This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

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SIMULATION SOFTWARE

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20/02/2019	4	BCNecologia		Correction

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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 quick 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).

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

The software results should not be used for precise sizing, but rather just to have an idea of the system sizing, 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 a 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 in 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 centres…).

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.

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 is public and available in the CHESS SETUP webpage (http://chess-setup-similator.net/login.php) and can be accessed for free using the following codes:

User: demo Password: demo

For each project, a report with the main results can be created and most relevant data can be extracted in an *.csv file.

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1.2. Software structure

The software is composed of 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.

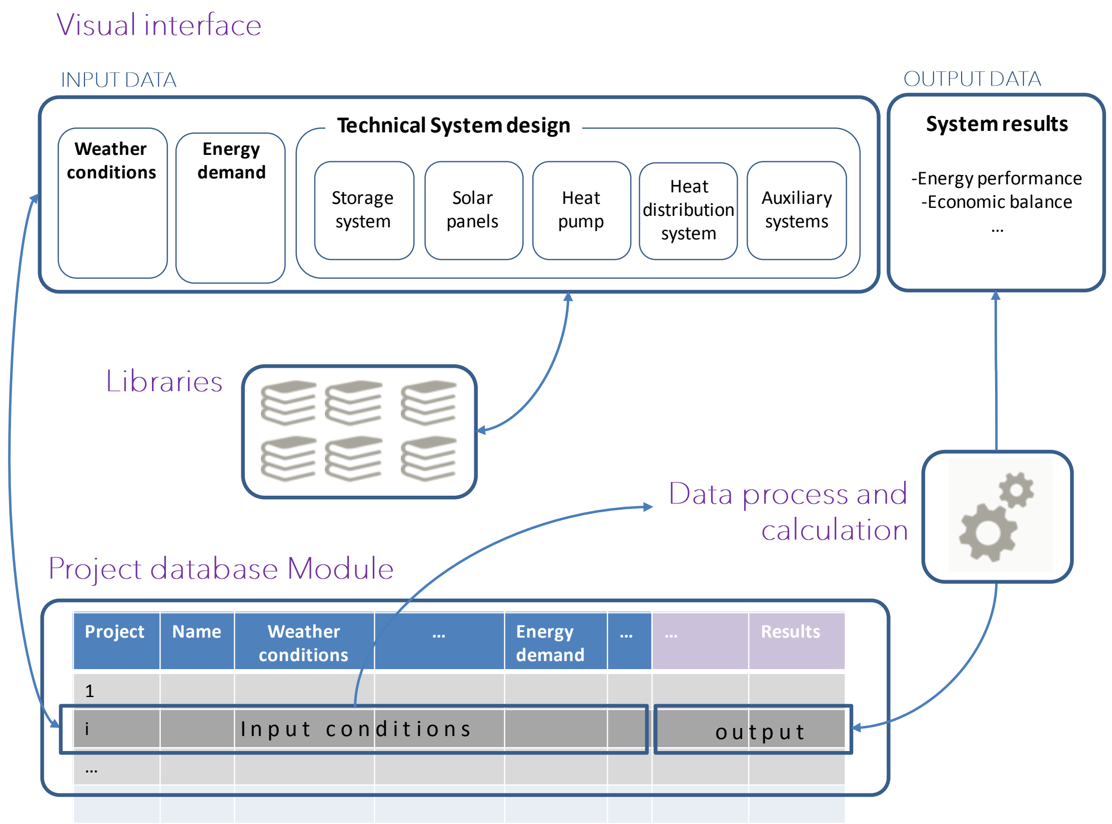

Figure 1: Software structure

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1.3. Type of users

There are two types of users - the administrators (CHESS SETUP partners) and general users. Bellow has been 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 user's possibilities
   - Manage libraries
   - Create, save and load their projects

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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.

Figure 2: Software sign in

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.

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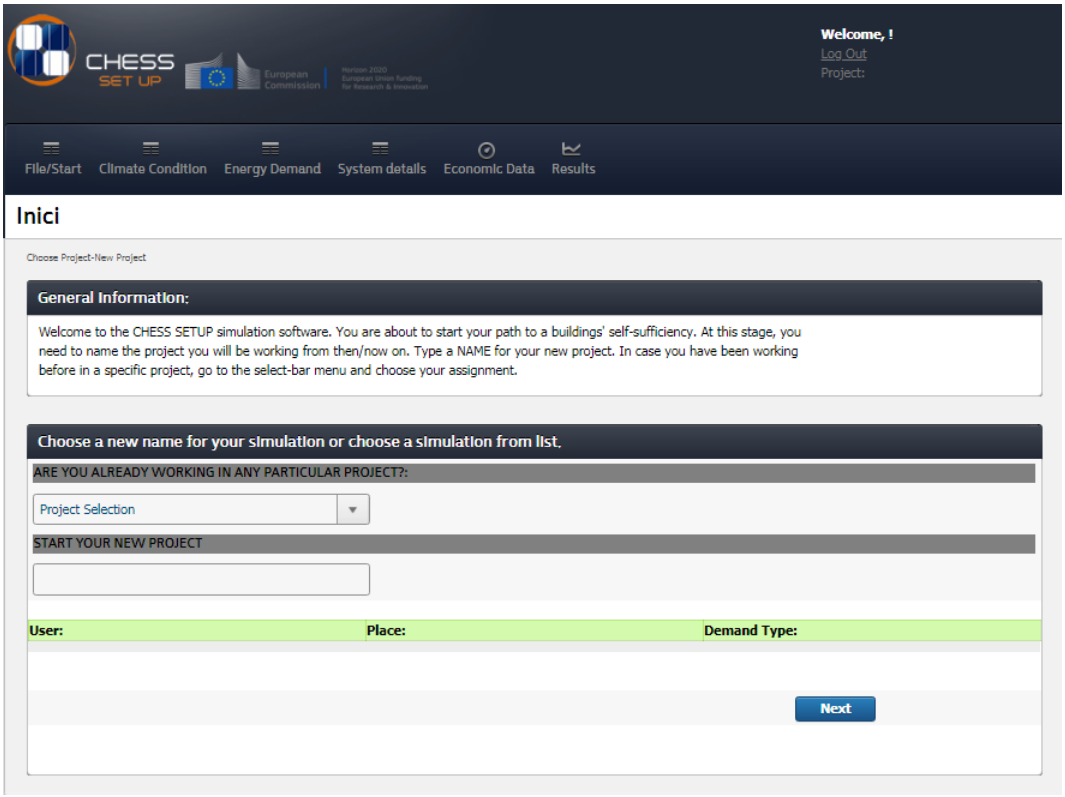

Figure 3: File / Start

2.4. Climate conditions

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

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

- Find out if the location you are applying to has already been defined.
- ADD a 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 is available from the library, you may already have the information required in order to define the climate conditions (SOLAR RADIATION, AIR TEMPERATURE, GROUND TEMPERATURE and IRRADIATION). You need to click the green buttons (Ref) so that data is transferred into the project (the second row of buttons will become green).

If you have introduced a location for the first time, you need to fill in the information necessary to correctly define the climate conditions of your location.

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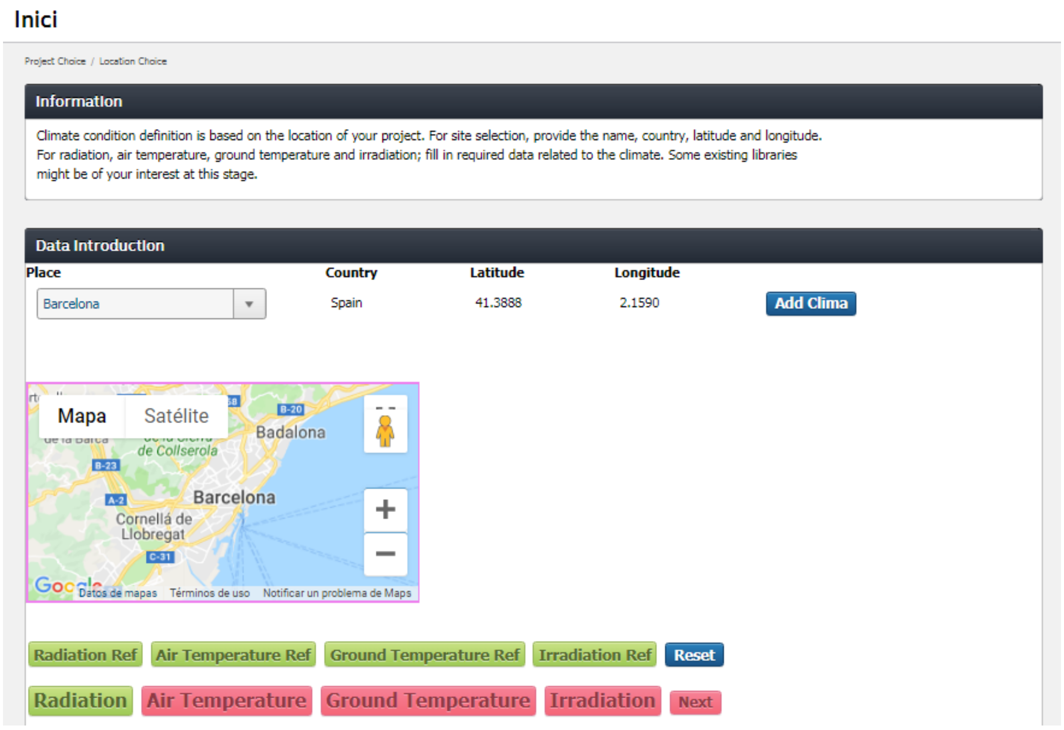

Figure 4: Location / Climate conditions

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 of how solar radiation can be calculated:

1. Go to Photovoltaic Geographical Information System website (European Commission Joint Research Centre, 2018).
2. Look for your location.
3. Click on DAILY DATA tab (average daily solar irradiance). It is considered that solar radiation will be the same during all days in a month.
4. Fill in the window:
   - Solar Radiation database: PVSIG CMSAF.
   - Select month: monthly selection
   - Select 'irradiance'
   - Slope: 0º (horizontal = 0).
   - Azimut: 0º (south = 0).
5. Press visualize (or download *.csv) and the results will appear.
6. Work out an average value for each hour, based on available data in G column (Global irradiance on a fixed plane (W/m^2)). (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.

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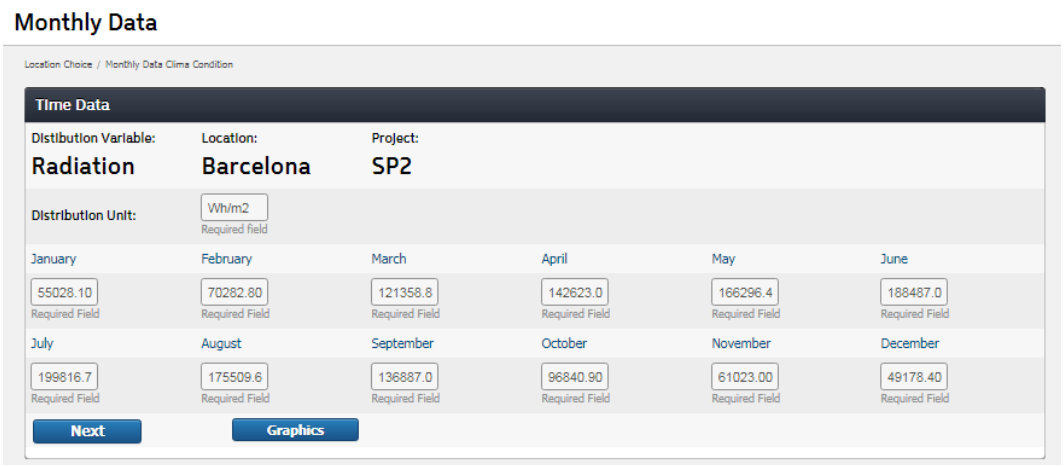

Figure 5: Monthly Radiation Data

Figure 6: Monthly Radiation Graph

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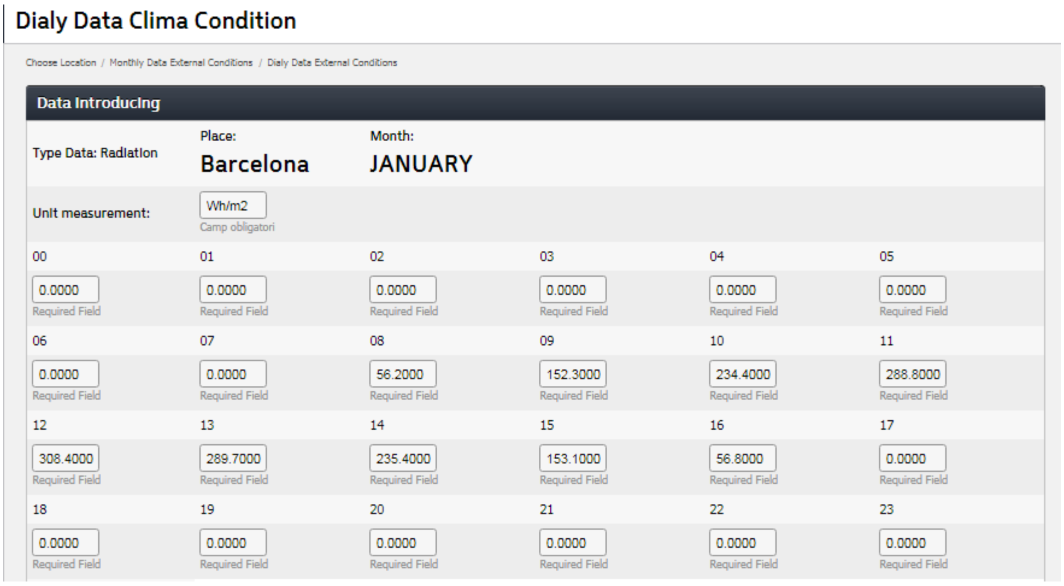

Figure 7: Daily Radiation Data

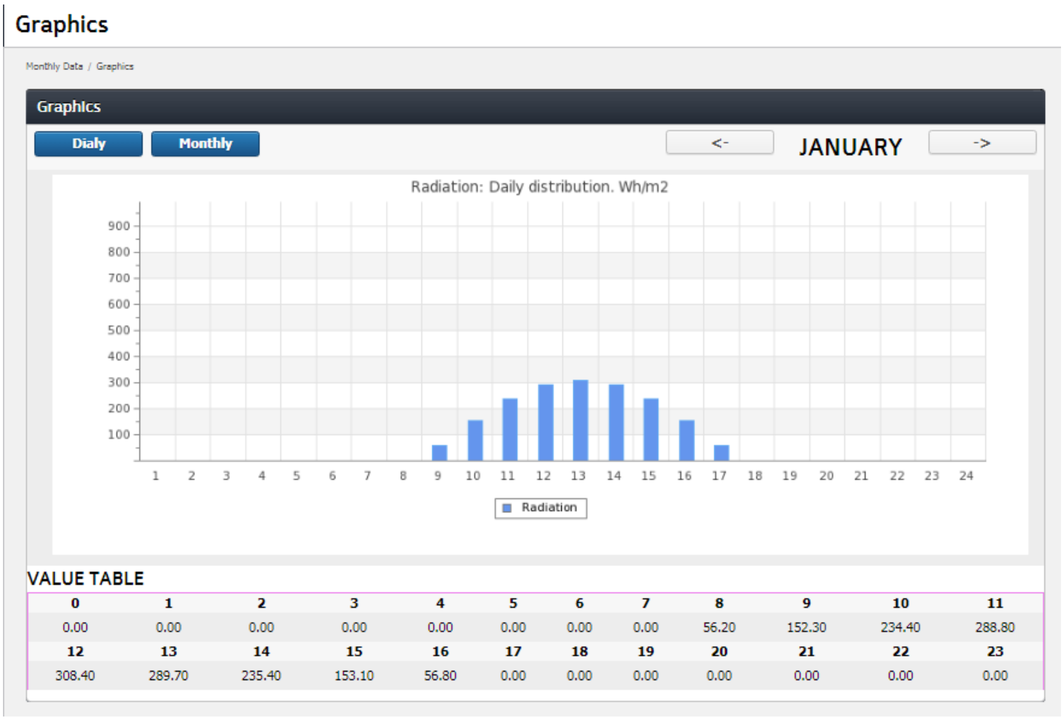

Figure 8: Daily Radiation Graph

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 obtained from the Joint Research Centre (JRC), from EU Science Hub, based on the Photovoltaic Geographical Information System (PVGIS).

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This is an explanation of how air temperature can be obtained:

1. Go to Photovoltaic Geographical Information System website (European Commission Joint Research Centre, 2018).
2. Look for your location.
3. Click on DAILY DATA tab (average daily irradiance data). It is considered that solar radiation will be the same during all days in a month.
4. Fill in the window:
    - Solar Radiation database: PVSIG CMSAF.
    - Select month: monthly selection
    - Select 'Daily temperature profile'
5. Press VISUALIZE (or download csv) and the results will appear.
6. Find the hourly average temperatures diagram and copy the 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.

Temperatures at depths below 10-15 meters are considered to be constant throughout the year and can be approximated to the average annual air temperature (Banks, 2008). This has been considered in this manner for the Simulator. Ground temperature will affect the thermal losses of the seasonal water tank when it is located underground.

In case you are interested in modifying some of the information, there will be an option.

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.

For the purposes of the Simulator, the total daily radiation has been averaged and distributed through the sunlight hours of a typical day of every month.

2.5. Energy demand

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

First of all, you need to select the type of building you are working with, which will have the temporal distribution of the energy demand defined.

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Afterwards, the total annual energy demand has to be defined. Fill in Heating and Hot water demand (kWh/annum) for your project. Some reference data will be available for the Supply Temperature.

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

Energy demand is divided in two main themes: HEATING and HOT WATER. In this software version, only heating and hot water demand are required.

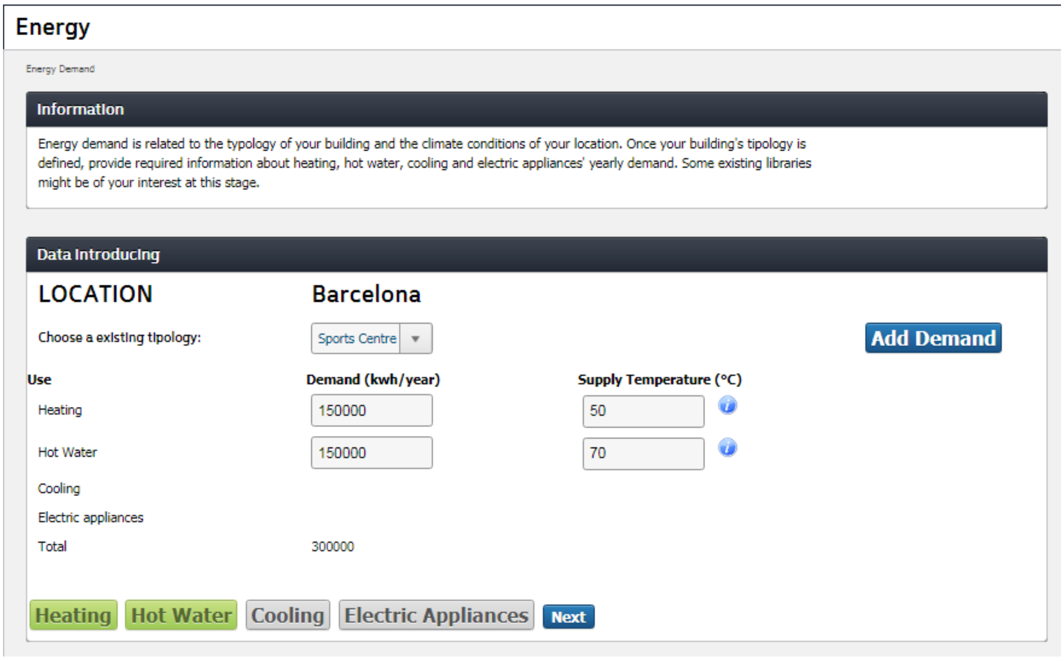

Figure 9: Energy Demands

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 into account that monthly distribution is related to the location and daily distribution is related to building typology.

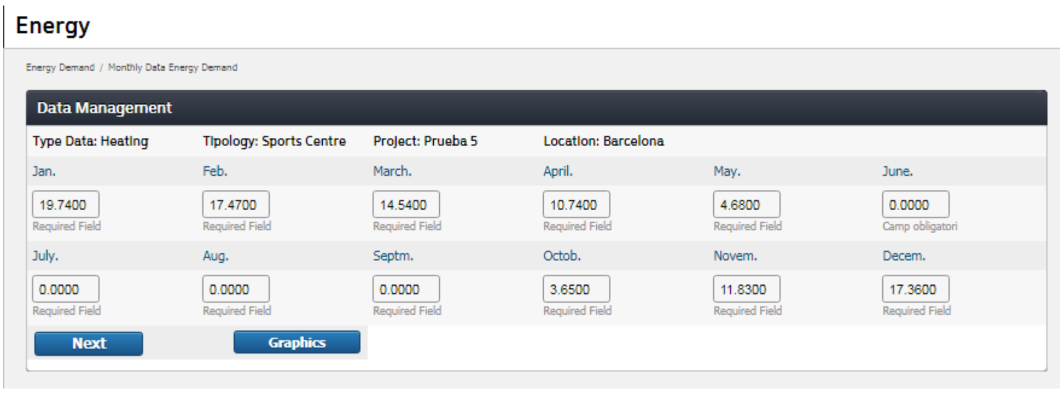

Figure 10: Fraction of monthly Demand (%)

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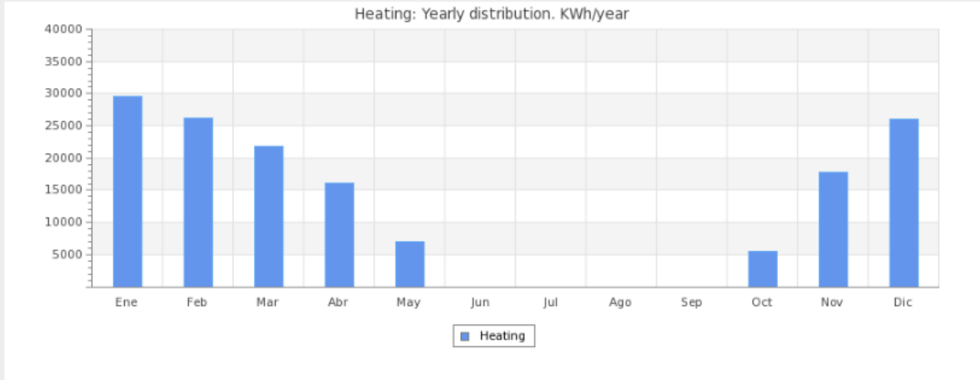
'Graphic Monthly Energy Demand'

Monthly Data / Graphics

Graphics

Dialy Monthly



VALUE TABLE

Jan.	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

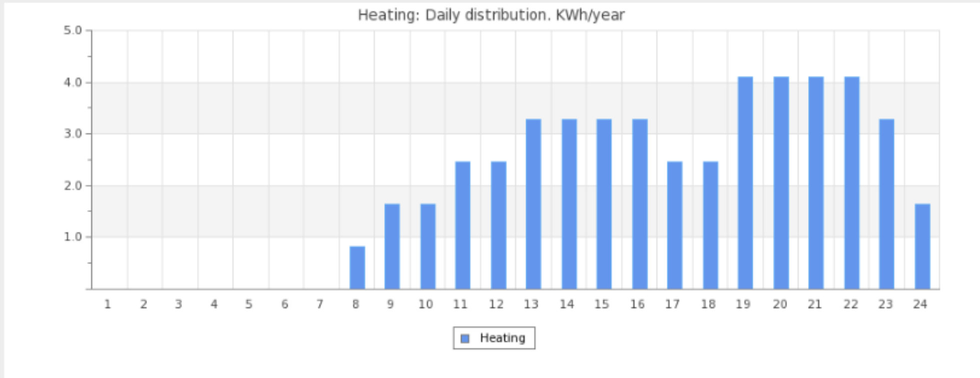
Figure 11: Fraction of monthly Demand (%) - Graph

Graphics

Monthly Data / Graphics

Graphics

Dialy Monthly <- JANUARY ->



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	0.82	1.64	1.64	2.46	2.46
12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
3.28	3.28	3.28	3.28	2.46	2.46	4.10	4.10	4.10	4.10	3.28	1.64

Figure 12: Fraction of hourly Demand (%)

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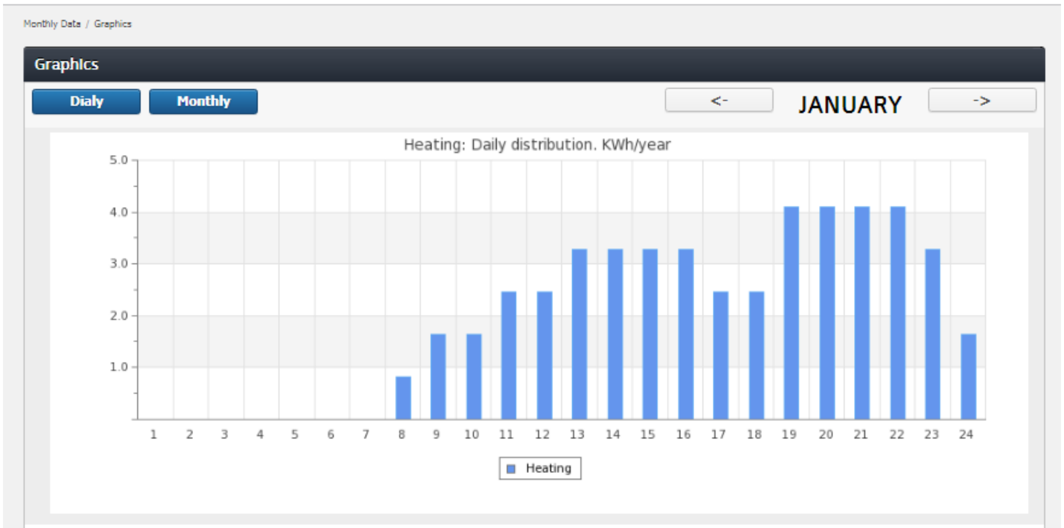
Graphics



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	0.82	1.64	1.64	2.46	2.46
12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
3.28	3.28	3.28	3.28	2.46	2.46	4.10	4.10	4.10	4.10	3.28	1.64

Figure 13: Fraction of hourly Demand (%) - Graph

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 into 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. In case the slope or azimuth are different to zero, it is required to introduce the solar radiation using the following steps:

1. Go to Photovoltaic Geographical Information System website.
2. Look for your location.
3. Select the PV system type (Grid-connected, tracking PV, Off-grid)

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4. Fill in the window:
    - Solar Radiation database: PVSIG CMSAF.
    - Mounting position: Free-standing.
    - Introduce your slope.
    - Introduce your Azimuth.
5. Press VISUALIZE (or download *.csv) and the results will appear.
6. Work out an average value for each hour, based on available data in G column (Global irradiance on a fixed plane (W/m^2)). (Take in account that lack of data is interpreted as lack of solar irradiance at that specific hour).
7. Copy the monthly-data for in-plane irradiation (Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)). In order to adjust the data to the required unit (Wh/m^2) multiply the results by 1000.

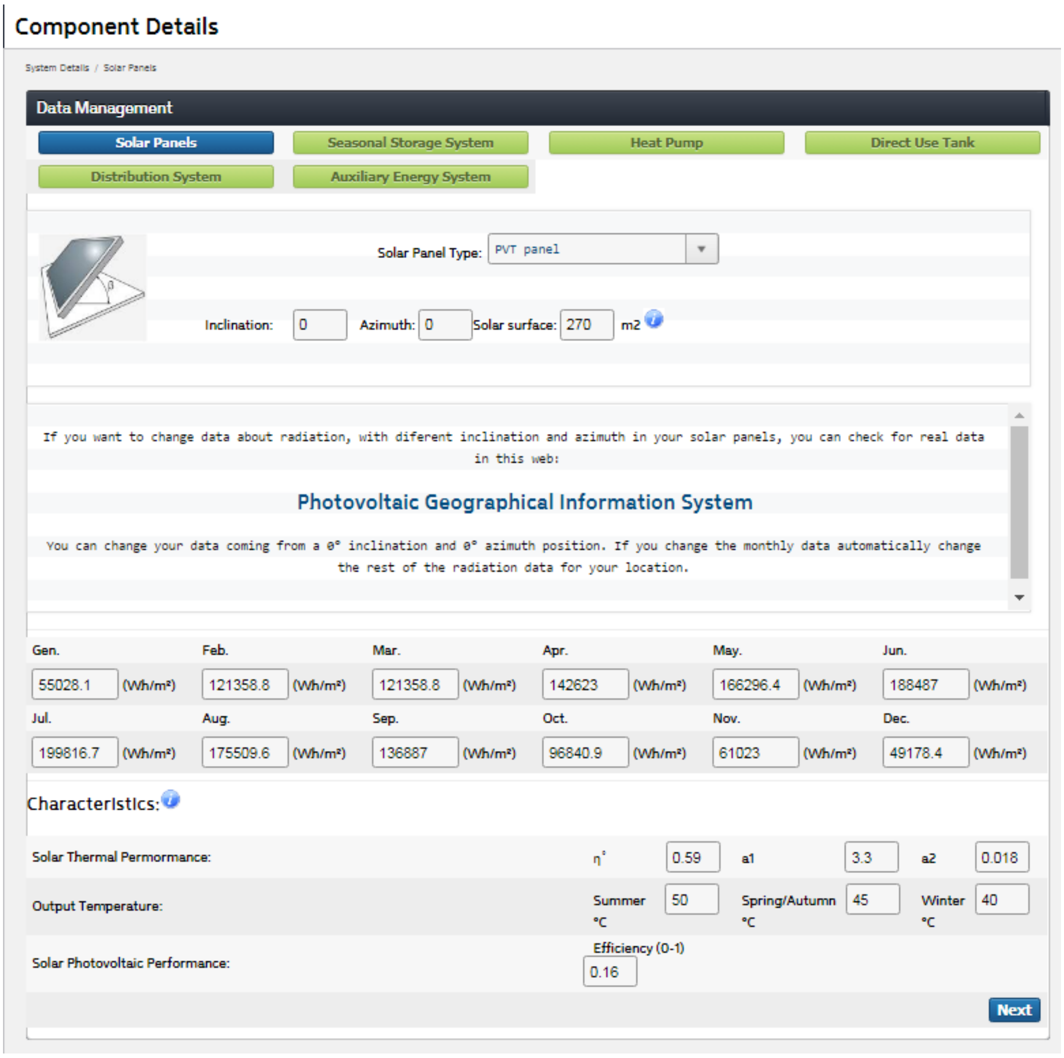

Figure 14: Solar panels configuration

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Seasonal storage system

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

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

Ideally, storage systems are located underground to reduce thermal losses. Otherwise, please change the location cell to "Air".

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 the tank's VOLUME, SURFACE and MAXIMUM and MINIMUM TEMPERATURES. If known, modify the heat transfer value.

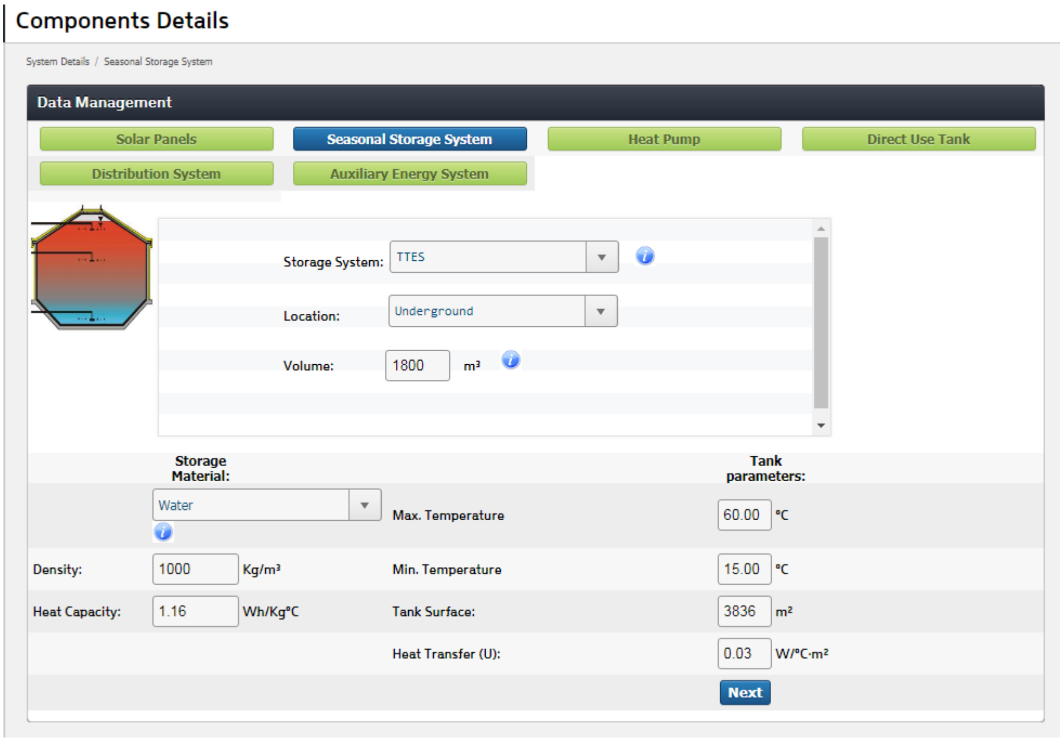

Figure 15: Seasonal storage system configuration

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.

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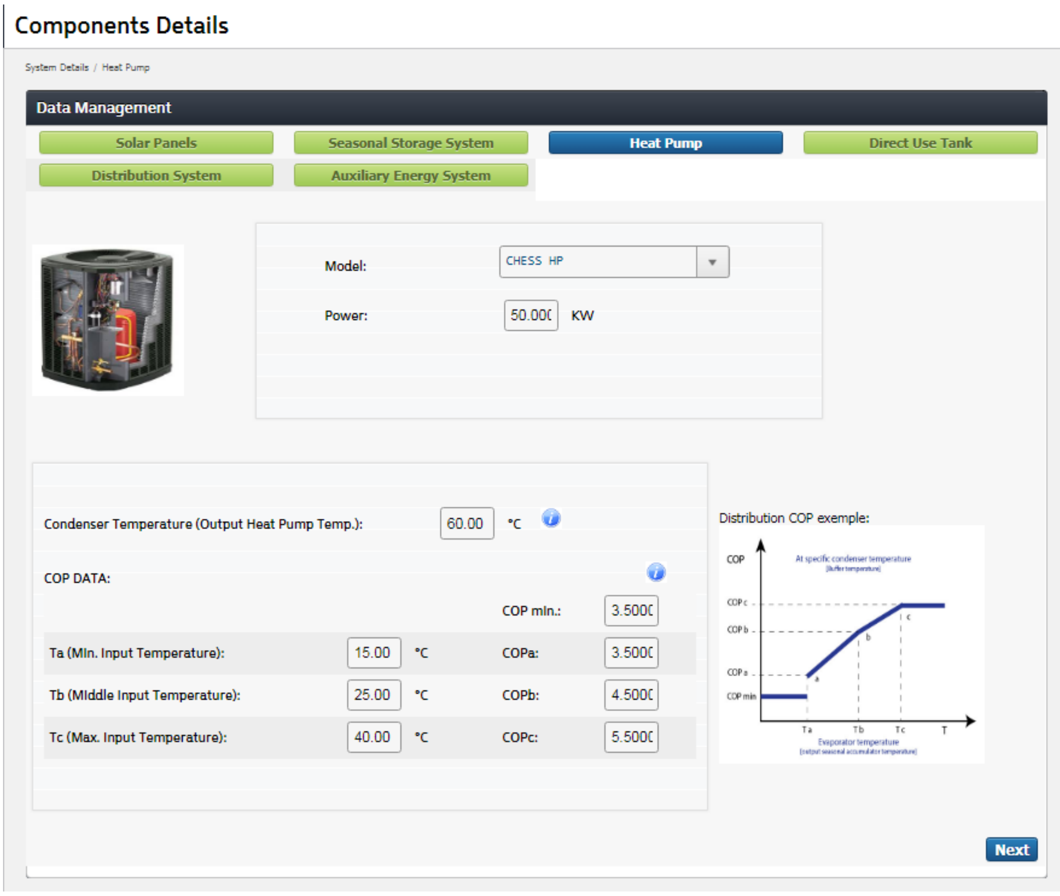

Figure 16: Heat pump configuration

Direct use tank

The inputs you need to add are the tank's VOLUME, SURFACE and MAXIMUM and MINIMUM TEMPERATURES. If known, modify the heat transfer value.

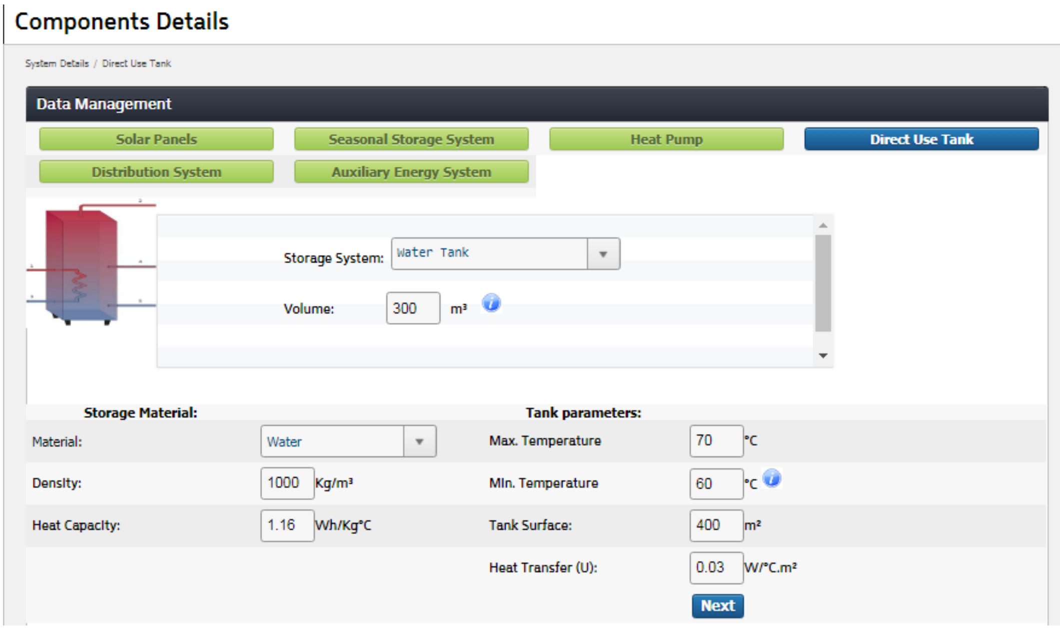

Figure 17: Direct use tank configuration

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Distribution system

The distribution system is composed of two stretches: from the solar panels to the storage system and from the storage system to the demand.

The inputs you need to add are the LENGTH, DIAMETER, INSULATION WIDTH and THERMAL CONDUCTIVITY (λ).

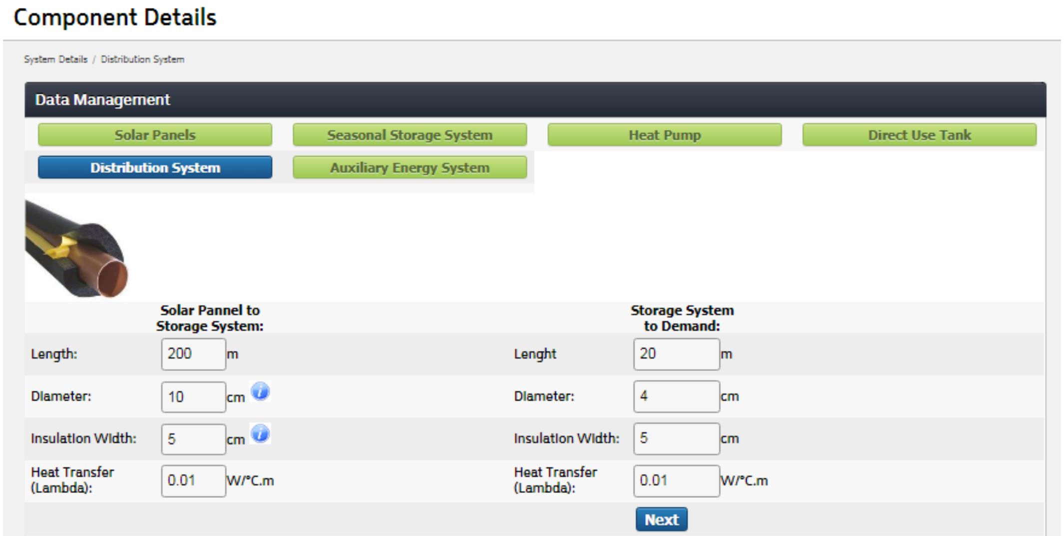

Figure 18: Distribution system configuration

Auxiliary energy source

Some auxiliary energy system (back-up) 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, we recommend to add 1-2 kW to the Direct Use Tank for each MWh of Heat Demand.

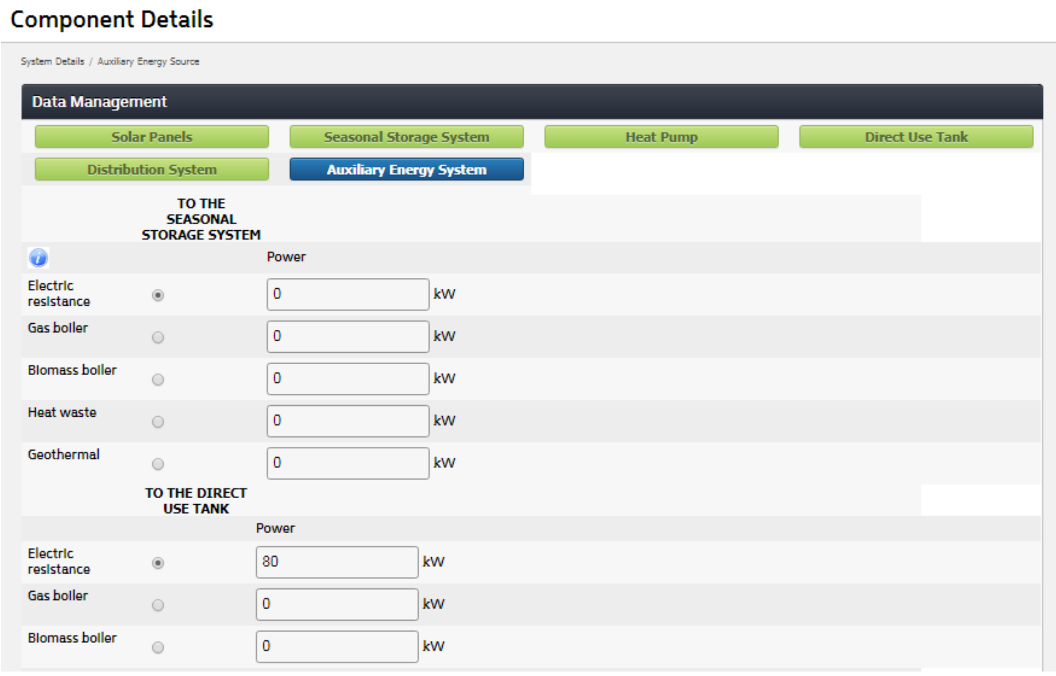

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Figure 19: Auxiliary energy source configuration

2.7. Economic data

Investment and Maintenance Costs

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, giving reference values, might be of your interest at this stage.

Economic Data

Economic Data / Economic Data

Data Management

	INVESTMENT				O.M.			
	Ratio		Total Amount		Ratio		Total Amount	
Solar Panel	500.00	€/m2	135000	€	10.00	€/m2/year	2700	€/year
Storage System	220.00	€/m3	396000	€	4.4	€/m3/year	7920	€/year
Heat Pump	736.43	€/Kw	36821.28	€	14.73	€/Kw/year	736.43	€/year
Direct Use Tank	200.00	€/m3	60000	€	4.00	€/m3/year	1200	€/year
Distribution System	1.00	€/m	220	€	0.02	€/m/year	4.4	€/year
Power Auxiliar	250	€/kw	0	€		€/kw/year	0	€/year
			628041.28	€			12560.83	€/year

Figure 20: Economic data

Energy costs

The energy prices can be defined in this section.

Energy Prices

Economic Data / Energy Costs

Data Management

	Recommended current cost €/kwh	ENERGY COST
Natural Gas	0.066	0.07
Electricity	0.239	0.24
Biomass	0.035	0.035
Heat Waste	0.050	0.05
Geothermal	0.050	0.05

Figure 21: Energy Costs

2.8. Results

Once all sections are completed, 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, a screen with the main simulation outputs will appear. A file in CSV format will be created with these results.

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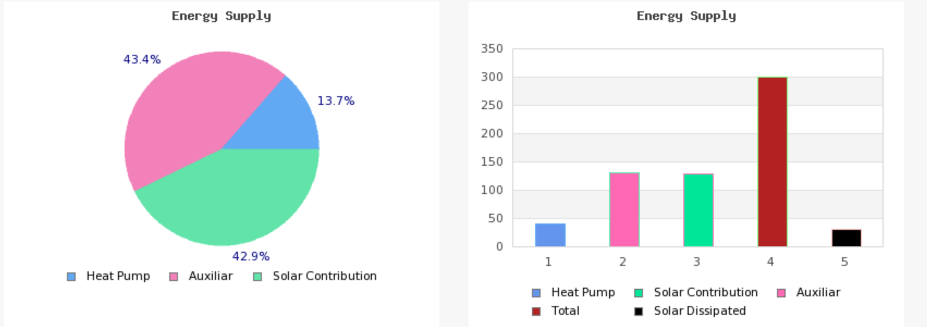
At the same time, you will have the opportunity to observe and analyze the key results in the form of graphics and data by browsing the RESULTS bar. Energy Demand Results, Storage Temperatures and Results, will be available in order to analyze your proposal.

Results

Thermal and Energy Supply Distribution / Data & Graphics

Data & Graphics



Download CSV

Thermal self sufficiency:	56.56	%
Energy consumption saving:	146,439.09	kWh/year
Total demand:	300,030.00	kWh/year
Economic Saving:	47792.83	Euros/year
Payback:	8.46	Years
CO2 emissions reduction:	97714.33	kgCO2/kWh
Energy Cost:	14413.2	Euros/year
SOLAR PANEL		
Solar panel type:	PVT panel	
Panel Surface:	270	m2
Thermal production:	176,471.55	kWh/year
Thermal energy dissipated:	17.02	%
Electrical production:	65,422.41	kWh/year
HEAT PUMP		
Heat Pump:	50.00	kW
Yearly COP:	4.10	
Energy consumption:	41,050.00	kWh/year
AUXILIARY SYSTEM		
Auxiliary System Direct Use Tank:	Biomass Boiler	
Energy consumption:	130320	kWh/year
SEASONAL STORAGE SYSTEM		
Storage System:	Water	
Storage Volume:	1,800.00	m3
Max. Temperature:	37.21	°C
Min. Temperature:	14.91	°C
LOSSES		
Thermal losses:	5.93	%
Total losses:	17,779.09	kWh/year
Direct Tank Use losses:	4,706.54	kWh/year
Storage Deposit losses:	7,985.80	kWh/year
Distribution losses:	5,086.74	kWh/year

Figure 22: Results

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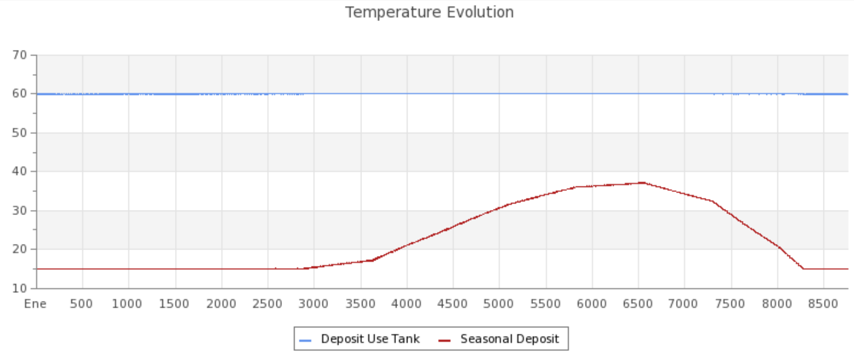
Storage Temperatures

Temperature Evolution / Data & Graphics

Data & Graphics



SOME TIPS:

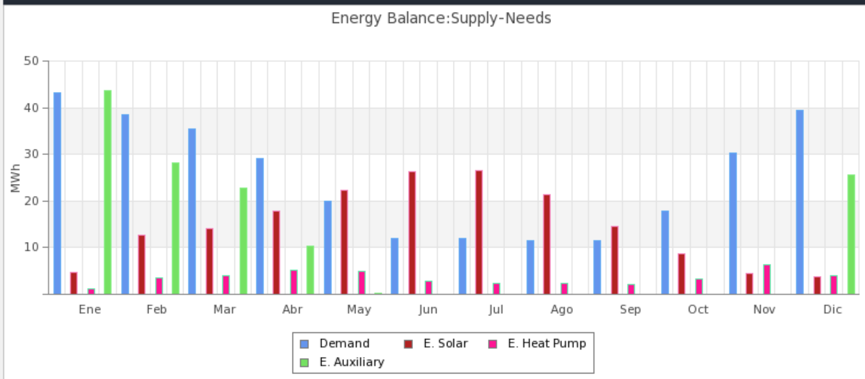
- When the temperature of the seasonal storage system gets values greater than the maximum temperature defined, you must increase the size of the seasonal system or reduce the solar panel surface.
- When the temperature of the buffer is not stable you should increase the buffer tank size, increase the heat pump power or auxiliary system power.

Figure 23: Storage temperatures

Energy Demand Results

Energy Monthly Balance / Data & Graphics

Data & Graphics



VALUE TABLE

Variables	Gen.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Agt.	Spt.	Oct.	Nov.	Dec.
Demand (DT)	43.17	38.55	35.35	29.05	19.96	12.00	11.82	11.48	11.31	17.73	30.24	39.36
Energy Solar Panel (Est)	4.54	12.53	13.97	17.86	22.33	26.12	26.58	21.39	14.55	8.48	4.42	3.68
Energy Heat Pump (Ee)	1.10	3.45	3.85	5.05	4.90	2.75	2.35	2.15	2.10	3.25	6.15	3.95
Energy Auxiliary (Eaux)	43.60	28.08	22.64	10.24	0.08	0.00	0.00	0.00	0.00	0.00	0.00	25.60

Figure 24: Energy demand results

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

3. Calculation Methodology

3.1. Introduction

This chapter defines all the formulas and variables used in order to simulate the CHESS SETUP. These balances are calculated through mass and energy balances and applied to all components of the system (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.

The increment time simulation (step) has been set to 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) Direct use tank (Buffer)
3) Solar panels
4) Seasonal thermal energy storage (STES)
5) Heat pump

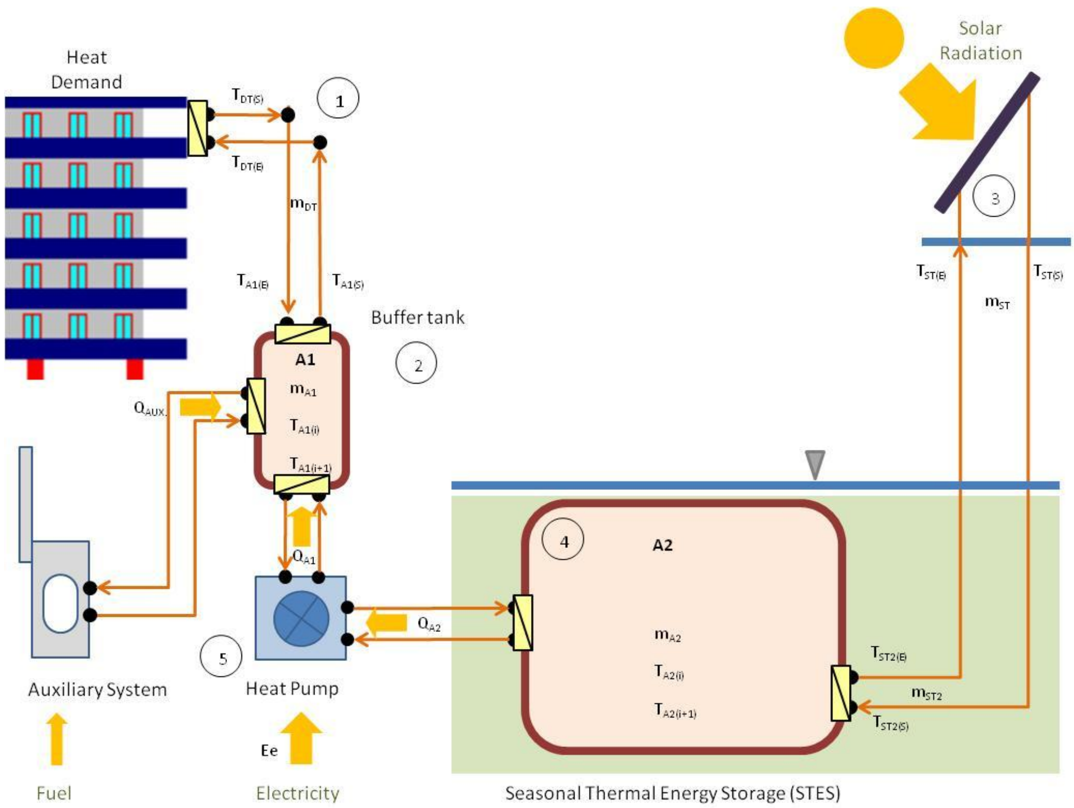


Figure 25: General scheme and variables of CHESS SETUP

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

$T_{TD(O)}$ = 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 panels [ºC]
$T_{ST(I)}$ = inlet temperature of the solar panels [ºC]
m_{ST} = total water mass in the solar 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]
$T_{ST2(O)}$ = outlet water temperature from solar panels to the seasonal tank (A2) [ºC]
$T_{ST2(I)}$ = inlet water temperature of to solar panels coming from the seasonal tank (A2) [ºC]
m_{ST} = water mass from solar circuit to the seasonal tank (A2) [kg]
Q_{A1} = supplied heat from the heat pump to the buffer [kWh]
Q_{A2} = absorbed heat from the seasonal tank by the heat pump [kWh]
Ee = electric energy consumed by the heat pump [kWh]
Q_{aux} = energy consumed by the auxiliary system (boiler) [kWh]
Ce_{H2O}= water specific heat [1.16 Wh/(kg·ºC)]

3.3. Thermal demand circuit

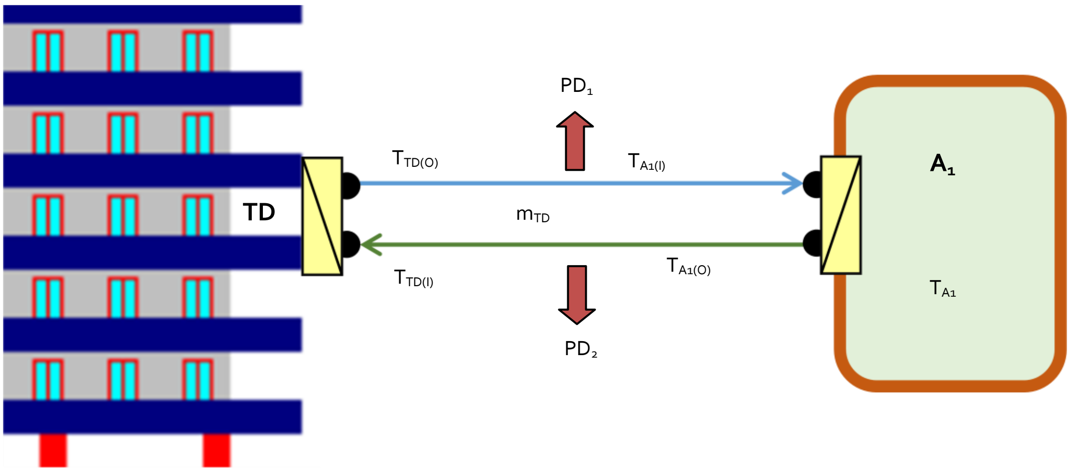


Figure 26: Heat demand circuit scheme and variables

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]

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

T_{A1} = Average temperature in accumulator 1 [ºC]
r_1 = Internal radius of the distribution pipes [m]
r_2 = External radius (internal radius + insulation) of the distribution pipes [m]
$long_1$ = length of the distribution pipes [m]
$long_2$ = length of the distribution pipes [m]
λ_1= thermal conductivity c oefficient [W/m.K]
λ_2= thermal conductivity coefficient [W/m.K]
h_1= heat transfer by convection coefficient [W/m^2.K]

Next considerations are taken:

- Heat exchangers are highly efficient: $T_{A1(O)} = T_{A1}$
- 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.
- The temperature inside the building is assumed to be constant at 20ºC.

$$T_{A1} = \frac{T_{A1(i)} + T_{A1(i+1)}}{2}$$

$$m_{DT} = \frac{TD}{ce_{H2O} \cdot (T_{TD(I)} - T_{TD(O)})}$$

$$P_{D1} = m_{TD}.ce_{H2O}.\rho_{H2O}(T_{DT(O)} - 20).\left(1 - \frac{1}{e^{k_1.long_1}}\right)$$

$$k_1 = \frac{2.\pi}{m_{TD}.ce_{H2O}.\rho_{H2O}.\left(\frac{\ln({}^{r_2}/_{r_1})}{\lambda_1} - \frac{1}{r_2.h_1}\right)}$$

$$P_{D2} = m_{TD}.ce_{H2O}.\rho_{H2O}(T_{A1(0)} - 20).\left(1 - \frac{1}{e^{k_2.long_2}}\right)$$

$$k_2 = \frac{2.\pi}{m_{TD}.ce_{H2O}.\rho_{H2O}.\left(\frac{\ln({}^{r_2}/_{r_1})}{\lambda_2} - \frac{1}{r_2.h_1}\right)}$$

3.4. Direct Use Tank (Buffer tank)

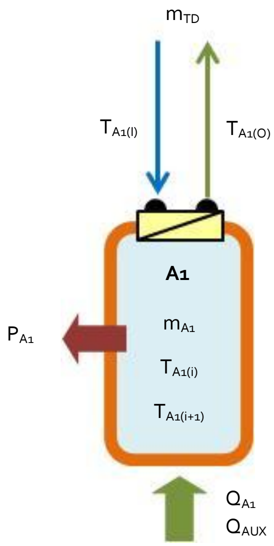


Figure 27: buffer tank scheme and variables

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

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

Next considerations are taken:

- Heat exchangers are highly efficient: $T_{A1(O)} = T_{A1}$
- The temperature inside the building is assumed to be constant at 20ºC.

Buffer tank thermal balance:

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

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

$$P_{A1} = S_{A1} \cdot U_{A1} \cdot (T_{A1} - 20)$$

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

3.5. Seasonal storage tank

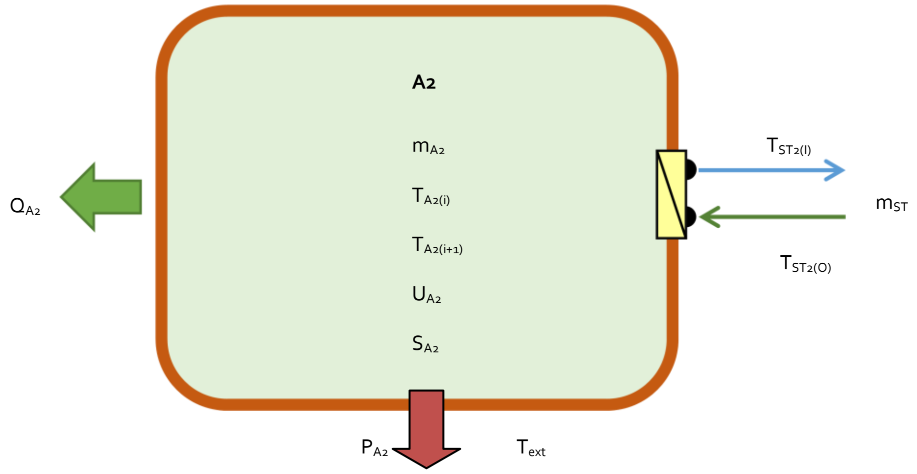


Figure 28: Seasonal storage scheme

P_{A2} = thermal loses in the seasonal tank (A2)
U_{A2} = thermal transmission coefficient of the seasonal tank [W/m^2K]
S_{A2} = surface of seasonal tank [m^2]
T_{ext} = external temperature [ºC]

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Next considerations are taken:

- The 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

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

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

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

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

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

3.6. Solar system

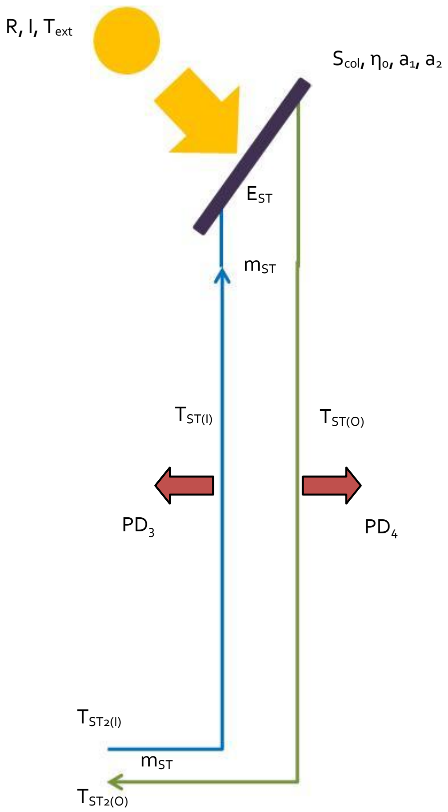

Figure 29: Solar system scheme and variables

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

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, n_{FV}= *coefficients that define the efficiency of the solar thermal panel*
T_{col} *= colector temperature [ºC]*
E_{ST} *= Thermal energy captured by solar panels [Wh]*
E_{FV} *= Electric energy captured by solar panels [Wh]*
r_3 *= Internal radius of the distribution pipes [m]*
r_4 *= External radius (internal radius + insulation) of the distribution pipes [m]*
$long_3$ *= length of the distribution pipes [m]*
$long_4$ *= length of the distribution pipes [m]*
λ_3*= thermal conductivity c oefficient [W/m.K]*
λ_4*= thermal conductivity coefficient [W/m.K]*
h_2*= heat transfer by convection coefficient [W/m².K]*

Next considerations are taken:

- The outlet temperature of the solar system is constant through the day but it changes on depending on the season. (Higher on summer and lower on winter).
- The return temperatures to the solar system will be equal to the temperatures of the accumulator from which comes from: $T_{ST1(I)}=T_{A1}$; $T_{ST2(I)}=T_{A2}$

Solar production:

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

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

$$P_{D3} = m_{ST}.ce_{H2O}.\rho_{H2O}(T_{A2}-T_{ext}).\left(1-\frac{1}{e^{k_3.long_3}}\right) \qquad k_3 = \frac{2.\pi}{m_{ST}.ce_{H2O}.\rho_{H2O}.\left(\frac{\ln(r_4/r_3)}{\lambda_3}-\frac{1}{r_4.h_2}\right)}$$

$$P_{D4} = m_{ST}.ce_{H2O}.\rho_{H2O}(T_{ST(0)}-T_{ext}).\left(1-\frac{1}{e^{k_4.long_4}}\right) \qquad k_4 = \frac{2.\pi}{m_{ST}.ce_{H2O}.\rho_{H2O}.\left(\frac{\ln(r_4/r_3)}{\lambda_4}-\frac{1}{r_4.h_2}\right)}$$

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3.7. Heat pump

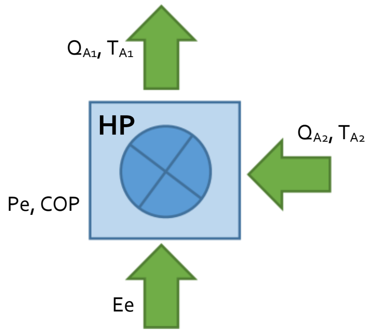

Figure 30: Heat pump scheme and variables

COP = Coefficient of Performance
Pe = Heat pump electrical power

Thermal balance:

$$Q_{A2} = Q_{A1} - Pe$$

$$Q_{A1} = COP \cdot Pe$$

The COP will be provided by the heat pump supplier. It's required to have the COP for different range of 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 T_{A2min} the heat will be supplied by the auxiliary system.

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

$T_{A1(i+1)} \leq T_{A1min};\ T_{A2(i+1)} > T_{A2min} \rightarrow Pe > 0$ (ON)

$T_{A1(i+1)} \leq T_{A1min};\ T_{A2(i+1)} \leq T_{A2min} \rightarrow Pe = 0\ (OFF); Q_{AUX} \geq 0\ (ON)$

The heat pump electrical power (Pe) and the auxiliary system power (Q_{AUX}) will satisfy the thermal demand.

T_{A1min} = minimum temperature for the buffer (ºC)
T_{A2min} = minimum temperature of the seasonal tank (ºC)

3.8. Investment costs

The main investment costs of the CHESS SETUP system are related to the solar panels, seasonal tank and heat pumps. The investment is related to the system size. As the solar surface becomes larger, the lower investment cost per m^2 of solar panel will be required.

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

Data and results from the Einstein project (EINSTEIN PROJECT - Co-founded by EC, grant no 284932, 2018) have been used:

Solar thermal panels

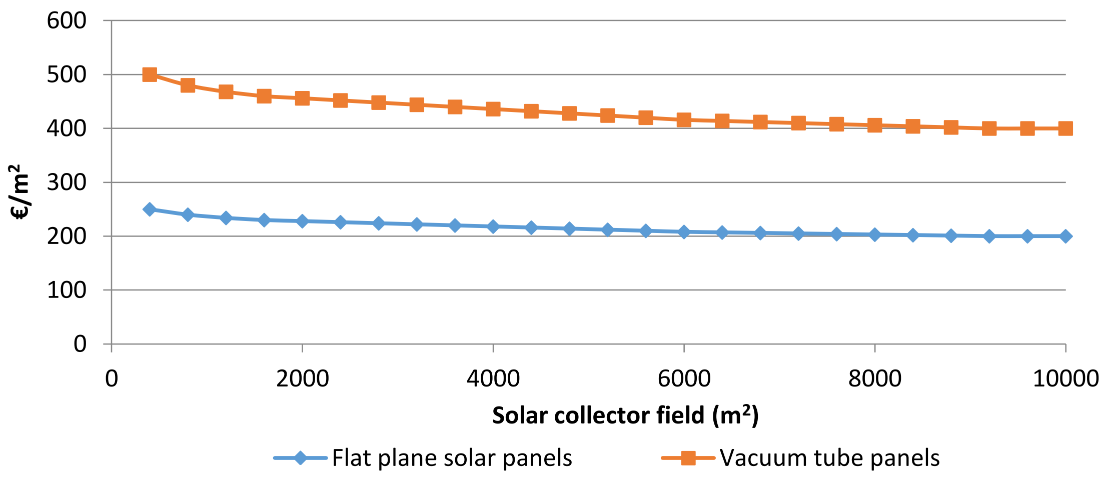

Figure 31: Solar panels price according to the solar collector surface. (Source: adaptation from Einstein project)

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

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

Seasonal storage system

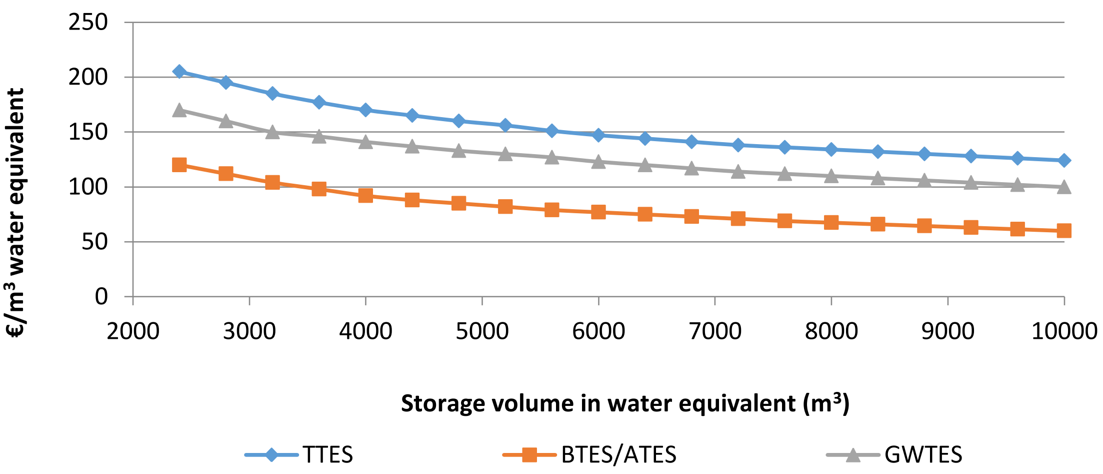

Figure 32: Seasonal storage price according to the storage volume. (Source: adaptation from Einstein project)

TTES
V<2.000 m3 → 250 €/m2
V>2.000 m3 < V < 10.000 m3→ (3162,8*V)-0,3505 €/m3

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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

Heat pump

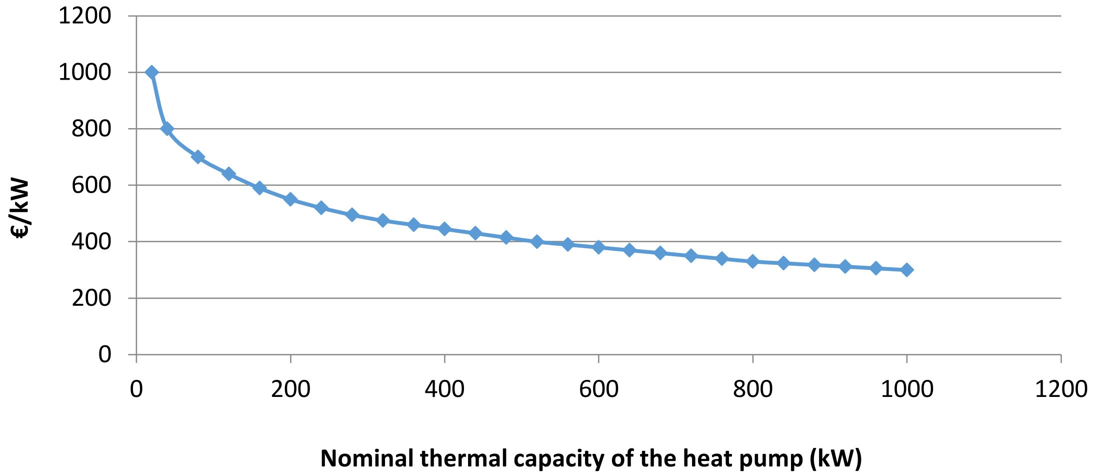

Figure 33: Heat pump price according to the nominal thermal capacity. (Source: adaptation from Einstein project)

P<20 kW → 1.000 €/kW
20 kW < P < 1.000 kW → $(2720{,}1*P)^{-0{,}334}$ €/kW
P>1.000 kW → 300 €/kW

Other equipment

For the other CHESS SETUP pieces of equipment have been used next values:

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

3.9. Energy costs

Energy costs can be incorporated in order to calculate the running costs and potential savings. These include the following (in €/kWh):

- Natural gas

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

- Electricity
- Biomass

For the economic payback, the baseline case has been considered as 50% energy supplied by gas boilers and the other 50% by electric resistances.

3.10. CO_2 emissions

For the CO_2 emissions savings, the baseline case has been considered as 50% energy supplied by gas boilers and the other 50% by electric resistances.

CO_2 emissions have been calculated based on baseline CO_2 factors provided by IDAE (IDAE, 2014).

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

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