# **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* (<u>https://ihoga.unizar.es/en/descarga/</u>)

This guide is designed to follow sequentially.

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

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# **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 (<u>http://www.dopdf.com/es/</u>)

# 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.

← Settings		-	×
ය Home	Display		
Find a setting	Scale and layout		^
System	Change the size of text, apps, and other items		
	125% ~		
🖵 Display	Advanced scaling settings		
ゆり Sound	Display resolution		
Notifications & actions	2560 × 1440 (Recommended) V		- 1
	Display orientation		
J Focus assist	Landscape ~		
() Power & sleep	Multiple displays		
📼 Storage	Multiple displays		
Tablet	Extend these displays $\sim$		
曰: Multitasking	Make this my main display		
Projecting to this PC	Advanced display settings		~

#### 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 (<u>https://ihoga.unizar.es/en/descarga/</u>). In that case the economic results that will appear later in this guide (in  $\in$ ) 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.

🦹 Create new p	project		×
Guardar en:	DATOS (D:)	- 🗈 📸 🖛	
4	Nombre	Fecha de modifica	Tipo ^
	📄 8m.mho	26/05/2021 12:39	Archiv
Acceso rapido	🗋 7m.mho	26/05/2021 7:10	Archiv
	📄 6m.mho	26/05/2021 7:08	Archiv
Escritorio	5m.mho	26/05/2021 7:05	Archiv
	3m.mho	26/05/2021 7:02	Archiv
<b>1</b>	4m.mho	26/05/2021 7:02	Archiv
Bibliotecas	10-SG170-6.0.mho	26/05/2021 7:02	Archiv
	2M.mho	26/05/2021 6:55	Archiv
	1M.mho	26/05/2021 6:45	Archiv
Este equipo	📄 1.mho	26/05/2021 5:52	Archiv
	📄 solidera2.mho	25/05/2021 13:13	Archiv
Bed	📄 11.mho	23/05/2021 9:29	Archiv
neu	2.mho	21/05/2021 16:31	Archiv Y
	<		>
	Nombre: MHOGA1	•	Guardar
	Tipo: MHOGA project (*.mho)	-	Cancelar

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).

👔 Proj	ect: D:\	MHOGA1.m	ho
Project	Data	Calculate	Data
🗋 New			
🖨 Oper	ı		
F Save		Ctr	I+S
📓 Save	as		
Save	as Defa	ult Project	
OPTIC	DNS		
Resto	re Origi	inal Tables	
Creat	e Table	s backup	
Resto	re back	ed up Table	5
Resto	re Defa	ult Currency	
📔 Exit			

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.

Simulation and optimization:	
Simulation of the 1st year and extrapolate results	
Multiperiod: simulate all the years of the system lifetime ( 25 years)	
Economic optimization:	
○ Minimize Net Present Cost (NPC), usually for off-grid systems and high load on-grid ——→	<ul> <li>Min. NPC</li> <li>Min. LCOH</li> <li>Min. Payback period</li> </ul>
Maximize Net Present Value (NPV), usually for low load or no-load on-grid systems	
Define Wind Farm with 16 power curves, one for each wind direction sector	Min. LCOH
DC renewable include own charger and controller	Max. Cap.F. min. LCOE
When saving the project update all the results of the table to the present conditions	O Min. Payback period
$\hfill \square$ In the simulation window, show the probability density function (PDF) of the main results	
When clickin a component in a table, update the component with the values of the databas	e
Number of decimal places in results of costs 3 ~	
Number of decimal places in results of energy 3 🗸	

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.

OUNCCES       COMPONENTS         ✓ SOLAR       V/ Gen.         WND       Wind Turbines         Hydro T.       Batterise in parallel: Min.       Max.         Ø V CGEN       Battery bank         Backup Gen.       Vind Til parallel: Min.       Max.         WIND TURB       Backup Gen.       Vind Til parallel: Min.       Max.         WIND TURB       Backup Gen.       Min Capacity Factor       %       Simulation:         Wineerfer/char.       H2 (F.C Elyzer)       Min Capacity Factor       %       Simulation:         H2 (F.C Elyzer)       Max. Unmetload       100       %       Simulation stats:         Backup Gen.       Min Capacity Factor       %       Presention of %       Max. Unmetload       00 %         H2 (F.C Elyzer)       Max. Unmetload       100       %       Simulation:       Simulation stats:         Backup Gend       Wix stat parallel > P min.       Sec.       Simulation stats:       00 %       Simulation stats:         Backup Gend       W.S. Land use       1E10       he bats       Simulation stats:       00 %       Simulation stats:         Backup Gend       W/ Socda       Interfercharge       Interfercharge       Interfercharge       Interfercharge       Interfercha	🖌 LOAD / AC GRID	GENERAL DATA OPTIMIZATION	CONTROL STRATEGIES FINANCIAL DATA RESULTS CHART
✓ SOLAR       ✓ PV Gen.       Bateries in parallet Min.       Max.       ●       ● HOGA ● USER         ✓ WND       Wind Turbines       ♥ / Gen.       ♥ / Gen.       ● Hoga       ● Justice       ● J	ESOURCES	COMPONENTS	MIN. AND MAX. No COMPONENTS IN PARALLEL: OPTIMIZATION PARAMETERS SELECTED BY:
WIND   HYDRO   HYDRO   JMPONENTS   PYOGEN   MIND TURB   HYDRO T.   Ø Battery bank   Backup Gen.   Minorum time for the Genetic Algorithms   Ø Inverter/char.   Minorum time for the Genetic Algorithms   Max. Investment Cost   I Inverter/char.   H2 (F.C Elyzer.)   Water Pump in Load/AC grid Yothes Pump in Load/AC grid<	SOLAR	🗹 PV Gen.	Bateries in parallel: Min. 1 Max. 5
HYDRO         DMPONENTS         PVGEN         Wind T. in parallel: Min         MUDDURA         Battery bank         Constraints under NFV maximizator:         MINDTURB         Exclusion         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Display the formation starts:         Minimum time for the Genetic Algorithms         Display the formation starts:         Minin time for the formation starts: <tr< td=""><td>WIND</td><td>Wind Turbines</td><td>PV gen. in parallel: Min. 0 Max. 8 Maximum execution time:</td></tr<>	WIND	Wind Turbines	PV gen. in parallel: Min. 0 Max. 8 Maximum execution time:
PMPONENTS   I Hydro I.   V KVGEN   WIND TURB   MURD TURB   MORD TURB   MINE TERICHAR   Backup Gen.   Minemut Intericitation	HYDRO		Wind T. in parallel: Min. 1 Max. 1 0 h. 15 min. Parameters
✓ PY GEN WIND TURB MORD TURB Backup Gen. Minverter/char. Minverter/char. Min Renew Fraction Min Renew Fraction Backup Gen. Ba	MPONENTS	Hydro I.	AC Gen. in parallel: Min. 1 Max. 1 Minimum time for the Genetic Algorithms
WIND TURB         HODBO TURB         I Inverter/char.         MAX Longetor         Max Longetor         Max Longetor         BACKUP GEN         H2 (F.C Elyzer)         Max Longetor         Max Mapper parallel > P min.         Sensitivity Analysis         Probability Analysis	V PV GEN.	Battery bank	Constraints under NPV maximization:
HYDROTURB       Inverter/char.         Max Landuse       Signature         H2 (F.C Elyzer.)       Max Landuse         H2 (F.C	WIND TURB.	Backup Gen.	- Simulation: Mex_Investment cost 1E10 Mf. Step (min.): Simulation starts:
✓ BATTERIES         ✓ INVERTER/CHAR         BACKUP GEN         H2 (F.C Elyzer.)         Max Lunduise         1E10         has Deta         Voltage 1         VV > Socd.         PRESIZING         wks.tu parallel > Pmin.         Max Londuise         Press/Zind         Sensitivity Analysis         Probability Analysis	HYDRO TURB.		Min. Capacity Factor 0 % Pmax_sell 60 v hour 0 day 1 month 1
Immetrete/CHAR   BACKUP GEN   H2 (F.C Elyzer)     Max Land use     Itel ID   has Land use     Itel ID   has Land use     Itel ID   has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Itel ID     has Land use     Has Land use<	✓ BATTERIES	Minvener/char.	Min. Renew. Fraction 0 %
BACKUP GEN     Max Lond use     TE10     ha     Data       H2 (FC - Elyzer)     Work Lond use     TE10     ha     Data       Workinge 1     W     SOCIL     PV       PRE-SIZING     Garage     AC     AC       rgy storage 2     days auton.     Wax Ved garage     AC     AC       Wax Ved garage     Pre-Sizing     AC     AC     Load /       Wax Ved garage     Prime     AC     AC     Load /       Werk Wind T porallel > P min.     Wax AC Gen. parallel > P min.     Max Endury     AC     Load /       Sensitivity Analysis     Probability Analysis     Battery     Battery     AC	VINVERTER/CHAR.	H2 (F.C Elyzer.)	Max. Unmet load 100 %
H2 (FC - Elyrer)         Wotre Pump in Load/AC grid         "Votrage 1         Votrage 2         Vv         PRE-SIZING         rys storage 4         days auton.         Wax PV gen; parallel > P min.         Wax Wind Tp parallel > P min.         Wax AC Gen; parallel > P min.         Wax AC Gen; parallel > P min.         Wax AC Gen; parallel > P min.         Wax Mort Tp and P and P min.         Bensitivity Analysis         Probability Analysis	BACKUP GEN.		Max Land use 1E10 ha. Data
Water Pumpi In Load/AC grid Voltage 1 W SOCd Voltage 2 W PRE-SIZING rgy storage: 4 days auton. Wascht parallel > Pmin. Wascht parallel > Pmin. Wascht parallel > Pmin. Wascht parallel > Pmin. Max PV agn. parallel > Pmin. Sensitivity Analysis Probability Analysis	H2 (F.C Elvzer)		
PRE-SIZING         trgy storage: 4       days auton.         Wax bxd parallel > P min.         Wax Wind Ti, parallel > P min.         Wax Wind Ti, parallel > P min.         Wax Ko C Gen, parallel > P min.         Wax Ko C Gen, parallel > P min.         Sensitivity Analysis         Probability Analysis         Probability Analysis	Voltage 1 kV SOCd. Voltage 20 kV		PV
Sensitivity Analysis Probability Analysis Battery	PRE-SIZING ergy storage: 4 days auton. Max bat parallel -> Cn min. Max PY gen. parallel -> P min. Max Wind T. parallel -> P min. Max AC Gen. parallel -> Pmin		Inverter/Charger AC AC (Bi-directional X) Load

# 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.

(	GENERAL DATA OPTIMIZATION C	10
	COMPONENTS IV PV Gen.	
$\langle$	Wind Turbines	
	Hydro T.	
	✓ Battery bank	
	🗖 Backup Gen.	
	✓ Inverter/cha	
	🔲 H2 (F.C Elyzer.)	

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.

Project: D:\MHOGA1.m	ho
Project Data Calculate	Data Base Report Help
🖌 LOAD / AC GRID	GENERAL DATA
RESOURCES	COMPONENTS
V SULAR	PV Gen.
. WIND	
HYDRO	Wind Turbines
COMPONENTS	🗌 Hydro T.
🗸 PV GEN.	Rattern bank
I WIND TURB.	
HYDRO TURB.	Backup Gen.
V BATTERIES	Inverter/cha
VINVERTER/CHAR.	🗌 🗖 H2 (F.C Elyze
BACKUP GEN.	
H2 (F.C Elyzer)	
Water Pump in Load/AC gri	id

# 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.

DC Voltage	1	kV 🗖 SOCd
AC Voltage	20	kV

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).

an and optio	ons of Se	eiling / Puro	masing Er	lergy from	r the AC g	gnu									_	-
Data source:	-		-			_				_ 8	Hours Min		H2	Water		_
O Monthly Ave	erage 🔘	) Load Profil	e () Impo	ort File (MW	/, tH2/h, da	am3/h)				ŏ	1 ~ Min	utes each utes-1 per	row	Im	port	Export
AC LOAD (MW)	DC	LOAD (MV	V) H2	LOAD (t	H2/h)	WATER	(dam3/day	) FROM	WATER T	ANK P	URCHAS	E / SELL				
Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16h -
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEBRUARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MARCH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APRIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JULY	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
REDTEMPED	0	0	0	0	0	0	0	0	0	0	U	0	0	0	0	U
OCTOBED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOVEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DECEMBER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Import AC tabl	le	s	cale factor	U for Monday	u y to Friday	, U	U	Scale fact	tor for the w	veekend:	1		0			),
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Import AC tabl	le	S	u cale factor	for Monday	u y to Friday	c 1	AVE	Scale fact	torforthe w	eekend:	1	cale factor		) MWb/day		,
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Import AC tabl oad profile: Zero 'ariability		dd load profi	cale factor	for Monday	y to Friday	c 1	AVE	Scale fact	tor for the w	reekend: EMBER (i Cload I	ncluded so	cale factor	, TOTAL ( Nater (E pu	) MWh/day		
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Import AC tabl ocad profile: Zero /ariability Daily Variability Hourty Variability Minutes Variability Correlation minute Generate Add load of	le Ac AC 0 0 2 3 5 0.9 AC lo 0 0	dd load profi 3% 0 3% 0 3% 90 3% 90	cale factor	for Monday 12 % 1 % 1 % 1 %	y to Friday	c 1	AVE	Scale fact	AD IN DEC	EEMBER (i Cload	1 https://www.internationalizations.internationalizatio	cale factor; ∨) ♥■	, TOTAL ( Water (E pu	) MWh/day umped)		_
Import AC table coad profile: Zero /ariability Daily Variability Minutes Variability Correlation minute Generate Add load of m: min 0 hour [0	Le Ac 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	Id load profit MWV AC MWV AC	cale factor	for Monday 12 % % % hi): 1 5 min Repeat eve 1 day	y to Friday	c 1	AVE	Scale fact	AD IN DEC	AC pumpin	1 ncluded so H2 (HH hour ng): 0 MW; 1	cale factor	), TOTAL ( Water (E pu	0 MWh/day imped) 18		
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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").

AC LOAD (MW) DC LOAD (MW) H2 LOAD (tH2/h)	WATER (dam3/day) FROM WATER TANK PURCHASE	/ SELL E
Purchase from AC grid Unmet Load (Non Served	Sell Excess Energy to AC grid	AC GRID AVAILABILITY
Energy by Stand-alone system)         Fixed Buy Price (¢/kWh)         15         Hourly Price         Annual Inflation (%):         Emission (kgC02/kWh):         3       0.4         Fixed Pmax (MW)       Fixed Cost P (¢/kW/yr)         30       Options       40         Hourly Values         Access Charge Price (¢/kWh)       Hourly Values         Back-up Charge Price (¢/kWh)       Hourly Price         Back-up Charge Price (¢/kWh)       Hourly Price         Will be added to the E purchased)       Add negative gen. charge	✓ Fixed Sell Price (¢/kWh)       0.12       Hourly Price         ● Pr. sell = pr. buyx	Priority to supply E not covered by renewables: Storage/Generator OAC Grid Sto./Gen. priority if Pr.buyE >= 0 Sell surplus H2 in tank (difference between the H2 in the tank at the end of the year and at the beginning) Price (0/kg) Annuel Inflation (%): 10 3
Total tax for electricity costs (buy + charges) (%): 0	Total tax for electricity sold (%): 0	sses in wire and transformer (%): 0

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.

AC LOAD (MW)	DC LOAD (MW)	H2 LOAD (tH2/h)	WATER (dam3/day) FROM WATER TANK PURCHA	ASE / SELL E	
Purchase from AC grid Unmet Load (Non Served Energy by Stand-alone system)           ✓ Fixed Buy Price (€/kWh)         0.15         Hourly Price           Annual Inflation (%):         Emission (kgC02/kWh):         3         0.4           3         0.4         Emissions data           ✓ Fixed Pmax (MW)         Fixed Cost P (€/kW/yr)         30         Options         40           Access Charge Price (€/kWh)         0         Hourly Values           Access price (€/kWh)         0         Hourly Price           Back-up Charge Price (€/kWh)         0         Hourly Price           Will be added to the E purchased)         Add negative gen. charge		d (Non Served Hourly Price 02/kWh): Emissions data /kW/yr) Hourly Values Hourly Price Hourly Price d negative gen. charge	Sell Excess Energy to AC grid Fixed Sell Price (£/kWh) O.12 Hourly Price Annual Inflation (%); 3 Max. Power(MW) Generation Charge (Transfer Charge) Price (£/kWh) Fixed Transfer price (£/kWh	AC GRID AVAILABILITY Priority to supply E not covered by renewables: Storage/Generator AC Grid Sto /Gen. priority if Pr.buyE >= 0 Sell surplus H2 in tank (difference between the H2 in the tank at the end of the year and at the beginning) Price (£/kg) Annual Inflation (%): 10 3	
Total tax for electricit	y costs (buy + charges)	(%): 0	Total tax for electricity sold (%):	Losses in wire and transformer (%): 0	
		Sell Excess	s Energy to AC grid ice (€/kWh) 0.12 Hourly	Price	

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 (.).

lourly Price Data (€/kWh) Hourly, all days the same		
From file (8760 hourly values)	Graph 🖾 D.max-mir	
Hourly Periods	Importiouny Files	PDF 🖾 PDF D.m-r

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  $0.06 \notin kWh$ , its maximum is 0.329 and its minimum  $0.001 \notin kWh$ .

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  $0.06 \notin kWh$ ; 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  $0.18 \in /kWh$ , 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.

Sell Excess Energy to AC grid						
Fixed Sell Price (€/kWh) 0.12	Hourly Price					
Pr. sell = pr. buy x 1						
Annual Inflation (%): 2						
Max. Power(MW) 23 =Pmax buy						
Energy Generation Charge (Transfer Charge) P	rice (€/kWh)					
✓ Fixed Transfer price (€/kWh)	Hourly Price					
Self-consumption and Net Mettering:	Sell only					
No net mettering	$\sim$					
Cost of net metering service (€/kWh) 0						
Buy-back: Export E is paid at (€/kWh)						
Total tax for electricity sold (%): 0	Los					

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).

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



#### 6. Grid-connected battery management.

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>

Global strategy Load Followi	nq		ENERGY ARBITRAGE: System with batteries and grid connected		
Cycle Charging   ✓ Continue up to SOC stp			Price E<= 0 €/kWh // Price E>= 0.11 €/kWh □ D-% ☑ (Compare with Sell price		
◯ Try Both			Optimize strategy of grid-conneted batteries:		
/ariables to opt	imize relative to the	global strategy:			
Pmin_gen	Pmin_FC	H2TANKstp			
P1_gen	P1_FC	P2	Batteries can inject electricity to the AC grid		
SOCstp_gen	SOCstp_FC	SOCmin	1 day at low SOC-> charge battery with AC grid		
Pcritical_gen	Pcritical_FC	Plim_charge	When batteries are off, compensate autodisch.		

# 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.</li>
- 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  $0.11 \notin kWh$ .

# 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 <u>https://www.google.com/maps</u> 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):

Latitude (*) (+N, -S) :	Get data from local DB
Longitude (º) (+E, -W) : -15.5	Download hourly data
Locate on map Update coord.	Download NASA monthly data

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

- Monthly average data:

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

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

- Hourly data:

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

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

- 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:

HOGA ×
Data downloaded from https://power.larc.nasa.gov
Data updated for lat. 28.06, long15.5, year 2019:
-Monthly average daily irradiation: 3.6 4.92 5.38 6.28 5.86 7.26 6.02 6.21 5.92 4.33 3.58 3.44 . Average of the year: 5.23 kWh/m2/day
-Monthly average temperature: 17.59 17.94 17.77 18.46 19.4 20.92 21.66 22.37 22.37 22.01 20.46 19.17 . Average of the year: 20.01 °C
-Monthly average wind speed at 10 m height: 4.73 4.39 5.12 4.65 5.49 4.61 6.97 7.05 5.48 4.86 6.33 4.57 . Average of the year: 5.35 m/s. (Converted from downloaded data of land type airport) -Wind speed Weibull shape factor: not updated (not found local database)
-Altitude above sea level: 109 m
ОК

Note that these values are average values of year 2019 for 1° lat x 1° long. around the location (solar data source is a global 1° x 1° latitude/longitude grid while the meteorological data sources are  $\frac{1}{2}$ ° x  $\frac{5}{8}$ ° 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:

	Irradiation av. horiz. s.
January	3.6
Februray	4.92
March	5.38
April	6.28
Мау	5.86
June	7.26
July	6.02
August	6.21
September	5.92
October	4.33
November	3.58
December	3.44

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". (Available 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<sup>2</sup> 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 35° for the slope and 0° for the azimuth (that is, south oriented).



The optimal azimuth will be 0° (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:

	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 (*) Rad. Slope Opt (*) Rad. 50 pe Opt (*)								
January	3.67	4.59	5.27	5.65	5.69	5.4	4.8	55	5.72
ebruary	4.73	5.69	6.32	6.57	6.42	5.9	5.02	47	6.57
vlarch	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
/lay	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
luly	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
lovember	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
	5.2	5.58	5.67	5.45	4.96	4.21	3.29	27	5.68

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 90<sup>o</sup> 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 27<sup>o</sup>.

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.

#1: PV panels slope (º) : 27 ; F						
#2: PV panels slope (²) : 35						
PV gen. #1: 100 %						
Optimal Slope#1	🗌 Optimize P\					

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<sup>2</sup>). 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:

OK	Calculate	🔄 Graph in steps of	60 ~ min.	Export horiz.	Export tilted
	$\sim$				

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*).

	Daily Average Irradiation (Horiz. Surf.	): 5.1 kWh/m2	Daily Average Irradi	ation (Tilt Surf.):	5.6 kWh/m2	
$\subset$	Total Annual Irradiation (Horiz. Surf.):	1862.11 kWh/m2	Total Annual Irradi	iation (Tilt Surf.):	2045.98 kWh/m2	>
			Annual Irr. Back surface /	Direct for CPV:	144.28 kWh/m2 / 1655.44 kWh/m2	
r	: 0.9 std. dev.: 0.2 Updat	e minutes	Import Back (hourly, tilt)	Import Direct	t (hourly, tilt)	
	Calculate	🔽 Graph in step	os of 60 Y min	Export G. tilted	Export G. horiz.	

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 (27<sup>o</sup>) 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".

SOLAR RESOURCE	
Latitude (º) (+N, -S) : 28.06	Get data from local DB
Longitude (º) (+E, -W) : -15.5	Download hourly data
Locate on map Update coord.	Download NASA monthly 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 <u>https://www.tunnelbear.com/</u>) you can do 5 downloads each time you have a new IP. These restrictions are not for PVGIS or NASA databases.

Download from:	○PVGIS-Year 2015 ~
	Renewable Ninja (year 2019)
	ONASA-Year 2020 ✓
Hourly Irradiatio	in
Hourly Temper	ature for: PV VWind T. Batt.
Hourly Wind Sp	eed
O	Cancel

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<sup>2</sup>, compared to 2046 kWh/m<sup>2</sup> 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.

Download from:	OPVGIS-Year 2015 ~
_	🔿 Renewable Ninja (year 2019)
	●NASA-Year 2015 ~
Hourly Irradiatio	n (inc. albedo)
Hourly Tempera	ature for: PV VWind T. Batt.
Hourly Wind Sp	eed 💿 10 m 🔿 50 m
Altitude above s	ea level
Ok	Cancel

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<sup>2</sup>, compared to 2337 kWh/m<sup>2</sup> obtained with Renewables Ninja and 2046 kWh/m<sup>2</sup> obtained with NASA monthly data.

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

# PVGIS hourly data:

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).

_	
Download from:	● PVGIS - Year 2015 ∨
_	Renewable Ninja (year 2019)
	○NASA-Year 2015 ∨
Hourly Irradiatio	n
Hourly Tempera	ature for: PV VWind T Batt.
Hourly Wind Sp	eed
Ok	Cancel

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<sup>2</sup>, compared to 1974 kWh/m<sup>2</sup> from hourly NASA, 2337 kWh/m<sup>2</sup> obtained with Renewables Ninja and 2046 kWh/m<sup>2</sup> 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.

👔 Proje	ct: D:\P	r1.hoga	
Project	Data	Calculate	Data
	🗸 LOAD	) / AC GRID	
RES	OURC	ES	4
-	V :		

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.

Download from:	O PVGIS - Year
Download nom.	Renewable Ninja (year 2019)
	ONASA - Year 2015 V
Hourly Irradiati	on
Hourly Tempe	rature for 🔽 PV 🗹 Wind T. 🗌 Batt.
Hourly Wind S	peed
Ok	Cancel

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.

👔 Project: D:	Pr1.hoga			
Project Data	Calculate Data Base	Report	Help	
🗸 LOA	D / AC GRID	ponents D	)ata Base	ATI

The following screen appears:

/ Gen.	Wind turbines	Batteries	AC Genera	tors	inverter/Cha	rgers	Hydro tur	rbines Ele	strolyzers	Fuel cells	•		
								▶ +	-				
Name		P. nom(MV	/p_dci Cost (M	1C)	C. 0&M (%/yr	) [	.ife (years)	NOCT (°C)	Power T.coe	ef. (%/ºC)	BIFACIALITY(0-1) CPV	Emissions (kqCO2/kWp)	^
Zero			0	0		0	10	0 43		-0.4	0 NO	800	
PV1			1	1		1	2	5 43		-0.4	0 NO	800	
PV10			10	10		1	2	5 43		-0.4	0 NO	800	
P∨100			100	100		1	2	5 43		-0.4	0 NO	800	
CPV10			10	12		1	2	5 43		-0.14	0 OK	800	
PV10-B	BIF		10	11		1	25	5 43		-0.4	8.7 NO	800	
													~
							Multip	aly costs of P	/ by	1			
	Cione s	selected co	mponent		Add co	mpon	Multip ents from th	aly costs of P	/ by PV table	1			

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:

PV GENE	Add PV Gen.	Zero		~ ~	4 4 4	+ - 4	× ×	9			-	
PHO Name PV10	TOVOLTAIC GENER	RATOR DATA	k: Power(MWp) 10	Cost(M€) 10	С.О&М(%/ул) 1	Life(years) 25	NOCT(*C) 43	Power T. coef.(%/°C) -0.4	BIFACIALITY(0-1) 0	CPV Emi NO	ssions(kgCO) 800	2/kWp)
												>
Efficienc Stand	cy due to degradation o lard conditions	f the modules,	losses in wire	es, dirt in panel:	s, etc. 0.95						Fixed 0 Mainte 0	Dperation a nance Cos
	Consider effect of Ter Data of ambient temper Monthly average From file (8760 hourt	nperature rature (*C) V Erbs m y values)	odel J	J 17.6 F 17.9 Import	м 17.8 A 18 FROM PVC	5 M 19.4 .	20.9 J 21.7	A 22.4 S 22.4 O 22	2 N 20.5 D 19.2	Wind fo	or CPV	
	Annual Inflation F Generator Cost :	Rate for PV	-2 %		imit is reached	Max. Vari reduction	ation of PV ge on current PV	PV inverter data n. Cost (e.g., for an expe gen. cost, introduce "-70	cted 70% -70	%		
						in oo.o youro						

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.

👔 PV GENERATORS								_		×
Add PV Gen. Zerc Add PV Gen. family PHOTOVOL TAIC GENERATO	R DATA:	~	4		▶ +	-				
Name ▶ PV10	Power(MWp_dc) 10	Cost(M€) 10	C.O&M(%/yr) 1	Life(years) 25	NOCT(*C) 43	Power T. coef.(%/#C) -0.4	BIFACIALITY(0-1) CPV 0 NO	Emissions(kgC 800	D2/kWp)	]

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.".

Ņ	PV GENERATORS			
	Add PV Gen.	<u>PV1</u>	-	
	Add PV Gen. family	Zara PV1		1
	PHOTOVOLTAIC GENERA	FV10 FV100		
	Name		Power(M\u/p)	<u> </u>

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):

N	V PV GENERATORS								- 0	×
	Add PV Gen. PV1 Add PV Gen. family		~ ~	•		▶ +	-			
	PHOTOVOLIAIC GENERATO	CDATA:								
	Name	Power(MWp_dc)	Cost(M€)	C.O&M(%/yr)	Life(years)	NOCT(°C)	Power T. coef.(%/ºC)	BIFACIALITY(0-1) C	PV Emissions(kgCO2/kWp	)
	PV1	1	1	1	25	43	-0.4	1 0	NO 800	

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  $1.2 M \in$  (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":

Name	F
PV1-mod	

And then we change the cost to  $1.2 \text{ M} \in$  (if the decimal spacing of your computer is dot, write "1.2"; if it is comma you should write "1,2").

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)
I PV1-mod	1	1.2	ノ 1	25	43	-0.4	0 NO	800
		$\sim$						

We can see in the table that O&M annual cost (OPEX) is 1% of the CAPEX (which now is 1.2 M $\in$ ), that is, now it will be 12,000  $\notin$ /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  $0 \notin$ ) 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).

Efficiency due to degradation of the modules, losses in Standard conditions	wires, dirt in panels, etc. 0.95		Fixed Operation and Maintenance Cost 0 €/yr
Consider effect of Temperature     Data of ambient temperature (*C)     Monthly average     From file (8760 hourly values)	J 17.6 F 17.9 M 17.8 A 18.5 M 19.4 J 20.9 J Import FR0M PVGIS year 2015	21.7 A 22.4 S 22.4 O 22 N 20.5 D 19.2 Wind fo	rCPV

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.

From file (8760 hourly values)	Import ,FROM PVGIS	i year 2015	Graph
		PV inverter dat	a

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.

⊠ PV ir inclu	verter c ded in O	ost includ &M PV co	led in the ost	e PV cos	t PV inv	. replace	ement
Rated po	ower of the t the outpu	inverter =	1 the PV to	x Peak	power of P. of the in	the PV ge ∨erter	nerator
0% 0 40% 89	2% 30 50% 88	3% 50 60% 87	4% 70 70% 86	5% 85 80% 85	10% 93 90% 84	20% 92 100% 83	30% ] 90
96 64 0 0 0 20 40 60 80 100 Output power (%)							
			OK.				

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.

Annual Inflation Rate for PV Generator Cost : 2	Max. Variation of PV gen. Cost (e.g., for an expected 70% reduction on current PV gen. cost, introduce "-70%"); -70 %				
Limit is reached in 59.6 years					
ОК					

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.

COMPONENTS				
🖌 PV GEN.				
WIND TURB.				
1				

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  $(M \in)$ ") 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.

WIND TURBINES / GROUPS OF WIND TURBINE	S	-
Add a Wind Turbine Zero Add a Wind Turbines family	✓	
GENERAL DATA	Output Power (MW) vs Wind Speed	
Name Bus Cost (MC) C. Pepl. ( WindT1 AC 2 1.6	ME)         C. O&M (%/yr)         Lifespan (yr)         Height (m)         Emis.CO2(kt)         1 m/s         2m/s         3m/s         4m/s         5m/s         6m/s         7m/s           2         20         100         1.5         0         0         0.05         0.2         0.3         0.5	8m/s 9m/s Im 0.7 1
(	ne WindT4	Fixed Operation and
b height considering roughness		Maintenance Cost
over curve measured at air density (kg/m3): 1.225 eight above sea level: 109 m r density at that height is (ISA) 1.212 kg/m3 Consider the effect of temperature	WIND SPEED (m/s)	Wake effect Wake effect
hen simulating, adjust power curve with air density. ) Use height above sea level and temp. Graph ) Import air density (kg/m3) Import	Ambient Temperature at hub height (*C)         J         17.6         F         17.9         M         17.8         A         18.5         M         19.4         J         20.9         J         17.7         A         22.4         S         22.4 <td< td=""><td>0 22 N 20.5 D 19.2</td></td<>	0 22 N 20.5 D 19.2
Do not consider reduction in Power after: 4 m/s v (check if wind t are pitch controlled)	Annual Inflation Rate expected for Wind 1 Max. Variation of Wind Turbines Cost expected (e.g., for an expected for Wind Turbine Costs: Limit is reached in 42.9 years	cted 35% -35 %

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:

Surface Rou	ghness				
Class 2	$\sim$	Length	0.1	m	
Agricultural a hedges 8 m of 500 m.	area with eters higł	some bu n with an :	uildings approx	and pre imate di	serving stance
Power curve n	neasurec	l at air de	ensity (k	kg/m3):	1.225
Height above	sea leve	I: <mark>30</mark>	m		
Air density at t	hat heigh	tis (ISA	1.221 k	lg/mi	

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 15°C, that is, 1.225 kg/m<sup>3</sup>, 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<sup>2</sup>, 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.

Ambient Temperature at hub height (ºC)	1 102 E 170 M		
🛛 🔿 Monthly average 🛛 🔽 Erbs model		10.1 A 10.3 M 13.4 J 20.7 J 21.0 A 22.3 J 23	0[22.3 N[20.3 D[13.4
<ul> <li>File with 8760 hourly values</li> </ul>	Import	FROM PVGIS year 2015	Graph

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<sup>3</sup>). We don't change it.

-When simulating, adjust power curve with air density:					
Use height above sea leve	el and temp.				
C Import air density (kg/m3)	Import				

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.

Do not consider reduction in Power after: 14 m/s (check if wind t. are pitch controlled)

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:  $(1-0.01)^{42.9}$ =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).

Do not consider reduction in Power after: 14 m/s _ (check if wind t. are pitch controlled)	Annual Inflation Rate expected for Wind 1 Max. Variation of Wind Turbines Cost expected (e.g., for arreduction on current Wind Turbines cost, introduce "35%"	expected 35%	35	%
OK	Limit is reached in 42.9 years			

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.

WAKE EFFECT:	Thrust coefficient (Ct)
(Gonzalez-Longatt, et al., Renewable Energy, 2012)	0.8
Wind turbines divided in number of rows: 2	0.6
Distance between rows / rotor diameter: 10 alpha coefficient: 0.07 Wind turbines thrust coefficient (Ct):	0.4 0.2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 WIND SPEED (m/s)
1 m/s         2 m/s         3 m/s         4 m/s         5 m/s         6 m/s           0         0         0         0.86         0.86         0.8           14 m/s         15 m/s         16 m/s         17 m/s         18 m/s         19 m/s           043         0 35         0 27         0 22         0 19         0.16	7 m/s         8 m/s         9 m/s         10 m/s         11 m/s         12 m/s         13 m/s           0.76         0.76         0.74         0.7         0.63         0.58         0.52           20 m/s         21 m/s         22 m/s         23 m/s         24 m/s         25 m/s         10 m/s           15         0.14         0.13         0.12         0.11         0.1         0

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 20° 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.

M BATTERIES	- c	x c
Add Battery     Zero       Add Batteries family		
BATTERIES DATA: Float life at 20 °C Cycles to Failure vs. Depth of Discharge (%)		
Name         Cnom.(k-kh)         Valt.(k/V)         Cost(M/k)         SOCmin(%)         Self_d(%/mon.)         Imax(kA)         Eff(%)         Float(v/r)         10%         20%         30%         40%         50%         60%         70%         80%	90% 100	)% TYPE
▶ BatSMWh 5 1 1.5 1 10 1 2.5 92 15 46000 24000 16000 12000 9600 8000 6857 6000	5333 40	30 Li
Batteries Model	iiv / WWh ce	nacity
O Ah      ✓ Living nodel Ah     Total Operation and maintenance Cost:      Y)     Cost and a cost a co	inv / Kvvii ca	Jacity
O KIBAM (Manwell-McGowan 1993) Auxiliary cooling, UHIS, colis, AC (40 millior, F) Soliciary activity of similarity in the second of the beginning of similarity in the second of the beginning of similarity of the second of the beginning of the beginning of similarity of the second of the beginning of the begi		
O Schiffer 2007 Bat5MWh of 5 kAh		
Temp. J 18       F18       M20       A 20       M20       J 22       Meen (*C)         Bat.       (C)       J 22       A 22       S 20       O       N18       D 18       Meen (*C)         Coccept Schifter model.consider       mponhours/tile       Mon.       Hours       Mon.		
Reinfow (cycle counting)     Parameters     Annual Inflation Rate expected for     Annual Inflation Rate expected for     Batteries Costs:     Annual Inflation Rate expected for     Comparison of Wind Batteries expected (e.g. for an expected 60% reduction on current Batteries cost introduce "60%"):	-60 %	6
Remaining capacity at battery end of life (%): 80 Limit is reached in 45.4 years		
If there is an An AC Gen., every       14       days or       8       equivalent full cycles → charge battery bank at least up to       95       %         OK       0K       0K       0K       0K       0K       0K		

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.

		Batteries Model Fixed Operation and N													
		() Ah	$\mathcal{I}$	ŀ	🗸 Li-io	on	model	Ał	n						
		◯ KiBaM (Manwell-McGowan 1993)													
		O Copetti 1994													
		O Schiffer 2007													
		/	_											_	
	$\left( \right)$	Temp. J Bat	18	F	18	М	20	A	20		М	20	J	22	Mean (°C)
		(°C)	22	A	22	s	22	]0	20		N	18	D	18	
		Excep Tme	ot Schi an>=`	ffer Tflo	r mode bat life	el, (	consid	er		Ir	np	ort h	our	ly file	Mon. Hour
		Float lif	e redu	ces	50%	for	every	1	0	0	С	incre	ase		🔁 T Graph
$\langle$		Cycle	life de	epe	ends or	١T			Data					$\sum$	
	-	Capa	city de	pe	nds on	т			Data	_	_	-	_		
		Lead-ac	id Agir	ıg b	oattery	m	odel		Li-io	on	A	ging t	batt	ery m	odel
		⊖ Wan ⊖ Grot	g et al et al.,	., 2 20	2011 (L 15 (LiF	_iF∈ FeF	ePO4) PO4)								
			ena et	al., Ien	2016	(Li	CoO2)								
	$\langle$	Rain	flow (c	ycl	e cour	ntin	g)	$\geq$	)				P	aram	eters
		Naur	nann (	LIF	ero4 (	сус	+cal)								

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 20°C and being reduced as temperature increases (curve obtained from <u>https://midsummer.ie/pdfs/fronius-performance-solar-battery.pdf</u>). By default, the temperature considered is the temperature during all time (not only during charge/discharge), and below 20°C there is not considered any increase in cycle life. We leave the default values.

Cycles to failure (%) vs Temperatu Cycles (%) = 100 · (a + bT + cT^2) a = 1.62 b = -0.0354 c = 0.0002	<b>Ire (°C):</b> (for full eq. cycles and Rainflow models)
Temperature is the average: Ambient temperature during all time	C Ambient temperature during charge/discharge
☞ Below 20ºC no increase in cycle life	ОК

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 20°C. 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.

Remaining capacity at battery end o	if life (%	s): <mark>80</mark>			
If there is an An AC Gen., every	14	days or 8	equivalent full cycles -> charge battery bank at least up to	95	%

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.

Annual Inflation Rate expected for Batteries Costs: 2	Max. Variation of Wind Batteries expected (e.g., for an expected 60% reduction on current Batteries cost, introduce "-60%");	-60	%	
	Limit is reached in 45.4 years			

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:

MIN. AND MAX. No COMPONEN	NTS IN PARALLEL:
Bateries in parallel: Min. 1	Max. 5
PV gen. in parallel: Min. 0	Max. 8
Wind T. in parallel: Min. 1	Max. 1
AC Gen. in parallel: Min. 1	Max. 1

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:

MIN. AND MAX. No COMPONEN	NTS IN PARALLEL:
Bateries in parallel: Min. 0	Max. 5
PV gen. in parallel: Min. 0	Max. 30
Wind T. in parallel: Min. 0	Max. 15
AC Gen. in parallel: Min. 1	Max. 1

## 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):

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 $\in$  (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.

	NUM	BER OF C	ASES AND TH		D
Computation s	peed: 21.368 c	ases/second			
MAIN ALI	G. (COMB. COI	MPONENTS):	<u>EVAL. ALL</u> 11904 (1v11904)	<u>POP. (% ALL)</u> 1358 (11.41%)	<u>GEN. ALG. (% ALL)</u> 19229 (161.53%)
SEC. ALC	à. (COMB. STF	ATEGIES):	1	3 (300%)	41 (4100%)
	MAIN ALG.	SEC. ALG.	NUMBER OF CASE	s % J	
OPTION 1:	EVAL. ALL	EVAL. ALL.	11904	100 % 🤇	<u>0h 9' 17"</u>
OPTION 2:	EVAL. ALL	GEN. ALG.	488064	4100 %	6h 20'
OPTION 3:	GEN. ALG.	EVAL. ALL.	19229	161.5 %	0h 14' 59"
OPTION 4:	GEN. ALG.	GEN. ALG.	788389	6622.9 %	10h 14'
Optimization solution	by means of er	numerative me	thod (evaluating all co	ombinations). It is gu	aranteed to obtain the optimal

# 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%).

GENERAL DATA OPTIMIZATION CONTROL STRATEGIES FINANCIAL DATA RESULTS CHART	
GENERAL DATA       OPTIMIZATION       CONTROL STRATEGIES       FINANCIAL DATA       RESULTS CHART         ECONOMIC DATA:	Loan (constant quota, French system): Amount of Ioan: 100 % of the initial cost of investment Loan Interest: 7 % Duration of Ioan: 25 years
Corporate taxes (%)	Extra Cash Flow

# 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:



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

🗹 Show diagram

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 $\in$ , 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  $0 \in /kWh$ ; disch. (load + injecting to the grid) if price E. (sell) higher than  $0.11 \in /kWh$ 

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  $1^{st}$  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.



# 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":



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":

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.

	А	В		С	D	E	F	G	н	1	J	K	L	м	N	0	Р	Q	R	S	
1	Project: D:\P	OYECTO	S MHOG	A 3.4-2024	03XX\MHOGA	1.mho. Solutio	n#1														
2																					
3	COMPONEN'	FS: Wind t	urbines	of 30 MW.																	
4	STRATEGY: T	here <mark>is no</mark>	load co	nsumption	-> no control s	trategy related	d to the load co	onsumption su	pply. Arbitrage	: Control varia	bles for grid-co	onnected batt	eries: charge (o	only from rene	wable, not fro	m grid) if price	of E. (sell) is lo	wer than 0 €/	'kWh; disch. (	oad + injecti	ing to
5																					
6	HOURLY VAL	UES. All p	ower va	lues are exp	pressed in MW	(H2.load is in	MW referring t	o the HHV of	H2). The SOC d	ata of the bat	teries in energy	(MWh).									
7	Water tank (	Water_tai	nk) is en	ergy needer	d to pump the	water (MWh) v	while (Water_ta	ank_volume) i	is the volume st	ored (dam3).											
8	No.Gen_on is	s the num	ber of A	C generato	rs that are runi	ning during this	time step. Hou	irs_eq_Gen is	the number of	equivalent ho	urs (including o	ut-of-range p	enalty and star	t-up penalty) o	of AC generato	ors. The fuel co	nsumption of t	the Gen. AC (F	uel.Gen) is ex	pressed in x!	1E6litr
9	Costs of pure	hasing en	ergy to t	the grid, the	e fuel cost of th	ne AC Gen. (Fu	el.Cost), the co	st of the exte	rnal fuel used b	y the fuel cell	(C.fuel.ext_FC)	and incomes	of selling E and	d costs of buyir	ng E to the AC	grid (Inc.Sell a	nd Cost.Buy) a	re expressed in	n M€. They ar	e cash flow	values
10	Load of Hydr	ogen (H2_	load_m	ass) is expr	essed in t/h of	H2. H2 in tank	(H2_Tank_ma:	ss), H2 used b	y fuel cell, from	H2 tank (Fue	.FC) or externa	lly purchased	Fuel.ext_FC) a	ind hydrogen g	enerated by th	ne electrolyzer	(Prod_H2) are	expressed in t	t of H2.		
11	Hydrogen sto	red in H2	Tank (H	2_Tank_HH	IV) is expressed	l in MWh HHV	of H2														
12	Date	Hour	Lo	ad(MW)	AC_load(MW	DC_load(MW	H2_load(HHV	H2_load_ma	s Water_load()	PV(MW)	Wind(MW)	Hydro(MW)	Ef_turb(perce	AC.Gen.(MW	No.Gen_on	Hours_eq_Ge	Cons.Fuel(x1	E Fuel.Cost(M	EF.C.(MW)	Fuel.FC(t)	. F
13	01-January		0:00	0	) (	0	0		0 0	(	3.34	C	1	. 0	0	) (	0		D	0	0
14	01-January		1:00	0	) (	0	0		0 0	0	3.08	C	1	. 0	0	) (	0	(	0	0	0
15	01-January		2:00	C	) (	0	0	0	) 0	(	3.05	C	1	. 0	a	) (	a		0	0	0
16	01-January		3:00	0	) (	0	0		) 0	0	3.34	0	1	. 0	0	) (	0	(	0	0	0
17	01-January		4:00	C	0 0	0	0		0 0	(	3.81	C	1	. 0	0	) (	0		0	0	0
18	01-January		5:00	C	) (	0	0	(	0 0	(	5.53	C	1	. 0	a	) (	0	) (	D	0	0
19	01-January		6:00	0	) (	0	0		) 0	0	9.21	0	1	. 0	0	) (	0	(	0	0	0
20	01-January		7:00	C	0 0	0	0	(	0 0	(	13.35	C	1	. 0	a	) (	0		0	0	0
21	01-January		8:00	C	) (	0	0		0 0	(	14.26	C	1	. 0	0	) (	0		D	0	0
22	01-January		9:00	0	0 0	0	0		0 0	(	12.94	0	1	. 0	0	) (	0		0	0	0
23	01-January	1	0:00	C	0 0	0	0		) 0	(	11.73	C	1	. 0	0	) (	a		0	0	0
24	01-January	1	1:00	C	0 0	0	0		0 0	(	10.12	C	1	. 0	0	) (	0		0	0	0
25	01-January	3	12:00	0	0 0	0	0		0 0		8.76	C	1	. 0	0	) (	0		0	0	0
26	01-January	1	13:00	C	) (	0	0		) 0	0	7.62	C	1	. 0	0	) (	0		0	0	0
27	01-January	1	14:00	0	0 0	0	0		0 0	(	6.77	0	1	. 0	0	) (	0		0	0	0
28	01-January	3	15:00	C	0 0	0	0		0 0		6.29	C	1	. 0	0	) (	0		0	0	0
29	01-January	1	16:00	C	0 0	0	0	(	0 0	(	6.46	C	1	. 0	0	) (	0	0	D	0	0
30	01-January	1	17:00	0	0 0	0	0		0 0	(	7.25	0	1	. 0	0	) (	0		0	0	0
31	01-January	1	18:00	C	0 0	0	0	(	0 0	(	7.78	C	1	. 0	C	0 0	0	0	0	0	0
32	01-January	-	9:00		) (		0		0 0	(	8.41		1	0		) (	0	í (	n	0	0 *

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 1<sup>st</sup> 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.

0 U 0	117.661 119.212	0	117.661	0	117.661	114 555	0	
0	119.212	1.551			111.001	114.000	0	
0		1.001	117.661	0	119.212	115.89	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)	In∨estment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report	1.
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

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).

and then select the physical or vitual printer (in the example,

Press the print button Adobe PDF):

Print					×
Printer Name:	Adobe PDF			Prop	perties
Where:				Print to file	
Pages Al Current page Pages: Enter page nur separated by o	e hers and/or page ranges, ommas. For example, 1,3,5-1?	2	Copies Number of copies	1	T
Other Print Order Duplex	All pages Direct (1-9) Default	× × ×	Print mode	Default	~
				ОК	Cancel

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:

Unmet(GWh/yr) IRR(%) I	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report	Costs	P. PV (MWp)	Slope#1(º) Cn 🔨
0 18.48	540	37.5	43.31	0.03	SIMULATE	REPORT.	COSTS	<u>0</u> ∕1	26 1×C

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 $\in$ , that is, CAPEX of the wind turbines (2 M $\in$ /wind turbine \* 15 wind turbines = 30 M $\in$ ) 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 $\in$ .

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+interest rate)<sup>y</sup>, and this cash flow is converted to present cost or present value dividing by (1+inominal discount rate)<sup>y</sup>.

<u>We suppose all the costs and incomes are paid at the end of each year</u>, 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. <u>All the costs defined in the different windows of the software are for the year 0 (beginning of the system lifetime)</u>.

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 $\in$ /wind turbine \* 15 wind turbines = 30 M $\in$ ). 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  $30 \cdot 0.01 = 0.6 \text{ M} \in$ , but it is paid at the end of the year adding the general inflation (2%). Therefore, the wind turbines OPEX during the  $1^{\text{st}}$  year is 0.6 M $\in$ , but it is converted to cash flow at the end of the  $1^{\text{st}}$  year, it is  $0.6 \cdot 1.02^1 = 0.612$  M $\in$ ; this cash flow will be converted to present cost considering the nominal discount rate of 7%, that is:  $0.612/1.07^1 = 0.572 \text{ M} \in$  (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.



# Total Cost of Wind Turbines group (NPV): -41.033 M€

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  $24 \cdot (1-0.01)^{20} = 19.63 \text{ M} \in \text{ of cash flow in year 20}$ . However, we must convert this cash flow to present cost dividing by  $1.07^{20}$ , obtaining  $19.63/1.07^{20} = 5.073 \text{ M} \in$ , 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  $24 \text{ M} \notin 15/20 = 18 \text{ M} \notin$  (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  $18 \cdot (1-0.01)^{25} = 14.001 \text{ M} \notin$  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  $14.001/1.07^{25} = 3.618 \text{ M} \in$ , 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 $\in$ ). 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  $1.07^{\circ}$ , 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 1<sup>st</sup> 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 · 1.02<sup>1</sup> = 7.018 M€. It is converted to present value by dividing by 1.07<sup>1</sup>, obtaining 7.018/1.07<sup>1</sup> = 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 · 1.02<sup>25</sup> = 11.289 M€ and the present value 11.289/1.07<sup>25</sup> = 2.08 M€. The sum of all these present value incomes is 97.936 M€.



Total Incomes of E sold to AC grid (NPV): 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 $\in$ ).

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 $\in$ ) 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 $\in$  incomes (present value of incomes of year 1) - 3.007 M $\in$  (present cost of the financial cost of year 1) - 0.572 M $\in$  (present cost of the wind turbines OPEX of year 1) = 2.98 M $\in$  (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.

Save Data	×
Do you want to save cash flow?	
Sí No	

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

Microsoft	Excel				×
	El formato y la extensión de archiv menos que confíe en su origen. ¿D	o de 'prueba1tabla Desea abrirlo de tod	.xls' no coinciden. Pu dos modos?	ede que el archiv	o esté dañado o no sea seguro. No lo abra a
		Sí	No	Ayuda	

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 A		В	C	D	E	F	G	н		J	K	L	M	N	0	P	Q	R	S	Т	U	V	W	X	Y	Z
1 Project	MHOGAI	L Solutio	n#1																							
2	_																									
3 Inversi	on cost 3	7.5 MC(ii	ncluded in	stallation and	initial varia	ble costs of 7.	5 MC). Loan: 1	100 %, int. 7%	in 25 years.																	
4 CASH FI	OW THRO	DUGHOUT	T SYSTEM L	IFETIME.																						
5 CASH FI	OW OF IP	NCOMES	(+) AND CO	ISTS (-):																						
6 All valu	es in MC.	Incomes	s +, Costs	For each com	ponent, cash	flows corresp	ond to acqui:	sition cost (ye	ar 0), replacer	ment costs ()	ears in whic	h the compon	ent is replac	ed), and retu	in revenue at	the end of the	system's life	, if it has a us	eful life (inc	ome), the thre	e sums are i	represented in	the same colu	umn. In additio	on, in anothe	er column, the
7 YEAR	PV	Gen.		O&M PV G	en.	Wind T.		O&M Wind	Τ.	Hydro T.		O&M Hydro	οT.	AC Gen.		O&M AC Ge	en.	Inverter		Batteries		O&M Bat	teries	Charge Rep	4	Rectifier
8	cas	h 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 NPV	cash year	NPV	cash year
9	0	0		0	0	0 -3	0 -3	0 (	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 -0.61	-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 -0.63	-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 -0.64	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 -0.66	-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 -0.67	-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 -0.68	-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 -0.70	-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 -0.71	-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 -0.73	-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 -0.74	-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 -0.76	-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 -0.77	-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 -0.79	-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 -0.80	-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 -0.82	-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 -0.8	-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 -0.85	-0.254		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0
88	19	0		0	0	0	0	0 -0.87	-0.242		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0
9	20	0		0	0	0 -19.6	3 -5.07	3 -0.89	-0.23		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0
90	21	0		0	0	0	0	0.90	-0.22		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0
81	22	0		0	0	0	0	0 -0.92	-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 -0.94	i -0.2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0
13	24	0		0	0	0	0	0 -0.96	-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 14.00	1 2.5	8 -0.98	-0.181		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0
5 TOTAL	PV	Gen.		O&M PV G	en.	Wind T.		O&M Wind	т.	Hydro TTI	EG	O&M Hydro	TTEG	AC Gen.		O&M AC Ge	en.	Inverter		Batteries		O&M Bat	teries	Charge Rep	4	Rectifier
6 NPV				0		0	-32.49	3	-8.54			0		0		0		0		0		0		0		0
57																										
STOTAL N	let Preser	nt Value (	(NPV) = 49.	403 MC																						
39 INTERN	AL RATE O	FRETURN	N = 18.5 C%	6																						

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.

	/03(3	P. PV (WWP_ac)	Slope#1(*)	Cn Bat. (kAh)	P. Gen (MW)	P. In∨ (MW)	P. Wind T. (MW)	F. Turb (m3/s)	P. FC (MW)	P. Elyz. (MV 🔨
REPORT C	COSTS	3x1	27	1×0×5	1x0	5	15×2	0	0	
REPORT C	COSTS	5x1	27	1×0×5	1x0	0	15×2	0	0	
REPORT C	COSTS	0x1	27	1x1x5	1x0	0	15x2	0	0	
REPORT C	OSTS	1x1	27	1x0x5	1x0	0	14×2	0	0	
REPORT C	OSTS	2x1	27	1x0x5	1x0	10	15x2	0	0	
REPORT C	OSTS	4x1	27	1x0x5	1x0	5	15x2	0	0	
REPORT C	OSTS	2x1	27	1x0x5	1x0	0	14x2	0	0	
BEPOBT C	OSTS	1x1	27	1x1x5	1x0	0	15x2	0	0	
REPORT C	COSTS	0x1	27	1×1×5	1x0	5	15x2	0	0	
										~

Focusing on row 20 (solution 20<sup>th</sup>), 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	J
<										>	ک

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.

Ep∨(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	
6.202	117.661	0	123.863	119.687	(	) 0	0	
3.101	109.817	0	112.918	111.182	(	) 0	0	
1.551	117.661	0	119.212	115.89	(	) 0	0	
0	117.661	0	117.829	114.683	(	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  $1^{st}$ , 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) (MI	^
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	
	<b>,</b>								~

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

NPV WindT (M€)	C. Hydro (NPC) (MI NPV FC	(M€) NPV EI	yz. (M€) NPV Fuel	Gen (M€) NPV Fu	el FC (M€) NPV Buy	(M€) NPV S	Sell (M€) NP	~ ^
-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 20<sup>th</sup> row or the table, click in REPORT):



In the main screen again, we can see the simulation of the operation of this solution by clicking on the 20<sup>th</sup> 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  $0.11 \notin kWh$  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 29<sup>th</sup> has been updated to the simulation step of 5 min: the NPV has been slightly increased.

20	47.079	1.14	0	17.4	540.05	40	43.62	0.0317 SIMULATE	REPOR	
									*	41

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:

✓ LOAD / AC GRID	GENERAL DATA OPTIMIZATION C	CONTROL STRATEGIES FINANCIAL DATA RESULTS CHART
RESOURCES	COMPONENTS	MIN. AND MAX. No COMPONENTS IN PARALLEL: OPTIMIZATION PARAMETERS SELECTED BY:
✓ SOLAR	PV Gen.	Bateries in parallel: Min. 0 Max. 5 OUSEB
VIND	Wind Turbines	PV gen. in parallel: Min. 0 Max. 30 Maximum execution time:
HYDRO		Wind T. in parallel: Min. 0 Max. 15 0 h. 15 min. Parameters
COMPONENTS		AC Gen. in parallel: Min. 1 Max. 1 Minimum time for the Genetic Algorithms
🖌 PV GEN.	Battery bank	Constraints under NPV maximization:
VIND TURB.	Backup Gen.	Max. Investment cost 100 M€ Step (min.): Simulation starts:
HYDRO TURB.	✓ Inverter/char.	Min. Capacity Factor 0 % Pmax_sell 60 v hour 0 day1 month 1
V BATTERIES		Min. Renew. Fraction 0 %
VINVERTER/CHAR.	H2 (F.C Elyzer.)	Max. Unmet load 100 %
BACKUP GEN.		Max. Land use 100000000 ha Data

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

2	47.025	1.14	0	17.39	540.05	40	43.64	0.0317 SIMU	ULATE	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)	In∨estment(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
<										>
COMF	ONENTS: 15 Wind Turb.	WindT1 (2 MW at 15 n	n/s) // Unmetload	= 0 % // Tot	tal Net Prese	ent Value (NPV) =	49.929 M€, I	RR = 18.6%.		^
STRA from re	TEGY: There is no load c mewable, not from grid) if j	onsumption -> no cont price of E. (sell) is lowe	rol strategy related er than 0€/kWh; dis	to the load sch. (load +	consumptio injecting to t	n supply. Control ne grid) if price E.	∨ariables fo (sell) higher	r grid-connected b than 0.11 €/KWh	atteries: charge	(only
										~

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

Save Excel table

P	В	C D	D E	F G	H I	J K	L M	N O	P	Q	R	S	-
1 Project	: D:\PFOYECTOS	MHOGA 3.4-202403XX\M	HOGA1.mho										
2 No.		NPV(M€)	Em.CO2(kt/yr)	Unmet(GWh/yr)	Unmet(%)	IRR(%)	Land use(ha)	Investment(M	E)	Capacity Fact	or (%)	LCOE (€/kWh)	
3													
4	1	49.929	1.125	0	0	18.59	540	37.5		43.59		0.0298	
5	2	49.514	1.157	0	0	18.09	543	39		42.68		0.0304	
6	3	49.11	1.125	0	0	18.26	540	38.125		43.59		0.0303	
7	4	49.069	1.189	0	0	17.63	546	40.5		41.81		0.0311	
8	5	48.696	1.157	0	0	17.78	543	39.625		42.68		0.0309	
9	6	48.584	1.221	0	0	17.19	549	42		40.98		0.0318	
10	7	48.292	1.125	0	0	17.94	540	38.75		43.59		0.0308	
11	8	48.25	1.189	0	0	17.33	546	41.125		41.81		0.0316	
12	9	48.065	1.253	0	0	16.77	552	43.5		40.18		0.0324	
13	10	47.877	1.157	0	0	17.48	543	40.25		42.68		0.0314	
14	11	47.82	1.05	0	0	18.86	504	35		44.18		0.0294	
15	12	47.766	1.221	0	0	16.91	549	42.625		40.98		0.0322	
16	13	47.503	1.285	0	0	16.37	555	45		39.43		0.0331	
17	14	47.494	1.143	0	0	17.62	540.05	39.375		43.59		0.0313	
18	15	47.49	1.082	0	0	18.34	507	36.5		43.22		0.0301	
19	16	47.432	1.189	0	0	17.05	546	41.75		41.81		0.0321	
20	17	47.246	1.253	0	0	16.5	552	44.125		40.18		0.0329	
21	18	47.138	1.114	0	0	17.85	510	38		42.31		0.0307	
22	19	47.08	1.175	0	0	17.18	543.05	40.875		42.68		0.0319	
23	20	47.025	1.143	0	0	17.39	540.05	40		43.64		0.0317	
24	21	47.001	1.05	0	0	18.5	504	35.625		44.18		0.0299	
25	22	46.947	1.221	0	0	16.64	549	43.25		40.98		0.0327	
26	23	46.897	1.317	0	0	15.98	558	46.5		38.7		0.0337	
27	24	46.751	1.146	0	0	17.4	513	39.5		41.44		0.0314	
28	25	46.685	1.285	0	0	16.11	555	45.625		39.43		0.0335	
29	26	46.672	1.082	0	0	18.01	507	37.125		43.22		0.0306	
30	27	46.655	1.125	0	0	17.33	540	40		43.59		0.0318	
31	28	46.634	1.207	0	0	16.76	546.05	42.375		41.81		0.0326	
32	29	46.612	1,175	0	0	16.96	543.05	41.5		42.72		0.0324	¥

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.

CONTROL STRATEGY AND VARIABLES	TO OPTIMIZE	ENERGY ARBITRAGE: System with batteries and grid connected  Batt. charged by the AC grid // discharged if. Identical (also for Elyzer -> H2)  Elyzer. full load
<ul> <li>Cycle Charging  Continue up</li> <li>Try Both</li> </ul>	to SOC stp	Compare with Sell price Compa
Variables to optimize relative to th	e global strategy:	Q 2 variables: price E. min. and max. Min.> 0.0008 ; Max< 0.3615 €/kWh IDPCh <pr(< th=""></pr(<>
P1_gen     P1_FC       SOCstp_gen     SOCstp_FC       Pcritical_gen     H2TANKstp	P2 SOCmin Plim_charge	Batteries can inject electricity to the AC grid     1 day at low SOC-> charge battery with AC grid     When batteries are off, compensate autodisch.     Batteries availability
SOCmax Fix variables Variable	/s accuracy: 5 = 10 OC(%) < SOCmin(%) + 0	

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).

MIN. AND MAX. No CO	MPONEN	NTS IN PARALLEL:
Bateries in parallel: Min.	0	Max. 1
PV gen. in parallel: Min.	0	Max. 10
Wind T. in parallel: Min.	13	Max. 15
AC Gen. in parallel: Min	1	Max. 1

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	VERTER/CHARGERS														-		
	Add from Database	e Ze ole from family:	ro		~	~				M				+	_	× ×	¢
•	Name	Power(M/A)	Lifection (m)	Cost (ME)	Imax ch DC(kÅ)	Ef. charger(%)	Vdemin(k\A	Vdcmav(k\A	Pmax ran(MMA)	0%	2%	ENC1	4%	5%	10%	20%	%) -> ^
	Inv-Ch5MW	5	15	0.5	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	

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	
<										>	Ť
COMP	ONENTS: 15 Wind Turb.	WindT1 (2 MW at 15 n	n/s) // Unmet load	= 0 % // Tot	al Net Prese	nt Value (NPV) =	49.929 M€, I	RR = 18.6%.			
STRA (only fr	TEGY: There is no load c om renewable, not from g	onsumption → no cont rid) if price of E. (sell) i	rol strategy related s lower than 0.3615	to the load €/kWh; dis	consumptio ch. (load + in	n supply. ARB.: C jecting to the gric	Control varial ) if price E. h	oles for grid-conne igher than 0.3615 f	ected batteries: c €/kWh	:harge	~

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 20<sup>th</sup> 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)	1	NF 🔨
0x1	27	1x0x5	1×0	0	15x2	0	0	0		0	
1x1	27	1x0x5	1x0	0	15x2	0	0	0		0	
0x1	27	1x0x5	1×0	5	15x2	0	0	0		0	
2x1	27	1x0x5	1×0	0	15×2	0	0	0		0	
1x1	27	1x0x5	1×0	5	15x2	0	0	0		0	
3x1	27	1x0x5	1×0	0	15x2	0	0	0		0	
2x1	27	1x0x5	1x0	5	15x2	0	0	0		0	
0x1	27	1x1x5	1×0	5	15x2	0	0	0		0	
4x1	27	1x0x5	1×0	Ū	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 \land
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  $8^{th}$ ) we can also see the min. (0.07294  $\epsilon/kWh$ ) and max. (0.14508  $\epsilon/kWh$ ) price of sell electricity to charge / discharge:

Pr.max.C(€/k	<sup>(</sup> Pr.min.D(€/k\	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		117.661	0	117.661	0	117.561	114.3		
0.3615	0.3615		123.863	6.202	117.661	0	123.863	119.687		
<									>	Ť

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	
U	U	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) (MI 🔺
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) (MI 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	98.462		0	
0	0	) 0	0	0	99.718		0	
0	0	) 0	0	0	98.462		0	
0	0	) 0	0	0	100.944		0	
0	0	) 0	0	0	99.718		0	
0	0	) 0	0	0	102.13		0	
0	0	) 0	0	0	100 944		0	
0	0	) 0	0	0	100.303		0	
0	0	) 0	0	0	103.281		0	
								~
<							>	

We can see the simulation (row 8<sup>th</sup>, 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€:



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									E	FFICI	ENCY	(%) v	/s. OUT	PUT PO	NER (%	) ->
Name	Power(MVA)	Lifespan (yr)	Cost (M€)	lmax_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	U	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 (MP)	Emission (ktCO2Av)	Linmet(G\A/hAv)	IBB(%)	Land(ha)	Invoetmont(M€)	Can E(%)	LCOE(#JAAAb)	Simulato	Report	~
		1 1F	Onne(Giviiy)	10.51	E 40.0E	20.212	40,40	0.000		DEDOD	
1	50.565	1.15	U	10.01	540.05	30.313	45.49	0.0306	SIMULATE	REPUR	4
2	50.139	1.18	0	18.02	543.05	39.813	42.58	0.0312	SIMULATE	REPOR	6
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	i
											Ť
<											
COMP Presei STRA	ONENTS: Batteries Bat51 nt Value (NPV) = 50.563 M TEGY: There is no load c	MWh- (5 kAh): 1s. x1p. €, IRR = 18.5%. onsumption -> no cont	// 15 Wind Turb. V rol strategy related	vindT1 (2 M to the load	W at 15 m/s	) // Bat. Inverter Ir	n.: 10 %. AR	of 5 MVA // Unmet B.: Control variable	load = 0 % // To	otal Net ected	^
batteri	es: charge (only from rene	ewable, not from grid) if	f price of E. (sell) is	lower than	0.0729 €/kW	h; disch. (load + ii	njecting to th	e grid) if price E. h	igher than 0.1451	1€/kWh	
											$\sim$

The previous optimal solution (just 15 wind turbines) is now the third best one (3<sup>rd</sup> 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  $\xi/kWh$ .

Pr.max.C(€/⊮	Pr.min.D(€/k <mark>√E</mark> ptal(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:

ſ	#	Total NPV (M€) E	nission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	In∨estment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report /
J	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..."

Simulation and optimization:	
Simulation of the 1st year and extrapolate results	
Multiperiod: simulate all the years of the system lifetime ( 25 years) Options	
Economic optimization:	
$\bigcirc$ Minimize Net Present Cost (NPC), usually for off-grid systems and high load on-grid ———>	Min. NPC Min. LCOH
) Maximize Net Present Value (NPV), usually for low load or no-load on-grid systems ————————————————————————————————————	Max. NPV
Define Wind Farm with 16 power curves, one for each wind direction sector DC renewable include own charger and controller	Min. LCOE Min. LCOH Max. Cap.F. min. LCOE Max. IRR
When saving the project, update all the results of the table to the present conditions	
Number of decimal places in results of costs 3 🗸	
Number of decimal places in results of energy 3 🗸	
OK	

Then click in **Options** button.

MULTIPERIOD SIMULATION AND OPTIMIZATION OPTIONS:	[	Obtain ra	ndom values	for F	VRCHASE I	E. price inc.	✓ Ave	erage (%):	3	Std. dev	: (%): [1		
Show in the simulation during one year:	[	Obtain ra	ndom values	for	radiation var	riation over a	ve v Ave	erage (%):	0	Std. dev	. <b>(%)</b> : 2	!	
Aerage year	An	nual increa	ise in price	s and loa	d (%) / Varia	ation over	average i	n resourc	ces (%) /	O&M PV	- WT (%)	):	
O Year number 1	Year	Purch.E.	Sell E.	Sell H2	Inc. AC	Inc. DC	Inc. H2	Inc. W.	Irrad.	Wind	OM.P.	OM.W.	^
	1												
Annual increase in electricity and H2 price: Fixed	2												
(if fixed, same values as price inflations of LOAD/AC GRID)	3												
AC grid Electricity: Purchase: 3 %; Sell : 2 %	4												
H2 sold: 3 % Each year diff. hourly sell price: Data	5												
Hourly buy price = sell x 1	6												
Annual increase in load consumption: 🔽 Fixed	7												
AC: 1 % DC: 1 %	8												
H2: 1 % Water: 1 %	9												
	10	For var	iable unselec	t "Fixed"	F	or variable u	nselect "Fix	ed"	Unched	ck "No ch.'	Unche	ck "Fixed	
Annual decrease in generation:	11												
PV:1styear: 3 %; otheryears: 1 %	12												
Wind Turbines: 1 %	13												
Hydro Turbinos: 0 %	14												
	15												
Battery end of life when capacity reduction of 20 %	16												
	17												
	18												~
Annual O&M for PV and Wind T.: V Fixed		_											
		ОК											

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 6<sup>th</sup> year the inflation of the sell electricity price will be 5% and the 12<sup>th</sup> year it will be -4%, and the rest of the years 2%: uncheck the corresponding "Fixed" checkbox and change in the table.

MULTIPERIOD SIMULATION AND OPTIMIZATION OPTIONS:		Obtain r	andom values	for	URCHASE	E. price inc.	∼ Av	erage (%):	3	Std. dev	/. <b>(%)</b> :	1	
Show in the simulation during one year:		Obtain r	andom values	for	radiation va	riation over a	ave ~ Av	erage (%):	0	Std. dev	/. <b>(%)</b> :	2	
Aerage year	A	nnual incre	ise in price	and loa	d (%) / Vari	iation over	average	in resourc	ces (%) /	O&M PV	- WT (%	):	
O Year number 1	Year	Purch.E.	Sell E.	Sell H2	Inc. AC	Inc. DC	Inc. H2	Inc. W.	Irrad.	Wind	OM.P.	OM.W.	^
	1	3	2	3									
Annual increase in electricity and H2 price: Fixed	2	3	2	3									
(if fixed, same values as price inflations of LOAD/AC GRID)	3	3	2	3									
AC grid Electricity: Purchase: 3 %; Sell : 2 %	4	3	2	3									
H2 sold: 3 % Each year diff. hourly sell price: Data	5	3	2	3									
Hourly buy price = sell x 1	6	3	5	3									
Annual increase in load consumption: Fixed	7	3	2	3									
AC: 1 % DC: 1 %	8	3	2	3									
H2: 1 % Water: 1 %	9	3	2	3									
	10	3	2	3	F	for variable u	inselect "Fi	ked"	Unched	:k "No ch.'	' Unche	ck "Fixed	
Annual decrease in generation:	11	3	2	3									
PV: 1st year: 3 %; other years: 1 %	12	3	-4	3									
Wind Turbines: 1 %	13	3	2	3									
Hydro Turbines: 0 %	14	3	2	3									
	15	3	2	3									
Battery end of life when capacity reduction of 20 %	16	3	2	3									
Annual variation over average in resources: No change	17	3	2	3									
	18	3	2	3									~
Annual U&M for PV and Wind 1.: Y Fixed													
		OK											

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.

Annual variation over average in resources	🗆 No change
Annual O&M for PV and Wind T.: 🔽 Fixed	

MULTIPERIOD SIMULATION AND OPTIMIZATION OPTIONS:		Obtain ra	andom value	s for	PURCHASE	E. price inc.	~ A	verage (%)	3	Std. dev	. (%):	1	
Show in the simulation during one year:		Obtain re	andom value	s for	Irradiation va	iation over	ave v Av	verage (%)	0	Std. dev	. (%):	2	
Aerage year		Annual incre	ase in pric	es and loa	ad (%) / Varia	ation over	average	in resour	ces (%) /	O&M PV	- WT (%	):	
Verraumher 1	Year	Purch.E.	Sell E.	Sell H2	Inc. AC	Inc. DC	Inc. H2	Inc. W.	Irrad.	Wind	OM.P.	OM.W.	^
	1	3	2	3					0	0			
Annual increase in electricity and H2 price: Fixed	2	3	2	3					0	-7.89			
f fixed, same values as price inflations of LOAD/AC GRID)	3	3	2	3					0	14.05			
AC grid Electricity: Purchase: 3 %; Sell : 2 %	4	3	2	3					0	7			
H2 sold: 3 % Each year diff. hourly sell price: Data	5	3	2	3					0	0			
Hourly buy price = sell × 1	6	3	5	3					0	0			
Annual increase in load consumption: 🔽 Fixed	7	3	2	3					0	0			
AC: 1 % DC: 1 %	8	3	2	3					0	0			
H2: 1 % Water: 1 %	9	3	2	3					0	0			
	10	3	2	3	F	or variable (	unselect "F	ixed"	0	0	Unche	ck "Fixed	
Annual decrease in generation:	11	3	2	3					0	0			
PV: 1st year: 3 %; other years: 1 %	12	3	-4	3					0	0			
Wind Turbines: 1 %	13	3	2	3					0	0			
	14	3	2	3					0	0			
Hydro Turbines: 0 %	15	3	2	3					0	0			
20	16	3	2	3					0	0			
sattery end of life when capacity reduction of 20 1%	17	3	2	3					0	0			
Annual variation over average in resources	18	3	2	3					0	0			
Annual O&M for PV and Wind T.: Fixed					_								~
		ОК											

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 (2<sup>nd</sup> 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).



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:





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.

A	В	C D	E F	G H	- I	K	L M	N O	P Q	R S
Project	MHOGA-optC	ont-BatCheap-M.mho. Solution	n#1							
RESULT	S DURING THE	YEARS OF THE SYSTEM LIFETIN	ME, MULTIPERIOD SIMULA	TION.						
	12									
Costs a	nd incomes are	e cash flow of each year (not pr	esent 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
1	4	12.55	8.24	12.55	103.03	103.03	103.03	103.03	0	7
2	5	15.93	10.41	15.93	104.06	104.06	104.06	104.06	0	0
3	6	19.41	15.93	19.41	105.1	105.1	105.1	105.1	0	0
1	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
5	9	30.48	23.02	30.48	108.29	108.29	108.29	108.29	0	0
r	10	34.39	25.48	34.39	109.37	109.37	109.37	109.37	0	0
3	11	38.42	27.99	38.42	110.46	110.46	110.46	110.46	0	0
Э	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
1	14	51.26	27.84	51.26	113.81	113.81	113.81	113.81	0	0
2	15	55.8	30.4	55.8	114.95	114.95	114.95	114.95	0	0
5	16	60.47	33	60.47	116.1	116.1	116.1	116.1	0	0
1	17	65.28	35.66	65.28	117.26	117.26	117.26	117.26	0	0
5	18	70.24	38.38	70.24	118.43	118.43	118.43	118.43	0	0
5	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
8	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
1	24	103.28	65.23	103.28	125.72	125.72	125.72	125.72	0	0
1	25	109.38	70.19	109.38	126.97	126.97	126.97	126.97	0	0

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.

GENERAL DATA OPTIMIZATION	NTROL STRATEGIES FINANCIAL DATA RESULTS CHART	
COMPONENTS	MIN. AND MAX. No COMPONENTS IN PARALLEL: OPTIMIZATION PARAMETERS SELECTED BY:	
PV Gen.	Bateries in parallel: Mirt 0 Max. 1 OHOGA OUSER	
Wind Turbines	PV gen. in parallel: Min 0 Max. 10 Maximum execution time:	
Hydro T.	Wind T. in parallel: Min. 15 Max. 15 0 h. 15 min. Parameters	
🖂 Battery bank	AC Gen. in parallel: Min. 1 Max. 1 Minimum time for the Genetic Algorithms	
Backup Gen.	Max. Investment cost         100         Mc         Simulation:	
🗸 Inverter/char.	Min. Capacity Factor 0 % Pmax_sell 60 v hour 0 day 1 month 1	
H2 (F.C Elyzer.)	Min. Renew. Fraction     0     %       Max. Unmet load     100     %	
	Max Land use 100000000 ha. Data	

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.

		NUMBER	OF CASES AND T	IME EXPECTED	
computation :	speed: 0.846 c	ases/second			
			EVAL. ALL	POP. (% ALL)	<u>GEN. ALG. (% ALL)</u>
MAIN AL	.G. (COMB. CC	)MPONENTS):	: 4 (1x4)	10 (250%)	139 (3475%)
SEC. AL	G. (COMB. ST	RATEGIES):	21	12 (57.14%)	183 (871.43%)
	MAIN ALG.	SEC. ALG.	NUMBER OF CASES	%	TIME EXPECTED
OPTION 1:	EVAL. ALL	EVAL. ALL.	84	100 %	<u>0h 1' 39''</u>
OPTION 2:	EVAL. ALL	GEN. ALG.	732	871.4 %	0h 14' 24''
OPTION 3:	GEN. ALG.	EVAL. ALL.	2919	3475 %	0h 57' 28''
OPTION 4:	GEN. ALG.	GEN. ALG.	25437	30282.1 %	8h 19'

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.

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	In∨estment(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	B
2	45.112	1.8	0	17.92	540	37.5	40.95	0.0317	SIMULATE	REPOR	B
3	44.866	1.8	0	17.81	540	37.688	40.95	0.0318	SIMULATE	REPOR	R
4	44.3	1.82	0	17.57	540.05	38.125	40.95	0.0322	SIMULATE	REPOF	B
< COME	ONENTS: Batteries Bat5	//W/h-/5 k.4h)·1s y 1n	//15Wind Turb V	vindT1 (2 h	1W/ at 15 m/s	) // Bat Invertor I		nf 5 MVA // 1 Inmet	load = 0 % // Tr	>	~
COMP Prese STRA batteri	UNENTS: Batteries Batte nt Value (NPV) = 45.66 Mf TEGY: There is no load c es: charge (only from rene	vivin- (5 KAn): T.S. x Tp. , IRR = 17.8%. onsumption -> no cont wable, not from grid) i	// IS Wind Turb. V rol strategy related f price of E. (sell) is	to the load lower than	ivvatism/s Iconsumptio 0.0729€/kW	) // Bat. Inverter II n supply. SOC m h; disch. (load + i	iv-Cn5MW- ( in.: 10 %. AR njecting to th	B.: Control variable e grid) if price E. hi	ioad = 0 % // 10 es for grid-conni igher than 0.145	otai Net ected 1€/kWh	^
											$\sim$

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	R periods d	istribution:												
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 💌									
WINTER	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			
						0111	r-on	0.011	0.1011	10.1111	11 1211			
P3 🔽	P3 🔻	P3 💌	P3 💌	P3 💌	P3 💌	P3 👻	P3 👻	P2 -	P2 -	P2 -	P2 -			
P3 ▼ 12-13h	P3 💌 13-14h	P3 👻 14-15h	P3 💌 15-16h	P3 💌 16-17h	P3 💌 17-18h	P3 👻 18-19h	P3 👻 19-20h	P2 - 20-21h	P2 -	P2 👻 22-23h	P2 ▼ 23-24h			

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

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):

HOURLY PRICE OF THE ELECTRICITY PURCHASED FROM THE AC GRID											
Hourly Price Data (€/kWh) ○ Hourly, all days the same											
Hourly, all days the same     From file (8760 hourly values)											
Hourly Periods: Number of Hourly Periods: 3 V Summer/Winter OMon-Fri/Weekend OHourly (from file)											
Summer calendar: Period P1 Price: 0.15											
From day 30 month 3 Period P2 Price: 0.12											
To day 26 month 10 Period P3 Price: 0.08											
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 v											
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 v P1 v P2 v P2 v P2 v P2 v P2 v P2 v											
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 v											
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 v P2 v P3 v P3 v P3 v P1 v P1 v P1 v P1 v P2 v P2 v											
ОК											

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  $0.15 \notin kWh$ , P2 price  $0.12 \notin kWh$ , P3 price  $0.08 \notin kWh$ ). 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.

Fixed Pmax	(kW)	Fixed Cost P (€/kW	/vrì
100 0	ptions	0	Hourly Values

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):

Hourly peri	iods same of	f energy hourly price periods
	Pmax (MW)	Cost of Power (€/kW/yr)
Period P1	15	0
Period P2	18	0
Period P3	23	0
Period P4	d	0
Period P5	0	0
Period P6	0	0
		ОК

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				
<										>	ř			
COMF Prese STRA batteri	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 Ioad = 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<sup>3</sup> 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.

N HYDRO	-		×
Head (Vertical change Losses in power canal and c Available head, H' = H · loss Losses in Penstock: 8 Estimated Total Efficiency T	in elevation between the head water level and the tailwater level), H: $\boxed{3}$ data tube: $\boxed{2}$ m is = +28 m $\boxed{2}$ within - Generator. $\boxed{75}$ %, just for the estimation of the max generator output power	m	
Flow Data (m3/s) Monthly average C Ir	mport hourly data file (m3/s)	Impor	2
FLOW(m3/s) January 7	Variability Daily Variability 0 % Hourly Variability 0 %		
February 7	HYDRO		
March 7 April 7 May 7 June 7	7. 6. (% 5) W0 04. 2. 2. 2.		
July 7 August 7	Ш 2- т.		
September 7	0 F M A M J J A S O N D MONTH		
October 7 November 7	Max. flow: 7 m3/s; Average flow: 6.99 m3/s Max. generator output power: 1.33 MW		
December  7	OK Expor	ι	

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.

M HYDRO TURBINES	- 🗆 ×
Add from Database Zero 🗸	x
HYDRO TURBINE GENERAL DATA	EFF. TURBINE (%) vs. FLOW (% of F max.)
Name Pnom(MW) Max. flow(m3/s) Min. height (m) Max. height (m) Cost (M€) Lifespan (yr) C. 0	18.M (%/yr) 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
▶ Tur1MW 1 4 25 35 1 30	1 0 0 60 80 90 90 90 90 90 90 90
Check that reversible pump/turbines are suitable for an available head of 27 – 33 m. Available head if you want to consider Pumped Hydro Storage, check one of the check box below (reversible pump-turbine or pump and turbine different machines).	d must be between Min. height and Max. height of the turbine Tur1MW. F=4m3/s. Pnom=1MW; Pmax (max. height 35m)=1.09MW
In that case, data from HYDRO resource will not be considered. Water tank and pumping data (elevation head, friction losses, pumping efficiency, and pump minimum load) considered will be the ones shown in the LOAD/AC GRID window (Water tab). Water will be pumped from reservoir when there is renewable energy or when settled by the control strategy, turbine will generate electricity when water consumption or when settled by control strategy	96 88 80 72 & 64
PHS: Reversible Pump-Turbine, data here. Same height and triction losses (data in LOAD/AC qrid, water) PHS: Pump machine and pumping data in LOAD/AC grid window. Turbine data here:	20 56 10 48 148 22
Supply load with turb. when load > 50 % P. turb. and Water T.> 30 %	24
	0 10 20 30 40 50 60 70 80 90 10 % MAX.FLOW
Multiplier Gearbox Efficiency: 98 % Electrical Generator Efficiency: 90 %	
Emissions CO2 equiv. (manufacturing) 5 g CO2 equiv. / KWh generated	

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...."

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

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).

н	IYDRO TU	RBINE GENE	RAL DATA							EFF	. TUF	RBINE	: (%)	vs. Fl	LOW (	% of F	max.	)	
	Name	Pnom(MW)	Max. flow(m3/s)	Min. height (m)	Max. height (m)	Cost (M€)	Lifespan (yr)	C. O&M (%/yr)	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
►	Tur2M₩	2	8	25	5 35	2	30	1	0	0	60	80	90	90	90	90	90	90	90

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.density.g.height\_max.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<sup>3</sup>), the capacity at the beginning of the simulation (let's suppose it is at 50%, that is, 400 dam<sup>3</sup>), 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:

		20 /0	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
0	12	25	35	42	52	58	65	68	72	78
			]		] [				] [	
f reversibl	le pump/tu	urbine, ma	x. flow rate	of the turb	pine.				(044	

The max. flow rate is the one of the turbine  $(8 \text{ m}^3/\text{s})$  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·density·g·height·(1+friction\_losses)/Efficiency =

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

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):

MIN. AND MAX. No COM	PONENT	'S IN PA	ARALLEL:
Bateries in parallel: Min.	0	Max.	1
PV gen. in parallel: Min.	0	Max.	10
Wind T. in parallel: Min.	15	Max.	15
AC Gen. in parallel: Min.	1	Max.	1

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	$\sim$			
<										>				
COMP 5 MVA STRA turb./p grid) if	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 M6, 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 26<sup>th</sup>, 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<sup>3</sup> 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).

GENERAL DATA	OPTIMIZATION C
COMPONENTS -	
✓ Wind Turbines	:
🗖 Hydro T.	
🗌 Battery bank	
🔲 Backup Gen.	
🗌 Inverter/cha	]
₩ H2 (F.C Elyz	eer.

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  $10\cdot0.1=1$  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 n	nodify the	consun	nption a	nd efficie	ncy curv	es:	
	Curves	change in	H2 mass	flow limit	(% of rate	d): 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 $\in$ , lifetime and O&M in hours and  $\in$ /h will be 80,000 h and 100  $\in$ /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 mea	ns of their inverter a	nd rectifier respectivelly)	Inverter and rectifier data	
	ОК			

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

ELECTROLY Efficiency of	YZER: the rectifier of th	e electroly	zer: 90	%		
FUEL CELL: Efficiency of	the inverter of th	e Fuel Cel	l (%) vs Ou	utput powe	er (% of ra	ted):
0% 2 0 3	2% 3% 0  50	4% 70	5% 85	10% 93	20% 92	30% 90
40% 5 89 8	50% 60% 8 87	70% 86	80%  85	90% 84	100% 83	
		OK				

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.

Equivalent CO2 emissions (manufacturing fuel cells and electrolyzers): 330 kg CO2 equiv. / KW rated power	
Compression electrical consumption (kWh electricity per kg H2): 🔟	
Annual Inflation Rate for Fuel Cells, Electrolyzers and H2 Tanks Cost (e.g., for an expected 90% reduction on current cost, introduce "-90%"):	
Limit is reached in 21.9 years	
Fuel Cell and Electrolyzer are connected to AC bus (by means of their inverter and rectifier respectivelly) Inverter and rectifier data	
ОК	

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:

		ELECT	FROLYZER HO	URLY AVAILAI	BILITY		
🗸 0 - 1 h	🗸 1 - 2 h	🗹 2 - 3 h	🗹 3 - 4 h	🗸 4 - 5 h	✓ 5 - 6 h	🗸 6 - 7 h	🗸 7 - 8 h
🗸 8 - 9 h	🗹 9 - 10 h	🗹 10 - 11 h	🗹 11 - 12 h	🗹 12 - 13 h	🗹 13 - 14 h	🗹 14 - 15 h	🗹 15 - 16 h
🗹 16 - 17 h	🗹 17 - 18 h	🗹 18 - 19 h	🗹 19 - 20 h	🗹 20 - 21 h	🗹 21 - 22 h	🗹 22 - 23 h	🗹 23 - 24 h
	✓ Jan. ✓ Jul.	🗹 Feb. 🗹 Aug.	✓ Mar. ✓ Sep.	✓ Apr. ✓ Oct.	✓ May ✓ Nov.	✓ Jun. ✓ Dec.	
Not availe	able during no su able if calm wind	n hours if there is during 6 c	PV generator onsecutive hours	and there is Wine	d turbine		
				ок			

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 ( $0.15 \in$ /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  $\in$ /kW.

Also click on "**Sell surplus H2 in tank...**" to indicate we want to sell the H2 produced, and leave the default price of  $10 \notin$ kg and annual inflation of 3% for that price.

${\rm i}{\rm i}{\rm k}$ Load and options of Selling / Purchasing Energy from the AC	grid	- 🗆 X
Data source: Monthly Average O Load Profile Import File (MW, tH2/h, d	am3/h)	AC DC H2 Water Minutes- each hour in 1 row Import Export
AC LOAD (MW) DC LOAD (MW) H2 LOAD (tH2/h)	WATER (dam3/day) FROM WATER TANK PURCH	HASE / SELL E
Purchase from AC grid Unmet Load (Non Served Energy by Stand-alone system)     Fixed Buy Price (¢/kWh)     0.15     ourly Price     Annual Inflation (%):     Emission (kgC02/kWh);     3     0.4     Emissions deta     Fixed Pmax (MW)     Fixed Cost P (¢/kWlyr)     1.2     Options     40     Hourly Values     Access Charge Price (¢/kWh)     Fixed Access price (¢/kWh)     Hourly Price     Back-up Charge Price (¢/kWh)     Hourly Price     (KWh)     Hourly Price     (Mill be added to the E purchased)     Add negative gen. charge	Sell Excess Energy to AC grid Fixed Sell Price (£/kWh) O.12 Hourly Pri Pr. sell = pr. buy x Annual Inflation (%): C Max Power(MW) C3 = Pmax buy Energy Generation Charge (Transfer Charge) Price (£/kWh) Fixed Transfer price (£/kWh) Hourly Pri Self-consumption and Net Mettering: Cost of net mettering service (£/kWh) U Buy-back: Export E is paid at (£/kWh)	AC GRID AVAILABILITY         Priority to supply E not covered by renewables: <ul> <li>Storage/Generator</li> <li>AC Grid</li> <li>Sto /Gen. priority if Pr.buyE &gt;=</li> <li>Sell surplus H2 in tank (difference between the H2 in the tank at the end of the year and at the beginning)</li> <li>Price (£/kg) Annual Inflation (%):</li> <li>3</li> </ul>
Total tax for electricity costs (buy + charges) (%):	Total tax for electricity sold (%):	Losses in wire and transformer (%): 0

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( <sup>2</sup> )	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
10×1	27	0	1x0	0	15x2	0	0	10	1604.259	
9×1	27	0	1x0	0	15x2	0	0	10	1536,3000	1
8×1	27	0	1x0	0	15x2	0	0	10	1589.1389	
7x1	27	0	1x0	0	15x2	0	0	10	1580.7052	
6×1	27	0	1x0	0	15x2	0	0	10	1571.4611	
5×1	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	
10×1	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  $0,2172 \notin kWh$ , 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.



There is no load consumption



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):

$\widetilde{\mathbf{M}}$ Probabilistic analysis of variability of load, irradiation, wind speed and/or water flow (	(or fuel price inflation) – D ×
	@ PERFORM PROBABILITY ANALYSIS
Number of series to analyze each combination of components and control strategy:	Stopping rule in Monte Carlo Simulation                 © Confidence level (%)               99             ✓ max. error of the mean (%)               5                 th stopping rule               © Confidence level (%)               99             ✓ max. error of the mean (%)               5
Analyze variability of the average value of load	Analyze variability of the average value of irradiation
Analyze variability of the average value of wind speed WHYS SEFED AVERAGE VALUE Mean: 85 m/s Standard Deviation: 0.5 m/s Mean = 8.492, 2Min. = 7.84 m/s Hourty variability in the series: 0 % Std. deviation for temperature: 1 ±C Consider correlation between the variables	Analyze variability of the average value of water flow Analyze variability of the average value of fuel price inflation. Average (%):
In the simulation, show the case obtained with the following dat Load: Irradiation: Average Average In the case of the simulation, include hourly variability In the graphability analysis report, in the last two charts, show the Energy sold to AC grid (UE/yr) When clicking at any cell of the results table, do not update results When clicking on simulation button, do not consider the characteristic	ta: Vind speed Water flow Average V Average V e probability distribution of: Incomes of selling E to AC grid (currency) ccases Each year different mean value OK

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:

MAIN AL	.G. (COMB. CO	)MPONENTS):	EVAL. ALL 11904	<u>POP. (% ALL)</u> 81 (0.68%)	<u>GEN. ALG. (% ALL)</u> 1147 (9.64%)
SEC. AL	G. (COMB. ST	RATEGIES):	(1×11904) 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 %	<u>6h 35'</u>
OPTION 4:	GEN. ALG.	GEN. ALG.	47027	395.1 %	11 days 7h

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	^
	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, show the case obtained with the following data:					
Load:	Irradiation:	Wind speed	Water flow		
Average	<ul> <li>Average</li> </ul>	✓ Average		•	

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:



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):



It is observed that, in this case, the average case (mean wind speed, 8.5 m/s) has a NPV of 49.6  $M \in$ , 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 $\in$  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 $\in$ 

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:



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).



OTHER RESULTS OF THE PROBABILITY ANALYSIS: House ac, unning AC Generator mean 0 Mby Std. Dev: 0 Annual cost of the d AC Generator mean 0 Mby Std. Dev: 0 Hyds Turkine Energy: mean 0 GWhy, Std. Dev: 0 House of Batteries Charge media 0 hyl, Std. Dev: 0 House of Batteries Charge media 0 hyl, Std. Dev: 0 Restifier max. power mean 0 Wby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 Energy publices to AC grid: mean 0 Kby, Std. Dev: 0 House sunning Fuel Cell: mean 0 Kby, Std. Dev: 0 House sunning Fuel Cell: mean 0 Kby, Std. Dev: 0 External fuel publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 External fuel publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publicy, Std. Dev: 0 External fuel publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: Mean 0 Kby, Std. Dev: 0 Cot of divertimal publices to Bu used at Fuel Cell: mean 0 Kby, Std. Dev: 0 Variable cot of The Cell: (MPC) mean 72 Abz, bex. 0 Varia

2 of 4

RESULTS OF CHARACTERISTIC CASE & Combinations of: Irradiation, Wind speed, Water flow or Fusi inf. and Load (if seleobd); 5 Values per variable seleoted: mean, mean+8D, mean-8D, mean-8D, mean-3D.

DATA (vs. oharaoteristo cese#):





4 dt 4

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:

Fuente	G Párrato G Estilos
	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 OGWh/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
s []2 Inglés (Reino Unido)	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.
$\sim$									· · · · ·			~
M S	ensitivity A	naiysis	ī	1			1	1	1-	-		^
vvinc	6	olar	Load	Interest and In	flation (general or electric	city cost)	AC gen. fuel inflation	n	Components cost			
	SENSITI		NALYSIS	OF WIND SPE	ED							
	Wind1: (	Case bas	e: Average V	vind Speed: 8.4	49 m/s							
	Wind 2:	<ul> <li>Bas</li> <li>From</li> </ul>	e Case x Scale n file (hourly valu	Facor 1.2 ues in m/s)	Height (m) 10				Import	Av. Wind = 10	).19 m/s	
	Wind 3:	<ul> <li></li></ul>	e Case x Scale I I file (hourly valu	Factur 0.8 ues in m/s)	Height (m) 10				Import	Av. Wind = 6.	79 m/s	
		Add		Remove la	ast one				运 Graph			
							OK					

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.

🕅 Sensitivity Analysis	_		×
Wind Solar Load Interest and Inflation (general or electricity cost) AC gen. fuel inflation Components cost			
SENSITIVITY ANALYSIS OF ANNUAL INTEREST (I) AND INFLATION (g) RATES			
(I-g) 1: Case base: Interest: 7%; Inflation Electricity cost: (purchase and sell inflations shown in LOAD/AC GRID)			
Inflation refers to			
(I-g) 2: Interest: / % Initiation: / %	. a.c.	ר	
(I-g) 3: Interest: 7 z Inflation: 3 z	se inflation)		
Add Remove last one			
OK I			

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):

	Sensitivity Analysis # 1 $\sim$
1	Sensitivity Analysis # 1
	Sensitivity Analysis # 2
l	Sensitivity Analysis # 3
	Sensitivity Analysis # 4
	Sensitivity Analysis # 5
	Sensitivity Analysis # 6
	Sensitivity Analysis # 7
	Sensitivity Analysis # 8

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

			Sensitivity	Analysis i	12	~				ram.
Wind	1:8.5m/s × Rac	1.1: 5.45kWh/m2	V Load1: 0G	Wh/day	√ (l-g	E)2: 7%-1%	Inf.F	.1:Base	Pr.1: x1 x1 >	d x1
	Tetal NPV (M8)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report /
1	40.095	1.12	0	17.19	540	37.5	43.46	0.0299	SIMULATE	REPOR
2	39.277	1.12	0	16.86	540	38.125	43.46	0.0304	SIMULATE	REPOR
3	38.481	1.05	0	17.45	504	35	44.03	0.0295	SIMULATE	REPOR
4	38.458	1.12	0	16.54	540	38.75	43.46	0.0309	SIMULATE	REPOR
5	37.662	1.05	0	17.1	504	35.625	44.03	0.03	SIMULATE	REPOR
6	37.661	1.14	0	16.22	540.05	39.375	43.46	0.0314	SIMULATE	REPOR
7	37.164	1.14	0	15.99	540.05	40	43.51	0.0318	SIMULATE	REPOR
8	36.844	1.05	0	16.75	504	36.25	44.03	0.0305	SIMULATE	REPOR
9	36.821	1.12	0	15.93	540	40	43.46	0.0319	SIMULATE	REPOR
<										>
сомр	ONENTS: 15 Wind Turb.	WindT1/2 MW at 14 m	/s) // Unmet load	= 0 % // Tot	al Net Prese	nt Value (NPV) =	40.095 M€. II	R = 17.2%.		1
STRA' from re	TEGY: There is no load c newable, not from grid) if j	onsumption -> no cont price of E. (sell) is lowe	rol strategy related er than 0 €/KWh; dis	to the load sch. (load +	consumptio injecting to t	n supply. Control he grid) if price E.	variables fo (sell) higher	r grid-connected b ∵than 0.11 €/kWh	atteries: charge	(only

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:

Wind.1: 8.5m/s	•
Wind.1: 8.5m/s	
Wind.2: 10.2m/s	
Wind.3: 6.8m/s	

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

			Sensitivity /	Analysis i	5	~			Show diag	ram	
Win	d2:10.2m/s 🗸 Ra	V Load1: 0GV	Wh/day	(l-gl	E)2: 7%-1%	Inf.F	.1:Base	Pr.1: x1 x1 >	<1 x1		
#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(Mt)	Cap.F(%)	LCOE(€/kWh)	Simulate	Report	^
1	64.861	1.12	0	22.74	540	37.5	55.75	0.0233	SIMULATE	REPOR	t
2	64.233	1.05	0	23.61	504	35	57.68	0.0225	SIMULATE	REPOR	ŧ
3	64.043	1.12	0	22.35	540	38.125	55.75	0.0237	SIMULATE	REPOR	ŧ
4	63.415	i 1.05	0	23.17	504	35.625	57.68	0.0229	SIMULATE	REPOR	ŧ
5	63.224	1.12	0	21.96	540	38.75	55.75	0.0241	SIMULATE	REPOR	ŧ
6	62.694	0.98	0	24.37	468	32.5	59.39	0.0218	SIMULATE	REPOR	ŧ
7	62.596	i 1.05	0	22.75	504	36.25	57.68	0.0233	SIMULATE	REPOR	ŧ
8	62.427	1.14	0	21.57	540.05	39.375	55.75	0.0244	SIMULATE	REPOR	ŧ
9	62.097	1.14	0	21.31	540.05	40	55.82	0.0248	SIMULATE	REPOR	ŧ.
<										>	

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:

1	A	В	C	D	E	F	G	Н	1	J	K	L	M	N	0	Р	Q	R
1	Project: MH	OGA1-Sens.m	ho. Best system f	ound for each case	of the sense	sitivity analys	sis											
2	Sens.#		Wind (m/s)	Rad(	kWh/m2/d	)	Load(GWh/d)		Interest(%)		Inflation EE(P	urch/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	1	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: ENSIT. ANALYSIS # 1 (Wind1 8.5m/s; Load1 : 0GWh/day; (l+gE)1 7%-3/2%; Inf F 1.Base; P+1 : xt xt 1 xt); PV = 49.53 M€; CO 2 Emissions = 1.125 kt/y; Linnet load = 0 GWh/y; (0%), IRR = 18.52 %; Liand use = 540 ha apachy factor = 43.5%; Investment = 37.5 ME; LOCE = 0.3 G\*(WH; E. sold to AC grid (HPC) = 58 L26 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:): NPV = 40.095 MC CO2 Emissions = 1.125 kt/y. Unmet load = 0 GWh/yr (0%). IRR = 17.19 %. Land use = 540 ha Capacity factor = 43.5%. Investment = 37.5 ML CO2 = 0.03 %/Wh. E. sold to AC grid (NPC) = 88.629 ME. NSIT. ANALYSIS # 3 (Wind1:8.5m/s;Load1:0.GWh/day;(l-gE)3:7%-3%;lmf.F.1.Base;Pr.1:x1 x1 x1 x1): V = 60.504 M€.CO2 Emission s = 1.125 kt/yr. Ummet load = 0.GWh/yr (0%),lRR = 19.82 %. Land use = 540 ha pachyfactor = 4.35%. Investment = 37.5 M€.LOC = 0.03.8 (Wh.N. E. sold to Acg on (NPC) = 109.038 M€. SENSIT. ANALYSIS # 4 (Wind2: 10.2m/s; Load1: 0GWh/day; (I-gE)1: 7%-32%; Inf.F.1.Base; Pr.1: x1 x1 x1 x1): NPV = 77.013 MC. CO2 Emissions = 1.125 kt/yr. Unmet Ioad = 0 GWh/yr. (0%). IRR = 24.08 %. Land use = 540 ha Capacity factor = 55.7%. Imvestment = 37.5 ML COE = 0.023 eVk/Wh. E. sold to AC ord (NPC) = 125.546 MC. SENSIT. AVALYSIS # 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 MC: CO2 Emissions = 1.125 kt/y; Ummet Load = 0 GWh/y; (0%); IRR = 22.14 %; Land use = 64.0 Capacity factor = 65.7%. Investment = 37.5 MC: LCOE = 0.023 eVM/h. E. sold to AC gnd (INPC) = 113.395 MC.  $\begin{array}{l} \text{SENSIT. ANALYSIS \# 6 (Wind2: 10.2m/s; Load1: 0GWh/day, (IrgE)3: 7%-3%, Inf.F.1:Base, Pr.1: x1 x1 x1; x1); \\ \text{NPV} = 00.974 MC CO2 Emissions = 1.125 M/y; Unmet Ioad = 0 GWh/yr (0%), IRR = 25.4 %, IGM1 use = 540 h, Capacity factor = 57%, Intersteiner = 375 M/E.CDE = 0.023 e(WMK E: Sold to AC grid (NCC) = 135:07 M/E. \\ \end{array}$ SENSIT. ANALYSIS # 7 (Wind3: 6.8m/s; Load1: 0.GWh/day; (I+gE)1: 7%-3/2%, Inf.F.1:Base; Pr.1: x1 x1 x1 x1): NPV = 10.955 Mc CO2 Emissions = 1.125 ki/y; Ummet load = 0.GWh/yr (0%), IRR = 9.87 %, Land use = 540 ha. Capacity factor = 26.4%, Investment = 37.5 Mc LCOE = 0.049 eVM/h = Sold to ACg rid (INC) = 59.488 Mc.  $\begin{array}{l} {\sf SENSIT. ANALYSIS \# 8 (Wind3: 6.8 m/s; Load1: 0GWh/day; (i_gE)2: 7\%-1\%; Inf. F.1Base; Pr.1: x1 x1 x1 x1; NPV = 6.197 ME C026 minsions = 1.125 k1/y: Ummel toad = 0 GWh/yr (0%). IRR = 8.49 \% Land use = 540 hac Capacity factor = 26 4%. Investment = 37.5 ME COE = 0.045 eVM/N. E. sold to AC grid (NPC) = 5.73 ME. \\ \end{array}$ 

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): NFV = 49.593 MME. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 18.52 %. Investment = 37.5 MME. 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): NEV = 40.095 ME. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 17.19 %. Investment = 37.5 ME. 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 MME. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 19.82 %. Investment = 37.5 MME. 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: NFV = 77.013 ME. COZ Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%). IRR = 24.08 %. Investment = 37.5 ME. 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): NFV = 64.861 M€. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (%). IRF = 22.74 %. Investment = 37.5 M€. LCOE = 0.023 €/kWh. Capacity factor = 55.7%. Land use = 540 ha Components: Wind Turbines group AC of 0.0 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 MG. CO2 Emissions = 1.125 kt/yr. Unmet load = 0 GWh/yr (0%) TBE = 25.4 % Threatment = 37.5 ME LCOP = 0.023 E/kWh. Canacity

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"

Simulation and optimization:	
Simulation of the 1st year and extrapolate results	
O Multiperiod: simulate all the years of the system lifetime ( 25 years)	
Economic optimization:	F
Minimize Net Present Cost (NPC), usually for off-grid systems and high load on-grid ——>	Min. NPC
	Min. LCOH
O Maximize Net Present Value (NPV), usually for low load or no-load on-grid systems	Max. NPV
Define Wind Farm with 16 power curves, one for each wind direction sector	Min. LCOH
DC renewable include own charger and controller	Max. Cap.F. min. LCOI
When saving the project update all the results of the table to the present conditions	
Number of decimal places in results of costs $\qquad$ 3 $\qquad$ $\sim$	
Number of decimal places in results of energy $3$ $\sim$	

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.

₩ CONSTRAINTS	-		$\times$
If a combination of components and strategy does not meet any of the following restrictions, this solution will be discarded (for that c assigned infinite cost):	ombination	n itis	
Maximum Unmet Load allowed: 1 % of annual load			
(Max. energy not supplied by the stand-alone system nor by the AC grid)			
Minimum number of days of autonomy (betteries+hydrogen) 3 days (∠) if there is AC generator or fuel cell using external fuel or purchasing unmet load from AC grid is allowed, number of days of auto	nomy= in	ıfinitum)	
( if there is AC generator or fuel cell using external fuel or purchasing unmet load from AC grid is allowed, do not take into account Minimum renewable fraction:	it this cons	straint)	
Maximum Levelized Cost of Energy: 100 0/kWh			
Maximum annual capacity shortage:       100       %;       Data -> AC bus:       Load operating reserve (%):       0       Peak load operating reserve (%):       0       Wind power oper.         PV power oper.       reserve (%):       0       Wind power oper.       Wind power oper.	eserve (% aserve (%	6): 0 ): 0	]
DC bus: Load operating reserve (%): Peak load operating r	eserve (%	s): 0	
PV power oper, reserve (%): 0 Wind power oper, n	eserve (%	): 0	]
Maximum Land Use: 1000000 ha; Data -> PV Land Use (ha/MW): 3 Wind Land Use (ha/MW): 18 Batt. Land	Jse (ha/G	Wh): 10	
OK			

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):

Load profile:	Residential 100MWh/day 🗨
Variability	Zero Residential 100MWh/day TOWN 100MWh/day

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

-Data source:			chaoling L	nergy nen	i the AC <u>c</u>	jnu									-	
										۲	Hours	AC DO	H2	Water		
O Monthly Av	rerage 🖲	) Load Profi	le Olmp	ort File (MV	/, tH2/h, də	m3/h)				- 8	1 ~ Min Min	utes-each utes-1 per	hour in 1 ro row	Im Im	port	Export
C LOAD (MW)	DC		V) H:	2 LOAD (t	H2/h)	WATER	(dam3/da	y) FROM	WATER T		URCHAS	E / SELL	E			
Month	0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16t 🔿
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
c in the second s																>
oad profile: Res	idential 10	00MWh/day	Scale fact	or for Mond	ay to Frida	y: 1		Scale fac	tor for the w	eekend:	1					>
<	idential 10	00MWh/day	Scale facto	or for Mond	ay to Frida	y: 1	AVER	Scale fac	tor for the w	eekend: ARY (incl	1 uded scale	factor), T	OTAL 120.	.15 MWh/d	ay	>
<ul> <li>_oad profile: Res</li> <li>/ariability</li> </ul>	idential 10	00MWh/day dd load prof	Scale facto	or for Mond	ay to Frida	y: 1	AVER	Scale fac AGE LOAI	tor for the w	eekend: ARY (incl Cload 🗹	1 uded scale H2 (HH)	factor), T ⁄) ☑ ■ V	O <b>TAL 120</b> . Vater (E pu	.15 MWh/d mped)	ay	>
<ul> <li>Load profile: Res</li> <li>/ariability</li> <li>Daily Variability</li> </ul>	idential 10 Ac AC 0	00MWh/day dd Ioad prof % 0	Scale fact	or for Mond	ay to Frida	y: 1	AVER	Scale fac AGE LOAI AC Ioa	tor for the w	eekend: ARY (incl Cload I	1 uded scale H2 (HH)	factor), T ∕) ☑ ■ V	OTAL 120. Vater (E pu	.15 MWh/d mped)	ay	>
< Load profile: Res /ariability Daily Variability Hourly Variability	idential 10 Ac 0 0	00MWh/day dd load prof % 0 % 0	Scale fact ile % 0 % 0	or for Mond ~ 	ay to Frida	y: 1	AVER	Scale fac AGE LOAI	tor for the w	eekend: ARY (incl Cload IZ	1 uded scale H2 (HH)	factor), T /) ☑ ■ V	OTAL 120. Vater (E pu	<b>15 MWh/d</b> mped)	ay	>
<ul> <li>Load profile: Res</li> <li>/ariability</li> <li>Daily Variability</li> <li>Hourly Variability</li> <li>Minutes Variability</li> </ul>	AC AC 0 0 90	00MWh/day dd Ioad prof DC % 0 % 0 % 90	Scale fact ile   % 0 % 0 % 90	or for Mond	ay to Frida	y: 1	AVER	Scale fac AGE LOAI	tor for the w	eekend: ARY (incl Cload I	1 uded scale H2 (HH)	factor), T /) ☑ ■ V	OTAL 120. Vater (E pu	15 MWh/d mped)	ay	>
<ul> <li>Load profile: Res /ariability</li> <li>Daily Variability</li> <li>Hourly Variability</li> <li>Minutes Variability</li> <li>Correlation minute</li> </ul>	idential 10 AC 0 9 90 es 0.9	00MWh/day dd load prof % 0 % 0 % 90	Scale facto	or for Mond 	ay to Frida	y: 1	AVER	Scale fac AGE LOAI	tor for the w	eekend: ARY (incl C load V	1 uded scale H2 (HH)	factor), T ⁄) 🗹 🖿 V	OTAL 120. Vater (E pu	.15 MWh/d mped)	ay	>
Load profile: Res     Variability     Daily Variability     Minutes Variability     Correlation minute	AC 0 9 90 90 90 90	00MWh/day dd Ioad prof % 0 % 0 % 0	Scale factor	or for Mond	ay to Frida	y. 1	AVER	Scale fac	tor for the w D IN JANU d R D D	eekend: ARY (incl C load 🗹	1 uded scale	factor), T /) ☑ ■ V	OTAL 120. Vater (E pu	15 MWh/d mped)	ay	>
<ul> <li>Load profile: Res</li> <li>Variability</li> <li>Daily Variability</li> <li>Hourly Variability</li> <li>Minutes Variability</li> <li>Correlation minute</li> <li>Generate</li> </ul>	AC 0 9 9 90 AC 10 9 90 AC 10	00MWh/day dd Ioad prot % 0 % 0 % 90	Scale fact ile % 0 % 0 % 90 % 90	or for Mond	ay to Frida	y: 1 8- 6- 4- 2-	AVER	Scale fac	tor for the w	eekend: ARY (incl C load 🗹	1 uded scale	factor), T /) ☑ ■ V	OTAL 120. Vater (E pu	.15 MWh/d	ay	>
<ul> <li>Load profile: Res</li> <li>Variability</li> <li>Daily Variability</li> <li>Hourly Variability</li> <li>Minutes Variability</li> <li>Correlation minute</li> <li>Generate</li> </ul>	AC 0 90 90 AC 0 90 AC 0 90 AC 10	30MWh/day dd load prof % 0 % 0 % 90	Scale fact ile % 0 % 0 % 90 % 90	or for Mond	ay to Frida	y 1	AVER	Scale fac	tor for the w	eekend: ARY (incl C load 🔽	1 uded scale H2 (HH)	factor), T /) ☑ ■ V	OTAL 120. Vater (E pu	15 MWh/d mped)	ay	>
< Load profile: Res Variability Daily Variability Hourly Variability Minutes Variability Correlation minute Generate Add load of	idential 10 AC 0 y 90 es 0.9 AC lo	00MWh/day dd load prot % 0 % 0 % 0 % 90 mad power fe	Scale fact	or for Mond	ay to Frida	8- 6- 4- 2- 0- 0	AVER	Scale fac	tor for the w D IN JANU d P D D	eekend: ARY (incl C load I	1 uded scale H2 (HH) H2 (HH) 12 hour	factor), T	OTAL 120. Vater (E pu	15 MWh/d mped)	ay	>
< Load profile: Res Variability Daity Variability Hourty Variability Minutes Variability Correlation minute Generate Add load of m: min 0 hour	idential 10 Ac 0 90 90 AC 10 AC 10 0 0 0 dey	00MWh/day dd load prof % 0 % 0 % 90 } wad power fe MW AC	Scale fact	or for Mond	ay to Frida	y. 1 8- 6- 2- 0- 0 0 ax hourly a	AVER	Scale fac AGE LOAI AC Ioa AC Ioa r Ioad in th Active 4.2 h	tor for the w D IN JANU d V D D 6 e year (inc. IW: Aparen	eekend: ARY (incl C load V AC pumpi at 4.2 MVA	1 ■ H2 (HH\ 12 hour ng): 8.7 MW	factor), T () ♥ ♥ V : Mex. in 1/2	OTAL 120. Vater (E pu	15 MWh/d mped) 18 :: 9.6 MW	ay	>
< Load profile: Res variability Daily Variability Hourly Variability Minutes Variability Correlation minute Generate Add load of m: min 0 hour OK	idential 10 AC 0 90 es 0.9 AC to 0 0 dey 0 0 dey	00MWh/day dd Ioad prof % 0 % 0 % 90 % 90 mad power fe MW AC 1 month	Scale factor	or for Mond	ay to Frida	y 1 8- 6- 2- 0- 0 0 ax hourly a xge hourly A	AVER	Scale fac AGE LOAI AC Ioa AC Ioa r Ioad in th Active 4.2 N in the year	tor for the w D IN JANU d V D D 6 6 e year (inc. 7W; Aparen 9 MW; DC	ARY (incl C load I AC pumpi at 4.2 MVA power hou	1 uded scale H2 (HH) 12 hour ng): 8.7 MW	factor), Tr () ♥ ● V ()   ♥ = V	OTAL 120. Vater (E pu	15 MWh/d mped) 18	ay	>

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.

Data source: O Monthly Average  Load Profile  Import File (MW, tH2/h, c	dam3/h)	AC DC H2 Water Ites- each hour in 1 row Ites- 1 per row Import
CLOAD (MW) DC LOAD (MW) H2 LOAD (tH2/h)	WATER (dam3/day) FROM WATER TANK PURCHASE	E/ SELL E
Purchase from AC grid Unmet Load (Non Served Energy by Stand-alone system)         Fixed Buy Price (¢/kWh)       0.15         Hourly Price         Annual Inflation (%):       Emission (kgC02/kWh):         3       0.4         Fixed Pmax (MWY)       Fixed Cost P (¢/kWh)         30       Options         0       Hourly Values         Access Cha be Price (¢/kWh)       Hourly Values         Back-up Charge Price (¢/kWh)       Hourly Price         Will be added to the E purchased)       Add negative gen. charge	✓ Sell Excess Energy to AC grid         ✓ Fixed Sell Price (€/kWh)       0.12         Pr. sell = pr. buyx       1         Annual Inflation (%):       3         Max. Power(MW)       30       Image: Price Price Price (€/kWh)         ✓ Fixed Transfer price (€/kWh)       0       Hourly Price         Self-consumption and Net Mettering:       ✓ Sell only         No net mettering       ✓         Cost of net metering service (€/kWh)       0         Buy-back: Export E is paid at (€/kWh)       0	AC GRID AVAILABILITY         Priority to supply E not covered by renewables: <ul> <li>Storage/Generator</li> <li>AC Grid</li> <li>Sto /Gen. priority if Pr.buyE &gt;=</li> <li>Sell surplus H2 in tank (difference between the H2 in the tank at the end of the year and at the beginning)</li> <li>Price (6/kg)</li> <li>Annual Inflation (%):</li> <li>3</li> </ul> Data to compare with electrical supply only from AC conventional grid:           Total cost installation of AC grid;             08/M ennual cost of grid;         0.3

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  $0.15 \notin kWh$ , P2 price  $0.12 \notin kWh$ , P3 price  $0.08 \notin kWh$ , distributed in summer/winter):

HOURLY PRICE OF TH	HE ELECTRICITY	PURCHAS	ED FROM	THE AC G	RID				
Hourly Price Data (€/k	Wh) same								
C From file (8760 hou	urly values) [mpo	rt hourly Pric	e					D	raw
Hourly Periods									
Hourly Periods:	Number of Hourly I	Periods: 3	•	SummerA	Vinter (	∑ Mon-Fri∆	Weekend	C. Hourly (	from file)
Summer calendar:		Per	riod P1 Pric	e 015					
From day 30	month 3	Per	riod P2 Pric	e: 0.12					
Today 26	month 10	Per	riod P3 Pric	e: 0.08					
SUMMER periods dist	ribution:			,					
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 •	P2 •	P2 •	P2 •	P2 •	P2 •
WINTER periods distrit	bution: 2.3h 3.4h	4.5h	5.6h	6.7h	7.9h	9.9h	9.106	10.116	11.126
	P3 - P3 -	P3 ▼	P3 -	P3 -	P3 V	P2 ▼	P2 -	P2 -	P2 -
12-13h 13-14h 1	14-15h 15-16h	16-17h	17-18h	18-19h	19-20h	20-21h	21-22h	22-23h	23-24h
P2 - P2 - F	P2 🗸 P3 🗸	P3 👻	P3 👻	P1 🔻	P1 🔻	P1 👻	P1 👻	P2 👻	P2 💌
			0	К					

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

Fixed P	max (MW)	Fixed Cost	P (€/kW/yr)	
30	Options	40	Hourly Values	

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):

Hourly peri	iods same of	energy hourly price periods
	Pmax (MW)	Cost of Power (€/kW/yr)
Period P1	6	40
Period P2	8	20
Period P3	9	15
Period P4	0	0
Period P5	0	0
Period P6	0	0
		ОК

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 optimization, only valid for period P1), or the third option, which will be the one selected "**Not limited: Registered the maximum value** (average of...."

Options for the maximum peak power from the Grid:
Value of Pmax:
C Limited to value shown in Pmax
C Limited to a value optimized between 0 and Pmax. Number of values to consider: 5
Not limited: Registered the maximum value (average of 15
ŌK

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):

COST OF THE CONTRACTED POWER:
- If max. power registered is lower than A= 85 % of Pmax -> apply 85 % of cost of Pmax
- If max. power registered is higher than A and lower than B= 105 % of Pmax -> apply 100 % of cost of Pmax
- If max, power registered is higher than B -> apply 100% of cost of Pmax + 2 times diff. betwen registered and B
Pmax is the contracted power
Power registered is the maximum power registered by the maximeter
OK

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.

GENERAL DATA OPTIMIZATION CO
COMPONENTS
✓ Wind Turbines
🗖 Hydro T.
✓ Battery bank
🗖 Backup Gen.
✓ Inverter/cha
H2 (F.C Elyzer.)

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

Then download hourly irradiation and temperature from PVGIS year 2007.

<b>X</b> SOLAR RESOURCE		
Latitude (*) (+N, -S) : 42.57	Get data from local DB	Dural of the FMGIS Year 2007
Longitude (*) (+E, -W) : -0.31	Download hourly data	C Renewable Ninja (year 2019)
Locate on map Update coord.	Download NASA monthly data	C NASA - Year 2015 -
Data source		✓ Hourly Irradiation
O Monthly Average    Import from	File FROM RENEWABLE NINJA	I Hourly Temperature for: I PV I Wind T. ☐ Batt.
Generation (equivalen	of PV gen. (MW) normalized to 1 MW t to irradiance kW/m2 x PR)	P 🥅 Hourly Wind Speed
Data Source for Monthly Average D	aily Irradiation: Radiation Horizontal St	= /n
Irradiati av. tilt s	PV Tracking System: No	, OK Cancel

# 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).

WIND RESOURCE		
Latitude (º) (+N, -S) : 42.5	Get data from local DB	
Longitude (º) (+E, -W) : [-0.31	Download hourly data	Anemometer Height
Locate on map fro NASA	Download NASA data	

#### WIND RESOURCE

Latitude (*) (+N, -S) : 42.57 Longitude (*) (+E, -W) : -0.31	Get data from local DB Download hourly data	Download from: C PVGIS - Year C Renewable Ninja (year 2019)
Locate on map Update coord.	Download NASA Monthly data	○ NASA - Year 2015 -
Data source O Monthly Average O Impo	rt data file (in m/s) FROM RENEW, eration of wind turb. (MW) normalized	Hourly Irradiation     Hourly Temperature for:      PV     V     Wind T.     Batt.     Hourly Wind Speed
		OK Cancel

#### We obtain:

WIND RESOURCE	- 🗆 X
Latitude (*) (+N, -S):     42.57     Get data from local DB       Longitude (*) (+E, -V*):     0.31     Download hourly data       Locate on map     Update coord     Download NASA Monthly data	4
Data source OMonthly Average Generation of wind turb. (MW) normalized to 1 MW rated p.  Av. sp. (m/s) Jan. 7.78	Jurs Class 1 × Length 0.03 m Agricultural open area without fences Minutes- 1 per row Import Minutes- 1 per row
Odal, 710           Feb: 579           Mar, 6.16           Apr: 5.94           May, 6.30           Jun: 5.71           Jul: 4.98           Aug. 47.4           Sep: 5.25           Oct: 5.68           Nov 6.58           Nov 6.58           Dec: 6.46           Correlation factor:           0.82           Calculation of wind speed for each minute: std. dev.           My           Update min.	02         0           010         0           010         0           010         0           011         0           012         0
Calculate     Scale by (x by):     Scale Average Speed (m/s)     OK	0 5 10 15 20 25 30 Wind speed (m/s) Into time of calm wind Calm is considered Form factor of the wind speed serial: 2.8 Into time of calm wind Calm is considered < 3 m/s

In PV GEN. accept the default PV data:

	-										
Add PV Gen.	Zero	~									
Add PV Gen. family		~		•		+ -	🗸 🛛 🗙 🛛				
PHOTOVOLTAIC GEN	ERATOR DATA:										
me	Power(MWp_c	c) Cost(M€)	C.08	3M(%/yr)	Life(years)	NOCT(°C)	Power T. coef.(	%/*C) BIFACL	ALITY(0-1) CPV	Emissions(#	gCO2/kWp
/10	10	10		1	25	43	-0.4		0 NO	8	00
											>
iciency due to decredation	of the modules losses in v	ires dirtin ne	nale loca	ae in wirae	transforma	etc 0.95				Fixed O	) peration and
ciency due to degradation	of the modules, losses in v	ires, dirt in pai	nels, loss	es in wire:	s, transformer	, etc. 0.95				Fixed O Mainter	> peration and ance Cost
iciency due to degradation Standard conditions	of the modules, losses in v	ires, dirt in pai	nels, loss	es in wires	s, transformer	, etc. 0.95				Fixed O Mainter 0	> peration and ance Cost €/yr
iciency due to degradation Standard conditions Consider effect of Date of ambient term Monthly everage © From file (8760 ho	of the modules, losses in v <u>"emparature</u> perdure (°C) C fichs model urdy values)	J 4 F	nels, loss	es in wires	s, transformer M 16	, etc. 0.95	A 23 S 19	014 N 9	D 5	Fixed O Mainter 0 Wind for CPV	) peration an ance Cost 6/yr
iciency due to degradation Standard conditions	of the modules, losses in v <u>remperature</u> perature (tC) <u>C Erbs model</u> urly values) to AC bus (it has its own in	ires, dirt in per J 4 F Impo verter) →	nels, loss	ies in wires	s, transformer M 16 315 year 2007	; etc. 0.95	A 23 S 19 PV inverter da	0 14 N 9	D[5]	Fixed O Meinter	> peration ance cost €/yr
iciency due to degradation Standard conditions Consider effect of Data of ambient tem Monthy average	of the modules, losses in v <u>remperature</u> (PC) C Erbs model urly values) H to AC bus (It has its own in n Rate for PV st:	ires, dirt in per J 4 F Impo verter) -> %	5 M S	A 11 FROM PV	s, transformer M 16 315 year 2007 Max, Va reductio	; etc. 0.95	A 23 S 19 PV inverter da	0 14 N 9 ta ta ta ta ta ta ta ta ta ta	D5 •	Fixed O Mainter 0 Wind for CPV	> peration ance Cost c/yr

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).

Global strategy: Coad Followi Cycle Chargi	ng ng 🔽 Continue up ta	o SOC stp	Batt. churged by the AC grid // discharged if: (also for Elyzer> H2) Elyzer. full load
⊖ Try Both Variables to opti	mize relative to the	global strategy:	Optimize strategy of grid-conneted batteries:
Pmin_gen	Pmin_FC	H2TANKstp	
	SOCstp_FC	SOCmin	Batteries can inject electricity to the AC grid     1 day at low SOC-> charge battery with AC grid     Batteries availability

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

MIN. AND MAX. No COM	PONENT	'S IN PA	ARALLEL:
Bateries in parallel: Min.	1	Max.	143
PV gen. in parallel: Min.	0	Max.	6
Wind T. in parallel: Min.	1	Max.	18
AC Gen. in parallel: Min.	1	Max.	1

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.

#### -MIN. AND MAX. No COMPONENTS IN PARALLEL:-

Bateries in parallel: Min.	1	Max.	5
PV gen. in parallel: Min.	0	Max.	6
Wind T. in parallel: Min.	1	Max.	18

#### 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)

	А	В	С	D	E	F	G	н	1	J	
43	RESULTS OF T	HE POWER RE	GISTERED AND	THE POWER	COSTS:						
44											
45	*RESULTS OF	THE MAXIMU	M POWER (MV	V) FROM THE G	GRID REGISTER	ED, 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 contr	act power is, f	for the differe	nt peridos: 6 M	NW; 8 MW; 9 N	ww;					
60	*RESULTS OF	THE VALUE OF	THE POWER (	MW) TO CALC	ULATE THE CO	ST OF THE POV	VER IN THE BI	LL, AND COST	FS (M€), 1st YE	AR:	
61	MONTH	Period P1(M)	Cost 1st yr.(N	Period P2(MV	Cost 1st yr.(N	Period P3(MV	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, 1	st year: 0.56 N	l€							
75	*If not consid	lering that cor	ntract power o	f period P1 <=	power of P2 <	<= power of P3					
76	Optimal cont	ract power wo	ould be: 6 MW	; 6.74 MW; 4.2	2 MW; With a	total cost of th	ne power, 1st	year: 0.507 N	1€		
77	*If considerin	ng that contrac	ct power of pe	riod P1 <= pov	ver of P2 <= po	ower of P3					
78	Optimal cont	ract power wo	ould be: 6 MW	; 6 MW; 6 MW	; With a total o	cost of the pov	ver, 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<sup>3</sup>/day. Water comes from a tank or reservoir of 100 dam<sup>3</sup>, 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<sup>3</sup>). The pump power is 1 MW and its efficiency is variable.

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

Ň	Load and	d option	s of Selling / Purch	nasing Energy	from the AG	C grid						-		×
	Data sou	urce: thly Avera	age 💿 Load Profile	Import Fil	∋ (MW, tH2/h,	dam3/h)			8	Hours AC DC H2 Minutes- each hour in 1 ro Minutes-1 per row	Wate	r mport	Export	
A	C LOAD (	(MW)	DC LOAD (MW	) H2 LO	AD (tH2/h)	WATER	(dam3/day) Fl	ROM WATER TAN	К РІ	URCHASE / SELL E				
	DAILY WA	ATER CC	INSUMPTION (dam	<u>3/day):</u>			HOURLYW	ATER CONSUMPT	ON (IN \$	% OF DAILY CONSUMPTION):				
1	January	30	(0.0048 GWh/day)	July	30 (0.0	0048 GWh/da	) Oh 1h	2h 3h 4h	5 h	6h 7h 8h 9h 10h	11 h	DECLI		
L	February	<b>y</b> 30	(0.0048 GWh/day)	August	30 (0.0	0048 GWh/da	/) 2 2	2 2 2	2	10 5 5 3 3	4	DEFINE	~	
L	March	30	(0.0048 GWh/day)	September	30 (0.0	048 GWh/da	/) <mark>12h 13h</mark> 5 8	14h 15h 16h 8 5 3	17 h	18h 19h 20h 21h 22h 2 5 7 7 4	23 h	Total =		
L	April	30	(0.0048 GWh/day)	October	30 (0.0	0048 GWh/da	n <u></u>					100%		
L	Мау	30	(0.0048 GWh/day)	November	30 (0.0	0048 GWh/da	0	10 1	R CONS	SUMPTION (% OF THE DAY)				
	June	30	(0.0048 GWh/day)	December	30 (0.0	0048 GWh/da	N .	5-						
	Scale fac	ctor for Mo	onday - Friday: 1	For the W	eekend: 1			0	<b>3 1 1 1 1 1</b> 6	18	Variab	ility minutes	(%): 90	
	WATERT	TANK:								hour				
	Water tanl	k capcac at the her	hity: 100 dan	13 3m 50	Smok	EL	ECTRICAL PU							
		<u>à DATA:</u>	gining of the simulation		ami	Pu	mp electrical ra	ted pow <mark>r</mark> r. 1	MW	Pump minimum power: 0	%	of rated		
	Elevation	head + s	uction lift 48	m	Extra num	(re	commended 0.	8 MW for 6h/day)	_	Priority to pump if surplu	s E > 0	% P.	pump	
	Friction Lo	osses 1	0 %		Extra puri	P To	tal pump efficie	ncy: 90 🛛 🕺 🖸	∠ Var.	Pump eff.				
L	oad profile	Reside	ential 100MWh/day		$\sim$		AVERAGE	LOAD IN JANUAR	Y (inclu	ided scale factor). TOTAL 124	.94 MWh	/dav		1
	lariabilit i		Add load profile	∋				AC load 💌 🔲 DC lo	ad 🗹 📕	H2 (HHV) 🗵 🔳 Water (E pu	mped)	]		
v			AC DC	H2		1.1					1 1	. <b></b>		
	Daily Varia	ability		% <sup>0</sup>	%	8-					_			
	Hourly Vari	ability	90 . 90	% 0 	%	> 6-								
	Minutes Va Camalatian	ariability	0.9	%	%	¥ 4-								
	Conelation	minutes	0.0			2-								
	Gene	erate	AC load power fac	tor (cos fi): 1										
	Add lood	l of		during 5	min	0		6		12 bour	18			
	Auuillau	101		Juning J	luun					nout				

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.

0%	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
0	12	25	35	42	52	58	65	68	72	9þ
							J L			
If reversible pump/turbine, max. flow rate of the turbine.										

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  $1.738 \text{ m}^3/\text{s}$ .

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:

AC LOAD (	MW)	DC LOAD (MW)	H2 LOA	D (tH2/	h)	WATER (da	ar
DAILY WA		INSUMPTION (dam3)	/day):				F
January	30	(0.0048 GWh/day)	July	30	(0.004	18 GWh/day)	-
February	30	(0.0048 GWh/day)	August	30	(0.004	18 GWh/day)	L
March	30	(0.0048 GWh/day)	September	30	(0.004	18 GWh/day)	Г
April	30	(0.0048 GWh/day)	October	30	(0.004	18 GWh/day)	L
May	30	(0.0048 GWh/day)	November	30	(0.004	18 GWh/day)	
June	30	(0.0048 GWh/day)	December	30	(0.004	l8 GWh/day)	

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

ELECTRICAL PUMP:	
Pump electrical rated power: 1	MW.
(recommended 0.8 MW for 6h/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):

Pump minimum power:0	% of ra	ted
Priority to pump if surplus E	• 0	% P. pump

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.

HOURLY W	TER CONSUMPTION (IN % OF DAILY CONSUMPTION);
10h 1h	2h 3h 4h 5h 6h 7h 8h 9h 10h 11h
121 121	
5 8	8 5 3 2 2 5 7 7 4 2 100%
	HOURLY WATER CONSUMPTION (% OF THE DAY)
I	
	0 6 12 18 Variability minutes (%):  90

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<sup>3</sup>/day are converted to dam<sup>3</sup>/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 1<sup>st</sup> 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<sup>3</sup>), 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·density·g·height·(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:

MIN. AND MAX. No COM	PONENT	'S IN P	ARALLEL:
Bateries in parallel: Min.	1	] Max.	146
PV gen. in parallel: Min.	0	Max.	6
Wind T. in parallel: Min.	1	Max.	18
AC Gen. in parallel: Min.	1	Max.	1

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:

-MIN. AND MAX. No COM	PONENT	'S IN P	ARALLEL:
Bateries in parallel: Min.	1	Max.	5
PV gen. in parallel: Min.	0	Max.	6
Wind T. in parallel: Min.	1	Max.	18
AC Gen. in parallel: Min.	1	Max.	1

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	C
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	٢.,
<										:	>
COMP Bat. In STRA	ONENTS: PV gen: PV10 /erter Inv-Ch5MW of 5 MV TEGY: LOAD FOLLOWIN	(10 MWp_dc)x 2 (100% A // Unmet load = 0 % G. SOC min.: 10 %.	6 PV#1: slope 35º, i // Total Cost (NPC	azimuth 0º) ) = 44.625 N	// Batte 4€ (0.08	ries Bat5MWh (5 kAh €/KWh)	i): 1s. x	1p. // 11 Wind Turł	o. WindT1 (2 M\	// at 15 m/s) //	^
											$\sim$

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 (1<sup>st</sup> 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.density.g.height.(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









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.

Simulation step (min.): 1 V		🔚 Back	Save data: All ~	h Save Simulation Data	Save Prob. Data						
COMPONENTS: PV generator of 20 MWp (100% PV#1: slope 35 <sup>®</sup> , azimuth 0 <sup>®</sup> ). Wind turbines of 22 MW. Battery bank of 5 MWh. Inverter of 5 MVA.											
STRATEGY: LOAD FOLLOWING. SOC min	.: 10 %. P max. grid: 9.175 MW.										

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 1<sup>st</sup>):



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:

Ger	Total Cost (NPC)(M€)	Emission (ktCO2A/r)	Unmet(GWh/vr)	Unmet(%)	D.aut	Cn(Wh)/(Ppv+Pw)(M	Ren(%	LCOE(€/kWh)	Simulate	Report	( ^
						and the bar of the					
	1 45 333	417	0	0	INE	0.1	82.57	0.0834	SIMLII ATE	REPORT	1
	10.000			•	10.80	0.1	02.07	0.0004	SINOLATE		`

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

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.





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)(V	Ren(?	LCOE(€/kWh)	Simulate	Report	( ^
1	45.931	4.3	0	0	INF	0.1	81.65	0.0845	SIMULATE	REPORT	(

Save the project.

# 39. Consider bifacial PV modules.

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 $\in$  (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(I) = 0.33:

Factor F(I) for the back albedo		4
(bifacial modules) (Durusoy 2020):	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</u> <u>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.

Daily Average Irradiation (Horiz. Surf.):	4.42 kWh/m2	Daily Average Irradiation (Tilt Surf.):	5.23 kWh/m2
Total Annual Irradiation (Horiz. Surf.):	1614.44 kWh/m2	Total Annual Irradiation (Tilt Surf.):	1909.58 kWh/m2
		Annual Irr. Back surface / Direct for CPV:	192.82 kWh/m2 / 1562.87 kWh/m2

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

✗ SOLAR RESOURCE			
Latitude (º) (+N, -S) : 42.57	Get data from local DB	Deumland france	2007 -
Longitude (º) (+E, -W) : -0.31	Download hourly data	Download from: (	Renewable Ninja (year 2019)
Locate on map Update coord.	Download NASA monthly data		NASA - Year 2020 V
Data source		Hourly Irradiation	
O Monthly Average Import from	n File FROM PVGIS year 2015	Hourly Temperatu	re for: 🗹 PV 🛛 Wind T. 🗌 Batt.
Generation (equivalen	of PV gen. (MW) normalized to 1 MWp t to irradiance kW/m2 x PR)	Hourly Wind Spee	d
Data Source for Monthly Average Da	ally Irradiation: Radiation Horizontal Surfa		
Irradiatio av tilt s	n PV Tracking System: No T	ОК	Cancel

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

Daily Average Irradiation (Tilt Surf.): 5.11 kWh/m2 Total Annual Irradiation (Tilt Surf.): 1866.34 kWh/m2 Annual Irr. Back surface / Direct for CPV: 192.82 kWh/m2 / 1207.04 kWh/m2

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 DA	TA:								
Name	Power(MWp)	Cost(M€)	C.O&M(%/yr)	Life(years)	NOCT( <sup>2</sup> C)	Power T. coef.(%/ºC)	BIFACIALITY(0-1)	CPV	missions(kgCO2/kW; 🔨
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	C.,			
<											×			
COMP Bat. In STRA	COMPONENTS: PV gen: PV10 (10 MWp_dc)x2 (100% PV#1: slope 35 <sup>e</sup> , azimuth 0 <sup>e</sup> ) // 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 MC (0.08 C/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:



# 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	1
---------------------	-----------	---

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 35°).

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 GENERAT	OR 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)(V	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	ر )			
<											>			
COMP Invene STRA	COMPONENTS: PV gen: PV10-T2axes (10 MWp_dc)x1 (Track. Both axis) Batteries Bat5MWh (5 kAh): 1s. x1p. // 13 Wind Turb. WindT1 (2 MW at 15 m/s) // Bat.     Morener Inv-Ch5MW of 5 MVA // Onmetroad = 0 % // Total Cost (NPC) = 44.831 ME (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.

Γ	Name	Power(MWp dc)	Cost(M€)	C.O&M(%/yr)	Life(years)	NOCT(*C)	Power T. coef.(%/ºC)	BIFACIALITY(0-1) CPV	Emissions(kgCO2/kWp 🔨
Ľ	PV10-T2axes	10	13	1	25	43	-0.4	0 NO	800
1	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)(V	Ren(%	LCOE(€/kWh)	Simulate	Report	( ^
1	40.412	4.66	0	0	INF	0.1	79.25	0.0743	SIMULATE	REPORT	C
2	40.494	4.55	0	0	INF	0.1	80.48	0.0745	SIMULATE	REPORT	C
3	40.616	4.8	0	0	INF	0.1	77.88	0.0747	SIMULATE	REPORT	C
4	40.746	4.46	0	0	INF	0.1	81.55	0.0749	SIMULATE	REPORT	C
5	40.95	4.97	0	0	INF	0.1	76.25	0.0753	SIMULATE	REPORT	C
6	41.11	4.39	0	0	INF	0.1	82.48	0.0756	SIMULATE	REPORT	C
7	41.307	4.66	0	0	INF	0.1	79.29	0.076	SIMULATE	REPORT	C
8	41.307	4.55	0	0	INF	0.1	80.51	0.076	SIMULATE	REPORT	C
9	41.425	4.79	0	0	INF	0.1	77.92	0.0762	SIMULATE	REPORT	C
<											>
20MP 1V-Ch STRA	ONENTS: PV gen: CPV1( 5MW of 5 MVA // Unmet 1 TEGY: LOAD FOLLOWIN	0-m (10 MWp_dc)x 2 (1 bad = 0 % // Total Cost G. SOC min.: 10 %.	Track. Both axis) // ( (NPC) = 40.412 M€	atteries Bi (0.07 €/kW	at5MW 'h)	h (5 kAh): 1s. x 1p. // `	L1 Wind	d Turb. WindT1 (2	MW at 15 m/s) /	/ Bat. Inverter	1

#### 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 predefined 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:

GENERAL DATA OPTIMIZATI	ON CONTRO
COMPONENTS	
PV Gen.	
Wind Turbines	
Hydro T.	
Battery bank	
🗌 Backup Gen.	
🗹 Inverter/char.	
H2 (F.C Elyzer.)	

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).

DC Voltage	1	KV 🗌 SOCd.
AC Voltage	20	]kV

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.

Global strategy Load Followi	:		ENERGY ARBITRAGE: System with batteries and grid connected						
Cycle Chargi	i <b>ng</b> 🔽 Continue up to	) SOC stp	Price E<= 0 @c/kWh // Price E>= 0.11 @c/kWh D-2 // (Compare with Sell price						
🔵 Try Both			Optimize strategy of grid-conneted batteries:						
Pmin_gen	Pmin_FC	H2TANKstp							
			Batteries can inject electricity to the AC grid						

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.

	-	BA	TTERIES AVAIL		205			
	DEP		N THE ELECTR	ICITY PRICE (ARB	ITRAGE):			
CHARGE UND	ER ARBITRAG	E:		DISCHARGE UNI	DER ARBITRA	AGE:		
		C-rate A	ll 1st			C-rate	All 1st	
🗹 January	🗹 0 - 1 h	0.2		🗹 January	0-1h	0.3		•
	✓ 1 - 2 h	0.2		<b>—</b>	1 - 2 h	0.3		
I ⊢ebruary	[√]2-3h	0.2		February	2-3h	0.3		
March	- 3-4h	0.2		March	3-4h □⊑⊾	0.3		
C maron	V 4-5⊓	0.2			4-5fi 5-6b	0.3		
🗹 April	6-7h	0.2		🗸 April	6-7h	0.3		
_	7-8h	0.2			7-8h	0.3		
May May	8-9h	0.2		🗹 May	8-9h	0.3		
- June	🗌 9 - 10 h	0.2			🗌 9 - 10 h	0.3		
Joune	🗌 10 - 11 h	0.2		June 🗸	🗌 10 - 11 h	0.3		
July	🗌 11 - 12 h	0.2			11 - 12 h	0.3		
	12-13h	0.2		C outy	12-13 h	0.3		
🗸 August	13-14h	0.2		🖂 August	13-14h	0.3		
	14-15n	0.2			15-16k	0.3		
September	n 16-17h	0.2		🗹 September	16-17h	0.3		
October	17-18h	0.2		October	17-18h	0.3		
C OCIODEI	18-19h	0.2			√18-19h	0.3		
November	 19 - 20 h	0.2		November	🔽 19-20 h	0.3		
	🗌 20 - 21 h	0.2			🗹 20 - 21 h	0.3		
🗹 December	📃 21 - 22 h	0.2		🗸 December	📃 21 - 22 h	0.3		
	22 - 23 h	0.2			22 - 23 h	0.3		
	23 - 24 h	0.2			23 - 24 h	0.3		
🗸 Batt. charge	with surplus E. a	at unchecke	d hours allowed	🗹 Batt. disch. to s	supply load at	uncheck	ed hours all	lowed
Charge batt	eries at the sele	cted hours		Discharge bat	teries at the se	elected h	ours	
only from re	newables, not fr	om arid ('(Se	ell price)'),	injecting powe	r to the AC aria	d, at C-rat	te,	
regardless	of the price of ele	ectricity		regardless of t	he price of ele	ctricity		
(regardless	of arbitrage).			(regardless of	arbitrage).			)
Rest of th	ne time available	e for charge	(arbitrage)	Rest of the	time bat. avail	able for c	disch. (arbitr	age)
		FO	R PUMPING HY	DRO STORAGE:				
Pump at max	kimum power at t	the selected	ł	Turbine at max	kimum power a	at the sele	ected hours	
only from re	newables, not fr	om AC grid,	('(Sell price)')	injecting powe	r to the AC grid	ł		
(regardless	ot arbitrage).			(regardless of	<u>arbitrage)</u>			
			ОК					

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...

GENERAL DATA OPTIMIZATION CONTROL STRATEGIES FINANCIAL DATA RESULTS CHART	
ECONOMIC DATA:	Loan (constant quota, French system):
Nominal interest rate (capital cost): 7 % (nominal discount rate) Annual real discount ratel (%):	Amount of Ioan: 100 %
Annual inflation rate (0&M): 2 % 4.9 % Un LCOE include real disc. rate in Energy Study period (system lifetime): 25 years In maximize NPV systems use Inf. sell	Loan Interest: 7 %
At the end of the study period consider the residual cost of the components	Duration of Ioan: 25 years
Currency Euro (£) V	
Installation cost and variable initial cost: 0 M€ Fix + 25 % of initial cost	Extra Cash Flow

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:

👔 Load and optic	ons of Sel	ling / Pure	chasing E	nergy from	n the AC	grid						
Data source:												
Monthly Ave	Monthly Average O Load Profile O Import File (MW, tH2/h, dam3,											
AC LOAD (MW)	DC L	OAD (MV	V) H2	2 LOAD (t	H2/h)	w						
				•								
Month	0-1h	1-2h	2-3h	3-4h	4-5h							

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).

-	u options	s of Selling	/ Purchasi	ing Energy	from the	AC grid										- 0				
-Data so	urce:										Hours	AC	DC	H2 W	ater	1				
Mon	thly Avera	ige 🔾 Loai	d Profile	) Import File	∋ (MW, tH2	/h, dam3/h)					81~	Minutes-	each hour 1 per row	in 1 row	Import	Expo	rt			
	(MW)	DC LOA	D (MW)	H2 LO	AD (tH2/h	) WA	FER (dam	3/day) FR		ER TANK	PURC	HASE / S	ELL E							
7-8h	8-9h	9-10h	10-11h	11-12h	12-13h	13-14h	14-15h	15-16h	16-17h	17-18h	18-19h	19-20h	20-21h	21-22h	22-23h	23-24h				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.01				
Import	AC table		Scale	factor for M	onday to F	riday: 1		Scal	e factor for	the weeker	id: 1						>			
Import	AC table		Scale	factor for M	onday to F	riday: 1		Scal	e factor for	the weeker	ıd: 1						>			
Import	AC table		Scale	factor for M	onday to F	riday: 1		Scal	e factor for	the weeker	ıd: 1	ed scale fa	ctor), TOT	AL 0.56 MI	Wh/day		>			
Import	AC table	Add los	Scale ad profile	factor for M	onday to F	riday: 1	,	Scal	e factor for LOAD IN I	the weeker	ıd: 1 R (include	ed scale fa 2 (HHV)	ctor), TOT	AL 0.56 MV	Wh/day		>			
Import riability	AC table	Add los	Scale ad profile	factor for M	onday to F	iriday: 1		Scal	e factor for	the weeker	ıd: 1 R (include	ed scale fa 2 (HHV)	ctor), TOT 7 🔳 Wate	AL 0.56 MV	Wh/day		>			
Import triability taily Varia	AC table	Add los AC 0 %	Scale ad profile	factor for M	onday to F %	iriday: 1	05	Scal	e factor for LOAD IN I C load I	the weeker	nd: 1	ed scale fa 2 (HHV)	ctor), TOT 7 🔳 Water	AL 0.56 M\ (E pumped	Wh/day ਤ)		>			
Import riability taily Varie lourly Var	AC table ability riability	Add los AC 0 % 0 %	Scale	factor for M	onday to F % %	iriday: 1 0.1	05	Scal	e factor for	the weeker	ıd: 1 ₹ (include	d scale fa 2 (HHV)	ctor), TOT Z 🔳 Water	AL 0.56 M\ (E pumped	Wh/day		>			
Import triability baily Varie lourly Val	AC table ability riability	Add los AC 0 % 0 % 90 %	Scale ad profile DC % 0 % 90 %	factor for M	onday to F	riday: 1 0. 0. <b>№</b>	) 05 - 04 - 03 -	Scal	e factor for	the weeker	ıd: 1 <b>₹ (include</b>	d scale fa 2 (HHV)	ctor), TOT	AL 0.56 M\ (E pumped	Nh/day 1)		>			
Import ariability Daily Varia Hourly Varia Minutes Va	AC table ability riability ariability	Add los AC 0 % 90 %	Scale ad profile DC 0 % 0 % 90 %	factor for M	onday to F % % %	riday: 1 0. 0. M 0. 0.	05 - 04 - 03 - 02 -	Scal	e factor for LOAD IN I C load I	the weeker	id: 1 <b>₹ (include</b>	d scale fa 2 (HHV) F	ctor), TOT	AL 0.56 M	Wh/day j)		>			
Import ariability Daily Varia Hourly Var dinutes Va Correlation	AC table ability riability arriability a minutes	Add los AC 0 % 90 % 0.9	Scale ad profile DC % 0 % 90 %	factor for M	onday to F % % %	iriday: 1 0. 0. 0. 0.	05 - 04 - 03 - 02 -	Scal	e factor for LOAD IN I C load I	the weeker	ld: 1 ₹ (include ↓ 17 ■ H:	d scale fa 2 (HHV) F	ctor), TOT Z Water	AL 0.56 MV	Wh/day j)		>			
Import ariability Daily Varia Hourly Vari dinutes Va Correlation Gen	AC table ability itability ariability a minutes erate	Add loc AC 0 % 90 % 0.9 AC load po	Scale ad profile DC % 0 % 90 %	factor for M H2 0 . 0 . 90	onday to F % % %	riday: 1 0. 0. 0. 0. 0.	05 - 04 - 03 - 02 - 01 -	Scal	e factor for	the weeker	ld: 1 R (include	d scale fa	ctor), TOT 7 🔳 Water	AL 0.56 MV	Wh/day ۱		>			
Import ariability Daily Varia Hourly Var Ainutes Va Correlation Gen Add Ioac	AC table ability riability ariability an minutes erate	Add loc AC 0 % 90 % 90 % AC load pr	Scale	factor for M H2 0 . 0 90 (cos phi): 1 uring 5	onday to F	iriday: 1 0. 0. 0. 0. 0. 0.	05 - - 	Scal	e factor for LOAD IN C load IV	the weeker	Id: 1	td scale fa 2 (HHV) F 12 hour	ctor), TOT	AL 0.56 MV (E pumped) 18	Wh/day ع		>			
Import ariability Daily Varia Hourly Varia Add Ioad Add Ioad	AC table ability riability an aniutes erate d of 0 hour 0	Add loc AC 0 % 90 % 90 % AC load pr MW day1	Scale	factor for M	onday to F % % 1 min at every	ridey: 1 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.	05	Scal	e factor for LOAD IN C load V 6	DECEMBER	nd: 1	12 hour 12 hour 05 MW; Ma	ctor), TOT	AL 0.56 MV (E pumper 18	Mh/day j)		>			
Import ariability Daily Varie dourly Varie d	AC table ability riability arriability a minutes erate l of 0 hour 0	Add los AC 0 % 90 % AC load po day[1	Scale	factor for M	onday to F % % % I I I I I I I I I I I I I I I I	ridey: 1 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.	05	Scal	e factor for LOAD IN I C load V	DECEMBER	nd: 1 <b>₹ (include</b> <b>▼</b> • H mping): 0. 2 MVA	nd scale fa 2 (HHV) F 12 hour 05 MW; Me	ctor), TOT Water Water	AL 0.56 MV (E pumper (E pumper) 18	Nh/day j)					
Import ariability Daily Varia Hourly Varia Ainutes Va Correlation Gen Add Ioac a min 0	AC table ability riability arriability a minutes erate d of 0 hour 0	Add los AC 0 % 90 % AC load po AC load po dey[1	Scale	factor for M H2 0 90 (cos phi): 1 uring 5 Repen 1 60 ~	onday to F % % % I I days min.	ridey: 1 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.	05 - 04 - 03 - 02 - 0 urly active ourly AC po urly power	Scal	e factor for LOAD IN I C load V 6 in the yea 0.02 MW; / year; 0 MV	the weeker	rhourty avv	Ad scale fa 2 (HHV) F 12 hour 05 MW; Me erage 0 M	ctor), TOT Water water	AL 0.56 MV (E pumper 18 18	Nh/day j)					

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).

Purchase from AC grid Unmet Load (N Energy by Stand-alone system)	lon Served
Fixed Buy Price (€/kWh) 0.12	Hourly Price
Annual Inflation (%): Emission (kgCO2/ 3 0.4	≺Wh):
Fixed Pmax (MW) Fixed Cost P (€/kW	//yr)
12 Options 0	Hourly Values
Access Charge Price (€/kWh)	
Fixed Access price (€/kWh)	Hourly Price
Back-up Charge Price (€/kWh)	
Fixed Back-up price (€/kWh) 0	Hourly Price
(The cost of the back-up toll will be added to the	e E purchased)

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):

HOURLY		OF THE EL	ECTRICI		HASED F	ROM TH	E AC GRII	<u>D</u>			
Hourly P	rice Data (€ v ell devot	/kWh)									
From	file (8760 h	ne same ourly values	) Impo	ort hourly Pr	ice						)raw
Hourly pri	y Periods	the came:									
0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h
0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.12	0.12
12-13h	13-14h	14-15h	15-16h	16-17h	17-18h	18-19h	19-20h	20-21h	21-22h	22-23h	23-24h
0.12	0.12	0.12	0.12	0.12	0.12	0.15	0.15	0.15	0.15	0.12	0.12

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).

Sell Excess Energy to AC grid
Fixed Sell Price (€/kWh) 1.12 Hourly Price
Pr. sell = pr. buy x 0.8
Annual Inflation (%): 3
Max. Power(MW)
Energy Generation Charge (Transfer Charge) Price (€/kWh)
Fixed Transfer price (€/kWh) 0 Hourly Price
Self-consumption and Net Mettering:
No net mettering ~
Cost of net metering service (€/kWh)
Buy-back: Export E is paid at (€/kWh) 0

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.


Priority to supply E not covered by renewables:O Storage/Generator 

AC Grid

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:

Ň	BATTERIES																		-		×
	Add Battery Add Batteries family	Zero			~	4 ►	▶! ♦ =	<b>▲</b> ✓ :	× (*												
	BATTERIES DATA:							Flo	at life a	t 20 °C	:	Cyc	cles to F	ailure	/s. Dep	th of Di	scharge	∍ (%)			
	Name	Cnom.(kAh)	Volt.(kV)	Cost(M€)	C.08M(%/yr)	SOCmin(%)	Self_d(%/mon.)	lmax(kA)	Eff(%)	Float(yr)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	TYF
Þ	Bat10MWh	10	1	3	1	10	1	5	92	15	48000	24000	16000	12000	9600	8000	6857	6000	5333	4000	Li

We can see that the nominal capacity is 10 kAh and the voltage is 1 kV, therefore the energy capacity is  $10 \text{ kAh} \cdot 1 \text{ kV} = 10 \text{ MWh}$ .

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:

	Name	Cnom.(kAh)	Volt.(kV)	Cost(M€)	C.O&M(%/yr)	SOCmin(%)	Self_d(%/mon.)	lmax(kA)
Þ	Bat10MWh-2	10	1	3	1	10	1	10

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 20°C 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:

Temp. J 18 F 18 M 20 Bat	A 20 M	20 J 22	Mean (°C) 20
(°C) J 22 A 22 S 22	2 0 20 N	18 D 18	
Except Schiffer model, con Tmean>=Tfloat life	isider Impo	ort hourly file	Mon. Hour
Float life reduces 50% for ev	rery 10 °C i	ncrease	🔁 T Graph
└ Cycle life depends on T	Data		
Capacity depends on T	Data	]	

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:

Lead-acid Aging battery model	Li-ion Aging battery model
Wang et al., 2011 (LiFePO4) Grot et al., 2015 (LiFePO4) Saxena et al., 2016 (LiCoO2) Full equivalent cycles Rainflow (cycle counting) Naumann, 2020 (LiFePo4 cyc+c	Parameters

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):

Wang Grot Saxena Calendar ageing Naumann	
Data (Naumann et al., 2020): CYCLE ageing	Data (Naumann et al., 2018): CALENDAR ag.
Qloss_cyc(%)=(a·Crate+b)·(c·(DOD-0.6)^3+d)·FEC^z	Qloss_cal(%)=kref exp(-Ea/R (1/T-1/Tref) (c (SOC-0.5)^3+d) sort(t)
a 0.063 b 0.0971 c 4.0253	kref 0.001257 Fa 17126 Tref 298.1499
d 1.092300: z 0.5	c 2.875 d 0.60225
Graph: Crate 1 DOD(%) 60 SOC(%)	50 T(°C) 25
20	
\$ 16	20
S 12	16
eity	12
	8
Ŭ	4
0 5,000	0 10 20
Number of Full Eq. Cycles	rime (years)
ОК	

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.

Annual Inflation Rate expected for _2 % Batteries Costs:	Max. Variation of Wind Batteries expected (e.g., for an expected 60% reduction on current Batteries cost, introduce "-60%"):	-60 %
	Limit is reached in 45.4 years	

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).

℟ INVERTER/CHARGERS														-		×
Add from Databa	se Ze ble from family:	ero		~	~				•	•	•	M 🔶	_	• ✓	×	C
GENERAL DATA									E	FFICI	ENCY	(%) v	s. OUT	PUTPO	WER (	%) ->
Name	Power(MVA)	Lifespan (yr)	Cost (M€)	lmax_ch_DC(kA) E	f_charger(%)	Vdcmin(kV)	Vdcmax(kV)	Pmax_ren(MW)	0%	2%	3%	4%	5%	10%	20%	:0%
		16	0.5	5	98	0.9	11	1E15	10	30	50	70	85	93	92	

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):

		~	]								▶I 💠		▲ ✓	×C
									EF	FICIENC	CY (%) V	s. OUTF	PUTPO	WER (%) ->
0%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
10	60	80	90	95	97	97	97	97	97	97	97	97	97	97



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):

MIN. AND MAX. No COMPONENTS IN PARALLEL:									
Bateries in parallel: Min.	1	] Ma	X.	1					
PV gen. in parallel: Min.	0	] Ma	X.	8					
Wind T. in parallel: Min.	1	] Ma	X.	1					
AC Gen. in parallel: Min.	1	] Ma	X.	1					
Constraints under NPV maximization:									
Max. Investment cost	1E10		Mŧ	8					
Min. Capacity Factor	0		%	Pma	x_sell				
Min. Renew. Fraction	0		%						
Max. Unmet load	100		%						
Max. Land use	1E10		ha	Data					

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).

-		E 1 1 400001 N		100000		10.5	1 1 10 10	0.500	1005/01/110	0: 1.1	<b>D</b>	0
	tal NPV (M€)	Emission (ktCU2/yr)	Unmet(Gwh/yr)	IRR(%)	La	ind(ha)	Investment(Mt)	Cap.⊢(%)	LCUE(€/KVVh)	Simulate	Report	COS
	-3.198	1.49	0	1	0	0.1	4.375	0.1	0.188	SIMULATE	REPORT	CO
<												>
COL	MPONENTS: Batteries	: Bat10MWh-2 (10 kAł	n):1s.x1p.// Bat.Ir	nverter Inv	/-Ch5I	MW-2 of !	5 MVA // Unmet I	load = U % //	Total Net Present	Value (NPV) = -	3.198 M€, IRR =	
0%.												
OT												
SIF	RATEGY: There is no I	oad consumption -> r	io control strategy i	related to	the la	ad consi	umption supply. S	SUC min.: 10	%. ARB.: Control V	/ariables for grid	l-connected	
batt	eries: charge (buying t	<ol> <li>to the AC grid) if prid</li> </ol>	ce of E. is lower tha	in U €/KVVh	n; disc	ch. (load ·	+ injecting to the g	grid) if price i	<ol> <li>higher than 0.11</li> </ol>	€/KWN		
												$\sim$

# 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.

Hours eq. Gen	Bat. life (yr)	Hours Ch. Bat.	Hours Disch. Bat.	Hours FC	Hours Elyzer.	C. Fuel Gen.(M€/yr)	C. Fuel FC(M€/yr)	E Buy (M€/yr)	E Sell (Mŧ
0	10.64	0	0	0	0	0	0	-0.148	

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

MHOGA software. Report	NPC / NPV (ME)
Project: Bat-only.mho. Solution # 1 DC Voltage: 1 kV. AC: 20 kV.	BATTERIES
COMPONENTS:	
Without PV     POWER (MW)       Batt. Bart/MWh-2, fx1x10 kAh. E total = 0.01 GWh (15 d aut)     POWER (MW)       Without Wind Turbines     4       Without Hydro Turbine     4       Without Electrolyzer     3       Inverter Im-Ch5MW-2, 5MW     2       Land use: 0.1 ha     Fv	
CONTROL STRATEGY:	
THERE IS NO LOAD CONSUMPTION -> NO CONTROL STRATEGIES RELATED TO THE LOAD CONSUMPTION SUPPLY	
	ENERGY BALANCE DURING 1 YEAR (GWh/year):
Priority to supply net load with AC grid The whole not supply end power to meet the load must be supplied by the Batteries. If the Batteries cannot supply the whole, the rest will be urmet 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.	Overall Load Energy: 0 204 CWh/yr. Unmet Load: 0 GWh/yr (0 % Load) Export Energy: 1 206 GWh/yr Export Energy: 1 206 GWh/yr Renevable Capacly Factor (sold energy/(tenew_peak_power%760)): 0.1 %, Renew. fraction: 100 % Energy delivered by MY generator: 0 GWh/yr Energy delivered by MY antonias: 0 GWh/yr Energy delivered by AG tartains: 0 GWh/yr Energy discharged by Batteries: 3.124 GWh/yr Energy discharged by Batteries: 3.124 GWh/yr
ECONOMIC CALCULATION S:	OTHER RESULTS:
Initial Investment: 4.375 M€. Loan: 100 %, int. 7% in 25 years, annual quota: 0.375 M€.	Batteries Lifetime: 10.64 years
NPV OF THE SYSTEM (25 years lifetime) (Incomes +, expenses -):	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
Total Net Present Value (NPV): -3.198 M€. Internal Rate of Return (IRR): 0 %. LCOE : 0.188 €/kWh	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.
Distribution of NPV: Battery bank (NPV): -4.93 ME	Total CO2 emissions: 1.49kCO2yr H2 sold in one year. 01 H2/yr
Buy/Sell. Bought Energy (NPV): -2.346 M€ (included 0 M€ due emssions of bought E.). Sold Energy: Electrical E.	ENERGY BALANCE DURING 1 YEAR (GWh/year)
(NPV): 5.647 (Mc (FCR 0%), FI2 (NPV): 0.0Mc Installation + financing + extra cash (NPV): -0.875MC	

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<sup>nd</sup> (hiding selected rows and columns):

	Α	В	D	AA	AB	AC	AD	AE	AF	AG	AJ	AL	AO	AQ	BA	BB	BC
6	HOURLY VAL	UES. All power	values are exp	ressed in MW	(H2.load is in I	MW referring to	the HHV of H	2). The SOC da	ata of the batte	ries in energy	(MWh).						
7	Water tank (	Water_tank) is	energy needed	to pump the v	vater (MWh) v	vhile (Water_ta	nk_volume) is	the volume st	ored (dam3).								
8	No.Gen_on i	s the number o	f AC generators	s that are runn	ing during this	time step. Hou	irs_eq_Gen is	the number of	equivalent hou	rs (including or	ut-of-range pe	nalty and star	-up penalty)	of AC generato	s. The fuel co	nsumption of t	he Gen. AC (Fue
9	Costs of pure	chasing energy t	to the grid, the	fuel cost of th	e AC Gen. (Fue	el.Cost), the co	st of the exter	nal fuel used b	the fuel cell (	C.fuel.ext FC)	and incomes o	of selling E and	costs of buyi	ng E to the AC p	rid (Inc.Sell an	d Cost.Buy) an	e expressed in t
10	Load of Hydr	ogen (H2 load	mass) is expre	essed in t/h of I	H2. H2 in tank	(H2 Tank mas	s), H2 used by	fuel cell, from	H2 tank (Fuel.I	C) or external	ly purchased (I	Fuel.ext FC) a	nd hydrogen g	enerated by th	e electrolyzer	(Prod H2) are	expressed in t o
11	Hydrogen sto	ored in H2 Tank	(H2 Tank HHV	v) 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(N	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	C	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	C	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	C	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	C	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	C	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	C	0	10	1.2	10
43	02-January	6:00	0.01	0	0	0	0	0	0	0.01	0.032	0.04	C	0	10	1.2	10
44	02-January	7:00	0.01	0	0	0	0	0	0	0.01	0.032	0.04	C	0	10	1.2	10
45	02-January	8:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
46	02-January	9:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
47	02-January	10:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
48	02-January	11:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
49	02-January	12:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
50	02-January	13:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
51	02-January	14:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
52	02-January	15:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
53	02-January	16:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	0	10	1.2	10
54	02-January	17:00	0.01	0	0	0	0	0	0	0.01	0.096	0.12	C	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	C	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	C	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	C	0	1.2	1.2	10

We can see in column BA the SOC: January 2<sup>nd</sup> at 0 h battery SOC is 1.2 MWh (SOC min. is 10% of 10MWh, that is, 1 MWh, which would be for 20°C, however as temperature in January was set to 18°C, 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  $0.04 \notin kWh$  (column AL), therefore the cost of buying electricity to the grid during first hour is  $0.04 \notin kWh \cdot 2090kW \cdot 1h=83.6 \notin = 0.00008 M \notin$  (column AQ).

At the beginning of the second hour of January  $2^{nd}$ , 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  $3MW \cdot 0.97=2.91$  MW. As we have 0.05 MW AC consumption for auxiliary, we have only  $2.91 \cdot 0.05 = 2.86$  MW to be injected to the AC grid (columns AE and AF), which is valued at  $0.12 \notin kWh$  (0.15\*80%), column AJ, with a value of incomes for this hour of  $2860kW \cdot 1h \cdot 0.12 \notin kWh=343 \in 0.00034$  M $\in$  (column AO).

The SOC at the beginning of the next hour (row 56, column BA) is 10 MWh-3MW $\cdot$ 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:

Project: Bat-only.mho. Solution #1

Distribution of Incomes (+) and costs (-), NPV, during the years. RED: acqu. costs, replac. costs and incomes for final sale. BLUE: O&M. Currency: M€. Total NPV: -3.198 M€, IRR =0 %. Inversion cost: 4.375 M€. Loan of 100 %, int. 7% in 25 yr., quota: 0.375 M€/yr.



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...".

### 42. Green hydrogen production with electrolyzer at full load and battery

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):

Simulation and optimization:	
Simulation of the 1st year and extrapolate results	
Multiperiod: simulate all the years of the system lifetime ( 25 years)	
Economic optimization:	
$\bigcirc$ Minimize Net Present Cost (NPC), usually for off-grid systems and high load on-grid ————————————————————————————————————	Min. NPC Min. LCOH
$\odot$ Maximize Net Present Value (NPV), usually for low load or no-load on-grid systems	Max. NPV
Define Wind Farm with 16 power curves, one for each wind direction sector	Min. LCOE
DC renewable include own charger and controller	Max. Cap.F. min. LCOb Max. IRR
When saving the project, update all the results of the table to the present conditions	
Number of decimal places in results of costs 3 ~	
Number of decimal places in results of energy 3 ~	
ОК	

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.

Ň	WIND RESOURCE			- 🗆 X	
	Latitude (*) (+N, -S) : 41.66 Get data from local DB Longitude (*) (+E, -W) : -0.86 Download hourly data Locate on map Update coord Download NASA Monthly data	Anemometer Height		-	
	Data source O Monthly Average Import data file (MW) windprod txt Generation of wind turb. (MW) normalize	to 1 MW rated to	Import	Surface Roughness Class Length 0.03 m Agricultural open area without fences neither hedges and with very dispersed buildings. Only smoothly rounded hills	

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  $M \in$ , a replacement cost of 3.5  $M \in$ , 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									Outp	ut Powe	r (MW) v	s Wind S	Speed					
	Name	Bug	Cost (M€)	C. Repl. (M€)	C. O&M (%/yi)	ifespan (yr)	Height (m)	Emis.CO2(	(ke)	1m/s	2m/s	3m/s	4m/s	5m/s	6m/s	7m/s	8m/s	9m/s	Im
6	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):

									Out	tput Pov	ver (MW	) vs Win	d Speed	I			
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):

/ Project: D:\H2prod-wind-bat.mho									
Project Data Data Base Report	Visual Help License Updates								
V LOAD / AC GRID	GENERAL DATA OPTIMIZATION	CONTROL STRATEGIES	FINANCIAL	DATA	RESU	JLTS CHAI	RT		
RESOURCES	COMPONENTS	MIN. AND MAX	K. No COMP		S IN PA	ARALLEL:-			
	Wind Turbines	PV gen. in pan	allel: Min.	0	Max.	8			
HYDRO	Hydro T.	Wind T. in para	allel: Min.	10	Max.	20	>		
PV GEN.	✓ Battery bank	AC Gen. in par	allel: Min.	1	Max.	1			

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:

ctroiyzers	H2 Tank										
				Generation of	f H2 by electri	cal energy	Data to mo	dify the consu	umption and effi	ciency cu	Irvi
Add from E	Database	Zero			N L		Curves ch	ange in H2 mas	s flow limit (% of r	ated): 100	_
					T T				Factor efficie	ncy: 0.4	5
				0.001101.1	1.2 2.5		0.0110			·	-
	Name	P. Nom(MW)	Acq. cost (MC)	C. U&M (C/yr)	Lifespan (yr)	A (KVV/kg/h)	B (kvv/kg/h)	P. min. (%)			
<u> </u>	Elyzer10M	WW. Consumption(MW)	and Efficiency(%H	HV) 。	Power	r consumption in r cost (€/ka H2):	stand-by: 10	% of nominal p	power Ava	ilability	
6 8.192				6	0 I Stad	rehiscement co	sit ve or acdi cost	), [H0			
6.144 4.096 2.048	0	0.05 0.1 H2 OUTPUT MASS	0.15 5 FLOW (t/h)	4	0 0 Cold 0 Cold 0 Cold 0 Lifeti 0 y 0 y 0 y 0 y	start time (min): me and O&M cos ears and €/yr ours and €/h	20 ; Each sts data:	cold start equiv. Eler	to extra ageing (mi ctricity DC	n): 100	
6.144 4.096 2.048 U O ominal H2 m Equ	nass flow = 0.2 t/	0.05 0.1 H2 OUTPUT MASS /h: It is needed at leas issions (manufacturin sectrical consumption	0.15 5 FLOW (t/h) 12 MW to generate g fuel cells and ele on (kWh electrici	0.2 0.2 e H2 ectrolyzers): 330 ity per kg H2):	0 6 Cold 0 6 Cold 0 6 Cold 0 1 Fee 0 1 Fee 0 1 Fee 0 Y ○ Fee 0 Y ○ Fee 0 Y ○ Fee 0 Y ○ Fee 0 Y ○ Fee 0 S 0 S 0 S 0 S 0 S 0 S 0 S 0 S	start time (min): [ me and O&M cos sears and €/yr ours and €/h quiv. / KW rated p	20 ; Each sts data:	Eler Eler H2	to extra ageing (mi etricity DC ectrolyzer H <sub>2</sub> O	n): 100	
6.144 4.096 2.048 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	nass flow = 0.2 to	0.05 0.1 H2 OUTPUT MASS fr: It is needed at leas issions (manufacturin actrical consumptio	0.15 5 FLOW (t/h) t 2 MW to generate g fuel cells and ele on (kWh electric FUEL CELL	0.2 0.2 a H2 ectrolyzers): 330 ity per kg H2):	Cold Cold	start time (min): [ me and 0&M cos ears and €/yr ours and €/h quiv. / KW rated p DLYZER + H2 TA	20 ; Each sts data: ower	Eler H2	to extra ageing (mi etricity DC	n): 100	
E 6.144 4.096 2.048 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	o mass flow = 0.2 ty uivalent CO2 em mpression ele	0.05 0.1 H2 OUTPUT MASS ht: It is needed at leas issions (manufacturin actrical consumptio Cells, Electrolyzers ar	0.15 FLOW (t/h) t 2 MW to generate g fuel cells and ele fuel cells and fuel cells and f	expose 4 2 0 0 2 2 4 2 0 0 2 2 2 2 2 2 2 2 2 2 2 2 2	Cold Cold	start time (min): [ me and 0&M cos zers and 0/yr ours and 0/yr	20 ; Each ts data: ower WK ers and H2 Tank st, introduce *-905	Elec H2 S Cost (e.g., for e S^1):	an -90 %	n): 100	

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:

-Lifetime and O&M costs data: —	
⊖years and €/yr	
● Hours and €/h	

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 and factor efficiency until we fit the limit 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  $0.06 \notin$  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.

👔 на сомрог	ENTS			-	×
Electrolyzers	H2 Tank				
🗹 In F	2 generating systems, do not consider H2 tank (	costs 0, infinite allowed size)			

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.

DC Voltage	1	k٧
AC Voltage	20	kV

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):

Noject: D:\H2prod-wind-bat.ml	10	
Project Data Data Base Report	Visual Help License Updates	
🗸 LOAD / AC GRID	GENERAL DATA OPTIMIZATION	CONTROL STRATEGIES FINANCIAL DATA RESULTS CHART
RESOURCES	COMPONENTS	MIN. AND MAX. No COMPONENTS IN PARALLEL:
✓ WIND	Wind Turbines	Bateries in paralle Min. 0 Max. 10 PV gen. in parallel: Min. 0 Max. 8
HYDR0 COMPONENTS	🗌 Hydro T.	Wind T. in parallel: Min. 10 Max. 20
PV GEN.	🗹 Battery bank	AC Gen. in parallel: Min. 1 Max. 1

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  $0.5 \cdot 2/5 = 0.2$  M $\in$ , 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).

Data source:		_		Hours A	AC DC H2 Water
O Monthly Aver	rage () Load Profile (	) Import File (MW, tH2/h, c	Jam3/h)		utes-1 per row
C LOAD (MW)	DC LOAD (MW)	H2 LOAD (tH2/h)	WATER (dam3/day) FROM WATER TANK	PURCHASE	E / SELL E
Durate for	- +0:				AC GRID AVAILABILITY
Energy by St	and-alone system)	a (Non Servea	Sell Excess Energy to AC grid		Priority to supply E not covered by renewables
Fixed Buy Pric	e (€/kvh) 0.15	Hourly Price	Fixed Sell Price (C/kWh) 0.12	Hourly Price	Storage/Generator      AC Grid
Annual Inflation (	%): Emission (kaC	:02/k\\d/b):	Pr. sell = pr. buy x 0.8		Sto./Gen. priority if Pr.E >= 0
3	0.4		Annual Inflation (%): 3	(	Sell sur lus H2 in tank (difference
Fixed Pmax (N	/W) Fixed Cost P (f	S/KW/yr)	Max. Power(MW) 30 DPmax buy		of the year and at the beginning)
30 Op	tions 40	Hourly Values	Energy Generation Charge (Transfer Charge) Pri	ice (€/kWh)	Price (€/kg) Annual Inflation (%):
Access Charge Pr	ice (€/kWh)	-	Fixed Transfer price (€/kWh) 0.0005	Hourly Price	10 3
Fixed Access	price (€/kWh) 0	Hourly Price	Self-consumption and Net Mettering:		
Back-up Charge F	rice (€/kWh)		No net mettering	~	
Fixed Back-up	price (€/kWh) 0	Hourly Price	Cost of net metering service (€/kWh) 0		
The cost of the ba	.ck-up toll will be added t	o the E purchased)	Buyeback: Export E is paid at (\$1/W/b)		

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...":

AC LOAD (MW)	DC LOAI	) (MW)	H2 LOAD (tH2/h)
Purchase from Energy by Sta	AC grid U nd-alone s	nmet Loa ystem)	d (Non Served
Fixed Buy Price	(€/kWh)	0.15	Hourly Price
Annual Inflation (%	i): Emi	ssion (kqC	:02/kWh):

In the window that appears, select "From file (8760 values)" and import ("**Import hourly Price**" button) the "Hypothetical\_hourly\_pirce.txt" file.

O Hourly Periods	HOURLY PRICE OF THE ELECTRICITY PURCHASED FROM THE AC GRID Hourly Price Data (£/kWh) Hourly, all days the same From file (8760 hourly values) Hourly Price Hypothetical_hourly_pirce.txt	<b>E</b> Draw
------------------	--	---------------

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  $0.03 \notin kWh$  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  $0.1 \notin kWh$  in the first year):

GENERAL DATA OPTI	MIZATION CONT	ROL STRATEGIES	FINANCIAL DATA RESULTS CHART
CONTROL STRATEGY /	AND VARIABLES T	O OPTIMIZE	
Global strategy:			ENERGY ARBITRAGE: System with batteries and grid connected
Load Following			Batt. charged by the AC grid // discharged (also for Elyzer> H2 2 Elyzer. full load
O Cycle Charging	🗹 Continue up to	) SOC stp	Price E<= 0.03 E/kWh // Price E>= 0.1 E/kWh [] [ 2% [] (Compare with Sell price)
◯ Try Both			Optimize strategy of grid-conneted batteries:
Variables to optimiz	ze relative to the	global strategy:	
Pmin_gen	Pmin_FC	H2TANKstp	
P1_gen		P2	Batteries can inject electricity to the AC grid
Pcritical_gen	H2TANKstp	SUCmin Plim_charge	□ 1 day at low SOC-> charge battery with AC grid □ When batteries are off, compensate autodisch. Batteries availability
SOCmax Fix varial	oles Variables	accuracy: 5 = 1	00%
If SOCmin reached, disc	h. not allowed if SO	C(%) < SOCmin(%) +	D

#### In the **FINANCIAL DATA** tab, we can see the general economic data, we leave them by default:

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

ECONOMIC DATA: Nominal interest rate (capital cost): 7 % (nominal discount rate) Annual real discount ratel (%): Annual inflation rate (08M): 2 % 49 % ✓ In LCOE / LCOH include real disc. rate in Energy Study period (system lifetime): 25 years ✓ In maximize NPV systems use Inf. sell / H2	Loan (constant quota, French system): Amount of Ioan: 100 % of the initial cost of investment
Currency Euro (€) ✓ Installation cost and variable initial cost. 0 M€ Fix + 25 % of initial cost Corporate taxes (%) 0 ✓ If in a year costs>incomes, taxes=0 that year ✓ Negative taxes accumulate and are offset later when taxes >0	Duration of Ioan: 25 years Extra Cash Flow

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  $11 \times 11 \times 1 = 121$  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	C
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	C
274.24	25.68	0	23.53	1368.05	127.031	29.69	0.0825	SIMULATE	REPORT	C
274.136	27.44	0	24.77	1224.05	117.031	31.14	0.0848	SIMULATE	REPORT	C
273.396	24.92	0	22.93	1 4 4 0.05	132.031	28.97	0.0818	SIMULATE	REPORT	(
<									2	>
COMPONENTS: 18 Wind (NPV) = 275.832 M€, IRR STRATEGY: There is no hydrogen: Generate H2 w charge battery if price of f	Turb. WindT4MW (4 I = 24.5%. load consumption → n /ith elyzer. at full power E. is lower than 0.03 €/k	vfW at 15 m/s) // El o control strategy n all the time, buying Wh	ectroliz. Ely elated to th E. to the A	-20MW of 2 e load cons C grid if nece	) MW // Bat. Inve umption supply. F essary; Battery su	rter of 0 MVA ?. lim. charge pplies powe	A// Unmet load = 0 e: 15 MW. ARB.: Co er to elyzer. if price	) % // Total Net I ontrol variables f E. is higher thar	Present Value for green 10.1€/kWh;	^

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 1<sup>st</sup>, 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:







If we click in "**Save Simulation Data**" button, we will save all the simulation results, which can be open by Excel.

A	В	C		D	E	F	G	H		1	J	К	L	M	N	0	P	Q	R	S	(
Project: D:\PF	OYECTOS	MHOGA 3.4-2	02403	3XX\H2-prod-wir	nd-bat.mho.	. Solution # 1															
COMPONENT	S: Wind tu	bines of 72 N	IW. E	lectrolyzer of 20	OMW.																
TRATEGY: TH	nere is no lo	ad consumpti	on ->	no control strat	tegy related	to the load co	onsumption s	upply. Art	itrage: Contr	rol varia	bles for green	nydrogen: Ger	erate H2 with	elyzer, at full p	ower all the t	time, buying E.	to the AC grid	if necessary			
IOURLY VALU	UES. All pov	ver values are	expr	essed in MW (H2	2.load is in N	AW referring t	to the HHV of	H2). The	SOC data of	the batt	eries in energy	(MWh).									
Vater tank (V	Water_tank	) is energy nee	dedt	to pump the wat	er (MWh) w	rhile (Water_t	ank_volume)	is the vol	ume stored (i	dam3).											
lo.Gen_on is	the numbe	r of AC genera	ators	that are running	during this	time step. Ho	urs_eq_Gen i	s the num	ber of equiva	alent ho	urs (including o	ut-of-range p	enalty and star	t-up penalty) c	f AC generato	ors. The fuel co	nsumption of	the Gen. AC (	Fuel.Gen) is ex	opressed in	×.
osts of purcl	hasing ener	gy to the grid,	the f	uel cost of the A	C Gen. (Fue	I.Cost), the co	ost of the ext	ernal fuel	used by the f	uel cell (	C.fuel.ext_FC)	and incomes	of selling E and	costs of buyir	g E to the AC	grid (Inc.Sell a	nd Cost.Buy) a	re expressed	in M€. They a	re cash flov	w
oad of Hydro	ogen (H2_lo	ad_mass) is e	xpres	ssed in t/h of H2.	H2 in tank	(H2_Tank_ma	ss), H2 used l	oy fuel cel	, from H2 tai	nk (Fuel.	FC) or externa	ly purchased	(Fuel.ext_FC) a	nd hydrogen g	enerated by th	he electrolyzer	(Prod_H2) are	expressed in	t of H2.		
Hydrogen sto	red in H2 T	ank (H2_Tank_	HHV	) is expressed in	MWh HHV c	of H2															
)ate	Hour	Load(MW	) /	AC_load(MW) DC	_load(MW)	H2_load(HHV	H2_load_m	as Water_	load(NPV(M	W)	Wind(MW)	Hydro(MW)	Ef_turb(perce	AC.Gen.(MW)	No.Gen_on	Hours_eq_Ge	e Cons.Fuel(x1	E Fuel.Cost(N	€]F.C.(MW)	Fuel.FC	(t)
J1-January	0	:00	0	0	0	0		0	0	0	36.72	0	1	0	(	0 0		)	0	0	
1-January	1	:00	0	0	0	0		0	0	0	39.24	0	1	0		0 0		)	0	0	
1-January	2	:00	0	0	0	0		0	0	0	41.04	0	1	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	
01-January	4	:00	0	0	0	0		0	0	0	41.04	0	1	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	
01-January	6	:00	0	0	0	0		0	0	0	40.32	0	1	0	(	) ()	0	)	0	0	
01-January	7	:00	0	0	0	0		0	0	0	39.24	0	1	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	
01-January	9	:00	0	0	0	0		0	0	0	21.6	0	1	0	(	0 0		)	0	0	
01-January	10	:00	0	0	0	0		0	0	0	18	0	1	0	(	0 0		)	0	0	
01-January	11	:00	0	0	0	0		0	0	0	14.76	0	1	0	(	) ()		)	0	0	
01-January	12	:00	0	0	0	0		0	0	0	12.96	0	1	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	
1-January	14	:00	0	0	0	0		0	0	0	12.6	0	1	0	(	0 0	0	)	0	0	
1-January	15	:00	0	0	0	0		0	0	0	14.4	0	1	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	
01-January	17	:00	0	0	0	0		0	0	0	27.36	0	1	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	



# 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	NPC / NPV (ME)
Project: H2-prod-wind-bat mho. Solution # 1 DC Voltage: 1 kV. AC: 20 kV.	OWW
COMPONENTS:	
Without PV         POWER (MW)           Batt Batt/MVN, 15x0-5 kAh. E total = 0 GWh (0 d aut)         POWER (MW)           Without PV         Without PV           Without PV         Status           Elyzer: Ely208WV, 20 MW         Status           Land use: 1296 ha         Vit PV	EVZER HQ TANK
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	ENERGY BALANCE DURING 1 YEAR (GWh/year):
CONTROL STRATEGY FOR GENERATING GREEN H2: Max. electricity price for generating H2 (buy to the grid): 0.03 €/kWh.	Overall Load Energy: 0 GVM/yr. Umert Load CoWhy (Y 6 Joad) E. Purchased from AC grid: 61 045 GVM/yr Export Energy: 24 305 GVM/yr Renewable Gapacity Factor (sold: energy/(renew_peak_power*8760)): 30.43 %; Renew. fraction: 100 % Energy delwered by Ming Turbines: 218 972 GVM/yr E. Energy delwered by Ming Turbines: 0 GVM/yr E. Geliwered by Ming Turbine: 0 GVM/yr. Pumped 0 GVM/yr E. Energy delwered by Ming Turbine: 0 GVM/yr. Pumped 0 GVM/yr E. Energy delwered by Ming Turbine: 0 GVM/yr. Pumped 0 GVM/yr
ECONOMIC CALCULATION S:	Energy at Electrolyzer: 175.2 GWh/yr
Initial Investment: 120 M€. Loan: 100 %, int. 7% in 25 years, annual quota: 10.297 M€.	Energy discharged by Batteries: 0 GWh/yr
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	OTHER RESULTS:
Distribution of NPV: Wind turbines (NPV): 99 041 M€ Electrolyzer+N2Tank' (NPV): 49 620 M€ Bwy/Sell. Bought Energy (NPV): 49 533 M€ (included 0 M€ due emssions of bought E.). Sold Energy: Electrical E. (NPV): 56 393 M€ (FCR 0%). H2 (NPV): 466 842 M€. Installation + financing + extra cash (NPV): -24M€	Battenes Lietume: 100 years Hours eq. 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 Hydro Turb.: 0 h/yr, starts: 0 starts: 0 Hours of Hydro Turb.: 0 h/yr, starts: 0, Hours of Pump: 0 h/yr, starts: 0 Total CO2 emissions: 26 3404CO2/yr H2 sold in one year: 2964.31 H2/yr
	ENERGY BALANCE DURING 1 YEAR (GWh/year)
	200
	150

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.

Ņ	BATTERIES			
	Add Battery	Zero		
	Add Batteries family			
	BATTERIES DATA.			
	Name	Cnom.(kAh)	Volt.(kV)	Cost(M€)

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	
<										>	Ť
COMP Unmet STRA for gre €/kWh	ONENTS: Batteries Bat51 load = 0 % // Total Net Pr TEGY: There is no load c en hydrogen: Generate H : charge battery if price of	MWh- (5 kAh): 1s. x 10 p resent Value (NPV) = 2 onsumption -> no cont 2 with elyzer. at full pov E. is lower than 0.03 €/	). // 18 Wind Turb. ' 84.217 M€, IRR = 2 rol strategy related ver all the time, buy kWh	WindT4MV 4.6%. to the load ring E. to the	/ (4 MW at 1 consumptio e AC grid if n	5 m/s) // Electroli n supply. P. lim. c ecessary; Battery	z. Ely-20MW harge: 15 M / supplies p	/of20 MW // Bat. I W. SOC min.:10 % owerto elyzer. if pr	verter of 12.5 M . ARB.: Control v ice E. is higher t	VA // /ariables han 0.1	~

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 19<sup>th</sup> (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 19<sup>th</sup>) the purchase electricity price (upper curve, red) becomes lower than the "High limit charge" which is  $0.03 \notin kWh$  (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 ( $2.5 kA \cdot 1 kV \cdot 10$  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 19<sup>th</sup>) purchase price is higher than the "Low limit discharge" which is  $0.1 \notin MWh$  (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.

Simulation and optimization:	
Simulation of the 1st year and extrapolate results	
Multiperiod: simulate all the years of the system lifetime ( 25 years)	
Economic optimization:	
$\bigcirc$ Minimize Net Present Cost (NPC), usually for off-grid systems and high load on-grid ——>	Min. NPC
Maximize Net Present Value (NPV), usually for low load or no-load on-grid systems>	
Define Wind Farm with 16 power curves, one for each wind direction sector	Min. LCOH
DC renewable include own charger and controller	Max IRR
When saving the project update all the results of the table to the present conditions	
Number of decimal places in results of costs 3 ~	Data
Number of decimal places in results of energy 3 ~	
OK	

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  $3.938 \notin$ kg.

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOH(€/kgH2)	Simulate	Report A
1	284.217	26.79	0	24.59	1296.5	122.813	30.9	3.9379	SIMULATE	REPOR
2	284.191	27.76	0	25.25	1224.5	117.813	31.03	3.9385	SIMULATE	REPOR
3	283.712	28.83	0	25.93	1152.5	112.813	31.79	3.9487	SIMULATE	REPOR
4	283.648	25.92	0	23.95	1368.5	127.813	29.58	3.95	SIMULATE	REPOR
5	283.541	26.77	0	24.58	1296.45	122.531	30.3	3.9523	SIMULATE	REPOR
6	283.477	27.74	0	25.24	1224.45	117.531	31.04	3.9537	SIMULATE	REPOR
7	283.012	25.91	0	23.94	1368.45	127.531	29.59	3.9636	SIMULATE	REPOR
8	282.973	28.81	0	25.93	1152.45	112.531	31.79	3.9644	SIMULATE	REPOR
9	282.848	26.75	0	24.58	1296.4	122.25	30.31	3.9671	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 % // LCOH = 3.938 €/kgH2. 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										

If we go to the **LOAD / AC GRID** window, then tab **PURCHASE /SELL E.**, and we change the hydrogen price to  $3.9379 \notin /kg$ :

$\widetilde{\mathbf{M}}$ Load and options of Selling / Purchasing Energy from the A	C grid	- 🗆 ×
Data source: O Monthly Average  Load Profile  Import File (MW, tH2/h,	dam3/h)	AC DC H2 Water nutes- each hour in 1 row Intes- 1 per row Import
AC LOAD (MW) DC LOAD (MW) H2 LOAD (tH2/h)	WATER (dam3/day) FROM WATER TANK PURCHAS	E / SELL E
Purchase from AC grid Unmet Load (Non Served Energy by Stand-alone system)     Fixed Buy Price (¢,KWh)     0.15     Hourly Price     Annual Inflation (%):     Emission (kgC02,KWh):     3     0.4     Emissions data     Fixed Pmax (MW)     Fixed Cost P (¢,KW/kyt)     30     Options     40     Hourly Values     Access Charge Price (¢,KWh)     Fixed Access price (¢,KWh)     Fixed Access price (¢,KWh)     Fixed Back-up price (¢,KWh)     Fixed Back-up price (¢,KWh)     Mourly Price     Hourly Price     (Will be added to the E purchased)     Add negative gen. charge	✓ Sell Excess Energy to AC grid         Fixed Sell Price (¢/kWh)       0.12         ✓ Pr. sell = pr. buy x       0.8         Annual Inflation (%): [3	AC GRID AVAILABILITY Priority to supply E not covered by renewables:
Total tax for electricity costs (buy + charges) (%):	Total tax for electricity sold (%):	osses in wire and transformer (%): 0

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):

-	ł	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOH(€/kgH2)	Simulate	Report	^
	1	0	26.79	0	7	1296.5	122.813	30.3	3.9379	SIMULATE	REPOR	
	~			~	00.00					~~ ~ ~ ~ ~ ~ ~ ~ ~		

Now we go back to the LOAD / AC GRID window, then tab PURCHASE /SELL E., and we change the hydrogen price to the original  $10 \notin kg$ .

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 gridconnected 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.

Global strategy:			ENERGY ARBITRAGE: System with batteries and grid connected					
Load Following  Cycle Charging Continue up to SOC stp  Try Both  Ariables to optimize relative to the global strategy:			Batt. charged by the AC grid // discharged if: 📿 (also for Elyzer> H2) 🖉 Elyzer. full load					
			Compare with Sell price					
			Optimize strategy of grid-conneted batteries:					
			O 3 variables: X1(dif.), X2(%), X3(%), X1:min. 0.029 max. 0.3251 €/kWh					
Pmin_gen	Pmin_FC	H2TANKstp	O 2 variables: price E. min. and max. 100n.> 0.0008 ; Max< 0.3615 €/K to PrCh <p< th=""></p<>					
P1_gen	P1_FC	P2	Batteries can inject electricity to the AC grid					
SOCstp_gen	SOCstp_FC	SOCmin	1 day at low SOC-> charge battery with AC grid					
Pcritical_gen	H2TANKstp	Plim_charge	When batteries are off, compensate autodisch.					

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):

MIN. AND MAX. No COMPONENTS IN PARALLEL:										
Bateries in parallel: Min.	10	Max.	10							
PV gen. in parallel: Min.	0	Max.	8							
Wind T. in parallel: Min.	17	Max.	17							
AC Gen. in parallel: Min.	1	Max.	1							

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).

#	Total NPV (M€)	Emission (ktCO2/yr)	Unmet(GWh/yr)	IRR(%)	Land(ha)	Investment(M€)	Cap.F(%)	LCOH(€/kgH2)	Simulate	Report
1	284.243	27.72	0	25.25	1224.5	117.813	31.03	3.9373	SIMULATE	REPORT
<										>
COMF Unme STRA for gre suppli	COMPONENTS: Batteries Bat5MWh- (5 kAh): 1s. x 10p. // 17 Wind Turb. WindT4MW (4 MW at 15 m/s) // Electroliz. Ely-20MW of 20 MW // Bat. Inverter of 12.5 MVA // Jamet load = 0 % // LCOH = 3.937 &/kgH2, IRR = 25.3%. 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 or green hydrogen: Generate H2 with elyzer. at full power all the time, buying E. to the AC grid if necessary: charge battery if E. price is lower than 0.0188 &/kWh; Battery supplies power to elyzer. if price E. higher than 0.127045 &/kWh									

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.

### 2<sup>nd</sup> tab:



3<sup>rd</sup> tab (before, in Project->Options, check "In the simulation window, show the probability density function (PDF) of the main results").

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:

lobal strategy:		ENERGY ARBITRAGE: System with batteries and grid connected					
Load Following		🗌 Batt. charged by the AC grid // discharged if. 🛛 🗹 (also for Elyzer> Hor 🗌 Elyzer. full load					
Cycle Charging 🔽 Continue up	to SOC stp	Compare with Sell price					
) Try Both		Optimize strategy of grid-conneted batteries:					
ariables to optimize relative to th	e global strategy:	O 3 variables: X1(dif), X2(%), X3(%). X1:min. 0.029 max 0.3251 0/KWh					
Pmin_gen Pmin_FC	H2TANKstp	2 variables: price E. min. and max. Min.> 0.0008 ; Max< 0.3615 €/KWh ☑ PrCh <prt< th=""></prt<>					
P1_gen P1_FC	P2	Patteries can inject electricit de AC mid					
SOCstp_gen SOCstp_FC	SOCmin	✓ Datteries can inject electricity to the AC grid 1 day at low SOC→ charge batten/with AC grid					
Pcritical_gen H2TANKstp	Plim_charge	When hatteries are off compensate autodisch					

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  $0.0188 \notin$  (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  $\notin$ /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 3<sup>rd</sup> and 4<sup>th</sup> (next figure, 2 days display), we can see in the evening of January 3<sup>rd</sup> 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:

GENERAL DATA OPTIMIZATION CONTR	ROL STRATEGIES FINANCIAL DATA RESULTS CHART	
	MIN. AND MAX. No COMPONENTS IN PARALLAL	OPTIMIZATION PARAMETERS SELECTED BY:
Wind Turbines	Bateries in parallel: Min. 0 Max. 10	HOGA
	PV gen. in parallel: Min 0 Max. 8	Maximum execution time:
Hydro T.	Wind T. in parallel: Min. 10 Max. 20	0 h. 15 min Parameters
Battery bank	AC Gen. in parallel: Min. Max. 1	Minimum time for the Genetic Algorithms

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):

MAIN AL	.G. (COMB. CO	MPONENTS):	EVAL. ALL 121 (1x121)	<u>POP. (% ALL)</u> 10 (8.26%)	<u>GEN. ALG. (% ALL)</u> 139 (114.88%)
SEC. ALC	G. (COMB. ST	RATEGIES):	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 %	<u>0h 14' 34''</u>
OPTION 3:	GEN. ALG.	EVAL. ALL.	61299	114.9 %	0h 43' 55"
OPTION 4:	GEN. ALG.	GEN. ALG.	23352	43.8 %	Oh 16' 44''
Optimizatior It is not guar near the opt	n of the Control anteed to obta imal	Strategy by m ain the optimal	eans of Genetic Algorit Control Strategy, but thi	hms. s is probable to c	btain the optimal or a solution

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)	In∨estment(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	ť
2	136.701	14.45	0	18.77	864.5	92.813	35.43	1.9428	SIMULATE	REPOR	ť
3	129.102	14.9	0	18.78	792.45	87.531	36.19	1.9638	SIMULATE	REPOR	ť
4	122.647	15.14	0	18.89	720.4	82.25	36.92	2.0274	SIMULATE	REPOR	ť
5	161.739	15.17	0	20.05	936.5	97.813	34.53	2.0373	SIMULATE	REPOR	ť
6	142.278	17.05	0	20.52	720.45	82.531	37.06	2.0547	SIMULATE	REPOR	ť
7	121.55	15.01	0	18.83	720.35	81.969	36.84	2.0898	SIMULATE	REPOR	ť
8	127.132	14.21	0	18.68	792.35	86.969	35.84	2.0924	SIMULATE	REPOR	ť –
9	167.691	14.6	0	19.9	1008.5	102.813	33.78	2.0993	SIMULATE	REPOR	ť.,
<										>	Ň
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 0.019 €/kWh											

We could optimize again, maximizing NPV.