higher than in the previous study.

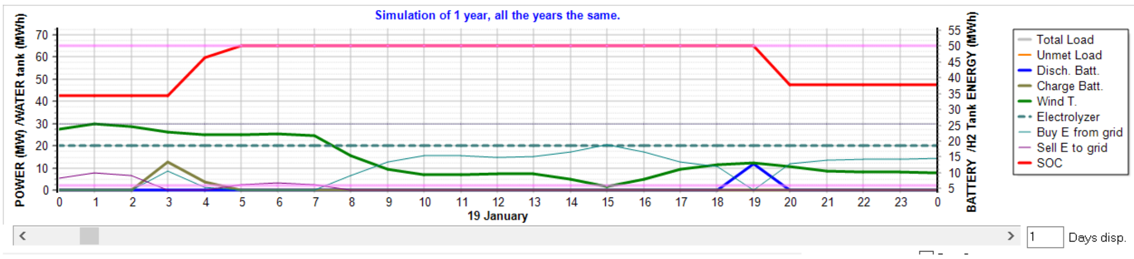
If we click in **SIMULATE** in the first row (optimal system), we can see, with 1 day display, for example for January 19th (move the displacement bar):



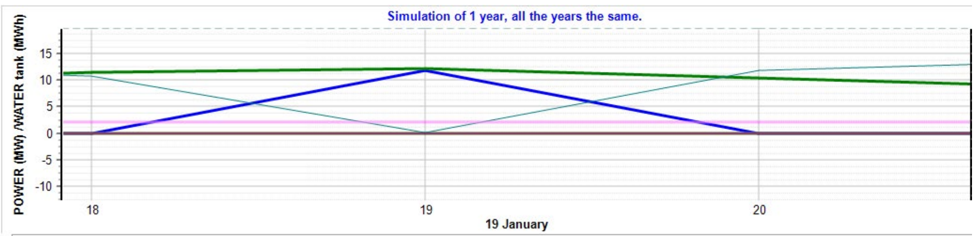
This day, at 3h we can see the battery is charged and at 19h it is discharged. It is due to the control strategy (for each time step, in this case, hours, we see a point for each variable, that point is the value of the variable for the whole time step). As both the hydrogen cumulated (in HHV) and the battery SOC are shown in the right axis, and they are very different in this case, to see the SOC we must unselect the energy in H2 tank: unselect “**E.H2 tank (HHV H2)**”. Also, to see the electricity price over the simulation graph, click in “**See over**” and “**Legend**” to see its legend. We can also see the grid of the graphs with “**H.L.Gr.**” and “**V.Grid**” checkboxes.

We can see that at 3 h (January 19th) the purchase electricity price (upper curve, red) becomes lower than the “High limit charge” which is 0.03 €/kWh (light blue line), then the battery must be charged. Wind turbines generation is roughly 25 MW, while electrolyzer AC consumption (including rectifier is 22.2 MW), therefore roughly 2.8 MW are for battery charge in AC. The battery must be charged at its maximum rate (2.5 kA · 1 kV · 10 batteries = 25 MW) but also there is the limitation of the inverter/charger, which is 12.5 MW, therefore the battery is charged at 12.5 MW DC (brown curve). As there are 2.8 MW AC surplus from the wind farm, we need from the grid (considering the rectifier efficiency of the inverter/charger of 98%) 12.5/0.98-2.8, roughly 9.8 MW.

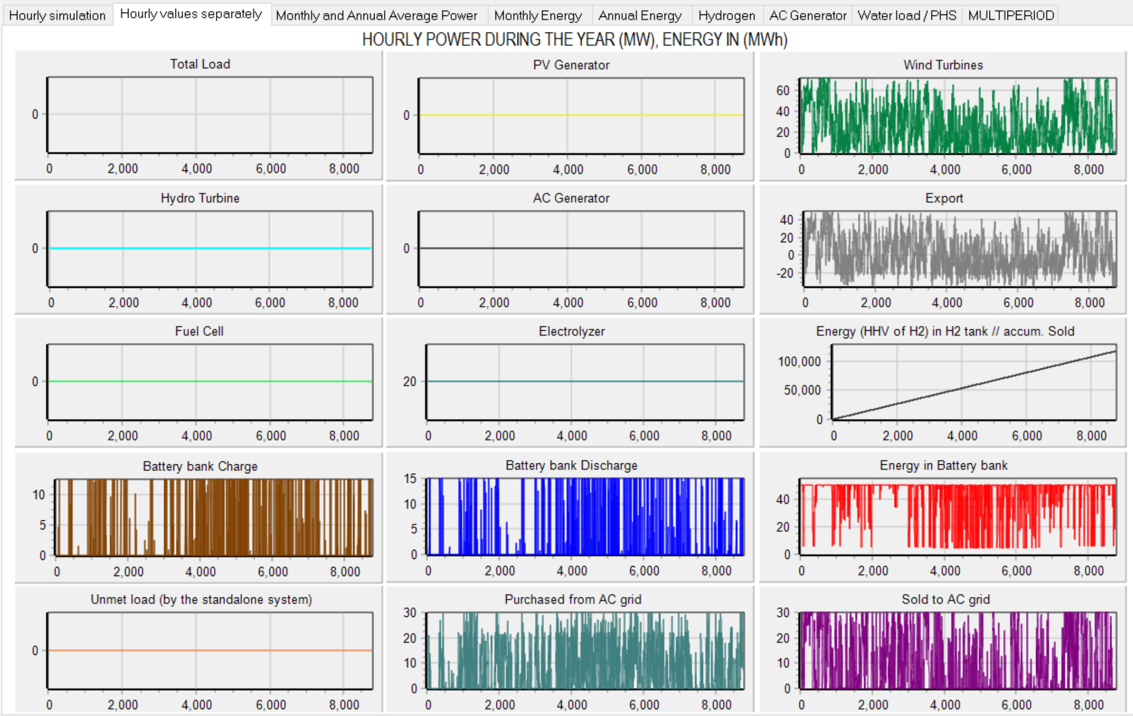
Next hour battery must also be charged, but it cannot charge at 12.5 MW because only few MW are allowed as the maximum SOC is near to be reached (we can see the red curve, SOC, referred to right axis). If we uncheck the “**E.H2 tank (HHV H2)**” checkbox, in red we can see the SOC.



At 19 h (January 19th) purchase price is higher than the “Low limit discharge” which is 0.1 €/MWh (upper graph, turquoise line). As the wind farm only generates roughly 12.5 MW, it cannot supply the whole 22.2 MW AC power needed by the electrolyzer: the rest (22.2-12.5 = 9.7 MW AC) must be supplied by the battery. But the blue curve is the discharge of the battery in the DC bus, in AC is this value multiplied by the inverter efficiency. Inverter efficiency for 9.7 MW (that is, 85% of the rated power of the inverter) is about 84%, therefore 9.7/0.84 = 11.5 MW must be supplied by the battery in DC (blue curve). Zoom in the graph:



In the tab of the hourly values separately we can see the charge and discharge of the battery, and also the energy in battery bank (SOC in MWh) for the whole year.

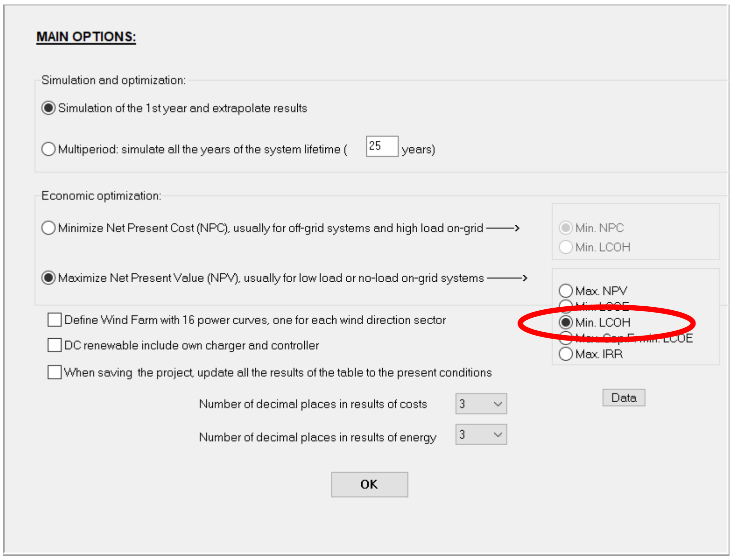


We return to the main window of the software.

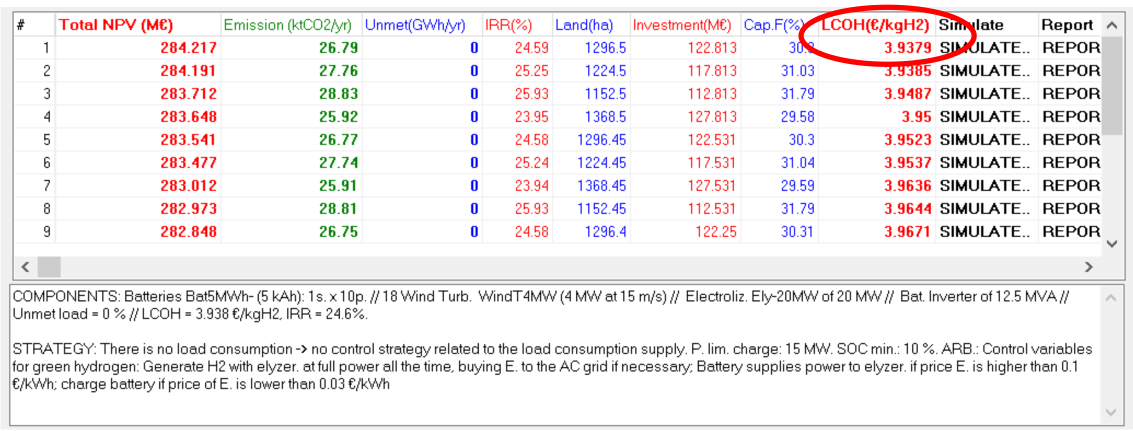
Now let's see the results when we optimize minimizing the LCOH.

Go to **Project -> OPTIONS**.

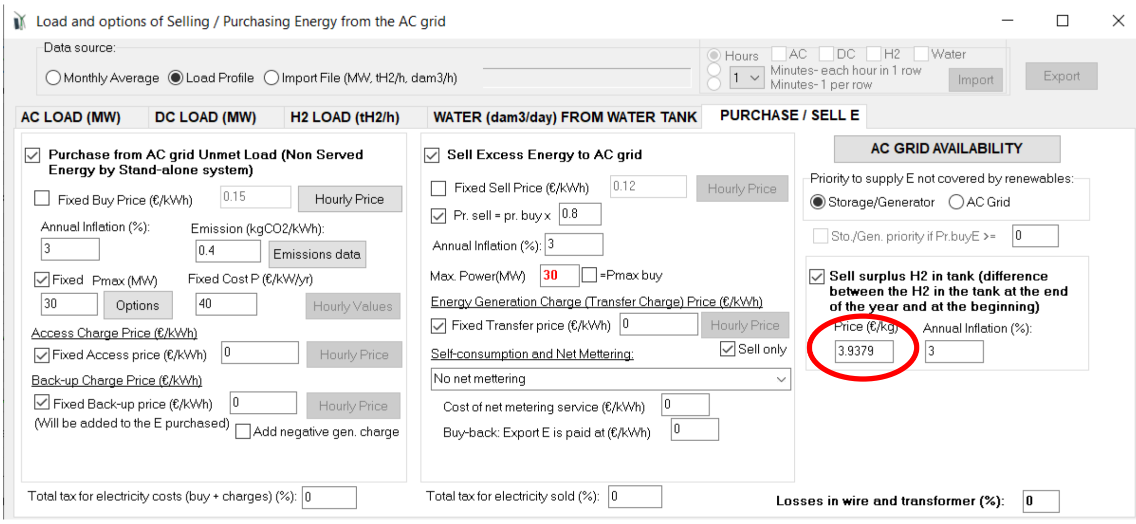
Select **Min. LCOH.**



Optimize again. The optimal system is the same (in other cases it can be different). Now, the column at the left of SIMULATE cell shows the LCOH instead of the LCOE. We can see that the optimal system has a LCOH of 3.938 €/kg.



If we go to the **LOAD / AC GRID** window, then tab **PURCHASE /SELL E.**, and we change the hydrogen price to 3.9379 €/kg:

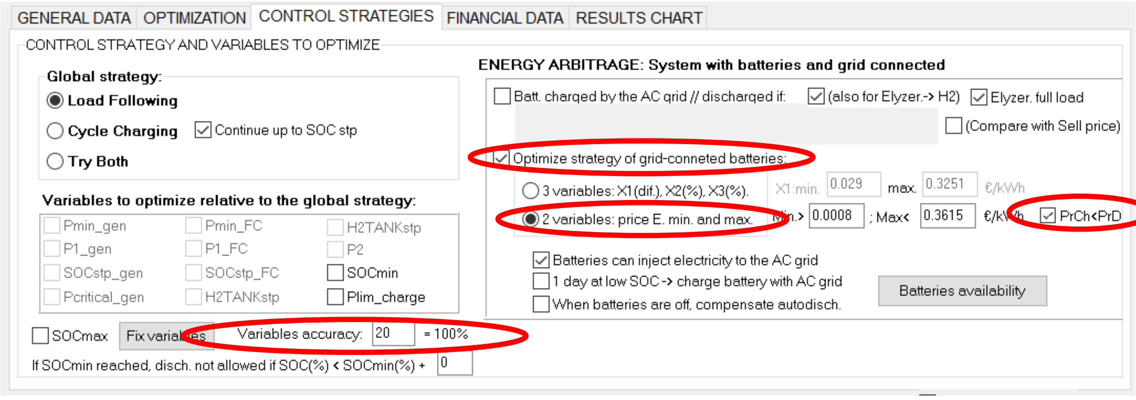


And now we return to the main screen, and we click in the first row of the results table, the results of that combination are updated, obtaining a NPV of 0 (as we have set for the price of hydrogen the LCOH, therefore NPV is 0):

Now we go back to the **LOAD / AC GRID** window, then tab **PURCHASE /SELL E.**, and we change the hydrogen price to the original 10 €/kg.

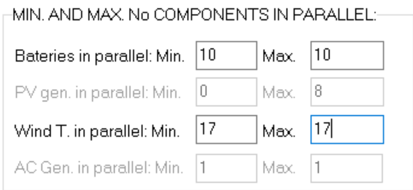
We could optimize the limits for charge/discharge the battery.

We go to the main screen, and select in **CONTROL STRATEGIES** tab "**Optimize strategy of grid-connected batteries**", "**2 variables**" and change variables accuracy to 20=100% (more precision). We have two variables to be optimized for the control, minimum and maximum purchase electricity price setpoints to charge/discharge the battery. Each variable will have 21 values (from 0 to 100%, as 100% is 20), therefore there will be 21x21=441 combinations of control strategy for each combination of components. However, as the "**PrCh<PrD**" checkbox is checked, it forces the discharge price to be higher than the charge price, so only 231 combinations will be for the control strategy.



We can see that the computation time increases dramatically, as each combination of components will be evaluated 231 times to obtain the optimal strategy for the batteries (unless we use genetic algorithms).

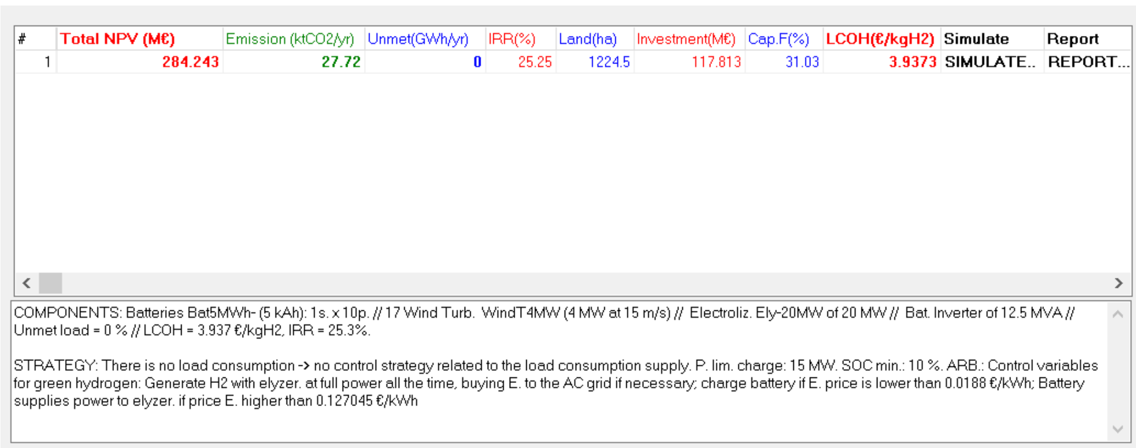
To reduce the computation time (if we don't want to wait 20-30 minutes nor use genetic algorithms), we can fix the min. and max. number of batteries and wind turbines to the optimal previous result (10 and 17, respectively):



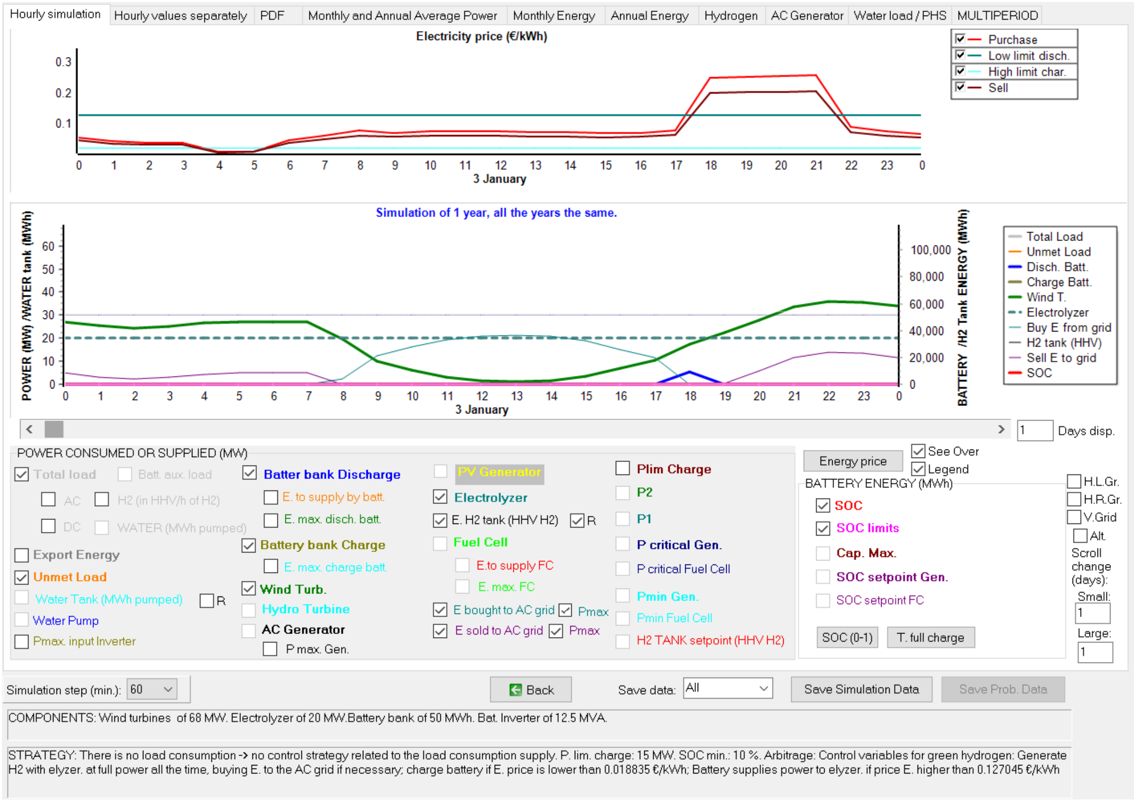
And then we will consider a fixed value of 10 batteries (10x5 = 50 MWh) with the inverter charger for 4 h duration (12.5 MVA), 17 wind turbines of 4 MW and the electrolyzer of 20 MW.

We calculate again:

The optimal system is a bit better than the previous one (a little more NPV, a little less LCOH). The optimal price limit setpoints are 0.0188 €/kWh and 0.127045 €/kWh (when we previously set them by hand, we used 0.03 and 0.1, not very different).

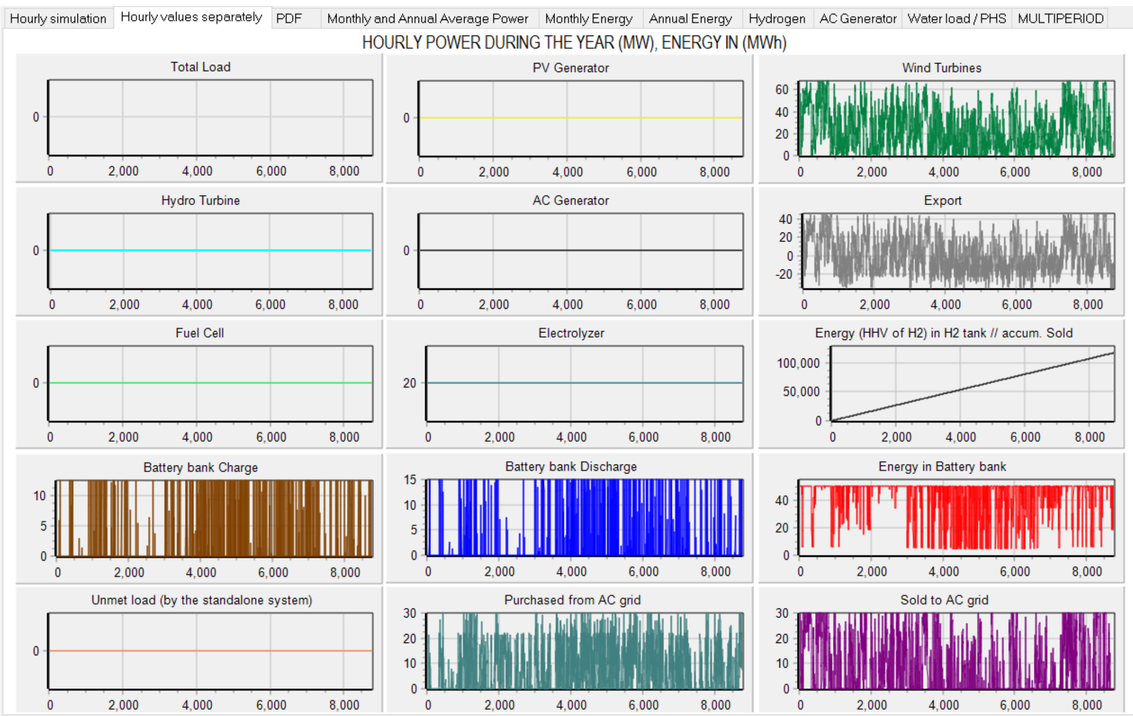


The simulation:

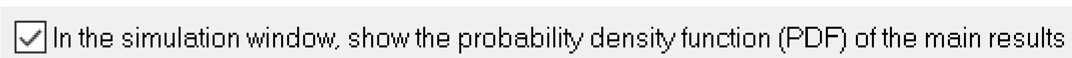


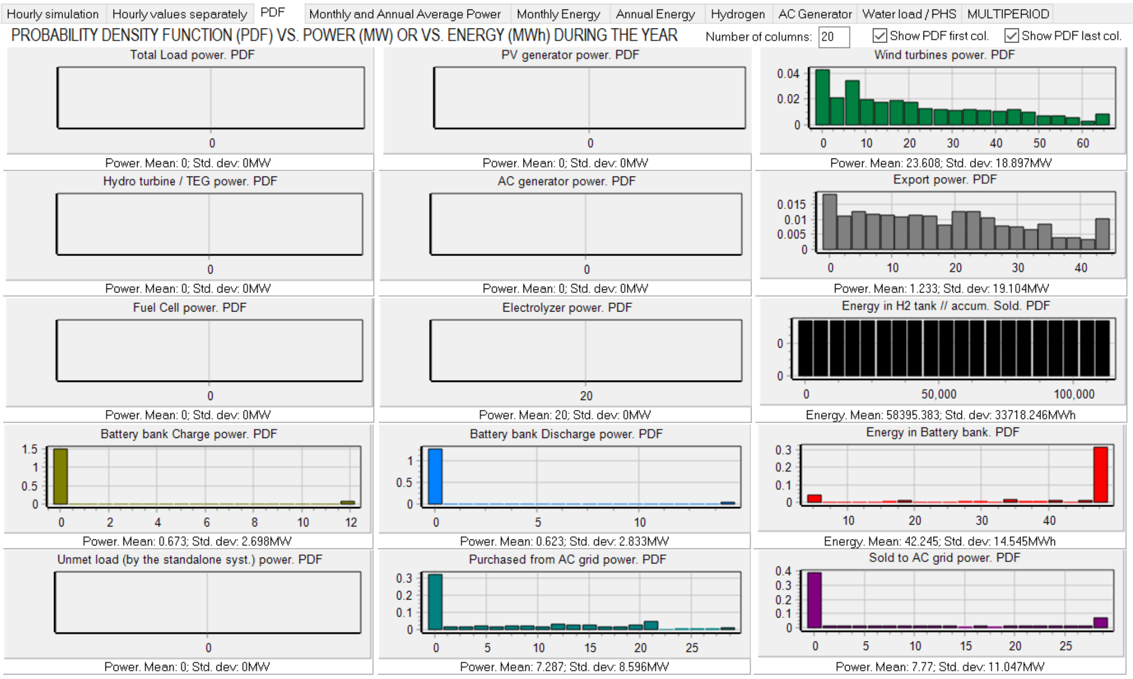
For example, January the 3rd, we can see at 18 h purchase price is higher than the limit, therefore the difference between the rated power of the electrolyzer and the wind turbine generating power is supplied by the battery.

2nd tab:



3rd tab (before, in Project->Options, check "In the simulation window, show the probability density function (PDF) of the main results").





We see the PDF of the different results, for example, we can see that the most of the time of the year the battery is at high SOC (last column is the highest, and the mean is 42.245 MWh (nominal battery capacity is 50 MWh).

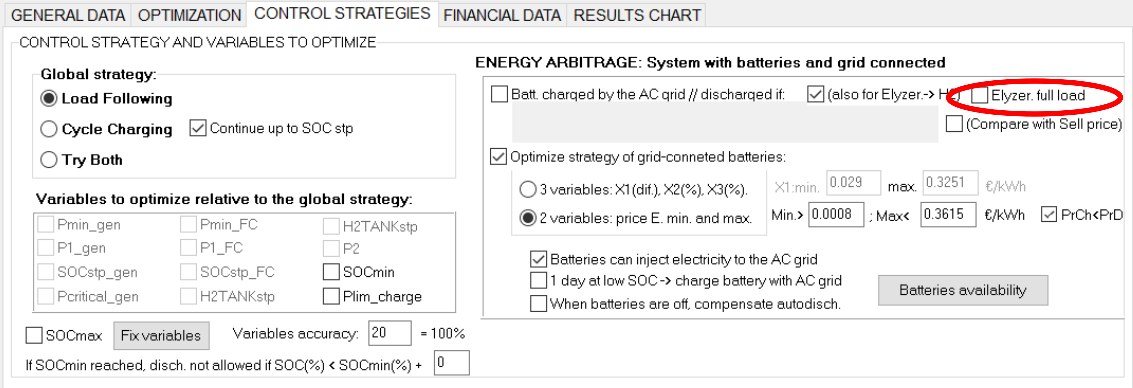
Variant:

Let's see what happens if we don't want the electrolyzer to be at full load all the time, we want that electrolyzer runs only when electricity price is low. Also, batteries are charged only when electricity price is low (as previously), but they are discharged when electricity price is high to inject electricity to the grid (not to supply the electrolyzer as previously).

Therefore:

- Low electricity price: energy from the wind farm is used to feed the electrolyzer and chage the battery. If not enough, buy to the grid.
- Medium electricity price: Sell all the electricity from the wind farm to the grid.
- High electricity price: Sell all the electricity from the wind farm to the grid and discharge the battery to inject (sell) to the grid.

We get this control strategy just unchecking "**Elyzer. full load**" checkbox from the **CONTROL STRATEGIES** tab:

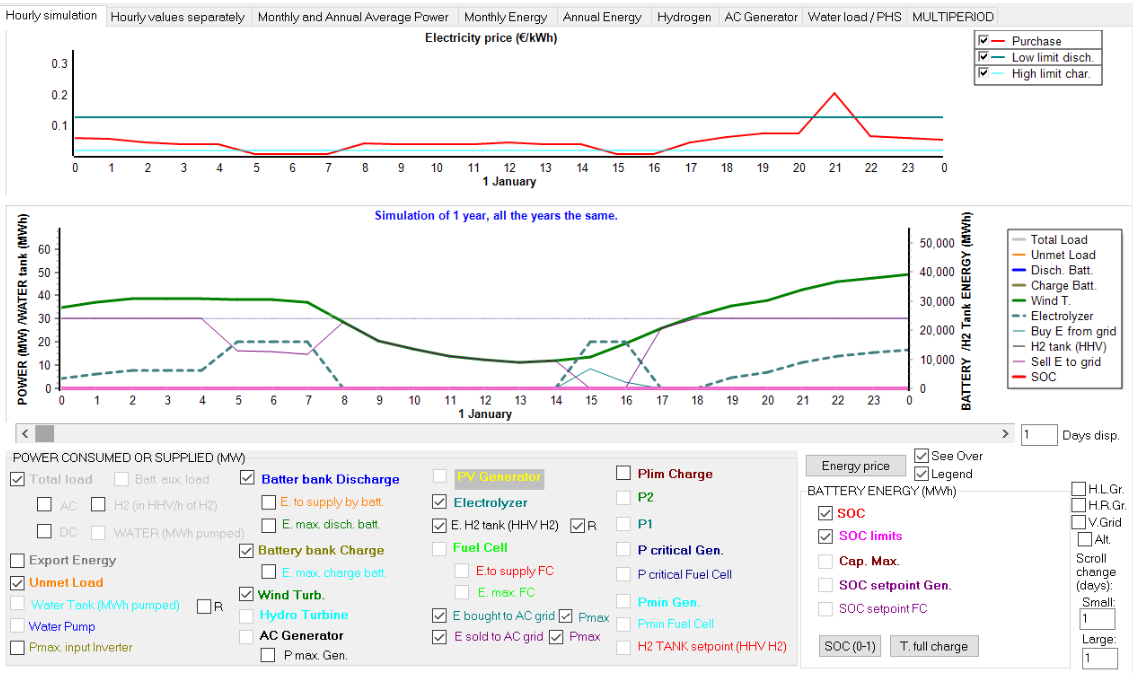


Now, if we click in the results table, the results are updated to the new control strategy:

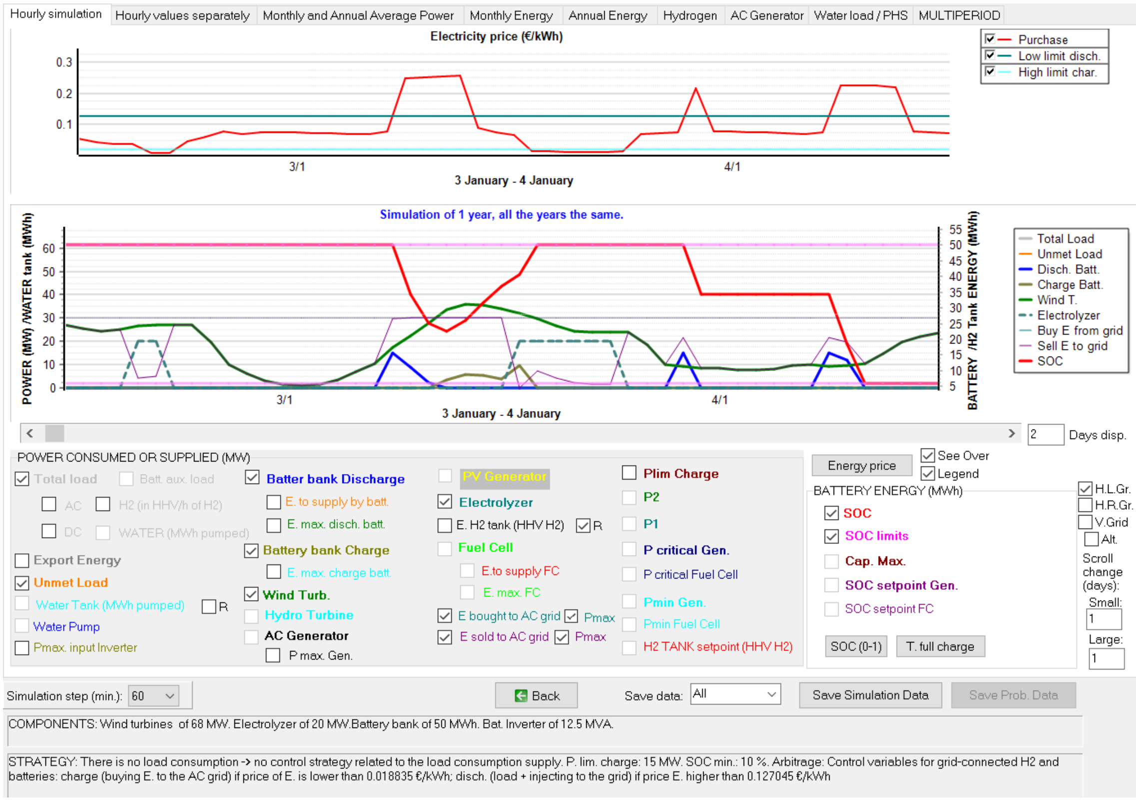
#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOH(€/kgH2)	Simulate	Report
1	161.194	11.18	0	18.04	1224.5	117.813	30.78	2.5927	SIMULATE..	REPORT...

NPV has been dramatically reduced, as now we will generate much less hydrogen, and hydrogen is valued at a high price (10 €/kg first year). LCOH is now 2.35 €/kg.

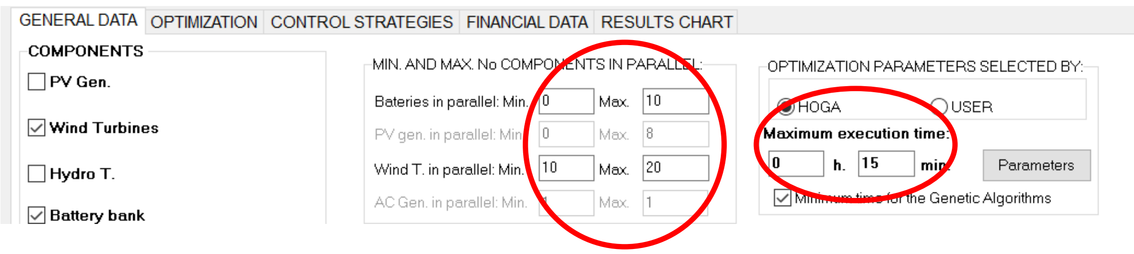
In the simulation, we can see, fir the first day, when electricity purchase price is lower than 0.0188 €/kg (it was the result of the previous optimization), electrolyzer runs at max. power (20 MW DC, 22.2 AC) and the rest is injected to the grid, batteries are fully charged because they are at 100% SOC the first day. The rest of the hours, we inject to the grid the maximum power allowed, 30 MW, and the rest is used to feed the electrolyzer (but if the rest power is lower than the minimum electrolyzer power, it does not work). When electricity purchase price is higher than 0.127 €/kg (it was the result of the previous optimization), the battery should inject to the grid, but in this day, at 21 h, it is not done, because just with the wind farm the power is higher than the maximum that can be injected to the grid (30 MW):



If we see the days January 3rd and 4th (next figure, 2 days display), we can see in the evening of January 3rd battery discharges injecting power to the grid, and later it is charged by the wind farm power because the maximum grid power (30 MW) is reached, therefore the rest power is used to charge the battery. We can see when electricity price is lower than the high limit charge, electrolyzer runs at full power and battery is charged at maximum power (or until reach max. SOC).



We can optimize the system with the new strategy (optimize size and control strategy setpoints). Go to the main screen, **GENERAL DATA** tab, change the min. and max. wind turbines to 10 – 20 and batteries in parallel to 0-10 as previously:



We can see the maximum execution time is 15 minutes (default, we don't change it).

When we pass the mouse over this area, we see the expected optimization time (it depends on the computer speed):

NUMBER OF CASES AND TIME EXPECTED

Computation speed: 23.256 cases/second

	EVAL. ALL	POP. (% ALL)	GEN. ALG. (% ALL)
MAIN ALG. (COMB. COMPONENTS):	121 (1x121)	10 (8.26%)	139 (114.88%)
SEC. ALG. (COMB. STRATEGIES):	441	11 (2.49%)	168 (38.1%)

	MAIN ALG.	SEC. ALG.	NUMBER OF CASES	%	TIME EXPECTED
OPTION 1:	EVAL. ALL	EVAL. ALL	53361	100 %	0h 38' 14''
OPTION 2:	EVAL. ALL	GEN. ALG.	20328	38.1 %	**0h 14' 34''**
OPTION 3:	GEN. ALG.	EVAL. ALL	61299	114.9 %	0h 43' 55''
OPTION 4:	GEN. ALG.	GEN. ALG.	23352	43.8 %	0h 16' 44''

Optimization of the Control Strategy by means of Genetic Algorithms.
It is not guaranteed to obtain the optimal Control Strategy, but this is probable to obtain the optimal or a solution near the optimal

In our case, it can simulate 23.2 combinations per second, so it would need 38 minutes (OPTION 1) to evaluate all the combinations. However, in order not to use more than 15 minutes, it will use genetic algorithms for the optimization of the control strategy (OPTION 2, in red). If we click in CALCULATE, we must wait around 15 minutes to finish.

The optimal system found has an LCOH lower than before (we are minimizing LCOH), although NPV is lower than before:

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOH(€/kgH2)	Simulate	Report
1	130.16	15.03	0	18.83	792.5	87.813	36.28	1.9084	SIMULATE..	REPOR
2	136.701	14.45	0	18.77	864.5	92.813	35.43	1.9428	SIMULATE..	REPOR
3	129.102	14.9	0	18.78	792.45	87.531	36.19	1.9638	SIMULATE..	REPOR
4	122.647	15.14	0	18.89	720.4	82.25	36.92	2.0274	SIMULATE..	REPOR
5	161.739	15.17	0	20.05	936.5	97.813	34.53	2.0373	SIMULATE..	REPOR
6	142.278	17.05	0	20.52	720.45	82.531	37.06	2.0547	SIMULATE..	REPOR
7	121.55	15.01	0	18.83	720.35	81.969	36.84	2.0898	SIMULATE..	REPOR
8	127.132	14.21	0	18.68	792.35	86.969	35.84	2.0924	SIMULATE..	REPOR
9	167.691	14.6	0	19.9	1008.5	102.813	33.78	2.0993	SIMULATE..	REPOR

COMPONENTS: Batteries Bat5MWh- (5 kAh): 1s. x 10p. // 11 Wind Turb. WindT4MW (4 MW at 15 m/s) // Electroliz. Ely-20MW of 20 MW // Bat. Inverter of 12.5 MVA // Unmet load = 0 % // LCOH = 1.908 €/kgH2, IRR = 18.8%.

STRATEGY: There is no load consumption -> no control strategy related to the load consumption supply. P. lim. charge: 15 MW. SOC min.: 10 %. ARB.: Control variables for grid-connected H2 and batteries: charge (buying E. to the AC grid) if price of E. is lower than 0.0188 €/kWh; disch. (load + injecting to the grid) if price E. higher than 0.109 €/kWh

We could optimize again, maximizing NPV.