Horizon 2020

Research and Innovation Framework Program

CHESS SET UP

Deliverable 3.1
SIMULATION SOFTWARE

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29/11/2016	3	BCNecologia		Final version

Index

1. Software description

1.1. Introduction

CHESS SETUP system is composed by a sort of elements (water tanks, solar panels, heat pumps, etc.) that interact with each other. In order to analyze the feasibility of the proposed system and calculate the results, it's necessary to perform a simulation of mass and energy balance between the different components.

This software is intended to carry out a preliminary system sizing in a very quickly and simple way. The software allows a calculation of the required solar surface and storage volume, power and energy performance of the equipments, solar production, electrical consumption of the heat pump, gas consumption, and thermal losses among other parameters. It also executes an economic analysis (investment cost, economic saving and payback).

Software performs an hourly simulation of all systems and components (energy balances, water flows, thermal losses, energy performance...) during a two-year period. It's important to have more than one year simulation due to the high system inertia.

The software results should not be used for a precise dimensioning, but rather just to have an idea of the system dimensioning, performance and economic balance. To do an executive and definitive system sizing, more precise software and techniques should be used.

The aim is that any user with background in solar systems and HVAC systems is be able to use the software in just a few hours by consulting the user guide included in this document and with no need of a training course.

The software requires hourly data about weather conditions and energy demand profiles. This data can be hard to obtain is some cases. To simplify this task, the software includes libraries with the weather conditions for some European capitals representing the main climate regions in Europe and from the main building typologies (residential, hotels, offices, sports centers...).

The software also includes libraries with the typical technical parameters of the main system components (solar panels, heat pumps, storage systems, pipes...) and some reference values for the system operation.

These libraries are going to be updated during the development of CHESS SETUP project and after the end of it, using the main findings and data generated and adjusting some parameters, according to the real operation data from the three pilots.

This software is going to be used to do a preliminary sizing for the three pilots. Also, CHESS SETUP is going to be simulated for different building typologies (residential, sports centers, hospitals, hotels...) under different climatic regions in Europe. Finally, the software is going to be used to calculate the system for several real building or cases where it could be replicated in a near future. The results of these simulations are included in the delivery "D3.2. Reference cases report".

The software will be public and available in the CHESS SETUP webpage. For each project, a report with the main results can be created and most relevant data can be extracted in an Excel file.

1.2. Software structure

The software is composed by four modules:

1) **Visual interface**: this is the module visible for the user. It is classified by the input data (weather data, energy demand and all the technical parameters of the system) and the output data (energy performance, equipment efficiencies, economic balance...).

2) **Libraries:** the software requires some precise data such as hourly meteorological data, hourly energy demand, and technical parameters of the equipment, etc. In order to simplify this task, there are available several libraries which can be updated directly by the users.

3) **Project database module:** projects can be saved in a project database only by the software administrator. The software will include some reference projects, which can be uploaded by the users.

4) **Data process and calculation:** all the formulas and programming that perform the calculations is not accessible by users.

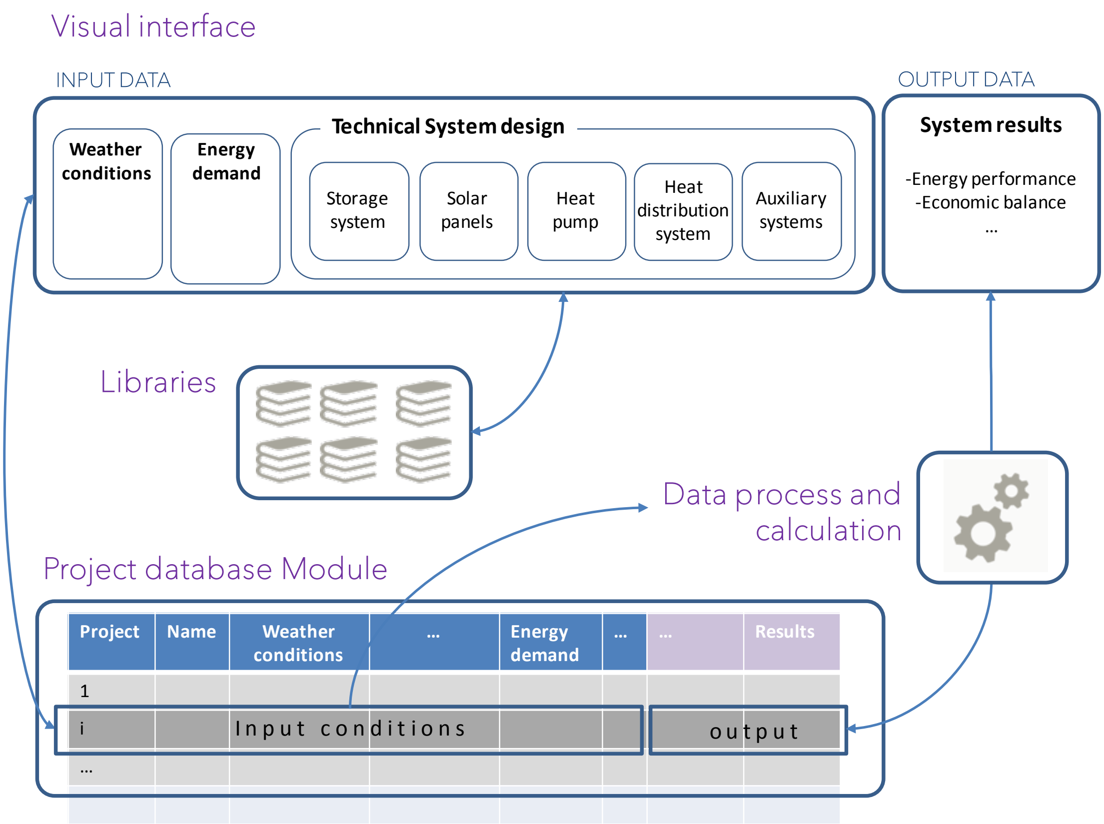


Figure: Software structure

1.3. Type of users

There are two types of users - the administrators (CHESS SETUP partners) and the general users. Bellow are defined the main possibilities for both types of users:

1) **External users:**

    - Create new projects and download results (pdf, csv…)
    - Use libraries
    - Load reference projects (created by administrator)
    - Not save new projects in DataBase

2) **Administrators:**

    - All the external users possibilities
    - Manage libraries
    - Create, save and load their projects

2. User guide

2.1. Introduction

Welcome to Chess Setup Simulator Manual!

The user guide, you are about to start reading, will introduce you to the common use of the software. The process will be explained step by step in order to keep up to the instructions.

Please note that the software is still under evaluation and continual development. This is why, along the project, the software may contain some improvements in terms of robustness and usability.

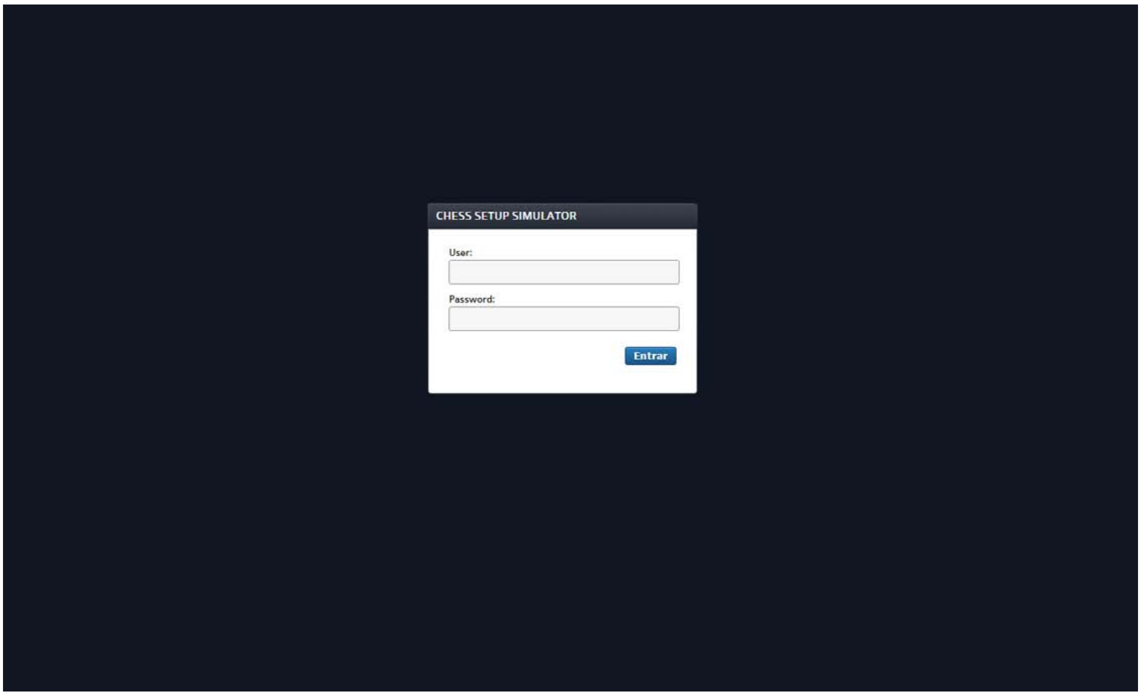
At the same time, in order to provide the best possible service, the look-and-feel of the user-interface will be kept up to date.

In the end, by completing this manual you will become more familiar with the structure of the simulator and its user-friendly interface.

2.2. Sign in / Sign up

First of all, an account will be provided by the CHESS SETUP SIMULATOR developer or administrator.

A username and a password will be required in order to sign in with your account.



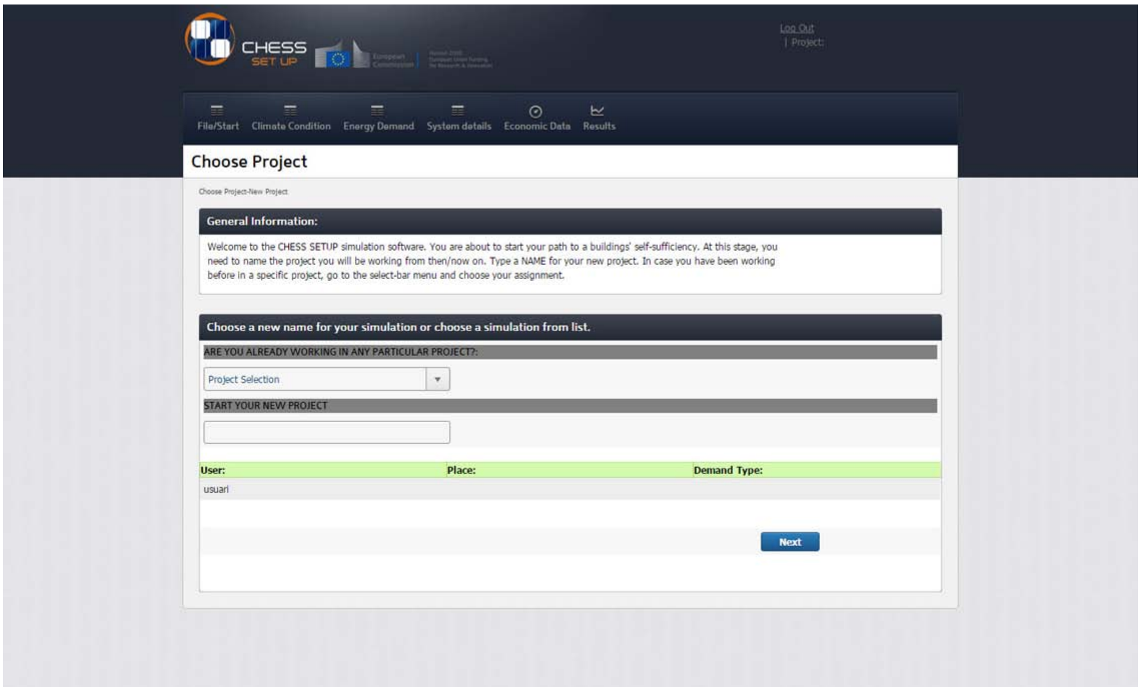
2.3. File / Start

At this stage, you need to name the project you will be working from then/now on.

Type a NAME for your new project. Since repeated names are not allowed, avoid using the same title as a project that already exists.

In case you have been working before in a specific project, go to the select-bar menu and choose your assignment.

Once the project is selected, click NEXT to move on.



2.4. Climate conditions

Climate condition definition is based on the location of your project.

First of all, location is required. At this stage, there are two options:

- Find out if the location you are applying to has already been defined.

- ADD new location. Press ADD CLIMA and fill in the blanks. (NEW PLACE, COUNTRY, LATITUDE and LONGITUDE). And press ADD NEW TYPE.

A map of your location will be visualized in the window as a sign of the correct procedure.

If your location has been selected before, you might already have filled out the information required in order to define the climate conditions (SOLAR RADIATION, AIR TEMPERATURE, GROUND TEMPERATURE and IRRADIATION). If so, the buttons related to climate conditions will appear in green.

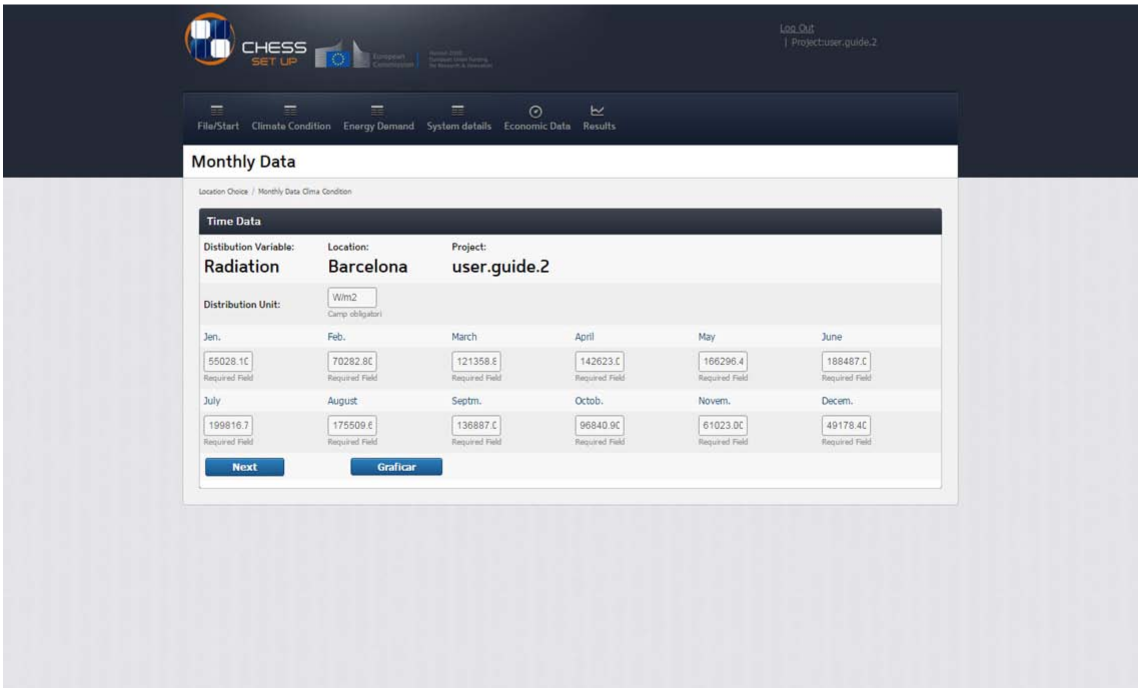
But if you have introduced a location for the first time, you need to go topic by topic, filling in the information necessary to correctly define the climate conditions of your place.

Solar radiation:

Solar radiation is one of the most important data as it will be directly related to the solar panels energy production. The solar radiation in your location can be obtained from the Joint Research Centre (JRC), from EU Science Hub, based on the Photovoltaic Geographical Information System (PVGIS). This is an explanation on how solar radiation can be calculated:

1. Go to Photovoltaic Geographical Information System website.
2. Look for your location.
3. Click on DAILY RADIATION tab (-average daily solar irradiance-). It is considered that the solar radiation will be the same during all days in a month.
4. Fill in the window:
    - Radiation database: Climate-SAF PVSIG.
    - Select month: monthly selection
    - Inclination: 0º (horizontal = 0).
    - Orientation: 0º (south = 0).
    - Select 'Average global irradiance'
5. Press CALCULATE and a pop-up window will appear with the results.
6. Work out an average value for each hour, based on available data in G column (Global irradiance on a fixed plane (W/m2). (Take in account that lack of data is interpreted as lack of solar irradiance at that specific hour).

SOLAR RADIATION is based on hourly data inputs, which define average values for daily basis. Afterwards, monthly values will be automatically generated by our CHESS SETUP SIMULATOR.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Economic Data
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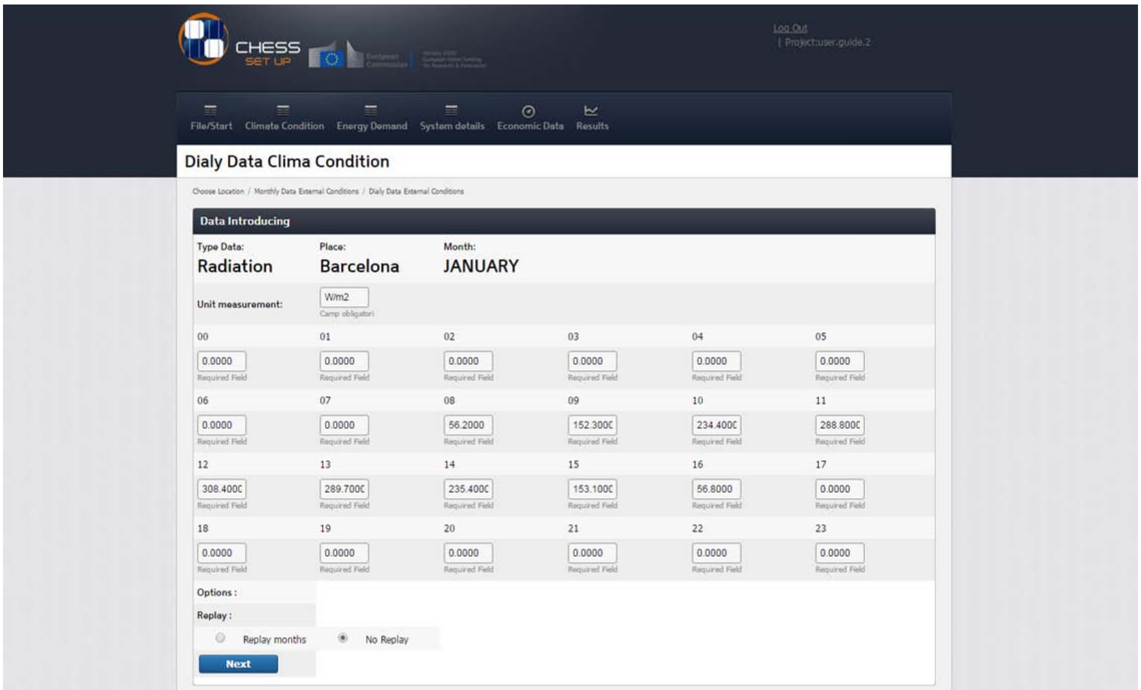
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10
234.400C
11
288.800C
12
308.400C
13
289.700C
14
235.400C
15
153.100C
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17
0.0000
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23
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Options :
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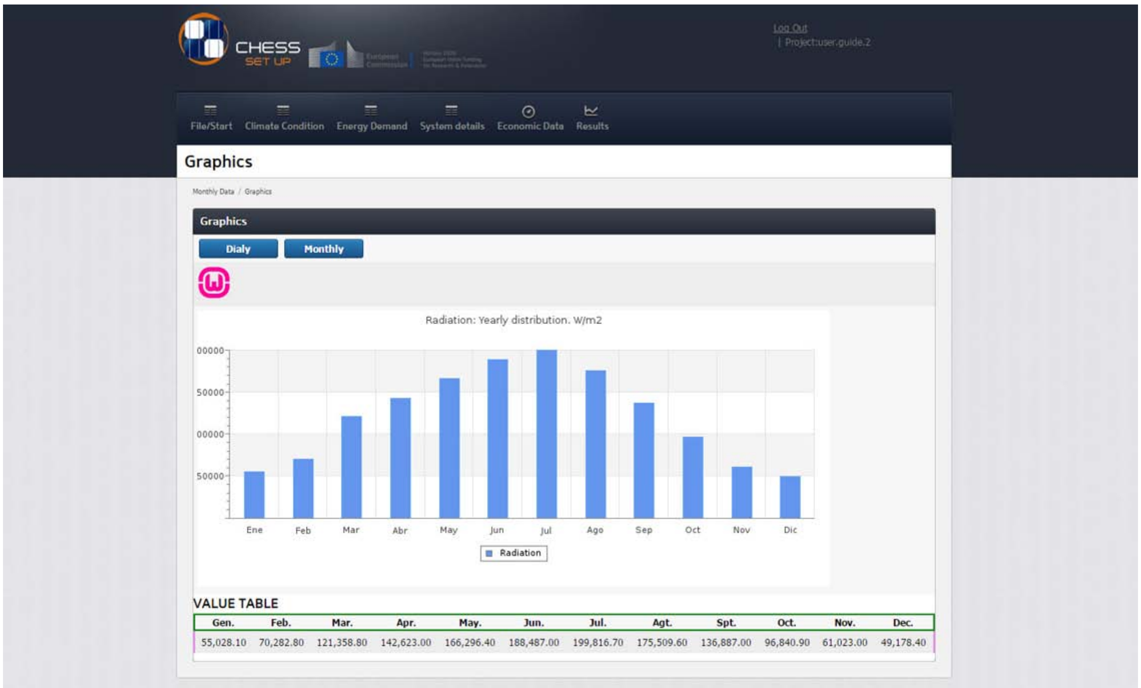
No Replay
Next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File/Start
Climate Condition
Energy Demand
System details
Economic Data
Results
Graphics
Monthly Data / Graphics
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Monthly
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Radiation
VALUE TABLE
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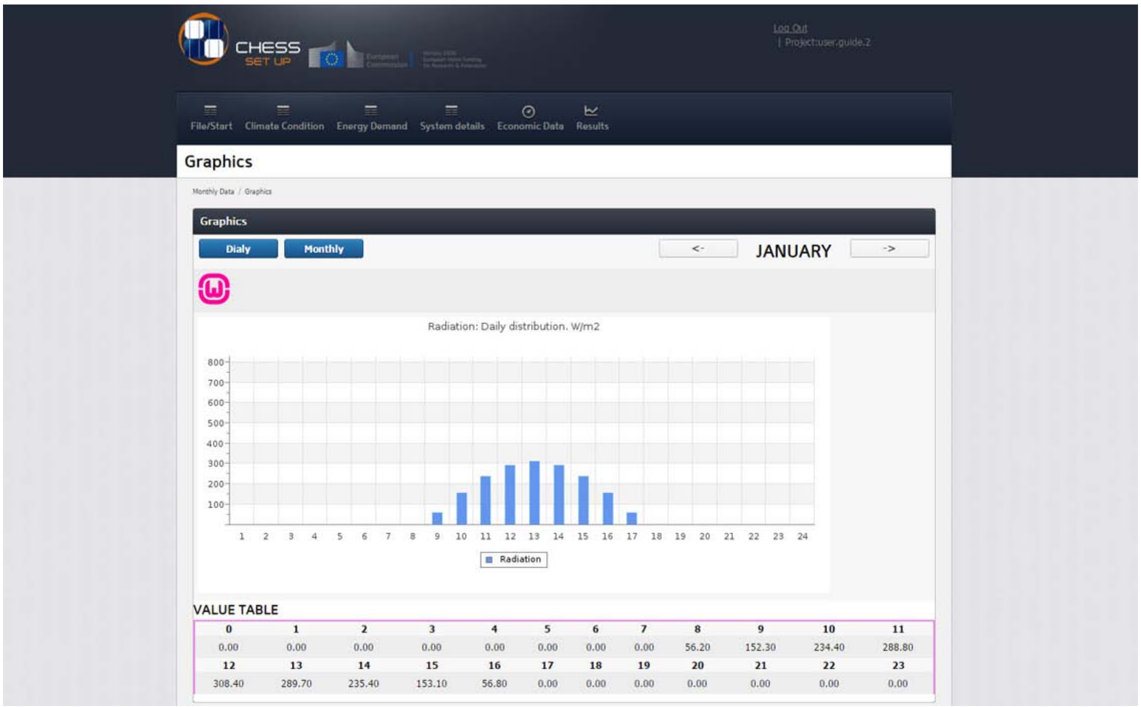
55,028.10 70,282.80 121,358.80 142,623.00 166,296.40 188,487.00 199,816.70 175,509.60 136,887.00 96,840.90 61,023.00 49,178.40


Log Out
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File/Start
Climate Condition
Energy Demand
System details
Economic Data
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Monthly
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JANUARY
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Radiation: Daily distribution. W/m2
800
700
600
500
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200
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Radiation
VALUE TABLE
0 1 2 3 4 5 6 7 8 9 10 11
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 56.20 152.30 234.40 288.80
12 13 14 15 16 17 18 19 20 21 22 23
308.40 289.70 235.40 153.10 56.80 0.00 0.00 0.00 0.00 0.00 0.00 0.00

Air temperature:

This chapter aims to measure the average kinetic energy of air molecules, usually referring to the quantity that would be measured by a thermometer exposed to the air but sheltered from direct solar radiation. Air temperature influences the efficiency of the solar panels as well as the thermal losses of the thermal storage and distribution systems.

The temperature information can be downloaded from climate-data.org. This is an explanation on how air temperature can be calculated:

1. Go to climate-data.org website.
2. Look for your location.
3. Find the monthly average temperatures diagram and copy the data.

AIR TEMPERATURE is based on monthly data inputs. Afterwards, hourly/daily values will be automatically generated by our CHESS SETUP SIMULATOR by considering that air temperature is constant during whole day. For a more precise simulation, please enter hourly temperature data.

Ground temperature:

Soil temperature varies from month to month as it is dependent on various factors, such as solar radiation, rainfall, seasonal swings in overlying air temperature, local vegetation cover, type of soil, and depth in the earth. Due to the much higher heat capacity of soil relative to air and the thermal insulation provided by vegetation and soil surface layers, seasonal changes in soil temperature deep in the ground are minor and lag significantly behind seasonal changes in overlying air temperature.

At soil depths greater than 10 meters below the surface, the ground temperature is relatively constant. That is why we will be applying a constant value of 15ºC for this chapter. Ground temperature will affect the thermal losses of the seasonal water tank when it is located underground.

GROUND TEMPERATURE is based on a previously defined yearly constant data input (15ºC). In case you are interested in adapting and adding some different monthly information, there will be an option. Otherwise, values will be automatically generated by our CHESS SETUP SIMULATOR.

Irradiation:

Solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. Irradiance may be measured in Space or at the Earth's surface after atmospheric absorption and scattering. It is measured perpendicular to the incoming sunlight.

2.5. Energy demand

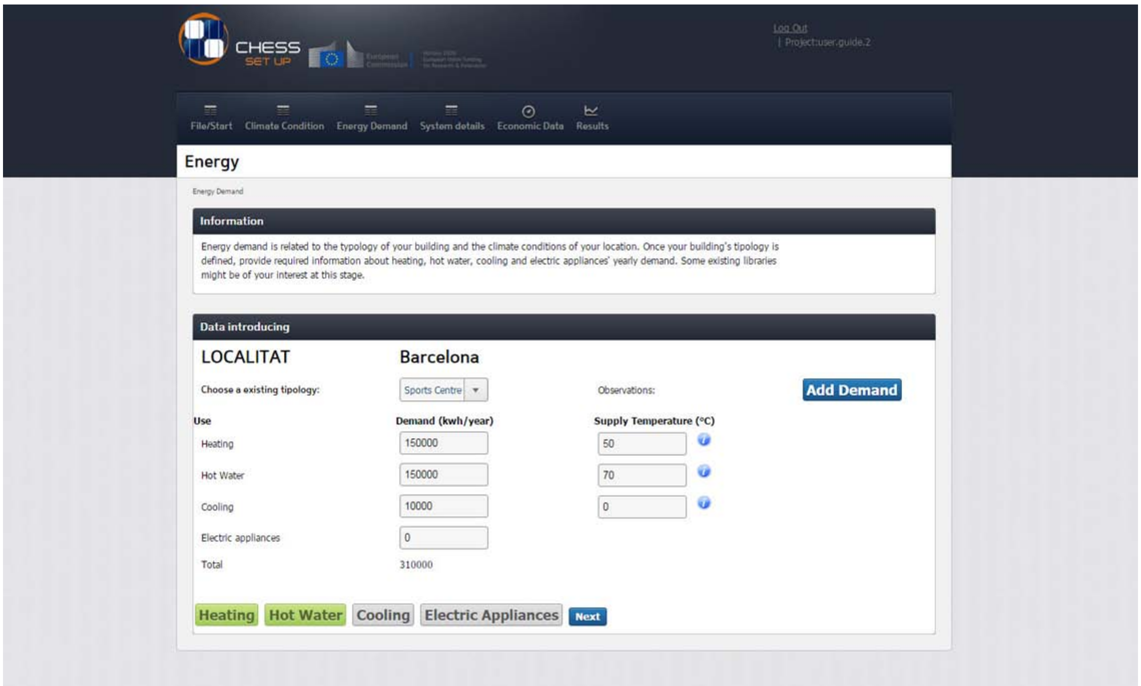
Energy demand is related to the typology of your building and the climate conditions of your location.

First of all, you need to select the type of building you are working with. In the library type of building is defined the temporal distribution of the energy demand.

Afterwards, total annual energy demand has to be defined. Fill in Heating, Hot water, Cooling and Electric appliances demand (kWh/annum) for your project. About Supply Temperature, some reference data will be available depending on the use.

There is a library with the most common typologies already defined with reference values.

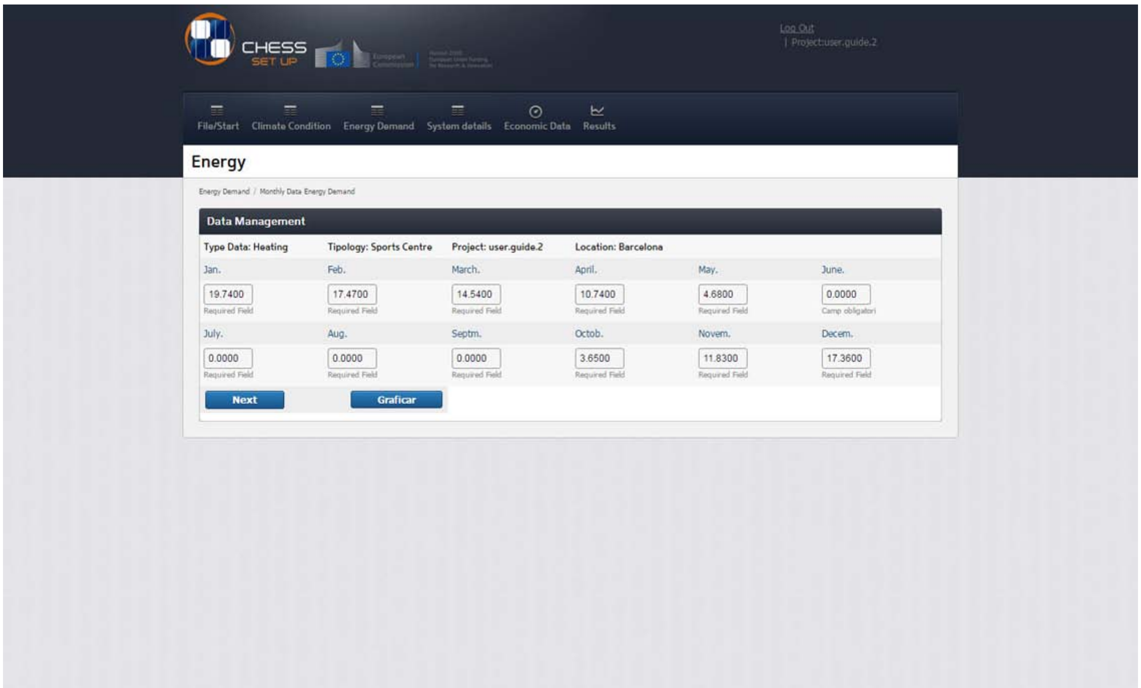
Energy demand is divided in four main themes: HEATING, HOT WATER, COOLING, ELECTRIC APPLIANCES. In this software version only heating and hot water demand are required. In future versions cooling and electric demands will be included, as well as other technologies will be considered, for example, solar cooling or hybrid solar panels.

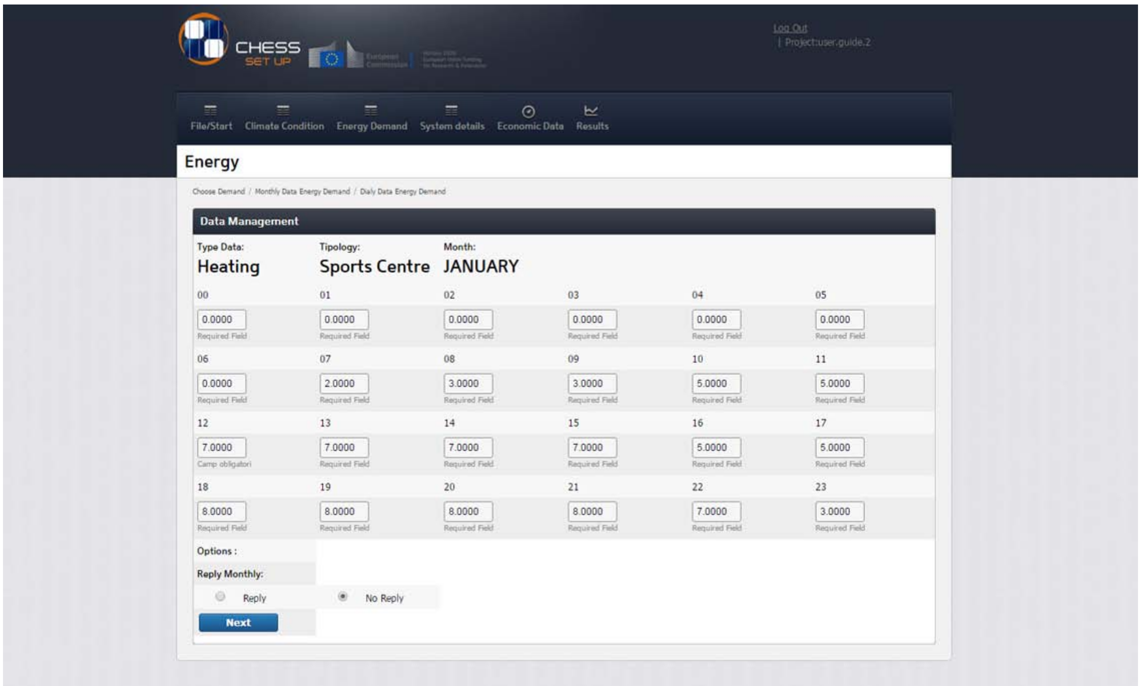


Heating

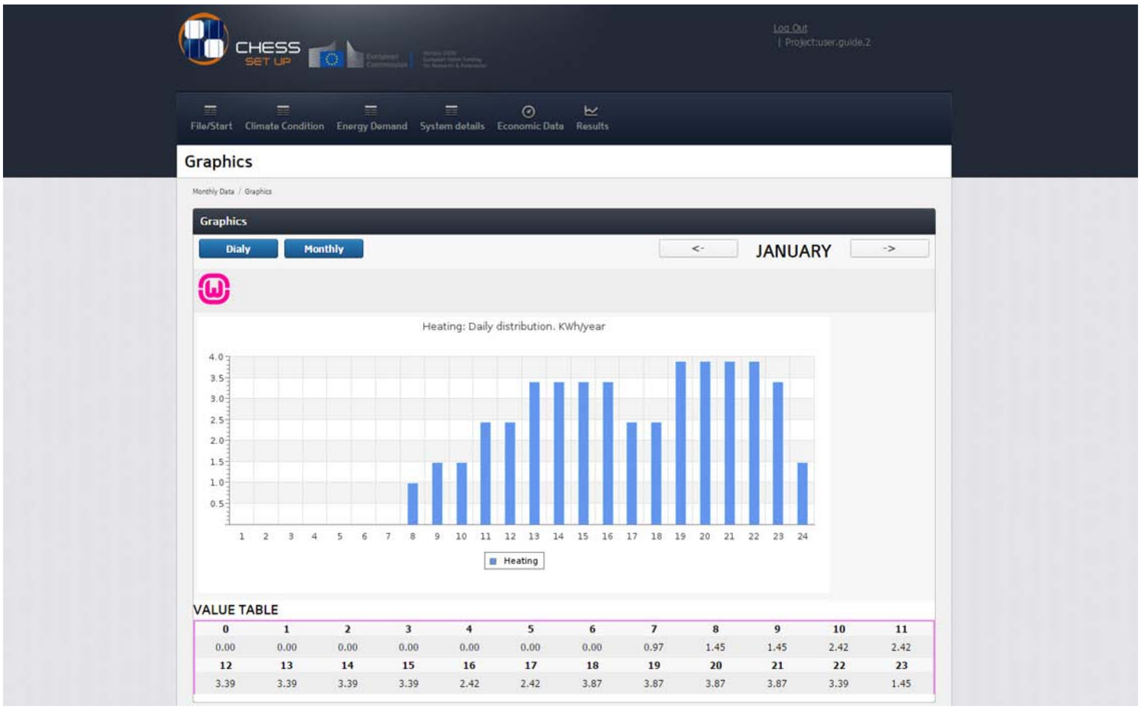
The HEATING DEMAND is defined by the location and by the building typology.

There are already libraries with reference values for the energy demand temporal distribution (month and day) related to location and building typology required data. If new input is needed, take in account that monthly distribution is related to the location and daily distribution is related to building typology.





Gen.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Agt.	Spt.	Oct.	Nov.	Dec.
29,610.00	26,205.00	21,810.00	16,110.00	7,020.00	0.00	0.00	0.00	0.00	5,475.00	17,745.00	26,040.00



0	1	2	3	4	5	6	7	8	9	10	11
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.97	1.45	1.45	2.42	2.42
12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
3.39	3.39	3.39	3.39	2.42	2.42	3.87	3.87	3.87	3.87	3.39	1.45

Hot water

The HOT WATER DEMAND is defined by the location and by the building typology.

There are already libraries with reference values related to location and building typology required data. If new input is needed, take in account that monthly data is related to the location and daily data is related to building typology.

2.6. System details

This section is oriented to select and define the technologies that promote sustainable energy (these include renewable energy sources and technologies designed to improve energy efficiency).

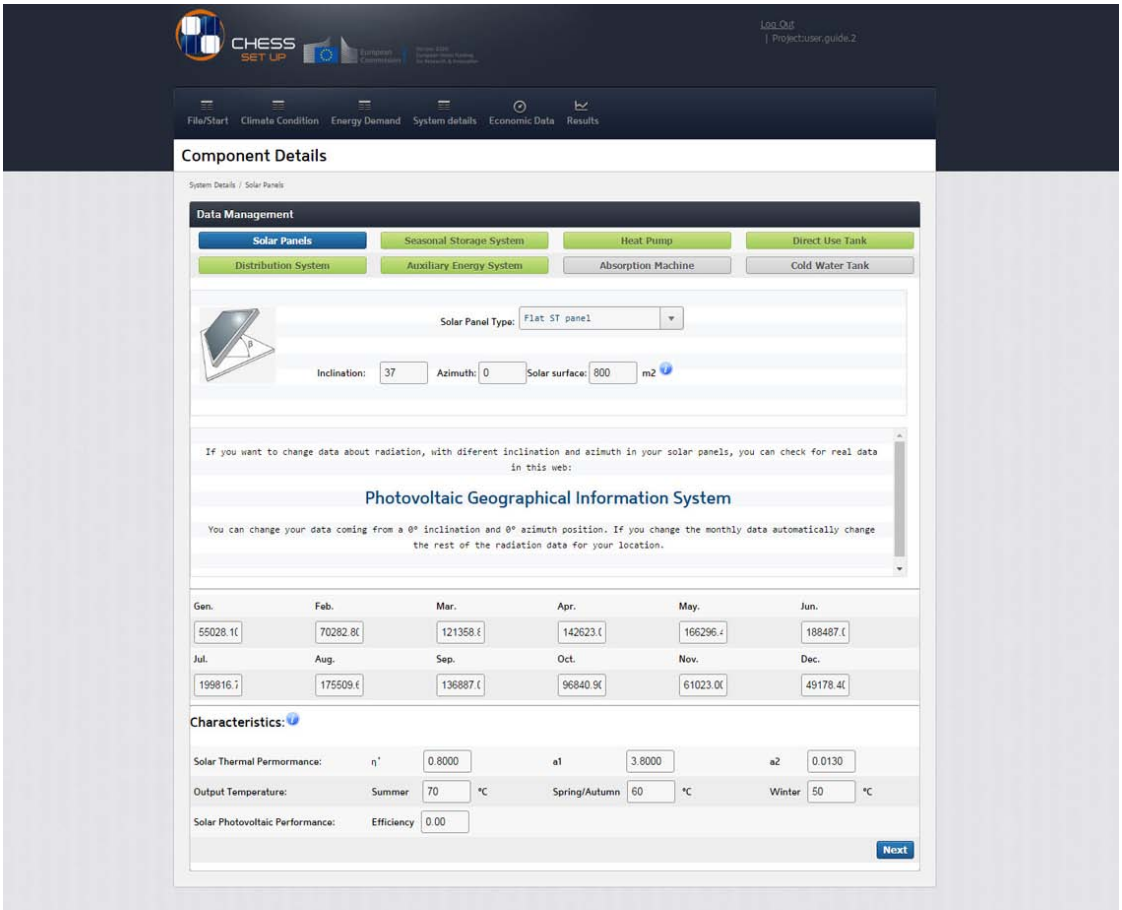
This is how, step by step, CHESS SETUP system works:

Solar panels

Select the Solar Panel Type. The software includes three panel options (vacuum tube panel, flat panel and hybrid solar panel). For each type the software has some reference values of their performance and recommended operation temperatures.

Define the Inclination, Azimuth and Solar surface of your solar panel proposal. It's required to introduce the solar radiation for your inclination and azimuth values.

1. Go to [Photovoltaic Geographical Information System]() website.
2. Look for your location.
3. Click on PV ESTIMATION tab.
4. Fill in the window:
    - Mounting position: Free-standing.
    - Introduce your slope.
    - Introduce your azimuth: (south = 0).
5. Press CALCULATE and a pop-up window will appear with the results.
6. Copy the monthly-data for SOLAR PANELS PERFORMANCE SIMULATION, based on available data in Hm column (Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)). (In order to adjust the data to the required unit (Wh/m2) multiply the results by 1000).



Seasonal storage system

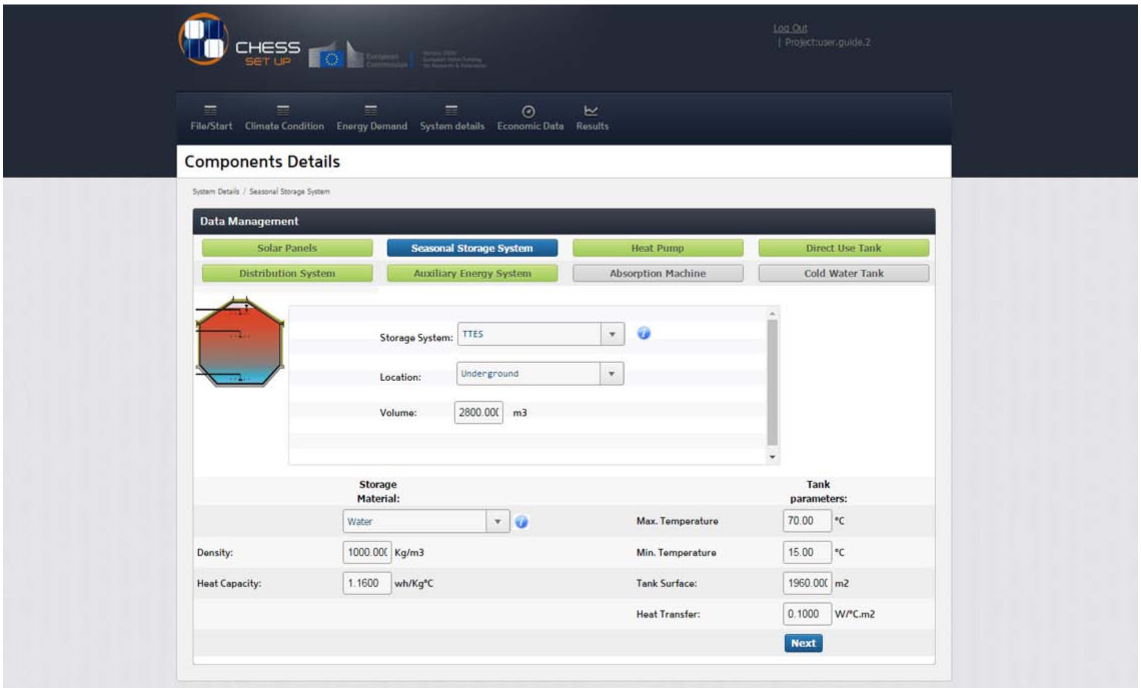
Select your seasonal storage system. There are four types available:

- TTES: Tank Thermal Energy Storage.
- PTES: Pit Thermal energy store.
- ATES: Aquifer Thermal Energy Storage.
- BTES: Borehole Thermal Energy Storage.

Ideally, storage systems are located underground to reduce thermal losses. If the storage system is located outdoor, please change the location cell.

There are some reference parameters already defined for the storage system and storage material selected, but they can be modified.

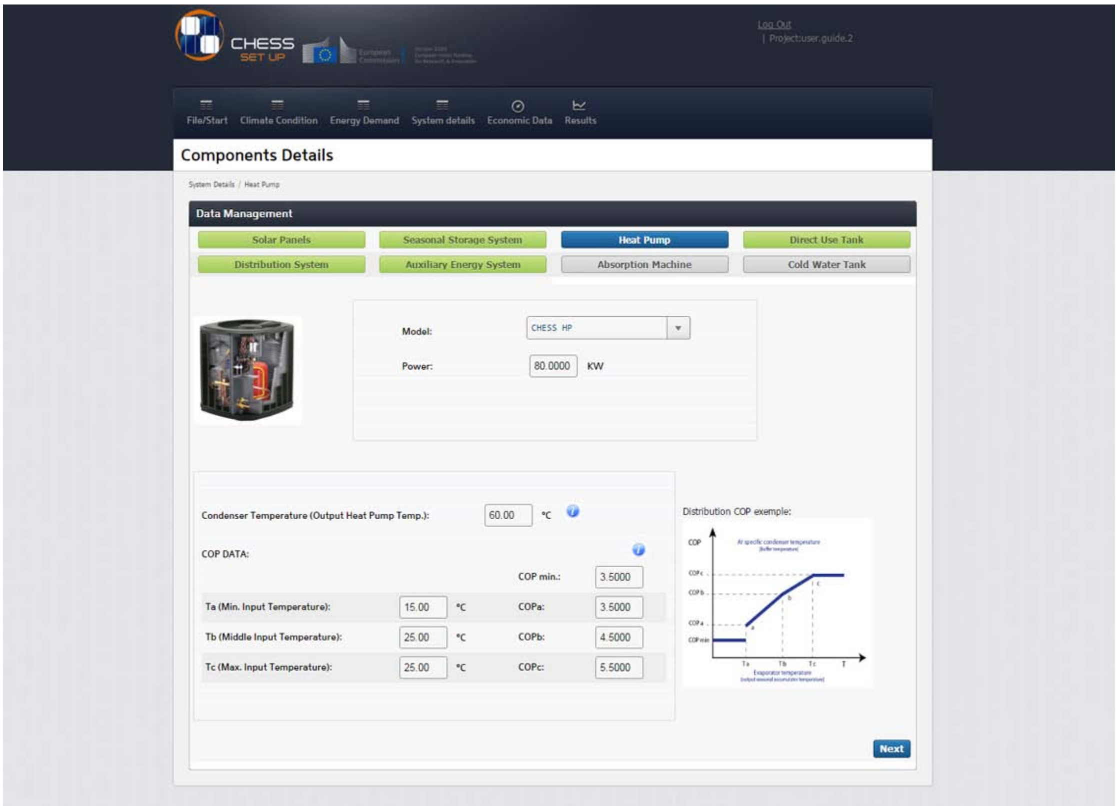
The inputs, you need to add, are tank's VOLUME and SURFACE. Both values are strictly related, as they are shaping the seasonal storage.



Heat pump

There is one model already defined (CHESS HP) with the parameters suitable for the CHESS SETUP system. But, at the same time, you have the opportunity to define your specific heat pump. You will need to fill in every blank; and some assistance will be provided with the pop-up information previously developed by CHESS SETUP SIMULATOR.

Then enter your heat pump power.

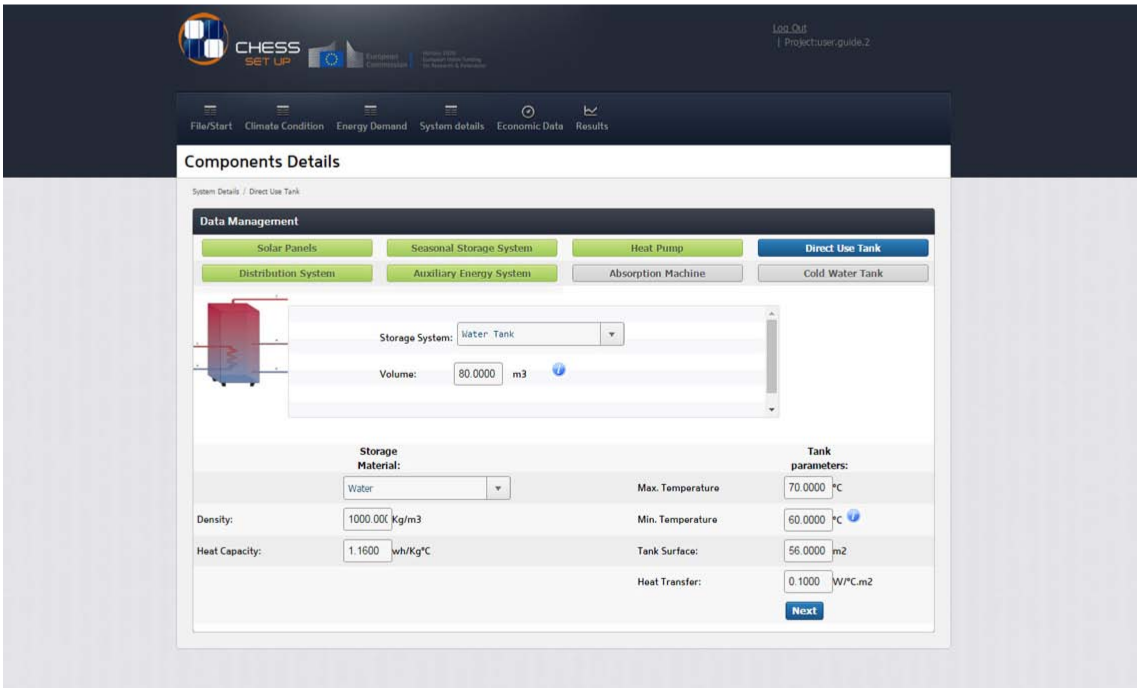


Direct use tank

Select the storage system you are using for this purpose.

Some reference values are already defined, depending on the storage system and storage material selected.

The inputs, you need to add, are tank's VOLUME and SURFACE. Both values are strictly related, as they are shaping the direct-use- storage.

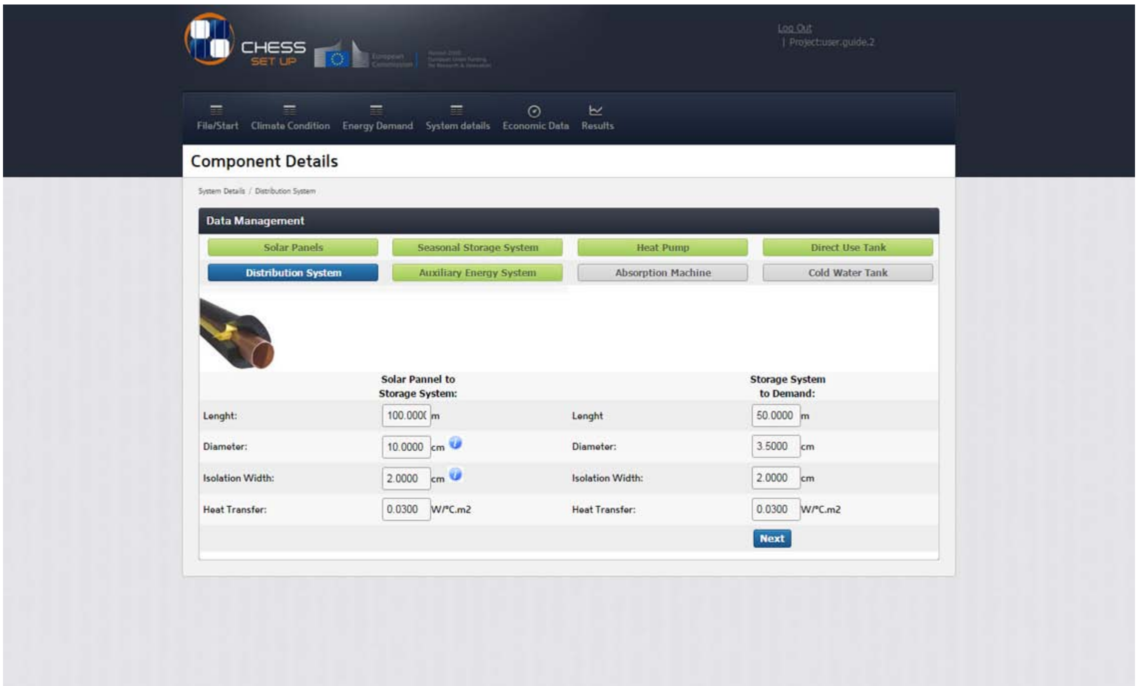


Distribution system

The distribution system is compound of two stretches: a tube from the solar panel to the storage system and a tube from the storage system to the demand.

The length of both sections needs to be measured.

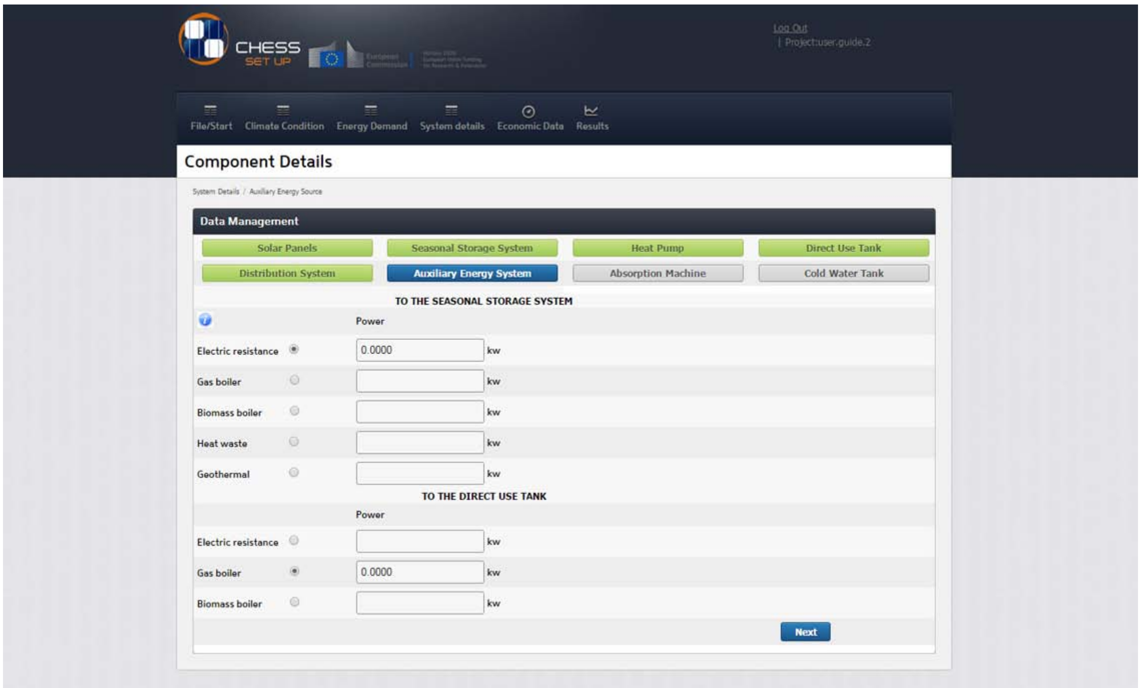
For the rest of the blanks, some reference information will be provided in order to help completing the required data.



Auxiliary energy source

Some auxiliary energy system might be required to achieve the energy demand when there is no available energy in the seasonal storage tank.

In order to size proportionally the auxiliary energy system, for each MWH of Heat Demand, we recommend 1 kW.

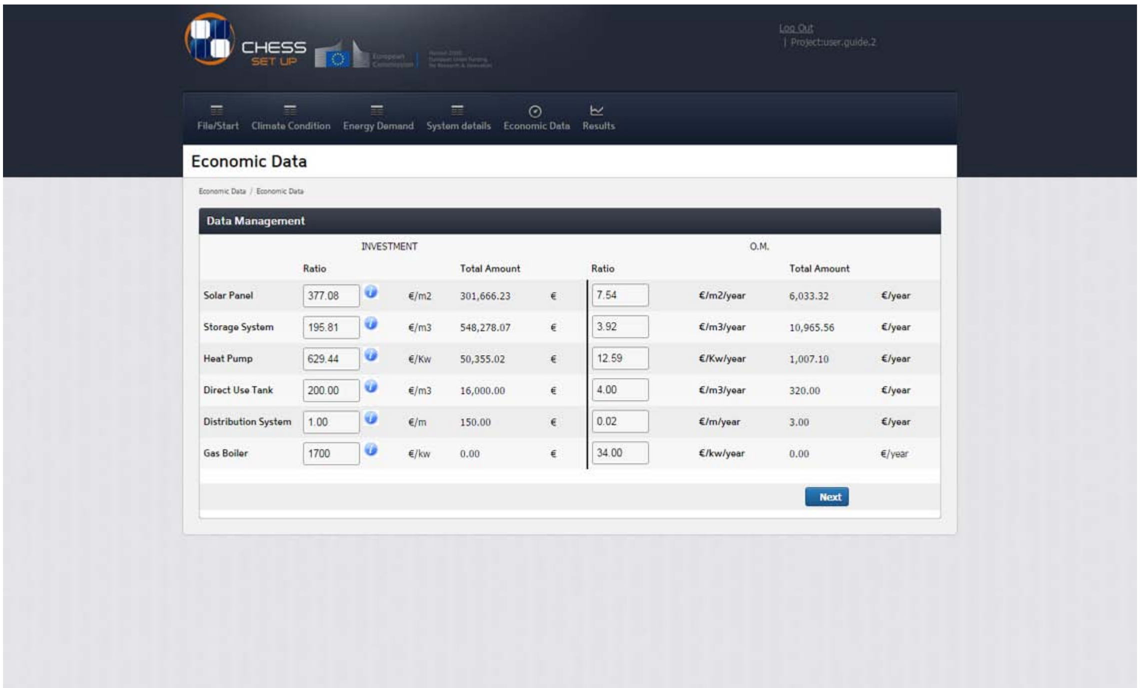


2.7. Economic data

The economic data section provides information about the initial investment and yearly operational maintenance, as well as the energy prices.

The software has some reference values, which are dependent to the size of the system. (See chapter 3.8. Investment costs).

Available pop-ups, explaining the process, might be of your interest at this stage.



2.8. Results

Once every previous section is completed, RESULTS is the last phase. In this phase every available data is processed by the CHESS SETUP SIMULATOR in order to provide specific values for the proposed storage system.

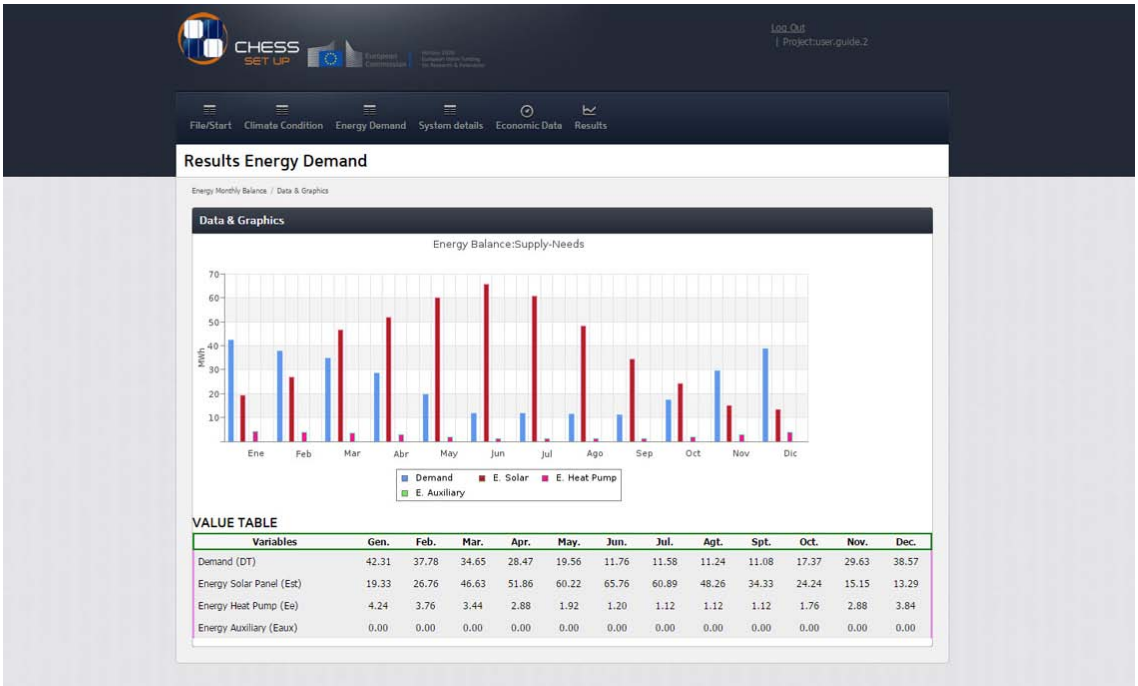
Result motor

Once every required data is gathered, click on RESULTS MOTOR.

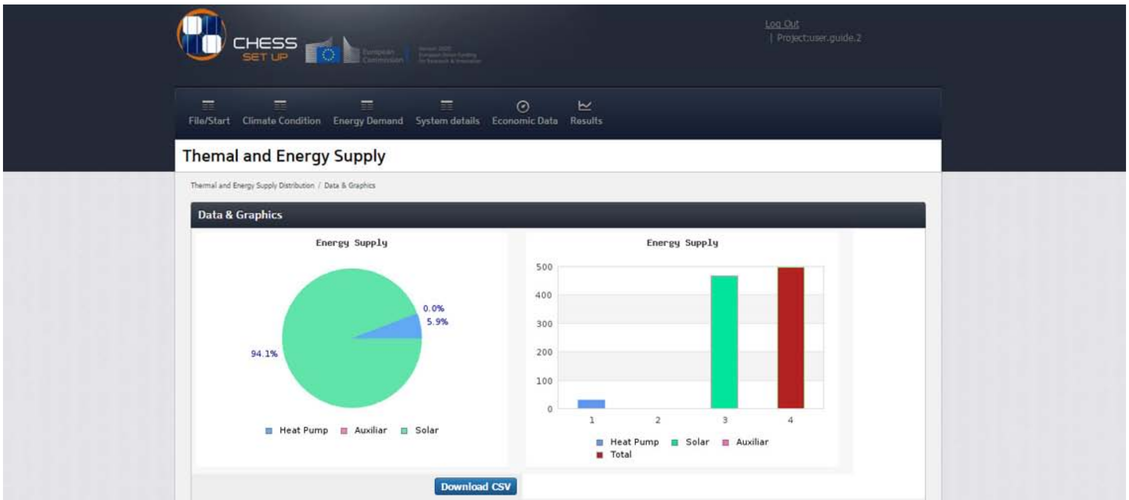
The software calculation will then take place, and due to its complexity, some extra time might be needed. Once the simulation is completed, screen with the main simulation outputs will be visible.

A file in CSV format will be created with these results.

At the same time, you will have the opportunity to observe and analyze some very valuable graphics and data by browsing the RESULTS bar. Monthly Balance, Deposits Temperature and Thermal and Energy Supply Distribution, will be available in order to analyze your proposal.



Variables	Gen.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Agt.	Spt.	Oct.	Nov.	Dec.
Demand (DT)	42.31	37.78	34.65	28.47	19.56	11.76	11.58	11.24	11.08	17.37	29.63	38.57
Energy Solar Panel (Est)	19.33	26.76	46.63	51.86	60.22	65.76	60.89	48.26	34.33	24.24	15.15	13.29
Energy Heat Pump (Ee)	4.24	3.76	3.44	2.88	1.92	1.20	1.12	1.12	1.12	1.76	2.88	3.84
Energy Auxiliary (Eaux)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



Thermal self sufficiency:	0.90	%
Energy consumption saving:	316,619.47	kWh/year
Total demand:	294,014.55	kWh/year
Primary energy saving:		
CO2 emissions reduction:		
Economic Saving:		
Balance economics:		
SOLAR PANEL		
Solar panel type:	Flat ST panel	
Panel Surface:	800	m2
Thermal yearly efficiency:	0.00	%
Thermal production:	466,723.50	kWh/year
Electrical production:	0.00	kWh/year
Production ratio:	583.40	kWh/year/m2
HEAT PUMP		
Heat Pump:	80.00	kW
Yearly COP:	10.00	
Energy consumption:	29,280.00	kWh/year
AUXILIARY SYSTEM		
Auxiliary System:	Gas Boiler	
Yearly Efficiency:		%
Energy consumption:	0	kWh/year
SEASONAL STORAGE SYSTEM		
Storage System:	Water	
Storage Volume:	2,800.00	m3
Max. Temperature(2 years):	124.64	°C
Min. Temperature(2 years):	76.72	°C
Autonomy Days:	213.29	kWh/year
LOSSES		
Thermal losses:	0.35	%
Total losses:	175,683.10	kWh/year
Direct Tank Use losses:	2,226.35	kWh/year
Storage Deposit losses:	147,582.60	kWh/year
Distribution losses:	25,874.16	kWh/year

3. Calculation methodology

3.1. Introduction

This chapter defines all the formulas and variable used in order to simulate the CHESS SETUP. These balances are calculated through mass and energy balances and applied to all CHESS SETUP components (solar panels, storage tanks, heat pump, auxiliary systems...). The equations that solve all the system are known as implicit equations and are solved by iterative methods.

It is desirable that the increment time simulation (step) was 1 hour and the total period simulated was extended to 2 years of duration.

3.2. Global system and variables

The figure below describes the main variables and components of the CHESS SETUP, as well as some possible system configurations.

CHESS SETUP system can be divided into 5 subsystems.

1) Thermal demand circuit
2) Buffer (direct use tank)
3) Thermal solar panels
4) Seasonal thermal energy storage (STES)
5) Heat pump

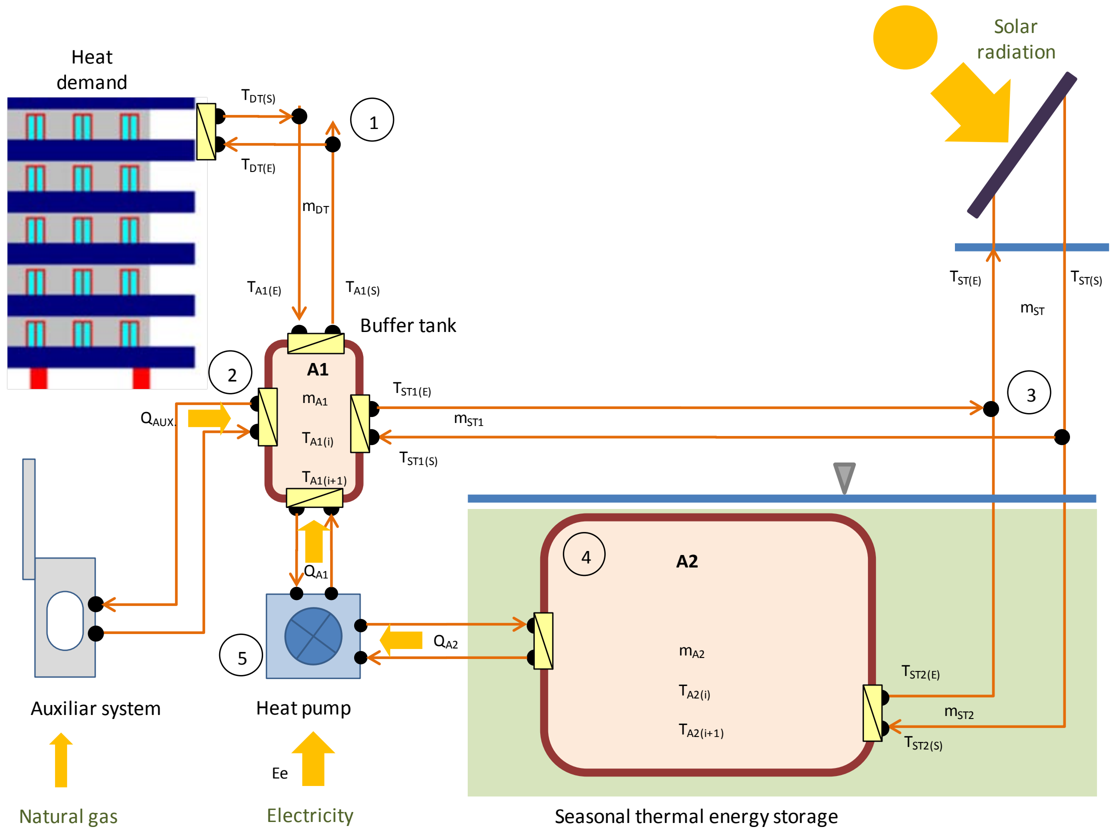


Figure: General scheme and variables of CHESS SETUP

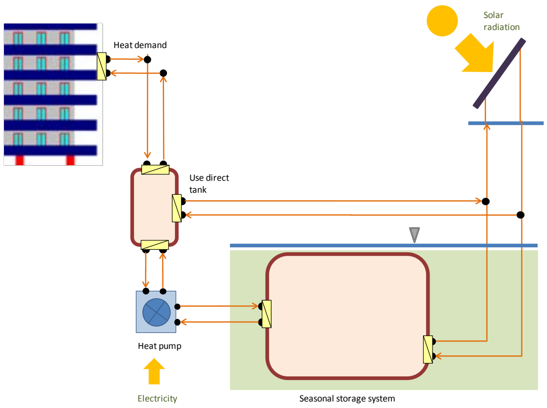
$T_{TD(O)}$ = outlet temperature at thermal demand point [ºC]
$T_{TD(I)}$ = inlet temperature (supply temperature) at thermal point [ºC]
m_{TD} = water mass of the thermal demand circuit [kg]
$T_{A1(O)}$ = outlet temperature from the buffer (A1) [ºC]
$T_{A1(I)}$ = inlet temperature from the buffer (A1) [ºC]
m_{A1} = water mass inside of the buffer[kg]
$T_{A1(i)}$ = water temperature of the buffer at time = i [ºC]
$T_{A1(i+1)}$ = water temperature of the buffer at time = i +1 [ºC]
m_{A2} = water mass inside of the seasonal tank [kg]
$T_{A2(i)}$ = water temperature of the seasonal tank at time = i [ºC]
$T_{A2(i+1)}$ = water temperature of the seasonal tank at time = i +2 [ºC]
$T_{ST(O)}$ = outlet temperature of the solar thermal panels [ºC]
$T_{ST(I)}$ = inlet temperature of the solar thermal panels [ºC]
m_{ST} = total water mass in the solar thermal circuit [ºC]
$T_{ST1(O)}$ = outlet water temperature from solar panels to the buffer (A1) [ºC]
$T_{ST1(I)}$ = inlet water temperature from solar panels to the buffer (A1) [ºC]
m_{ST1} = water mass of the thermal demand circuit to the buffer (A1) [ºC]
$T_{ST2(O)}$ = outlet water temperature from solar panels to the seasonal tank (A2) [ºC]

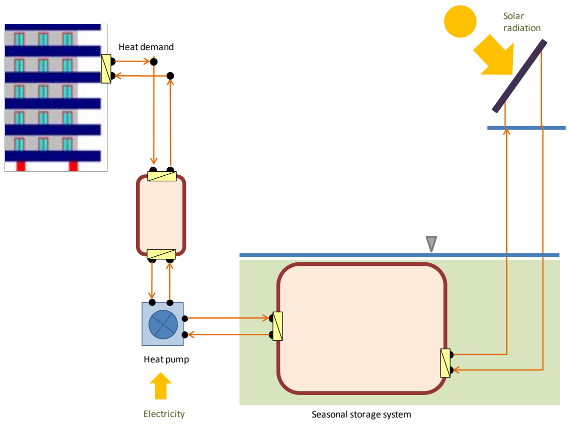
$T_{ST2(I)}$ = *inlet water temperature of to solar pannels coming from the seasonal tank (A2) [ºC]*
m_{ST2} = *water mass from solar thermal circuit to the seasonal tank (A2) [kg]*
H_{A1} = *supplied heat for the heat pump to the buffer [kWh]*
H_{A2} = *absorbed heat from the seasonal tank by the heat pump [kWh]*
Ee = electric energy consumed by the heat pump [kWh]
H_{aux} = *energy consumed by the auxiliary system (boiler) [kWh]*
Ce_{H_2O}= *water specific heat [1.16 Wh/(kg·ºC)]*

There are many possible configurations for the CHESS SYSTEM. However the software only takes in consideration two next configurations:

Configuration 1: Solar panels can supply energy directly to the use tank or to the seasonal storage system.

Configuration 2: Solar panels always supply energy to the seasonal storage system





3.3. Thermal demand circuit

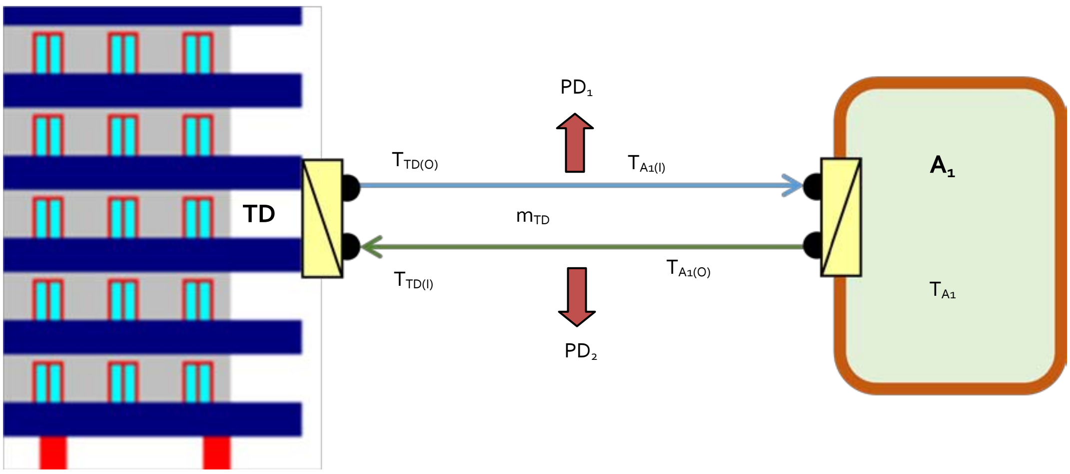


Figure: Heat demand circuit schema and variables

TD = heat demand in a particular period of time [kWh]
PD = heat losses in distribution [kWh]
PD_1 = heat losses in the return circuit [kWh]
PD_2 = heat losses in the supply circuit [kWh]
T_{A1} = Average temperature in accumulator 1 [ºC]

Next considerations are taken:

- Heat exchangers are highly efficient: $T_{A1(O)} = T_{A1}$
- The temperature in heat pipes descends a 1%: $T_{TD(I)} = T_{A1(O)} \cdot 99\%$; $T_{A1(I)} = T_{TD(O)} \cdot 99\%$
- Temperature inside every accumulator is the average of temperatures between time *i* and time *i+1*
- Outlet temperature of heat demand $T_{TD(O)}$ is constant and equal to 50ºC.

$$T_{A1} = \frac{T_{A1(i)} + T_{A1(i+1)}}{2} \qquad m_{DT} = \frac{TD}{ce_{H2O} \cdot (T_{TD(I)} - T_{TD(O)})}$$

$$\left.\begin{array}{l} \boldsymbol{P_{D1} = m_{TD} \cdot ce_{H2O} \cdot (T_{A1(I)} - T_{DT(O)})} \\ \\ \boldsymbol{P_{D2} = m_{TD} \cdot ce_{H2O} \cdot (T_{DT(I)} - T_{A1(O)})} \end{array}\right\} \boldsymbol{P_D = P_{D1} + P_{D2} = m_{TD} \cdot ce_{H2O} \cdot (T_{TD(I)} + T_{A1(I)} - T_{TD(O)} - T_{A1(O)})}$$

3.4. Buffer tank

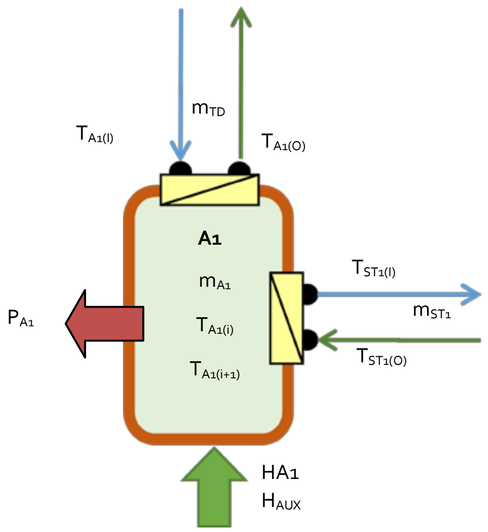


Figure: buffer tank schema and variables

P_{A1} = heat loses in the buffer [kWh]
U_{A1} = thermal transmission coefficient of the buffer [W/m^{2}K]
S_{A1} = surface of the buffer [m^2]
T_{ext} = external temperature [ºC]

Next considerations are taken:

- Heat exchangers are highly efficient: $T_{A1(O)} = T_{A1}$; $T_{ST1(I)} = T_{A1}$
- Outlet temperature of solar installations $T_{ST1(O)}$ is constant (variable according to the season of the month)

Buffer tank thermal balance:

$$\left(T_{ST1(O)} - T_{ST1(I)}\right) \cdot m_{ST1} \cdot Ce_{H2O} + H_{A1} + H_{AUX} = \left(T_{A1(i+1)} - T_{A1(i)}\right) \cdot m_{A1} \cdot Ce_{H2O} + \left(T_{A1(O)} - T_{A1(I)}\right) \cdot m_{TD} \cdot Ce_{H2O} + P_{A1}$$

$$T_{A1(i+1)} = \frac{\left(T_{ST1(O)} - T_{A1}\right) \cdot m_{ST1} \cdot Ce_{H2O} + H_{A1} + H_{AUX} - \left(T_{A1} - T_{A1(I)}\right) \cdot m_{TD} \cdot Ce_{H2O} - P_{A1}}{m_{A1} \cdot Ce_{H2O}} + T_{A1(i)}$$

$$P_{A1} = S_{A1} \cdot U_{A1} \cdot (T_{A1} - T_{ext})$$

$$T_{A1(i+1)} = \frac{\left(T_{ST1(O)} - T_{A1}\right) \cdot m_{ST1} \cdot Ce_{H2O} + H_{A1} + H_{AUX} - \left(T_{A1} - T_{A1(I)}\right) \cdot m_{TD} \cdot Ce_{H2O} - S_{A1} \cdot U_{A1} \cdot (T_{A1} - T_{ext})}{m_{A1} \cdot Ce_{H2O}} + T_{A1(i)}$$

3.5. Seasonal storage tank

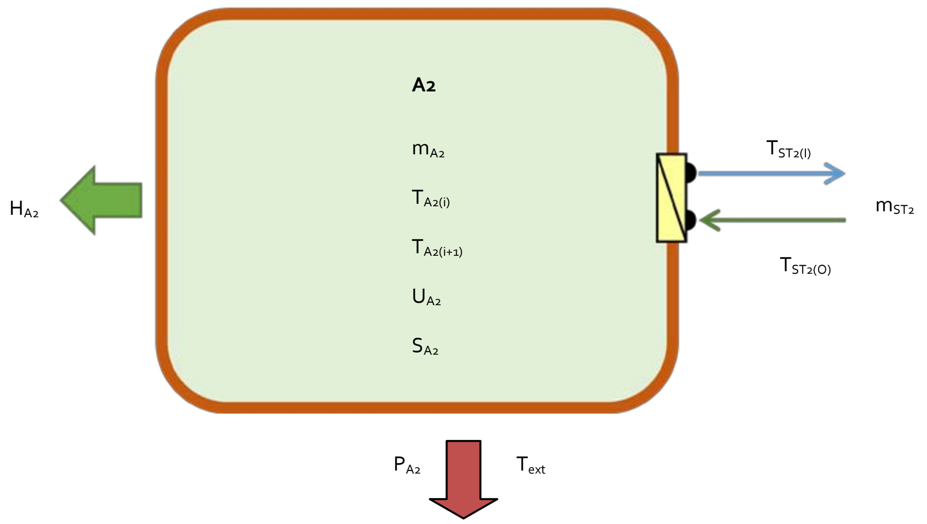


Figure: Seasonal storage scheme

P_{A2} = thermal loses in seasonal tank (A2)
U_{A2} = thermal transmission coefficient of seasonal tank [W/m²K]
S_{A2} = surface of seasonal tank [m²]
T_{ext} = external temperature [ºC]

Next considerations are taken:

- Temperature inside every accumulator is the average of temperatures between time *i* and time *i+1*
- Heat exchangers are highly efficient: $T_{ST2(I)} = T_{A2}$
- Outlet temperature from solar installation $T_{ST2(O)}$ is constant

$$T_{A2} = \frac{T_{A2(i)} + T_{A2(i+1)}}{2}$$

$$\left(T_{ST2(O)} - T_{ST2(I)}\right) \cdot m_{ST2} \cdot Ce_{H2O} = \left(T_{A2(i+1)} - T_{A2(i)}\right) \cdot m_{A2} \cdot Ce_{H2O} + P_{A2} + H_{A2}$$

$$T_{A2(i+1)} = \frac{\left(T_{ST2(O)} - T_{A2}\right) \cdot m_{ST2} \cdot Ce_{H2O} - H_{A2} - P_{A2}}{m_{A2} \cdot Ce_{H2O}} + T_{A2(i)}$$

$$P_{A2} = S_{A2} \cdot U_{A2} \cdot (T_{A2} - T_{ext})$$

$$T_{A2(i+1)} = \frac{\left(T_{ST2(O)} - T_{A2}\right) \cdot m_{ST2} \cdot Ce_{H2O} - H_{A2} - S_{A2} \cdot U_{A2} \cdot (T_{A2} - T_{ext})}{m_{A2} \cdot Ce_{H2O}} + T_{A2(i)}$$

3.6. Solar system

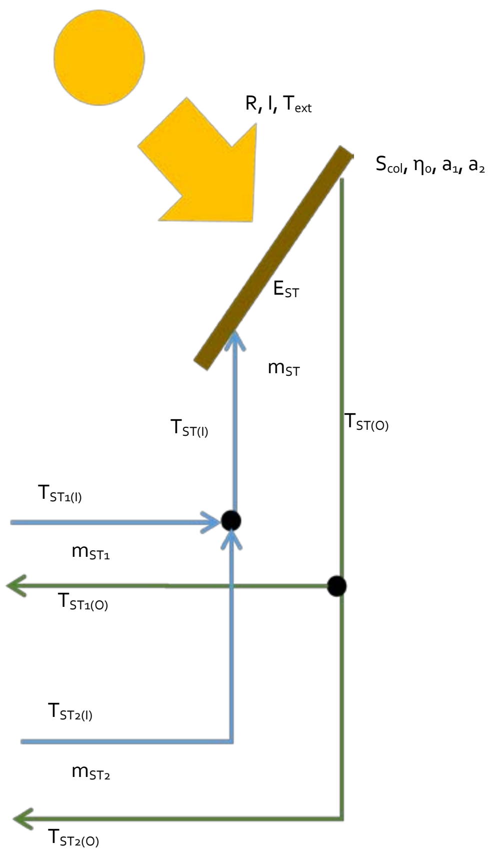


Figure: Solar system scheme and variables

R = solar radiation [Wh/m²]
I = solar irradiation [W/m²]
T_{ext} = outside temperature [ºC]
S_{col} = colector surface [m²]
η = colector performance [º/1]
η_0, a_1, a_2 = *coefficients that define the efficiency of the solar panel*
T_{col} = colector temperature [ºC]
E_{ST} = Energy captured by solar thermal panels [Wh]

Next considerations are taken:

- Outlet temperature of the solar system is constant through the day but it changes on depending of season. (Higher on summer and lower on winter).
- It is considered that the return water temperature that reaches the accumulator (A1) will be 1% less than the outlet temperature from solar system. $T_{ST1(O)} = T_{ST2(O)} = 99\% \cdot T_{ST(O)}$
- The return temperatures to the solar system will be equal to the temperatures of the accumulator from which comes from: $T_{ST1(I)}=T_{A1}$; $T_{ST2(I)}=T_{A2}$

Mass balance:

$$m_{ST} = m_{ST1} + m_{ST2}$$

Thermal balance

$$T_{ST(E)} = \frac{m_{ST1} \cdot T_{ST1(I)} + m_{ST2} \cdot T_{ST2(I)}}{m_{ST}} = \frac{m_{ST1} \cdot T_{A1} + m_{ST2} \cdot T_{A2}}{m_{ST}}$$

Solar production:

$$\left.\begin{aligned}
&\boldsymbol{m_{ST}} = \frac{\boldsymbol{E_{ST}}}{\boldsymbol{Ce_{H2O} \cdot (T_{ST(O)} - T_{ST(I)})}} \\
&\boldsymbol{E_{ST}} = \boldsymbol{R \cdot \eta \cdot S_{col}} \\
&\boldsymbol{\eta} = \boldsymbol{\eta_o - a_1 \cdot \frac{(T_{col} - T_{ext})}{I} - a_2 \cdot \frac{(T_{col} - T_{ext})^2}{I}} \\
&\boldsymbol{T_{col}} = \frac{\boldsymbol{T_{ST(O)} + T_{ST(I)}}}{\boldsymbol{2}}
\end{aligned}\right\}$$

$$m_{ST} = \frac{R \cdot \left(\eta_o - a_1 \cdot \frac{\left(\frac{T_{ST(O)} + T_{ST(I)}}{2} - T_{ext}\right)}{I} - a_2 \cdot \frac{\left(\frac{T_{ST(O)} + T_{ST(I)}}{2} - T_{ext}\right)^2}{I}\right) \cdot S_{col}}{Ce_{H2O} \cdot \left(T_{ST(O)} - T_{ST(I)}\right)}$$

As exposed before there are two possible configurations of the system:

<u>Configuration 1: Solar panels can supply energy directly to the use tank or to the seasonal storage system.</u>

It is defined a maximum temperature for the buffer (T_{A1max}). As default the solar panels will supply the heat directly to the buffer. But when the buffer temperature exceeds the TA1max the heat will be supplied to the seasonal tank.

If: $T_{A1(i+1)} \geq T_{A1max} \rightarrow m_{ST2} = m_{ST}$

$T_{A1(i+1)} < T_{A1max} \rightarrow m_{ST1} = m_{ST}$

<u>Configuration 2: Solar pannels always supply energy to the seasonal storage system</u>

$m_{ST2} = m_{ST}$

$m_{ST1} = 0$

3.7. Heat pump

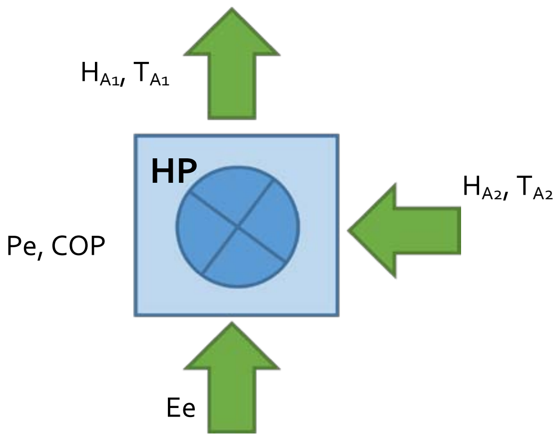


Figure: Heat pump scheme and variables

COP = Coefficient of Performance
Pe = Heat pump electrical power

Thermal balance:

$$H_{A1} = H_{A2} + Pe$$

$$H_{A2} = COP \cdot Pe$$

The COP will be provided by the heat pump supplier. It's required to have the COP for different operation temperatures of the cold focus (T_{A2}) and hot focus (T_{A1}).

To control the operation of the heat pump it's defined a minimum temperature for the buffer (T_{A1min}). When the buffer temperature is lower than T_{A1min} the heat pump is activated. Besides it's defined a minimum temperature of the seasonal tank (T_{A2min}). When the seasonal tank temperature is lower than TA2min the heat will be supplied by the auxiliary system.

If: $T_{A1(i+1)} > T_{A1min} \rightarrow Pe = 0 \rightarrow H_{A2} = 0 \rightarrow H_{A1} = 0$

$T_{A1(i+1)} \leq T_{A1min};\ T_{A2(i+1)} > T_{A2min} \rightarrow Pe \geq TD_{max}$

$T_{A1(i+1)} \leq T_{A1min};\ T_{A2(i+1)} \leq T_{A2min} \rightarrow Pe = 0; H_{AUX} \geq TD_{max}$

The heat pump electrical power (Pe) and the auxiliary system power (H_{AUX}) will be higher than the maximum thermal demand point during the year (TD_{max}).

TD_{max} = maximum thermal demand point [W]
T_{A1min} = minimum temperature for the buffer (ºC)
T_{A2min} = minimum temperature of the seasonal tank (ºC)

3.8. Investment costs

Main investment costs of CHESS SETUP are related to solar panels, seasonal tank and heat pumps. The investment is related to the system size. For example, as bigger is the solar surface lower investment cost per m² of solar panel will be required.

Maintenance costs are between 1-3% of the total investment costs.

Data and results from Einstein project have been used:

3.8.1. Solar thermal panels

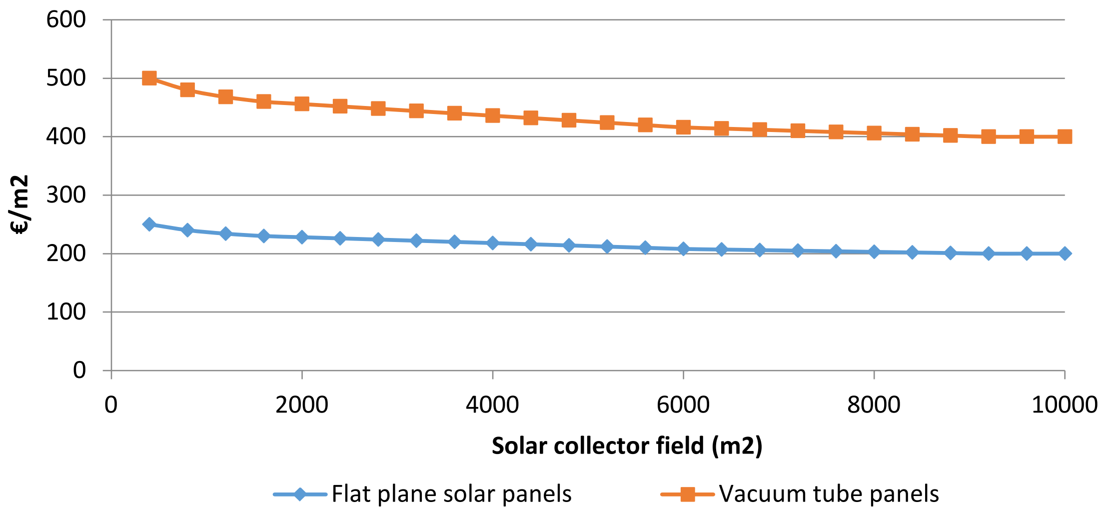


Figure: Solar panels price according to the solar collector surface. (Source: adaptation from Einstein project)

Flat plane solar panels:

Vacuum tube solar panels:

S<400 m² → 250 €/m²
S>400 m² → $(397^* S)^{-0,077}$ €/m²

S<400 m² → 500 €/m²
S>400 m² → $2^*(397^* S)^{-0,077}$ €/m²

3.8.2. Seasonal storage system

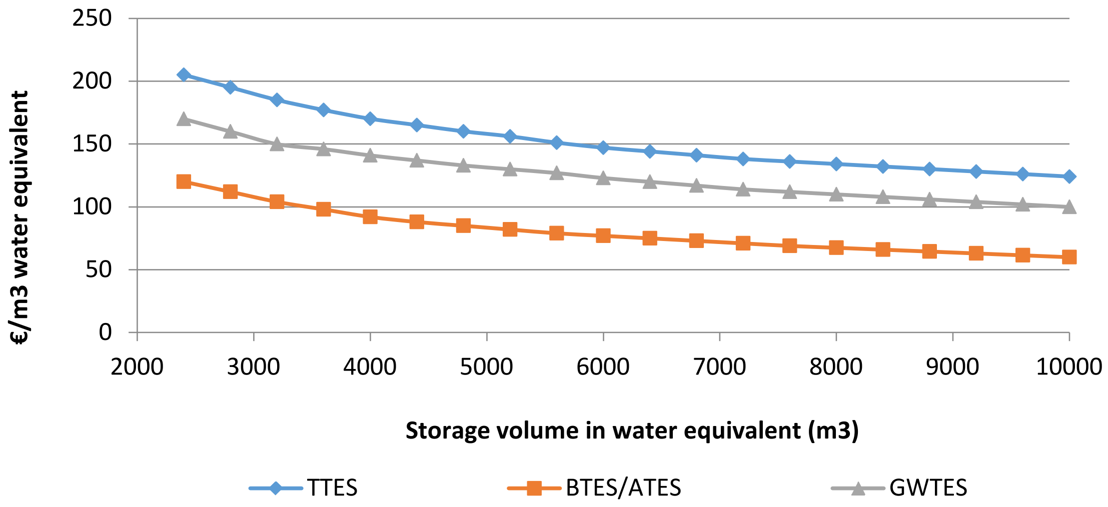


Figure: Seasonal storage price according to the storage volume. (Source: adaptation from Einstein project)

TTES

V<2.000 m³ → 250 €/m²

V>2.000 m³ < V < 10.000 m³ → $(3162,8^*V)^{-0,3505}$ €/m³

V>10.000 m3 → 125 €/m³

BTES/ATES

V<2.000 m³ → 175 €/m²

V>2.000 m³ < V < 10.000 m³ → $(2834,5^*V)^{-0,363}$ €/m³

V>10.000 m3 → 100 €/m³

GWTES

V<2.000 m³ → 128 €/m²

V>2.000 m³ < V < 10.000 m³ → $(4800,9^*V)^{-0,477}$ €/m³

V>10.000 m³ → 60 €/m³

3.8.3. Heat pump

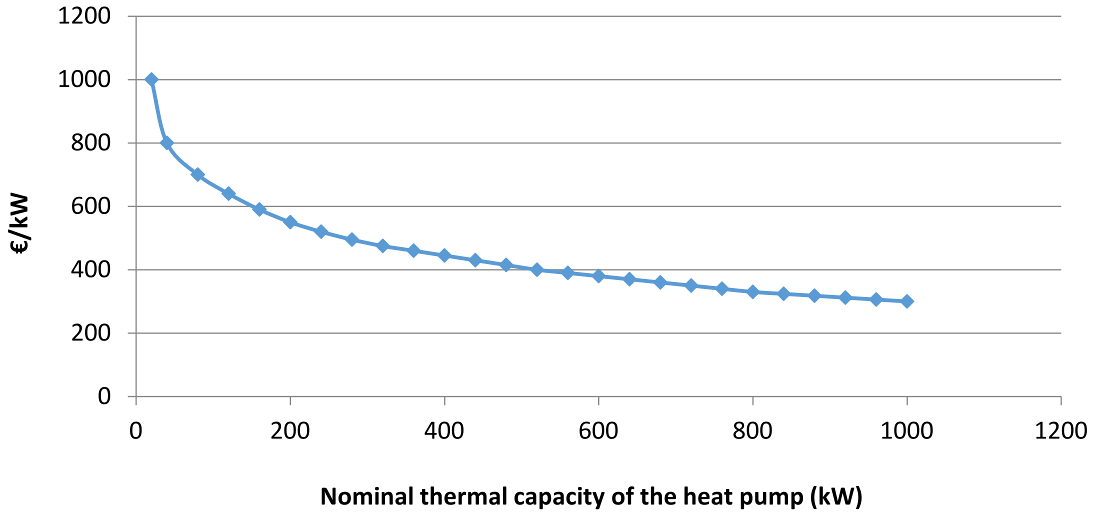


Figure: Heat pump price according to the nominal thermal capacity. (Source: adaptation from Einstein project)

P<20 kW → 1.000 €/kW

20 kW < P < 1.000 kW → $(2720{,}1*P)^{-0{,}334}$ €/kW

P>1.000 kW → 300 €/kW

3.8.4. Other equipment

For the other CHESS SETUP equipments have been used next values:

- Direct use tank (buffer): 200 €/m3
- Distribution system: 1 €/m
- Auxiliary system: 250 €/kW