D6.5 Development of the CHEST public tool

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R	Document, Report	**X**
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patent fillings, videos, etc.	
OTHER		
ETHICS	Ethics requirements	
ORDP	Open Research Data Pilot	

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V2.1	13/04/2021	A,Carrera	Update calculation engine after bug fixes

Contents

List of Figures

Glossary, Abbreviations and Acronyms

API	Application Programming Interface
BRP	Balance Responsible Party
CAPEX	Capital expenditure
CHEST	Compressed Heat Energy Storage
COP	Coefficient of performance
CPU	Central Processing Unit
CSS	Cascading Style Sheets
DAM	Day Ahead Market
DH	District Heating
DNS	Domain Name System
DSO	Distribution System Operators
ENTSO-E	European Network of Transmission System Operators of Electricity
EU	European Union
GB	Giga Byte
GUI	Graphical User Interface
HP	Heat Pump
HTML	Hyper Text Markup Language
IRR	Internal Rate of Return
OPEX	Operational expenditure
ORC	Organic Rankine Cycle
PCM	Phase Change Material
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RAM	Random Acess Memory
RES	Renewable energy source
RLS	Latent-Sensitive Heat Ratio
ROI	Return of Investment
SOC	State of Charge
STS	Solar Thermal System
TCO	Total Cost of Ownership
TSO	Transition System Operators
URL	Uniform Resource Locator

Executive Summary

The work done in Task 6.5 is the successful development of the CHEST tool. The tool is accessible from the "Tool" section of the CHESTER project website (https://www.chester-project.eu/). The tool allows, to any interested user, generate a predesign of the CHEST system and obtain results about the energetic and economic feasibility of implement it in their current energy system. Two different operational modes, or CHEST integration scenarios, can be simulated: A Stand-alone or Grid-connected mode.

The tool has been designed to be easy and intuitive to use due to the fact that different user profiles, with different knowledge, will use it. That's the reason why the definition of the inputs can be done with a more or less level of detail. Moreover, a set of control functions have been implemented, in the tool, in order to ensure that the user specifies the inputs properly. These control functions, realize a set of checks over the inputs introduced in each step of the tool. For instance, these functions checks that all the inputs requested in the step are: successfully introduced, their values are in a valid range, the values satisfy some correlations or technical limitations etc. Not only the inputs are provided in a different level of detail, also the results of the tool. A summary of the main tool results, is provided in the final step of it but additional detailed results can be obtained downloading the tool report. An example of the report can be seen in Annex I.

The tool is structured in two main parts, the Front End or graphical user interface (GUI) and the Back End or engine. The engine has been developed in Python and it is a simplification of the detailed CHEST TRNSYS model developed in D2.3. It contains the main equations that describe the performance of the CHEST system in both operational modes, stand-alone and grid connected. Moreover, it also contains relevant information used during the calculations of the CHEST performance, such as detailed electrical and prices profiles for each country of the EU, access to external tools (PVGIS) to obtain detailed meteorological data, additional methodologies to estimate the generation from renewable sources etc. The GUI has been developed using the standard programming languages used nowadays for that purpose: HTML, CSS and JavaScript. The tool is web responsive which means that it adapts the structure of the screen according to the screen of the device from which the user access to it, computers, tablets or mobile phones. The developing process of the GUI has been an iterative process where a mockup of it has been shared, commented and reviewed with the partners until an agreement on the content, to be shown in each of the steps of the tool, have been achieved.

The tool has been extensively tested and debugged by the partners of the project. The testing and debugging process of the GUI, has been focus on analyze that all the specifications made previously were properly implemented, such as the checking functions, inputs descriptions, graphical visualization of outputs etc. Some of the errors detected and solved during the GUI testing process, are shown in Annex III. The testing and debugging process of the Engine, has been focus on ensure the robustness of it. For that purpose, a battery of simulations has been performed to check that the engine is able to calculate each of the scenarios that can be defined in the tool. Moreover, has been reviewed that the results provided by the Engine are in line with previous results obtained with the detailed TRNSYS model.

1. Introduction

1.1. Purpose and Scope

Within task 6.5 of CHESTER project a predesign assessment tool has been designed, programmed, tested and set up for a free use. The tool is accessible through the "Tool" section of the CHESTER project webpage (https://www.chester-project.eu/).

The main function of the tool is to allow any potential planner or user to make a first assessment of the technical and economic potential of integrate a CHEST technology in their current electrical energy system. Due to the fact that, some current electrical energy systems may not still present favorable conditions for the integration of the CHEST system, the tool will also allow the evaluation of futuristic scenarios. These scenarios allow to modify the conditions, mainly electrical prices, that benefits the implementation of an efficient energy storage systems, such as CHEST, to balance the supply and demand of energy.

The tool is based on a simplified calculation engine developed based on the findings from the detailed TRNSYS model, already presented in D4.2. This model, allows sizing the principal components of the CHEST system (HP, PCM and ORC) according to the user electrical and heat demands, and available heat source if any. The model, also allows the user to evaluate the performance of the CHEST system operating as a Stand-alone or as a Grid-connected power system. Additionally, to the simplified model, the calculation engine also includes some basic economic equations to estimate the operational cost and investment of the CHEST system.

The tool will deliver a report to the user with useful information. This information will provide a first sizing of the CHEST system, and results about the energetic and economic performance of the system under the boundaries of its application case.

1.2. Structure of the Document

The document is structured as follows:

- Chapter 2 shows a general overview of the main tool components and explains the information workflow of it.
- Chapter 3 presents each of the screens of the tool and describes the parameters that must be specified in each of them.
- Chapter 4 is focused on explain the main equations used, by the tool engine, to calculate the performance of the CHEST system.
- Chapter 5 describes the principal functionalities of the main sections, Front end and Back end, of the CHEST tool.
- Chapter 6 describe the technical requirements needed for the hosting of the CHEST tool.
- Chapter 7 shows the debugging during the GUI and Engine beta testing processes.
- Chapter 8 presents the conclusions drawn from this task.

2. Tool concept and overview

The objective of the tool is to allow to an interested user to evaluate the implementation of the CHEST system in their current energy system. Even that the tool has been developed with the greatest accuracy possible, the results of it are only a first estimation about the energetic and economic feasibility of implement a CHEST system. The tool is composed mainly by two parts known as Front End and Back End.

The Front End is used by the user to introduce the inputs needed to perform the calculations. After the evaluation done in D6.3 a different user's profiles of CHEST tool have been identified. Each of these users, can have different level of knowledge about the factors that can affect the performance and profitability of the CHEST system. Keeping that in mind, the developer has decided to allow the introduction of the tool inputs with a different level of detail. Enabling the user to achieve a higher or lower degree of detail, depending on their current knowledge about their energy system.

The Back End is in charge of compute the calculations, once all the inputs have been specified. It contains all the energetic and economic equations required to evaluate the performance of the system under the desired boundary conditions. The equations of the engine have been mainly divided in two sections, the energetic and economic calculations. Where at the same time, the energetic equations are grouped in two sections depending if the CHEST system is planned to be operated as a Stand-alone power system or as a Grid-connected one. Once the results are calculated, these are sent back to the Front End where are shown to the user. The main results of the tool, are shown directly to the user in the results section of the Front End. The user can access to an additional, and more detailed, results downloading the report that the tool creates at the end of the process.
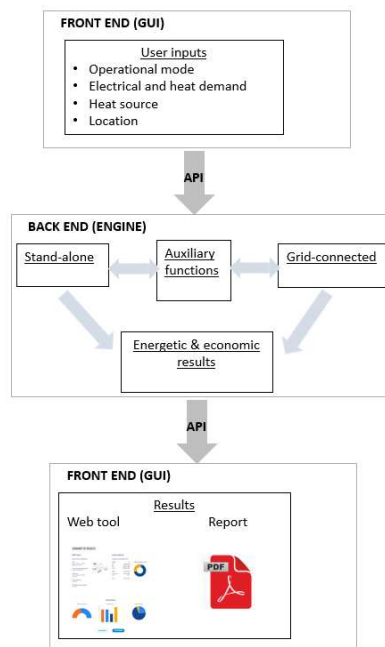
Figure 1 Workflow diagram of the CHEST tool

3. Tool description step by step

This section describes each step followed by the user using the tool, and the information that needs to be introduced at each step. Due to the fact that two different operational modes of the CHEST system can be analyzed, different data will be requested at each step depending on that.

3.1.   Step 1: Operational mode

In the first step the user must select which operational mode of the CHEST system wants to evaluate, the Stand-alone or Grid-connected mode.

As can be seen in Figure 2, if the Stand-alone mode is selected the tool will request the user to fill in data along five different steps.

Figure 2 Step 1 of CHEST tool, Stand-alone mode

In contrast, if the Grid-connected mode is selected the tool will request the user to fill in data along four different steps, as shown in Figure 3.

Figure 3 Step 1 of CHEST tool, Grid-connected mode

At this step the tool is requesting to select the following data:

Operational mode

1. **Stand-alone power systems**: If the user selects this option the CHEST system will be simulated considering that this is integrated in an energy system where heating and electrical micro-grids are completely isolated from external suppliers or costumers.
2. **Grid-connected power system:** If the user selects this option the CHEST system will be simulated performing an electricity arbitrage service. In this case the electrical supply is entirely provided by the grid and no self-generation of electricity is considered.

Only if the Grid-connected mode is selected the tool request also to define the following data:

Maximum charge & discharge capacity

1. **Charge capacity [MW]:** This parameter defines the maximum amount of power to be bought, during the arbitrage strategy, when the electricity price is under a predefined threshold. It is the electrical power of the heat pump compressor.
2. **Discharge capacity [MW]:** This parameter defines the maximum amount of power to be sold, during the arbitrage strategy, when the electricity price is above a predefined threshold. It is the electrical capacity of the ORC expander.

As have been analyzed in previous deliverables in order to achieve a good performance with the arbitrage strategy, it is mandatory to keep a relation between the charge and discharge capacity of:

$$1.5 \cdot Discharge\ capacity < Charge\ capacity < 2.5 \cdot Discharge\ capacity$$

In other words, the discharge capacity should be between 1.5 and 2.5 times the charge capacity. The tool will check and force the user to define the inputs following the specified rule. Otherwise, this would not be able to advance to the next step. In the case of the stand-alone system, the charge and discharge capacity are calculated by the tool according to the micro-grid requirements.

3.2. Step 2: Location

The second step of the tool is different depending on the operational mode selected in the previous step.

In one hand, if the user has selected the Stand-alone operational mode the GUI displays the screen shown in Figure 4. The user can select the location of the CHEST system clicking on the map. Additionally, to the location, the user must introduce the main characteristics of the renewable sources that their energy system may have.

COMPRESSED HEAT ENERGY STORAGE FOR ENERGY FROM RENEWABLE SOURCES

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764042

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STEP 2

Select or insert the coordinates of the location where the CHEST power system will operate and the renewable electricity sources.

Coordinates and country selected

Please click on the map or insert the coordinates of the desired location:

Coordinates selected: Country selected:

Latitude: [   ] ⓘ

Longitude: [   ] ⓘ

Renewable electricity sources

Please select and fill in the requested information about the renewable electricity sources:

☑ Wind power ⓘ

Number of Wind turbines: [   ] ⓘ

Turbine power: [   ] MW ⓘ

☑ Solar power (PV) ⓘ

Installed peak PV power: [   ] kWp ⓘ

Slope: [   ] ° ⓘ

Azimuth: [   ] ° ⓘ

← PREVIOUS   **NEXT**

Figure 4 Step 2 of CHEST tool, Stand-alone mode

In the other hand, if the Grid-connected mode has been selected the GUI displays the content shown in Figure 5. In this case the user has also to select the location of the CHEST system and must define the electrical price that will be used during the simulation. When the user selects a location, the tool provides a default electricity price for that country., which is the average price for available European countries at [1]

Figure 5 Step 2 of CHEST tool, Grid-connected mode

At this step the tool is requesting to select the following data:

The next parameters are requested in both operational modes. This data is used to get the meteorological data, of the selected location, from the PVGIS tool.

Coordinates and country selected

1. **Country selected**: Country of the selected location.
2. **Latitude [°]:** CHEST power system location's latitude.
3. **Longitude [°]:** CHEST power system location's longitude. 0 equals south, and positive values going westward.

The following parameters are only requested if the Stand-alone mode is selected and are used to estimate the energy generated through the defined renewable energy sources.

Renewable electricity

1. **Wind power:** Renewable energy generated through wind power plant.

2. **Number of wind turbines:** Total number of wind turbines in the plant.
3. **Average turbine power [MW]:** Average nominal power of wind turbines or nominal power if there is only one wind turbine.
4. **Solar power (PV):** Renewable energy generated through photovoltaic system.
5. **Installed peak PV power [kWp]:** Installed peak photovoltaic power.
6. **Slope [°]:** Slope angle (with respect to horizontal plane) of the PV system.
7. **Azimuth [°]:** Azimuth angle of the PV system (being 0° Sud, -90° East, 90° West and 180° North orientations)

The next parameters are only requested if the Grid-connected mode is selected. These are used, together with the DAM and balancing electricity market hourly prices to estimate the profits generated with the arbitrage. The electricity prices are from the year 2018 and were downloaded from the ENTSO-E transparency web portal [1].

Electricity price

1. **Average electricity price [€/kWh]:** Average electricity price of the DAM for the selected country. This is only an informative parameter, not editable by the user
2. **Forecasted price increment [%]:** Estimated electricity price increment from now to a desired future year, the simulation electricity price used will be the actual country electricity price multiplied by this forecasted increment.
3. **Simulation electricity price [€/kWh]:** Electricity price used during the CHEST simulation. This price is equal to the country electricity price multiplied by the percentage of increment forecasted. This is only informative, not editable, and corresponds to the average DAM prices for the simulation.

3.3. Step 3: Electrical load

This step is only needed if the user has selected the Stand-alone operational mode. As can be seen in Figure 6 Step 3 of CHEST tool, Stand-alone mode, the user is requested to define the electrical load that must be satisfied with the CHEST system and the renewable sources. If these do not produce enough energy, to cover the electrical consumption, an auxiliary back-up system is considered. The user has two different options to define this load, the standard or the advanced one.

Figure 6 Step 3 of CHEST tool, Stand-alone mode

If the user selects the standard option, it only has to define the annual electrical energy consumption. This value is used together with a default normalized electrical consumption curve taken from [1] [X], where a specific curve is load depending on the selected country, to create the hourly electrical consumption curve used in the simulation.

If the user selects the advanced option the hourly electrical consumption curve is generated from scratch using the parameters introduced by the user. As shown in the image, these parameters are the hours of the day, the days of the week, the percentage of the month hours with electrical consumption and the annual electrical consumption.

Thus, at this step the tool is requesting the user to define:

Electrical load of the system

If the standard option is selected:

1. **Standard load definition:** Standard country average load curve considered.
2. **Annual electrical consumption:** Annual electrical consumption.

If the advanced option is selected:

1. **Advanced load definition:** Specify user-defined load curve.
2. **Daily load profile:** Select daily hours with active electrical load.
3. **Weekly load profile:** Select days of the week with active electrical load.
4. **Yearly load profile:** Select a percentage of active electrical load per month.
5. **Annual electrical consumption:** Annual electrical consumption.

3.4. Step 4: Heat source

In step 4 the user has to introduce the data about the heat source. The heat delivered by this heat source is used in the CHEST heat pump, together with the electricity absorbed by this, to generate heat at high temperature. This high temperature heat, is generated when there is an excess of renewable electricity or when the electricity price is low, depending if the CHEST operates in the Stand-alone or Grid-connected mode. The heat generated, is stored in the PCM and later on used in the ORC to generate electricity again. The electricity, is generated when there isn't enough renewable energy to cover the electrical consumption or when the electrical price is high, depending again on the CHEST operational mode. As figure 7 shows, there are three different heat source options: waste heat, solar thermal or biomass. The tool only allows to define these three kinds of heat sources in order to incentivize the use of renewable sources or the reutilization of residual heat.

If the user selects the waste heat option it has to define the availability of this waste heat. In order to do that, the user has to fulfill the same parameters than in the advanced electrical load (hours of the day, the days of the week, the percentage of the month hours with waste heat and the annual available heat). Additionally, to these parameters, the tool asks for the temperature of this waste heat. With these data the tool creates and hourly curve of the heat that can be used by the CHEST heat pump. If the user selects the solar thermal system, it has to define the area of solar thermal collectors. The hourly amount of heat produced, by this system, is estimated by the tool using this area and the meteorological data, radiation and external temperature of the selected location, get from the PVGIS. Finally, if the user selects the biomass boiler, as a heat source, it hasn't to specify any parameter due to the fact that this system can be activated whenever the CHEST heat pump needs the production of heat. The required capacity of the biomass boiler will be specified in the report, as it will depend on the size of the CHEST heat pump.

As can be seen on the image the tool provides a fixed default values for the temperature of the solar thermal and biomass heat. These values are defined in order to achieve a good COP of the heat pump, this is better as lower is the delta temperature to cover, and a reasonable efficiency of the ORC. The efficiency of the ORC, is higher as higher is the temperature of the heat delivered to it. The values are fixed taking into account these objectives, the limitations of the technologies proposed and the results obtained in previous tasks of the project.

Figure 7 Step 4 of CHEST tool, Stand-alone mode

The heat source must be defined for both operational modes. The only difference between the screen shown in the Stand-alone mode, Figure 7, and the Grid-connected, Figure 8, is that the second one asks for an additional parameter, the heat source purchase price. This price is used in order to calculate the profits, or costs, between the purchase and sell of heat. As will be seen in the next step, step 5, the residual heat of the ORC could be sold to an external demand. This additional parameter is only requested if the heat source considered is a waste heat or a heat produced with a biomass boiler.

Figure 8 Step 4 of CHEST tool, Grid-connected mode

At this step the tool is requesting, in both operational modes, to the user to define:

 Heat source:

 If the waste heat option is selected:

1. **Waste heat:** Waste heat as a heat source
2. **Daily load profile:** Select daily hours with available waste heat.
3. **Weekly load profile:** Select days of the week with available waste heat.
4. **Yearly load profile:** Select a percentage of available waste heat per month.
5. **Heat source temperature:** Temperature of the heat source.
6. **Annual available heat:** Annual electrical consumption.

 If the solar thermal system option is selected:

1. **Solar thermal:** Solar thermal as a heat source.
2. **Area of the solar thermal system:** Area of the solar thermal system. It refers to the flat panel area not the panel occupied area.
3. **Heat source temperature:** Temperature of the heat source.

If the biomass system option is selected:

1. **Biomass:** Biomass as a heat source.
2. **Heat source temperature:** Temperature of the heat source.

As has been already mentioned, if the user has selected the Grid-connected mode and the heat source is waste heat or biomass boiler the tool also asks the user to define the:

1. **Heat source purchase price:** Heat source purchase price if any, else put 0.

3.5. Step 5: Heat demand

This is the last step of the tool where the user must define data. In this step, the user has to specify if there is any heat demand where the residual heat of the ORC can be used. As shown in Figure 9, there are three different options to select in this screen: None, District heating and other.

If the none option is selected, it means that there isn't any heat demand where the residual heat of the ORC can be delivered. In contrast, if the District heating option is selected it means that the residual heat of the ORC may be delivered, and use, in a district heating network. In order to know how much heat will be possible to deliver, the tools ask the user the annual heat demand and the supply and return temperatures of the network. The tool uses this data together with a default profile and the meteorological data to create an hourly heat demand profile. The meteorological data is used to adjust the default profile according to the weather conditions of the selected location. The last alternative is to select the other option where the user can define his own heat demand curve using the methodology and parameters explained in section 3.4 for the waste heat availability. Beyond the parameters used to create the hourly curve, hours of the day, the days of the week and the percentage of the month hours with heat demand, this options also requests the annual heat demand and the return and supply temperatures of it.

Figure 9 Step 5 of CHEST tool, Stand-alone mode

The heat demand must be also defined for both operational modes. In this case, the difference between the parameters requested in the Stand-alone mode, Figure 9, and the Grid-connected, Figure 10, is that in the Grid-connected mode the user has to specify the price at which the heat can be sold. This price must be only specified if there is any heat demand.

Figure 10 Step 5 of CHEST tool, Grid-connected mode

At this step the tool is requesting to the user, in both operational modes, to define:

Heat demand:

If the none option is selected:

1. **None:** No heat demand available.

If the district heating option is selected:

1. **District heating:** District heating as heat demand.
2. **Annual available heat:** Annual heat demand of the district heating.
3. **Supply temperature:** Supply temperature of the district heating.
4. **Return temperature:** Return temperature of the district heating.

If the other option is selected:

1. **Other:** Other sources of heat demand.
2. **Daily load profile:** Hours with active heat demand.
3. **Weekly load profile:** Days with active heat demand.
4. **Yearly load profile:** Monthly percentage of active heat demand.
5. **Annual available heat:** Annual heat demand.
6. **Supply temperature:** Supply temperature of the heat demand.
7. **Return temperature:** Return temperature of the heat demand.

Additionally, to the parameters described above, if the user has selected the Grid-connected mode and there is a heat demand, the tool also asks the user to define the:

1. **Heat selling price:** Selling price of the heat delivered to the heat demand.
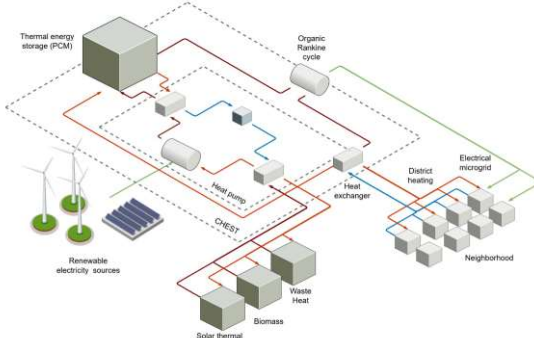
3.6.   Step 6: Calculate or change inputs

On this screen the user has two options: press "calculate" or "change inputs" button. The first option is to finish the process by clicking on the calculate button. Thus, the inputs are sent to the engine where the calculations are performed and the results of it are sent back to the GUI. The other option is to click on the change inputs button, in this case the user will be send back to the first step of the process and will be able to review the data, defined in each of the steps, and change it if is necessary.

The Figure 11 shows the screen of the GUI shown at this step in the Stand-alone mode. The Figure 12, shows screen of the GUI in this step for the Grid-connected case.

Figure 11 Step 6 of CHEST tool, Stand-alone mode
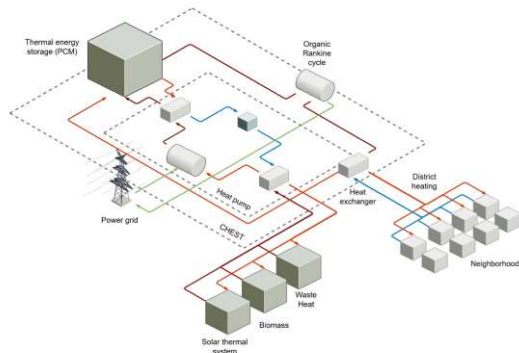
Figure 12 Step 6 of CHEST tool, Grid-connected mode

3.7. Step 7: Results & report content

The last step of the tool, is Step 7 where the user can see, or download, the results achieved with his simulation. The main results of it are directly shown in the GUI, while additional detailed results in monthly basis can be obtained downloading a report in .pdf format.

3.7.1. GUI Results

The results shown in the GUI are classified in three sections: technical, economic and energetic results. There are some differences on the results obtained depending on the CHEST operational model selected, Figure 13 and Figure 14.

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This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764042

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SUMMARY OF RESULTS

CHEST System

Main technical characteristics:

ORC
Nominal power: 0.10 MWel
Efficiency: 13.70%

Thermal energy storage (PCM)
Capacity: 29.67 MWth

Heat pump
Nominal power: 0.29 MWel
COP: 6.40

Thermal efficency
102.15%

Overall Power to Power Ratio
87.56%
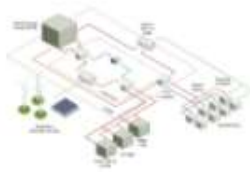
Financial indicators

Investment and operation costs:

CAPEX	2047k€
ORC	44k€
HP	83k€
PCM	1335k€
Other	585k€
OPEX	1228k€
Maintenance costs	41k€ /year
TCO	3275k€

CAPEX distribution [%]

ORC | HP | PCM | Other

Energy balance

CHEST Capacity factor [%]
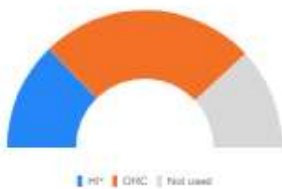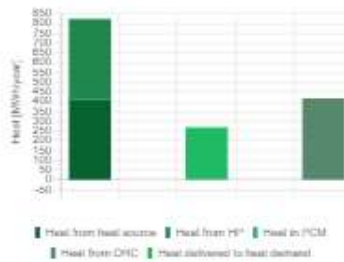
HP | ORC | Not used

Thermal balance

Heat from heat source | Heat from HP | Heat in PCM
Heat from ORC | Heat delivered to heat demand

Electrical Balance [MWh/year]

PV | WT | BACK-UP | ORC

CHANGE INPUTS   GET THE REPORT!

Figure 13 Step 7 of CHEST tool, Stand-alone mode

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SUMMARY OF RESULTS

CHEST System

Main technical characteristics:

ORC
Nominal power: 0.80 MW$_{el}$
Efficiency: 13.70%

Thermal energy storage (PCM)
Capacity: 165.32 MWh

Heat pump
Nominal power: 2.00 MW$_{el}$
COP: 6.40

Thermal efficency
102.86%

Overall Power to Power Ratio
88.18%
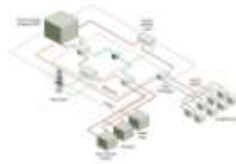
Financial indicators

Investment and operation costs:

CAPEX	11736k€
ORC	368k€
HP	575k€
PCM	7440k€
Other	3353k€
OPEX	2830k€
Maintenance costs	235k€ /year
TCO	14565k€

CAPEX distribution [%]

| ORC | HP | PCM | Other

Payback:

Not economically viable

IRR:

Not economically viable

Revenue:

215363.36

Energy balance

CHEST Capacity factor [%]

| HP | ORC | Not used

Thermal balance

| Heat from heat source | Heat from HP | Heat in PCM
| Heat from ORC | Heat delivered to heat demand

Electrical Balance [MWh/year]

| GRID | ORC
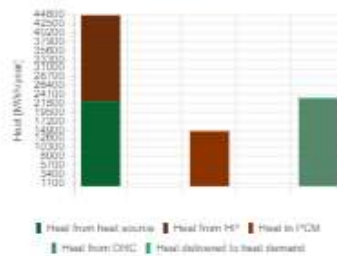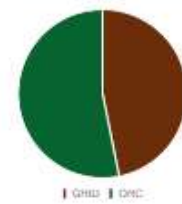
CHANGE INPUTS   GET THE REPORT!

Figure 14 Step 7 of CHEST tool, Grid-connected mode

The results provided in the technical sections are related with the sizing of the CHEST system and with the efficiency at which the CHEST system operates, specifically these are:

Main technical characteristics:

- ORC nominal power [MW$_{el}$]
- ORC efficiency [%]

- Capacity of the thermal energy storage (PCM) [MW$_{th}$]
- Heat pump nominal power [MW$_{el}$]
- Heat pump COP
- The CHEST thermal efficiency [%]
- The CHEST power to power ratio [%]

As the name indicates the economic results provides information about the economic aspects, investments and operational expenditures, of the CHEST system. The values shown includes the investment costs of different components of the system, total operational expenditures and yearly maintenance cost. Specifically, the results shown in this section are:

Investment and operation costs:

- Capital expenditures (CAPEX) [k€]
- ORC investment cost [k€]
- HP investment cost [k€]
- PCM investment cost [k€]
- Other investments costs [k€]
- Operational expenditures (OPEX) [k€]
- Maintenance costs [k€/year]
- Total cost of ownership (TCO) [k€]

In the Grid-connected case, additional financial indicators related with the profitability of the system, are provided. These are:

- Payback [years]
- IRR [%]
- Revenues [k€]

The energetic results provide information about the CHEST capacity factors, for the HP and the ORC, the heat flux or heat energy balance between the components of the CHEST system and the electrical balance between the electrical energy consumed and produced by the system. Concretely, the energy balance section contains the following results:

CHEST Capacity factor:

The capacity factor indicates ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period.. Therefore, the percentage shown here, indicates the percentage of annual hours at which the CHEST system, working at nominal power, is exchanging electricity with the grid or network.

- CHEST HP capacity factor [%]
- CHEST ORC capacity factor [%]

Thermal balance:

These results show how much heat energy is used and produced by the CHEST system, and as well if there is any reutilization of the residual heat of the ORC.

- Heat used from heat source [MWh/year]
- Heat generated by the HP [MWh/year]
- Heat in PCM [MWh/year]
- Heat generated by the ORC [MWh/year]

- Heat delivered from the ORC condenser to heat demand [MWh/year]

Electrical balance:

The electrical balance is different between each of the two CHEST modes. In the Stand-alone mode these results show how much electrical energy is consumed by the CHEST system and how much of this energy comes from renewable sources. Additionally, it also shows how much electricity the CHEST system generates, with the ORC, compared with the electricity absorbed, by the HP. In the Grid-connected mode, it only shows how much electrical energy the CHEST system produce compared with the energy absorbed from the grid. Thus:

If the CHEST is simulated in Stand-alone mode, the electrical balance includes:

- Electricity generated by Wind turbines [MWh/year], if any
- Electricity generated by photovoltaic panels [MWh/year], if any
- Electricity generated by the ORC [MWh/year]
- Electricity generated by Back-up system [MWh/year], if necessary

If the CHEST is simulated in Grid-connected mode, the electrical balance includes:

- Electricity generated by the ORC [MWh/year]
- Electricity consumed from the Grid [MWh/year]

3.7.2. Report content

This section describes the structure and items included in the CHEST Feasibility Assessment Tool Report, which is one of the main outputs of the web-based CHEST tool. An example of it is included in Appendix I, where the content can be analyzed in detail.

The report is structured as follows:

– **Introduction:** Brief explanation of the CHEST technology and aim of the report.

– **User Defined Parameters:** List of parameters characterizing the current energy system defined by the user, where the CHEST system will be integrated.

– **Results:** List of outputs of the tool including main design parameters of the CHEST, energy results, investment costs and financial results.

– **Disclaimer:** It indicates that results are only a first indication and to release and waive any liability from the developers of the tool.

4. Calculation engine

This section describes the equations used to estimate the performance of the CHEST system. As will be described next, these equations help the engine to estimate the production of electricity from different renewable sources, to estimate the availability or production of heat from different heat sources, to generate hourly profiles for heat and electricity consumptions, estimate the size of the CHEST components (HP, ORC and PCM), approximate the energy balances between the different CHEST components and evaluate the energetic and economic performance of the overall system.

4.1. Electrical resources

The production of electrical energy is an option only available for the Stand-alone power system mode, since in the other mode the electrical energy is purchased from the grid. First, the tool calculates the electrical production (elecProd) where two types of renewable sources, photovoltaic and wind, can be selected.

The calculation of the hourly photovoltaic production is carried out with a call to the PVGIS API [2], with the nominal power, slope, azimuth and location as input parameters. Figure 15 shows an example of the calculated hourly photovoltaic production.
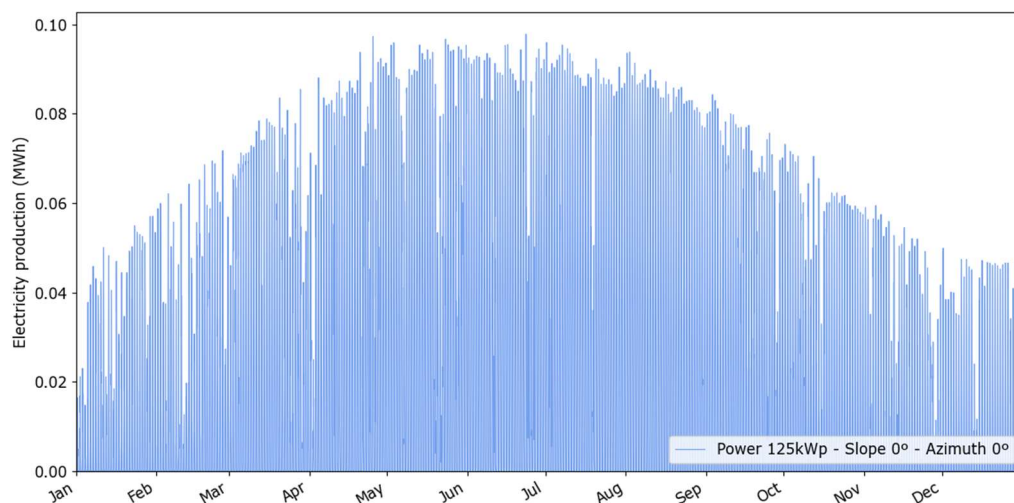
Figure 15 Hourly photovoltaic production with a nominal power of 100kWp, slope 0º and azimuth 0º.

Instead, the hourly wind production is calculated based on the wind velocity at 10 meters, which is also an output from the PVGIS API. Numerically, and based on production curves of multiple turbines, a relationship is established between the power of the selected turbine and its height.

From Hellmann's exponential law, the tool calculates the wind speed at the height of the turbine. Figure 16 shows the wind speed at different heights.
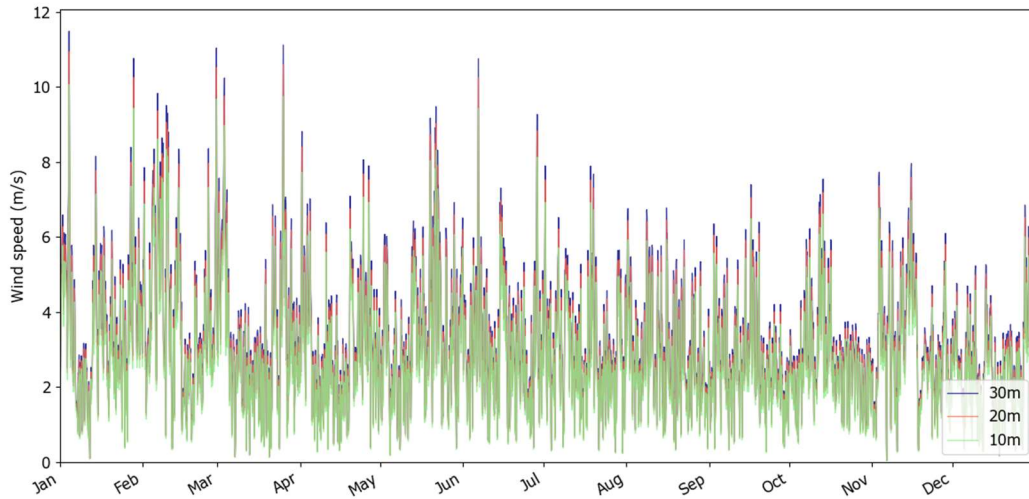
Figure 16 Hourly the wind speed at different heights.

Once wind speed is calculated, the hourly production is calculated based on production curves of turbines and taking into account the cut-out and cut-in speed, Figure 17 shows the electrical generation curve versus wind speed. Figure 18 shows the hourly production for a 80 m height turbine of 5 MW.
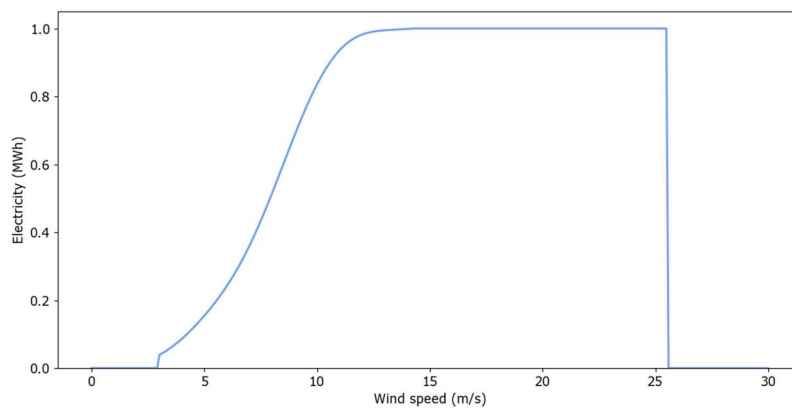
Figure 17 Wind speed and electrical generation curve.
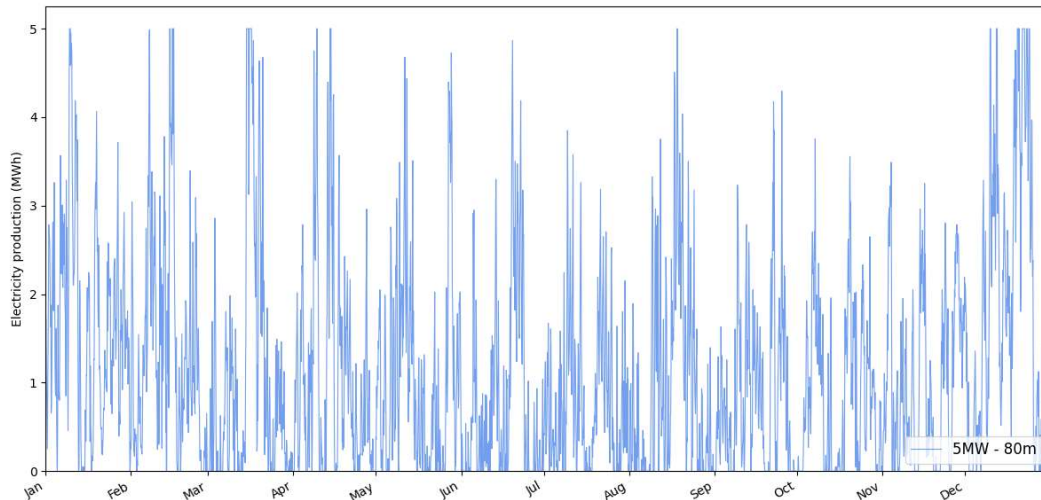
Figure 18 Wind electricity production for a 80m height turbine of 5MW.

4.2. Heat resources

The tool allows three types of heat available (avHeat): solar thermal system (STS), biomass or waste heat.

For waste heat, the hourly profile (wHeatProfile) is generated from the multiplication of the daily, weekly and annual profile introduced by the user. Using the waste heat profile and the annual thermal energy (annualAvHeat), the thermal energy available for each hour of the year is calculated.

$$\text{avHeat} = \frac{\text{wHeatProfile}}{\sum_{h=0}^{8760}\text{wHeatProfile[h]}} \cdot \text{annualAvHeat} \qquad [MWh] \qquad (1)$$

Figure 19 shows the waste heat consumption with the following profiles and annual thermal energy:

- Daily profile: [0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0]
- Weekly profile: [1, 1, 1, 1, 1, 0, 0]
- Annual profile: [0.9, 1, 0.9, 0.8, 0.7, 0.6, 0.7, 0.6, 0.7, 0.8, 1, 0.9]
- Annual thermal energy: 150 MWh/year
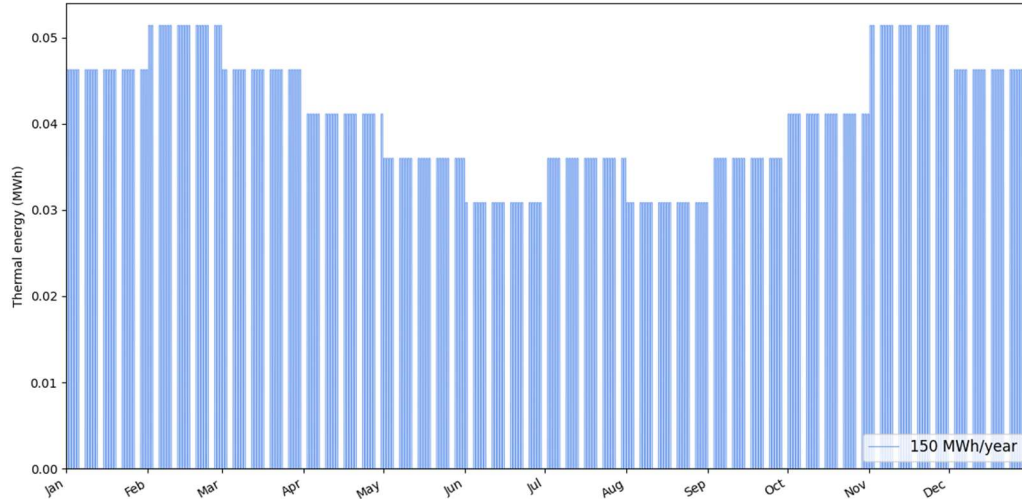
Figure 19 Available heat from waste heat with annual energy 150 MWh/year.

If the available heat is from a solar thermal system, first, the tool calculates the maximum accumulable energy by the system (STSen) with the equation (2). The parameters used are the area of the STS (STSarea) selected by the user, the hot water storage volume per unit of STS area (volAccRatio = 0.07 m³/m²), the water specific heat capacity (Cp = 4.18 kJ/kg·K) and the temperature difference between empty and full accumulator (AccAT = 75 K).

$$STSen = STSarea \cdot volAccRatio \cdot Cp \cdot accAT \cdot roW \ /3600 \cdot 10^3 \qquad [MWh] \qquad (2)$$

From the radiation (Gi [MWh]) obtained with PVGIS, the area of the STS and the heat demand of the PCM (PCMheatDem, explained in section 4.6), the energy available (avHeat) for each hour is established assuming an initial available heat of 50% of the maximum accumulable energy.

$$avHeat[h = 0] = 0.5 \cdot STSen \qquad [MWh] \qquad (3)$$

Equation (4) calculates the stored solar thermal energy for each hour of the year. The energy for each hour is defined as the energy of the previous hour, less the energy is supplied to the PCM, plus the energy generated with the radiation. This value cannot be greater than the maximum energy accumulated by the STS system or less than 0.

$$avHeat[h] = avHeat[h - 1] - PCMheatDem[h - 1] + STSarea \cdot Gi[h - 1] \qquad [MWh] \qquad (4)$$

Figure 20 shows an example of the available heat from a solar thermal system with a solar collector area of 112m².
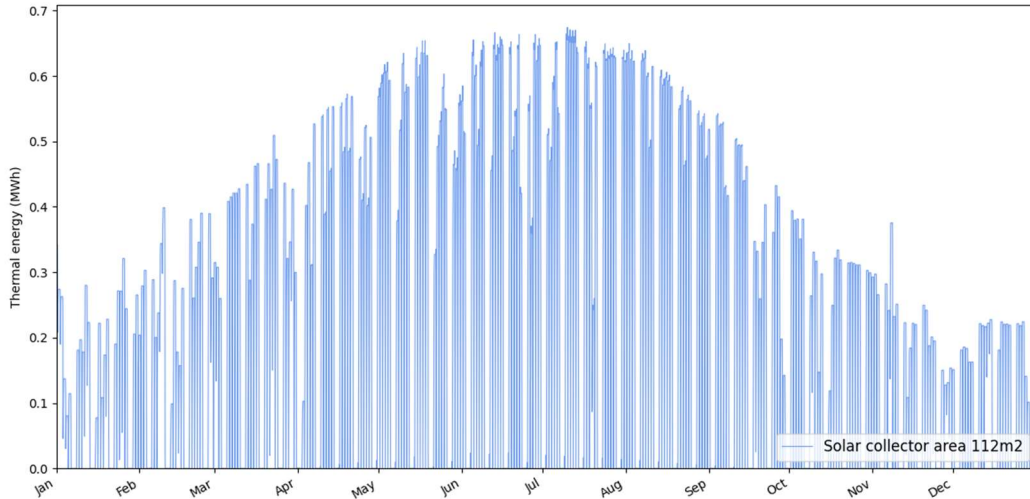
Figure 20 Available heat from solar thermal system with area 112 m².

If the user selected biomass as the source of heat, the available heat is equal to the heat demand of the PCM. Once the simulation is finished, the calculation engine returns the power of the biomass boiler needed. Figure 21 shows an example of the available heat from biomass.
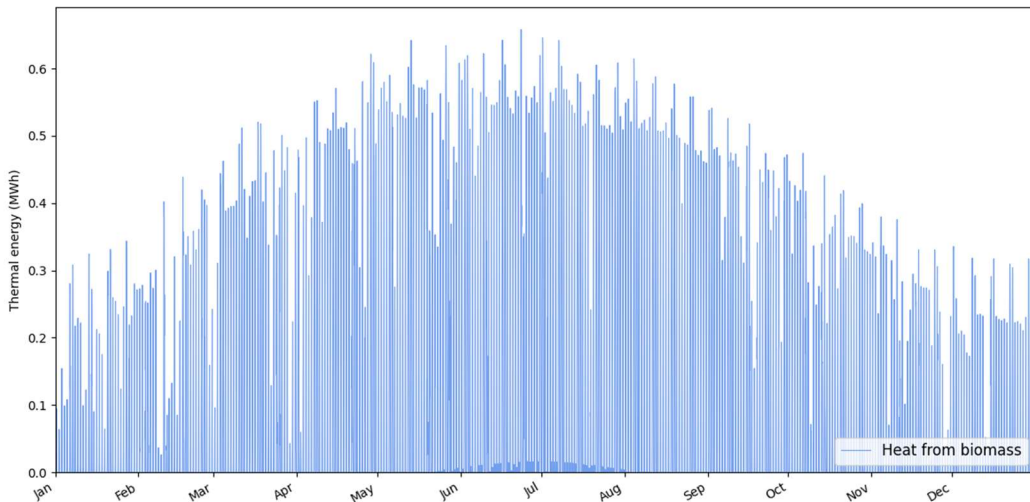
Figure 21 Available heat from biomass.

4.3. Electrical demand

The electricity demand can be defined in a standard or advanced way, this definition is only available for Stand-alone power systems.

The standard definition is based on the curves of the electrical energy consumed in the year 2018 of the selected country (elecCoProfile) [1]. The consumption curve is scaled so that the total energy consumed is the one selected by the user (annualElecDem), as it is shown in equation (5).

$$elecDem = \frac{elecCoProfile}{\sum_{h=0}^{8760} elecCoProfile[h]} \cdot annualElecDem \qquad [MWh] \qquad (5)$$

The demand curves are available for the following countries: Albania, Austria, Belgium, Bosnia, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Montenegro, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom of Great Britain and Northern Ireland.

If the curve for the selected country is not available, a curve generated from the average of all available curves is used. Figure 22 shows four electrical demands generated with the standard mode for Spain, Ireland, France and the generic curve.
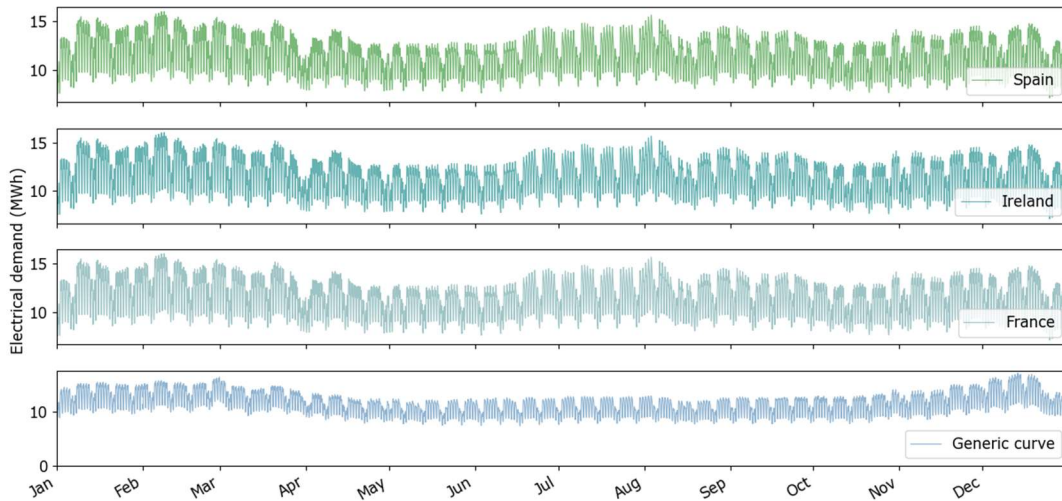
Figure 22 Electrical demand generated with standard method and annual demand 100GWh/year for Spain, Ireland, France and a generic curve.

The advanced definition of the electrical demand is based on the profiles defined by the user. The hourly profile (elecProfile) is generated from the multiplication of the daily, weekly and annual profile introduced by the user. Using the consumption profile and the annual electrical demand (annualElecDem), the electrical demand for each hour of the year is calculated.

$$elecDem = \frac{\text{elecProfile}}{\sum_{h=0}^{8760} \text{elecProfile}[h]} \cdot \text{annualElecDem} \qquad [MWh] \qquad (6)$$

Figure 23 shows the electrical demand with the following profiles and annual electrical demand:

- Daily profile: [0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
- Weekly profile: [1, 1, 1, 1, 1, 0, 0]
- Annual profile: [0.8, 0.9, 1, 0.95, 0.9, 0.85, 0.9, 0.95, 1, 1, 0.95, 1]
- Annual electrical demand: 100 GWh/year
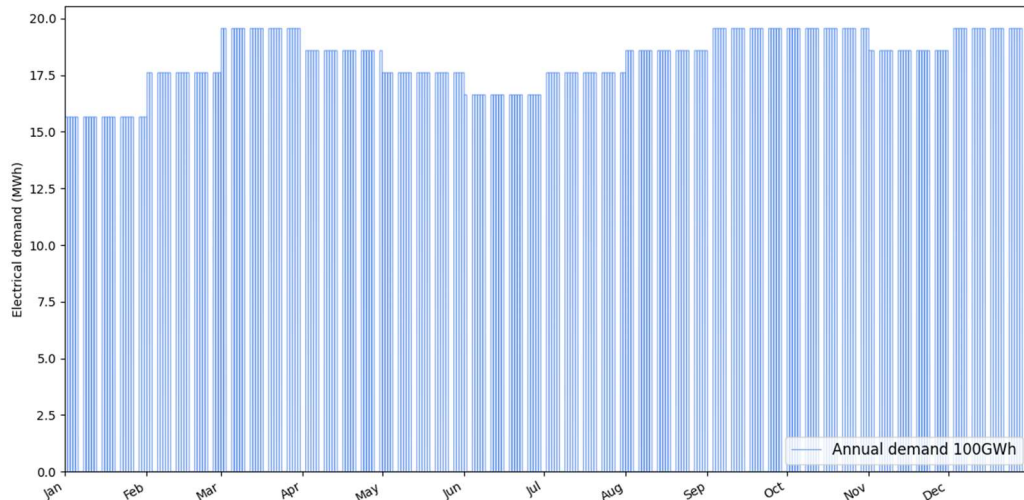
Figure 23 Electrical demand generated with advanced method and annual demand 100GWh/year.

4.4. Heat demand

The thermal demand can be of two types: district heating or other. If it is of another type, the demand is generated in the same way as advanced electrical demand or residual heat, with profiles and an annual value.

District heating demand uses the next parameters:

- Air temperature 2 meters from PVGIS (T2m)
- Reference temperature 11ºC from 00: 00-7: 00, and 15ºC from 8: 00-23: 00 (Tref)

The total district heating demand of the users is composed of a percentage of domestic hot water (demFracDHW = 15%), and a percentage of losses (lossesDH = 10%) that must be added to obtain the demand from the PCM point of view. The profiles are multiplied by the annual heat demand (annualHeatDem) set by the user. Figure 24 shows the profile of daily consumption of domestic hot water (profileDHW) [3].
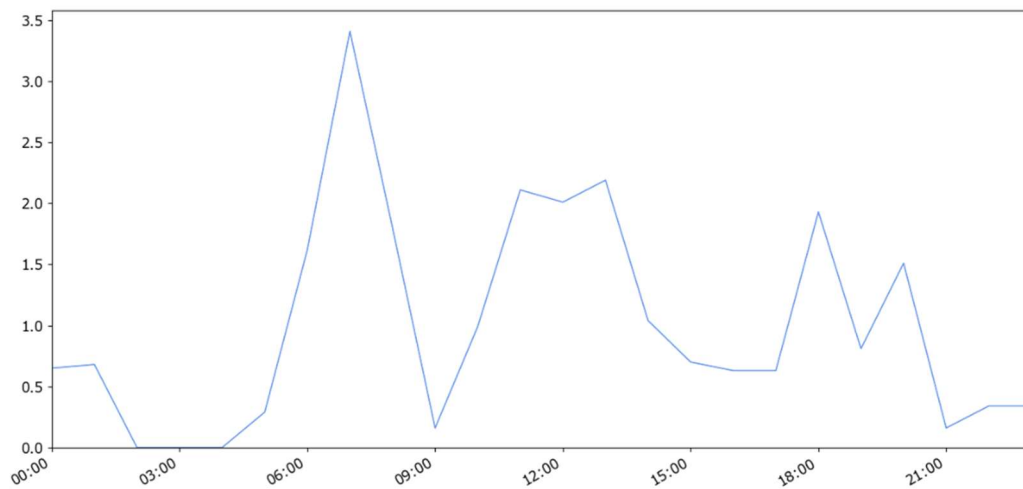
Figure 24 Domestic hot water consumption daily profile.

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The remaining consumption profile (profileHS) of the district heating depends on the temperature difference between the air temperature and the reference temperature of the selected country.

$$profileSH = \frac{\max{(Tref - T2m, 0)}}{\sum \max{(Tref - T2m, 0)}} \qquad [-] \qquad (7)$$
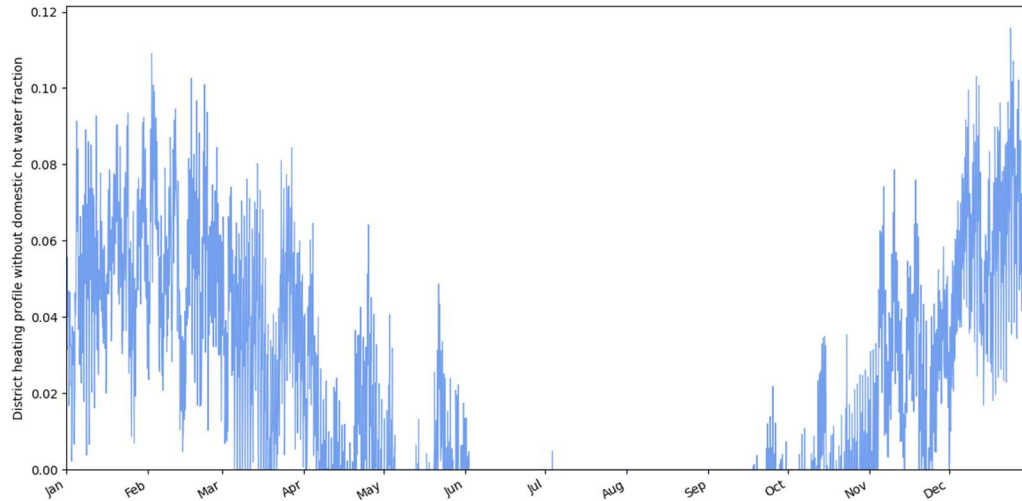
Figure 25 District heating profile without domestic hot water fraction

The total demand for domestic hot water is,

$$demSHW = \text{profileDHW} \cdot demFracDHW \cdot \text{annualHeatDem} \qquad [-] \qquad (8)$$

The rest of the district heating demand is,

$$demSH = \text{profileHS} \cdot (1 - demFracDHW) \cdot \text{annualHeatDem} \qquad [-] \qquad (9)$$

Total district heating demand from the PCM point of view,

$$extHeatDem = (demSH + demSHW) \cdot (1 + lossesDH) \qquad [-] \qquad (10)$$

Figure 26 shows an example of demand for district heating with an annual consumption of 200 MWh/year.
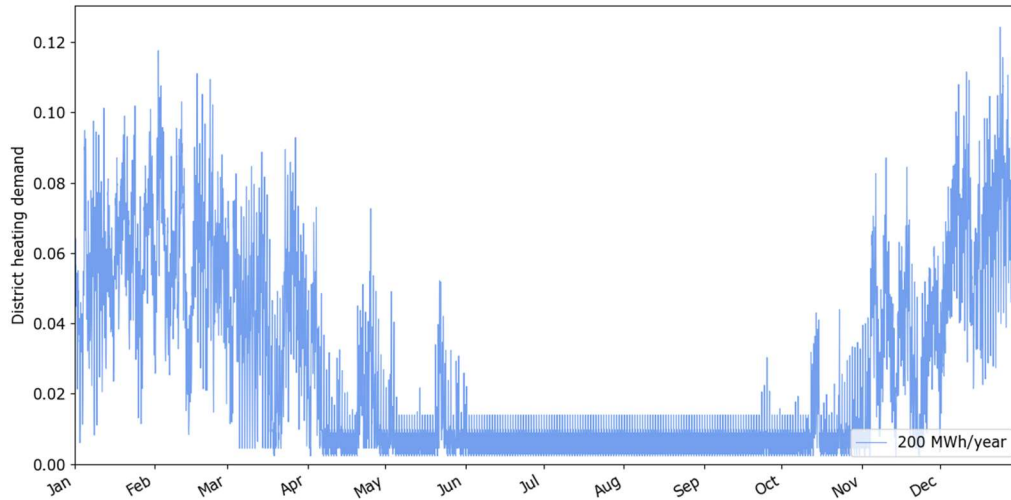
Figure 26 District heating demand with annual demand of 200MWh/year

4.5. Heat pump and organic ranking cycle

The sizing of the heat pump (HP) and the organic ranking cycle (ORC) is only done in Stand-alone systems, since in the Grid-connected systems, the user selects the ORC and HP powers by the discharge and charge capacity defined in Step 1.

The Stand-alone power system sizing is done with the relationship between production and demand. The balance is the hour-to-hour difference between renewable energy production and electricity consumption.

$$balance = elecProd - elecDem \qquad [MWh] \qquad (11)$$

Negative values of the balance imply an unmet demand (from now on called demand residue), and positive values a production surplus (from now on production residue),

$$resProd = balance > 0 \qquad [MWh] \qquad (12)$$

The absolute value of the demand residual is taken,

$$resDem = |balance < 0| \qquad [MWh] \qquad (13)$$

With the production and demand residues, the nominal power of the ORC and HP are calculated.

$$nomHP = \max(resProd) \qquad [MW] \qquad (14)$$

$$nomORC = \max(resDem) \qquad [MW] \qquad (15)$$

The ratio between powers is defined as:

$$ratioPCM = \frac{nomHP}{nomORC} \qquad [MW] \qquad (16)$$

If the ratio is less than 0.8 or greater than 3, it is necessary to resize the nominal powers. This happens when production is very small or very large compared to demand.

If it is necessary to resize the system because ratioPCM>3:

- The relationship between HP and ORC is 3,
- The smallest power other than 0 is kept,
- The other element (HP or ORC) is recalculated according to the power ratio

$$nomHP = nomORC \cdot 3 \qquad\qquad [MW] \qquad (17)$$

$$nomORC = \frac{nomHP}{3} \qquad\qquad [MW] \qquad (18)$$

While if it is necessary to resize the system due to ratioPCM<0.8:

- The relationship between HP and ORC is set to 0.8,
- The smallest power other than 0 is kept,
- The other element (HP or ORC) is recalculated as:

$$nomHP = nomORC \cdot 0.8 \qquad\qquad [MW] \qquad (19)$$

$$nomORC = \frac{nomHP}{0.8} \qquad\qquad [MW] \qquad (20)$$

4.6. Phase change material

The PCM exchanger transfer coefficient (UA) is calculated with the tube heat transfer coefficient (hHX = 80 W / m2 K for Stand-alone power system, hHX = 100 W / m2 K for Grid-connected power system), PCM heat exchanger tube diameter (diHX = 0.02 m) and fluid-PCM temperature difference (AT = 5 K).

$$UA = \pi \cdot hHX \cdot diHX \cdot AT \qquad\qquad [W/m] \qquad (21)$$

For the calculation of the length heat exchanger of the PCM (lHX), the highest result is selected between the equations (22) and (23).

$$lHX = (1 + COP) \cdot nomHP \cdot RLS \cdot 10^6 / UA \qquad\qquad [m] \qquad (22)$$

$$lHX = nomORC \cdot RLS \cdot 10^6 / UA \cdot effORC \qquad\qquad [m] \qquad (23)$$

The COP and efficiency of the ORC, as well as the PCM parameters are determined based on the heat source temperature introduced by the user, and the values correspond to specific refrigerants and PCM materials identified during the project as the most appropriate for the selected temperatures. Appendix II describes all the values based on such selection.

The PCM accumulator volume (accVol) is calculated with PCM volume per meter of heat exchanger (Epcm = 0.005 m3 / m) and the length of the PCM heat exchanger (lHX).

$$accVol = lHX \cdot ePCM \qquad\qquad [m^3] \qquad (24)$$

The PCM accumulator energy (accEn) is calculated from the PCM accumulator volume and PCM phase change enthalpy (ahPCM = 200 kJ / kg).

$$accEn = roPCM \cdot ahPCM \cdot accVol/3600 \cdot 10^3 \qquad [MWh] \qquad (25)$$

4.7. Energy balances

The energy balances of the Grid-connected system and the Stand-alone system are very similar, only the calculation of the PCM load changes. In the first case, the charge and discharge of the PCM is carried out according to the electricity price of the grid, while in the Stand-alone system, charge and discharge depends on the production surplus and the unmet demand to cover. In order to simplify the calculation, the SHS is not explicitly modelled and the heat stored there can be recovered in the charge and discharge process, so the only practical effect is the consideration of the SHS for sizing the PCM and the energy fluxes within the PCM.

In both cases, an initial PCM charge of 50% of its capacity is established.

$$SOC[h = 0] = 0.5 \cdot accEn \qquad [MWh] \qquad (26)$$

The calculation of the PCM state of charge on the Stand-alone system:

For each hour the state of charge is calculated with the equation (27) with the coefficient of performance (COP), latent-sensitive heat ratio (RLS) and ORC efficiency (effORC). The current state of charge (SOC[h]) is defined as the state of charge of the previous hour (SOC[h-1]), minus the energy that was discharged to meet demand, plus the surplus production that can be stored in the PCM. This value cannot be greater than PCM maximum capacity (accEn) or less than 0.

$$SOC[h] = SOC[h - 1]$$
$$- resDem[h - 1] \cdot RLS/effORC)$$
$$+ resProd[h - 1] \cdot RLS \cdot COP \qquad [MWh] \qquad (27)$$

The electrical production of the PCM (PCMelecProd) for each hour of the year is the minimum between the demand that remains to be covered and the energy that the PCM can supply.

$$PCMelecProd = \min(resDem,\ SOC \cdot effORC/RLS) \qquad [MWh] \qquad (28)$$

The electricity consumed by the PCM (PCMelecDem) for each hour of the year is the minimum between the production surplus and the energy that the PCM can absorb.

$$PCMelecDem = \min(resProd,\ (accEn - SOC)/RLS \cdot COP) \qquad [MWh] \qquad (29)$$

The back-up electricity (backUpElec) for each hour of the year is the difference between the demand residue and the electricity production of the PCM.

$$backUpElec = resDem - PCMelecProd \qquad [MWh] \qquad (30)$$

The calculation of the PCM state of charge on the Grid-connected system is calculated as follows:

First, the price percentiles from which the charge and discharge of the PCM begins are calculated with equations (31) and (32), limiting the result between 0.35 and 0.7.

$$dischPerc = 0.55 \cdot \frac{nomORC}{nomHP} \cdot powerRatio \qquad [-] \qquad (31)$$

$$chargePerc = 0.33 \cdot \frac{nomORC}{nomHP} \cdot powerRatio \qquad [-] \qquad (32)$$

Then, the price curves of the day ahead market (DAM) [1] the rising and falling curves of the balancing market (upBM, downBM) for 2018 of the selected country are downloaded. The sale price profile is multiplied by the increment of price defined by the user.

The sale price is the maximum price between the day ahead market and the upward balancing market, while, the purchase price is the minimum but different from zero price between the day ahead market and the downward balancing market.

$$up = \max{(dam, \text{upBM})} \cdot (1 + Fprice) \qquad [€/MWh] \qquad (33)$$

$$down = \min{(dam, \text{downBM})} \qquad [€/MWh] \qquad (34)$$

The discharge limit is fixed for each week, and is established as,

$$dischLim = percentile(\text{up}, dischPerc) \qquad [€/MWh] \qquad (35)$$

The charge limit is fixed for each week and is established as,

$$chargeLim = percentile(\text{down}, chargePerc) \qquad [€/MWh] \qquad (36)$$

Therefore, the PCM charge whenever the value of the down curve is less than the price limit. And the PCM discharge, as long as there is no load, when the price of the up curve is higher than the price limit.

When the discharge condition is met, the energy produced by the PCM is the minimum between the power of the ORC and the maximum production with the energy available in the PCM.

$$PCMelecProd = min(nomORC, \text{SOC}[\text{h} - 1] \cdot RLS/effORC) \qquad [MWh] \qquad (37)$$

When the charge condition is met, the energy produced by the PCM is the minimum between the HP power and the energy that can be stored in the PCM until reaching its maximum capacity.

$$PCMelecDem = \min{(nomHP,} \qquad [MWh] \qquad (38)$$
$$(\text{accEn} - \text{SOC}[\text{h} - 1])/RLS \cdot effORC)$$

The hourly PCM state of charge is the state of charge of the previous hour, plus stored energy, minus discharged energy.

$$SOC[h] = SOC[h - 1] + \qquad [MWh] \qquad (39)$$
$$PCMelecProd[h - 1] \cdot \frac{RLS}{effORC}$$
$$-PCMelecDem \cdot RLS \cdot COP$$

Then, for both cases, the thermal demand of the PCM is calculated from the electricity consumed by the PCM and the coefficient of performance (COP).

$$PCMheatDem = PCMelecDem\ (COP\ - 1) \qquad [MWh] \qquad (40)$$

Then, the energy stored in the PCM at each hour is,

$$storedPCM = (\ PCMheatDem\ +\ PCMelecDem) \cdot RLS \qquad [MWh] \qquad (41)$$

And the energy delivered by the PCM every hour is,

$$supplyPCM = PCMelecProd \cdot RLS/effORC \qquad [MWh] \qquad (42)$$

The heat needed to fulfill PCM heat demand (addHeat) is the PCM heat demand minus the available heat (avHeat).

$$addHeat = PCMheatDem - avHeat \qquad [MWh] \qquad (43)$$

The heat produced by the PCM (PCMheatProd) during electricity production is calculated with the electrical energy consumed from the PCM and the efficiency of the ORC.

$$PCMheatProd = PCMelecDem \cdot (1 - effORC)/effORC \qquad [MWh] \qquad (44)$$

The heat delivered on demand depends on the difference between supply (sTemp), condensation (condTemp) and return (rTemp) temperatures. The higher this value, the greater the heat transfer, and the energy to be delivered is the minimum between the heat produced by the PCM and the external heat demand (extHeatDem)

$$tempDiff = (condTemp - rTemp)/(sTemp - rTemp) \qquad [MWh] \qquad (45)$$

$$supplyHeat = tempDiff \cdot \min(PCMheatProd, extHeatDem) \qquad [MWh] \qquad (46)$$

4.8. Technical calculations

Some indicators of the operation of the system are:

Power to power ratio, total electricity production divided by the total electricity consumption of the system:

$$p2p = \sum PCMelecProd / \sum PCMelecDem \qquad [\%] \qquad (47)$$

Capacity factor, percentage of hours that the HP or the ORC is used:

$$cfHP = \sum(PCMelecDem \neq 0)/8760 \qquad [\%] \qquad (48)$$

$$cfORC = PCMelecProd/8760 \qquad [\%] \qquad (49)$$

Thermal efficiency, total heat production divided by the total heat consumption of the PCM:

$$thEff = \sum PCMheatProd / \sum PCMheatDem \qquad [\%] \qquad (50)$$

Percentage of cover external demand, total supplied thermal energy divided by the external heat demand.

$$extPer = \sum supplyHeat / extHeatDem \qquad [\%] \qquad (51)$$

The power of the boiler needed if biomass is used as the available heat source

$$boiler = (COP - 1) \cdot \text{nomHP} \qquad [MW] \qquad (52)$$

4.9. Economic calculations

The total investment or capital expenditures (CAPEX) is made up of the following elements:

$$HPinv = 287,500 \cdot nomHP \qquad [\text{€}] \qquad (53)$$

$$ORCinv = 460,000 \cdot nomORC \qquad [\text{€}] \qquad (54)$$

$$PCMinv = 45,000 \cdot accEn \qquad [\text{€}] \qquad (55)$$

$$CAPEX = (HPinv + ORCinv + PCMinv) \cdot 1.4 \qquad [\text{€}] \qquad (56)$$

The costs of the ORC, HP and PCM storage are taken from CHESTER deliverable 6.2.

The annual maintenance of the installation is considered 2% of the $CAPEX$:

$$OPEX = CAPEX \cdot 0.02 \qquad [\text{€}/year] \qquad (57)$$

Total Cost of Ownership (TCO):

$$TCO = CAPEX + lifetime \cdot OPEX \qquad [\text{€}] \qquad (58)$$

In grid-connected systems, the return on investment can be calculated.

The income and expenses for the operation of the system are:

$$heatIncome = heatSalePrice \cdot supplyHeat \qquad [\text{€}/year] \qquad (59)$$

$$heatExpenses = heatPurchasePrice \cdot avHeat \qquad [\text{€}/year] \qquad (60)$$

$$elecIncome = up \cdot PCMelecProd \qquad [\text{€}/year] \qquad (61)$$

$$elecExpenses = down \cdot PCMelecDem \qquad [\text{€}/year] \qquad (62)$$

$$income = heatIncome + elecIncome \qquad [\text{€}/year] \qquad (63)$$

$$expenses = heatExpenses + elecExpenses \qquad [\text{€}/year] \qquad (64)$$

Other indicators that are calculated are the internal rate of return (IRR) and the return of investment (ROI), using investment, income, expenses and maintenance.

5. Front end & Back end: languages used and technical specification

5.1. Introduction

As many other web services, the CHEST tool is split in two layers: the Front End, which contains the graphical user interface (GUI); and the Back End or calculation Engine. Both layers of the CHEST tool exchange information through an API protocol. Figure 27 below shows a diagram of the CHEST tool architecture.
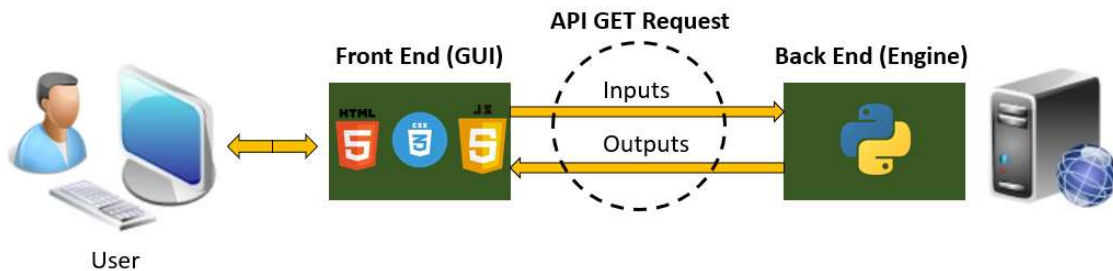
Figure 27 Architecture of the CHEST tool

5.2. Front End

The main functionally of the GUI is to collect all inputs, i.e. working conditions, introduced by the user. Once these are filled, and the calculation button is pressed, the GUI sends a request to the Engine with all the inputs. A continuation, the Engine execute the calculations and sends the computed results back to the GUI, where these are displayed in its last section. Additionally, another functionality of the tool is to generate the results report which can be downloaded by the user at the last section of the tool. The GUI presents a total of seven sections, where the user defines the working conditions and demands to be handled by the CHEST system. The chapter 3, of this document, describes in detail each of the screens and inputs of the tool.

The GUI is developed using three programing languages: HTML, CSS and JavaScript. The combination of these three programing languages is the most used nowadays to develop the majority of the GUI's for web services or mobile apps in the market. Basically, the HTML language is used to define the layout of the screen, e.g. location of text or titles. The CSS language is known as the style language as this defines the display of an HTML document, including color, letter style, size etc. Finally, JavaScript language provides flexibility to the GUI, allowing to perform simple operations at the client side not needing to exchange information with the server. Some examples of this flexibility provided include: activate cells required to be filled by user depending on the choices made by the user, check if all the information has been successfully entered in the webpage, display dynamic plots in the webpage etc.

5.3. Back End

The main purpose of the CHEST tool Engine is to calculate the performance of the CHEST system under the working conditions specified by the user in the GUI. Section 6.6 lists the outputs and details their definition and formulation. The Engine of the tool has several functions coded in Python. Python is an open-source object-oriented programing language with dynamic semantics and presents a large community of developers. One of the main strengths of Python is the

possibility to use a large number of already developed modules and packages, which facilitates and encourage the program modularity and code reuse.

As depicted in Section 2, the functions of the CHEST Engine fall under three main categories: Stand-alone, Grid-connected and economic equations. Additionally, to these three main categories, some complementary functions are used in each operational mode.

Stand-alone function:

- **stand_alone_system:** This function calculates all the hourly balances of energy, for an entire year, when the CHEST system operates as a Stand-alone power system. The main goal of the CHEST system operating in this mode is to increase the utilization of the renewable energy produced. Improving the balance between the generation of energy with the demand of it.

Grid-connected function:

- **grid_connected_system:** This function calculates all the hourly balances of energy, for an entire year, when the CHEST system operates as a Grid-connected. The main goal of the CHEST system operating in this mode is to increase the profits achieved with the arbitrage strategy. Another goal that could be achieved with the CHEST system operating in a grid-connected mode will be provide demand response services (DRS) to the grid, helping it with congestion problems.

Economic and energetic results functions:

- **sas_results:** This function uses the results of the energy balances, calculated by the *stand_alone_system* function, to compute the energetic and economic results of the Stand-alone power system.

- **gcs_results:** This function uses the results of the energy balances calculated by the *grid_connected_system* function to compute the energetic and economic results of the Grid-connected operational mode.

Auxiliary functions:

As have been already commented, both of these functions use a set of auxiliary functions. These are used to calculate the electrical and heat demand, the available heat from heat source or the renewable energy generated by the renewable sources (photovoltaic panels or wind turbines). Some of these functions are only used in one mode of operation or other, and some other functions are used in both modes.

Auxiliary functions used in both modes:

- **PVGIS_data:** This function is used to get the meteorological data of the country selected by the user and to calculate the PV production of the photovoltaic system defined, if any. This data is got from the EU tool PVGIS using the available API of this tool.

- **external_heat_demand:** This function is used to calculate the heat demand curve. Depending on the selected option in the GUI the curve is computed from scratch or modifying a default heat demand curve.

- **available_heat:** This function computes the heat that can be used from an available heat source. This heat can be provided from a biomass boiler, solar thermal system or from a waste heat source. Depending on the option selected in the GUI this available heat is calculated simulating a biomass boiler or a solar thermal system. If the waste heat source option is selected, the available heat source curve is calculated using the detailed inputs defined by the user.

Auxiliary functions used in Grid-connected mode:

- **market_bbdd:** This function is used to load the electrical prices of the country selected by the user.

- **charge_discharge_limit_price:** This function is used to identify under which price sell or buy electricity from the grid.

Auxiliary functions used in Stand-alone mode:

- **wind_power_generation:** This function contains the equations used to estimate the production of a wind turbine.

- **energy_production:** This function uses the previous one, *wind_power_generation*, to estimate the energy generated with the wind turbines. This production depends on the wind velocity of the country and the size and number of wind turbines specified.

- **load_profile:** This function is used to compute the electrical demand curve. This curve is generated using the detailed or simplified data specified by the user in the GUI.

5.4. CHESTER API: Front End – Back End communication

An Application Programing Interface (API) is a set of subroutines that establish communication protocols between a group of components. The CHEST API is the communication protocol between the GUI and the Engine. This API has two functions or communication points. The first function is a POST request point that manages the authentication. The second function is a GET request point that provides the inputs to the Engine and feeds the results back to the GUI. The GET request point only accepts inputs, and feeds results only to components that have been authorized previously, which in this case it only includes the GUI of the tool.

At the time this report has been written, there is no web domain acquired for the CHEST online tool. In the following section presenting the POST and GET APIs, the text "domain web address" is used to replace the final URL of the CHEST online tool.

POST *API_CHEST*

Any component making a request to the Engine will get a token value. To obtain a token value, a POST request is required with a corresponding username and password, as it is shown below. The token value must be delivered together with each GET request in order to get an answer from the Engine, otherwise this leads to a 500 error.

The URL or end point where perform the POST request is the following:

https://domain_web_address/auth

The content of the POST request to obtain a token must be the following: a header section with the content type specified and a body section with the username and password:

Headers

Content-Type	application/json

Body *(application/json)*

```
{
"username": "xxxx",
"password": "xxxx"
}
```

Figure 28 exhibits an example of the authentication POST request to the CHEST API

In the example a dummy URL has been used for tests, and within the body section username and password have been shadowed.

Figure 28 Example of the authentication POST request to the CHEST API.

Figure 29 shows an example of the response obtained after the authentication POST request. The response provided is the access token, that is the key used to validate that the request comes from an authorized device, in this case from the server where the GUI is hosted. It has been crossed out in Figure 29 because of security.

Figure 29 Response obtained after a POST request

GET API_CHEST

As mentioned earlier, the GET request provides the inputs, i.e. the working conditions for the CHEST system to be calculated, entered by the user in the Engine. Based on these working conditions, the Engine calculates the performance of the AHT and the associated outputs.

The URL or end point where the GET request is performed is the following:

https://domain_web_address/

The content of the GET request must be the following. Again, we have a headers section including the content type and an authorization at the heading, and the inputs for the engine in the body.

Headers

Content-Type	application/json
Authorization	JWT xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Body *raw (application/json)*

```
{
"baseline":{
    "operation": "Stand-alone power system"
},
"country":{
    "latitude": 40.416775,
    "longitude": -3.703790,
    "name": "ES",
    "FpriceInc": 0.05,
    "Celprice": 1.0,
    "Selprice": 1.05
},
"residHeat": {
    "heatSource": "Biomass",
    "annualEnergy": 200.0,
    "dayProfile": [1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0,
0, 0],
    "weekProfile": [1, 1, 0, 0, 1, 1, 1],
    "yearProfile": [0, 0.7, 1, 0, 0, 0.2, 0.5, 1, 0, 0, 0, 0],
    "areaSolarCol": 112.0,
    "heatSourceTemp": 70.0,
    "cost": 2.0
},
```

```
"heatDemand": {
    "typeHeat": "None",
    "supplyTemp": 100.0,
    "returnTemp": 40.0,
    "annualDemand": 230.0,
    "dayProfile": [1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0,
0, 0],
    "weekProfile": [1, 1, 1, 1, 1, 0, 0],
    "yearProfile": [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1],
    "income": 1.0
},

"electDemand": {
    "electDemand": "Standard",
    "annualDemand": 10000.0,
    "dayProfile": [1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0,
0, 0],
    "weekProfile": [1, 1, 1, 1, 1, 0, 0],
    "yearProfile": [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
},

"electSupply": {
    "electSource": "Wind turbine",
    "numTurbines": 1,
    "nomPower": 1.0,
    "pvPower": 100.0,
    "slope": 0.0,
    "azimuth": 0.0
},

"ORC_HP": {
    "nomPowerORC": 0.8,
    "nomPowerHP": 2.0
}
}
```

Figure 30 present an example of the GET request to the CHEST API.

```
cURL  ▼                                                    Copy to Clipboard

  1   curl -X GET \
  2     http://localhost:4001 \
  3     -H 'Authorization: JWT ████████████████████████████
                ████████████████████████████████████████████████████
                ████████████████████████████████████████ \
  4     -H 'Content-Type: application/json' \
  5     -H 'Postman-Token: b9db6000-1ecb-4269-a7f2-f799ed5b9950' \
  6     -H 'cache-control: no-cache' \
  7     -d '{
  8       "baseline":{
  9           "operation": "Stand-alone power system"
 10       },
 11       "country":{
 12           "latitude": 40.416775,
 13           "longitude": -3.703790,
 14           "name": "ES",
 15           "FpriceInc": 0.05,
 16           "Celprice": 1.0,
 17           "Selprice": 1.05
 18       },
 19       "residHeat": {
 20           "heatSource": "Biomass",
 21           "annualEnergy": 200.0,
 22           "dayProfile": [1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0],
 23           "weekProfile": [1, 1, 0, 0, 1, 1, 1],
 24           "yearProfile": [0, 0.7, 1, 0, 0, 0.2, 0.5, 1, 0, 0, 0, 0],
 25           "areaSolarCol": 112.0,
 26           "heatSourceTemp": 70.0,
 27           "cost": 2.0
 28       },
 29
 30       "heatDemand": {
 31           "typeHeat": "None",
 32           "supplyTemp": 100.0,
 33           "returnTemp": 40.0,
 34           "annualDemand": 230.0,
 35           "dayProfile": [1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0],
 36           "weekProfile": [1, 1, 1, 1, 1, 0, 0],
 37           "yearProfile": [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1],
 38           "income": 1.0
 39       },
 40
 41       "electDemand": {
 42           "electDemand": "Standard",
 43           "annualDemand": 10000.0,
 44           "dayProfile": [1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0],
 45           "weekProfile": [1, 1, 1, 1, 1, 0, 0],
 46           "yearProfile": [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
 47       },
 48
 49       "electSupply": {
 50           "electSource": "Wind turbine",
 51           "numTurbines": 1,
 52           "nomPower": 1.0,
 53           "pvPower": 100.0,
 54           "slope": 0.0,
 55           "azimuth": 0.0
 56       },
 57
 58       "ORC_HP": {
 59           "nomPowerORC": 0.8,
 60           "nomPowerHP": 2.0
 61       }
 62   }'
```

Figure 30 Example of the GET request to the CHEST API.

In Figure 31 the data transferred from the calculation engine to the Front End after a positive GET request can be seen. These data include all results from calculation engine that will be presented interactively in the results STEP of the tool and include in the report.

```
{
  "orcNP": 0.16016177984329985,              "elABS": [                              40.603569672666254,
  "orcEff": 7.9,                                160.94787695836814,                  53.45782325700293,
  "hpNP": 1.5561711704808794,                  999.9999999999999                    110.20612709238283,
  "hpCOP": 5.1,                              ],                                       23.48517016852431
  "pcmCAP": 117.16263599780402,             "wpEL": 704.363941957305,               ],
  "pcmMONTH": [                              "pvEL": 0,                              "BiomNP": 6.380301798971605
       142.2954801330989,                   "orcEL": 378.20215215431426,          },
       221.27397492262403,                  "elREN": 704.363941957305,            {
       124.30947685160001,                  "bpEL": 512.8903332386411,
       73.54289007071776,                   "hpEL": 160.94787695836814,             "typeHeat": "None",
       132.85968172820213,                  "loadEL": 378.20215215431426,           "supplyTemp": 100,
       86.29383928901412,                   "elDEM": 1160.947876958368,             "returnTemp": 40,
       61.182191365626295,                  "elPERREN": 0.4871096667613585          "annualDemand": 230,
       46.828044187988944,                  "elPERNONREN": 0.51289033323864         "dayProfile": [⬅],
       27.27371484842022,                   "elPTP": 42.55604470825383,             "weekProfile": [⬅],
       35.908011036533225,                  "orcCAPEX": 73674.41872791793           "yearProfile": [⬅],
       74.02626195424939,                   "hpCAPEX": 447399.2115132528,           "income": 1,
       15.775160644906329                   "pcmCAPEX": 5272318.619901181           "heatDemandCurve": [
  ],                                         "otherCAPEX": 2317356.90005694             211.84149184666128,
  "pcm": 1041.5687270329813,                 "CAPEX": 8110749.150199292,                329.4202241041245,
  "pcmCF": [                                 "CAPEXDistr": [                            185.06494375147437,
       24.863013698630137,                       0.9083552870835322,                   109.48651027231043,
       21.015981735159816                        5.516126848803598,                    197.79400693014836,
  ],                                             65.0040892926843,                     128.46940489649893,
  "thermBAL": [                                  28.571428571428577                    91.08459861985027,
       1550.628823832688,                   ],                                         69.7149532210438,
       1550.628823832688,                   "maiOPEX": 162214.98300398584              40.603569672666254,
       1041.5687270329813,                  "opex": 4866449.490119575,                 53.45782325700293,
       1876.367021248824,                   "tco": 12977198.640318867                  110.20612709238283,
       0                                  },                                           23.48517016852431
  ],                                      {                                       ]
  "hpResidualHeat": 1550.62882383,                                              },
  "hpHeat": 1550.628823832688,              "heatSource": "Biomass",            {
  "pcmHeat": 1041.5687270329813,            "annualEnergy": 200,
  "orcHeatAbs": 1876.367021248824,          "dayProfile": [⬅],                    "electDemand": "Standard",
  "thermEFF": 12100.684524946522,           "weekProfile": [⬅],                   "annualDemand": 1000,
  "extHeat": 0,                             "yearProfile": [⬅],                   "dayProfile": [⬅],
  "orcHeatDel": 0,                          "areaSolarCol": 112,                  "weekProfile": [⬅],
  "extPER": 0,                              "heatSourceTemp": 70,                 "yearProfile": [⬅],
  "elBAL_SA": [                             "cost": 2,                            "electLoadCurve": [
       0,                                   "wasteHeatCurve": [                        89.10995061029705,
       704.363941957305,                         211.84149184666128,                  83.90351159641934,
       512.8903332386411,                        329.4202241041245,                   87.1596454216725,
       378.20215215431426                        185.06494375147437,                  78.58092364313671,
  ],                                             109.48651027231043,                  79.21089094423861,
                                                 197.79400693014836,                  80.18509702585314,
                                                 128.46940489649893,                  87.49286127306104,
                                                 91.08459861985027,                   86.6856081998951,
                                                 69.7149532210438,                    81.77091200603915,
                                                                                      79.94293175217128,
```

Figure 31 Response obtained after a GET request.

6. Tool web hosting: concept and specifications

A web hosting enables the display of a website in Internet. The websites are hosted, or stored, in special computers usually called servers. The website of a company is identified by the user, the domain or URL. The contents of the website include the Front End and Back End and are stored in the server. Each time a user accesses the URL, the DNS (Domain Name System) redirects the request to the server that contains or stores the website requested and displays the front end (or GUI) of the website. The cost of the hosting service depends on the technical requirements of the server. In general, higher technical requirements of the server (and higher costs) are expected when dealing with large amounts of traffic or high number of visitors. Due to the fact that the target user of the CHEST tool is a specialized user with a high technical knowledge, it is not forecasted to have a large number of visitors on a daily basis. Based on this, the identified technical specifications of the CHEST hosting service will be as follows:

– Memory: 60GB,
– RAM: 2GB,
– Number of CPU's: 1.

A hosting service with the above technical specifications is estimated to cost in the range of 300-500 €/year. The final cost will depend on the hosting provider and extra services included, e.g. security certification, unlimited traffic, unlimited number of webpages displayed, email service etc. The hosting service usually has a number of hosting plans with different technical capacities, which gives the option to modify the technical specifications of the server if required. Once the Front End and Back End of the tool are developed, their implementation in a hosting service is a straightforward process: The first step is to buy the domain of the website, this domain will define the URL to access the website or tool in this case; second, the hosting service that best fits the required technical specifications must be contracted; third, the Front and Back ends have to be deployed in the server of the hosting service and redirect the DNS of the URL, or domain, to the IP of the hosting server. Usually, the hosting service provides technical assistance in order to guide the client through each of these steps.
The predesign tool developed within task 6.5 will be hosted at servers contracted by Aiguasol, once the tool development has been completed and until the end of the project. After the end of the project, a new hosting service could be contracted if any project partner is interested in the exploitation of the tool beyond the project life time.

7. Debugging and beta testing – Further Steps

At the time this deliverable is being developed, the beta version of the tool (including the versions for personal computer and mobile phones) is at the beta testing phase. In this testing, and debugging process, all End-users involved in the project will test the tool and give their feedback to the developing team. During February-March 2021 Aiguasol as the main developer of the tool, will host it at their server supplying access to the tool to all consortium members. The final alpha version will include improvements added during this beta testing phase, and will be the first one that will be usable for other than partners of the project.

The tool developed within Task 6.5 is a predesign tool for a CHEST system. The target users include owners of RES technologies, owners of energy plants or industries with excess heat, DSOs, TSO, BRPs, DH facilities and anyone interested in the use of the CHEST technology. The user of the tool must have a basic knowledge of the existing energy system in which the CHEST system will be integrated. The tool will provide a first technical and economic assessment of the suitability of the simulated CHEST system.

For a further development and improvement of the tool following issues can be address:

- Include the possibility that the user can upload his owns hourly loads profiles for the electrical consumptions, heat demand or heat sources steps.
- Adjust the units of the results depending on his value to improve the readability of them.
- Improve the schemes images shown in the tool, including more realistic components representation.

Due to the interactive nature of the tool, it is expected that after the first months with the tool being online, other aspects will be identified to improve it. A continuation, it is described some of the best practices and tests performed in order to ensure the robustness of the GUI and the Engine of the tool.

7.1. GUI Debugging and beta testing

The GUI has been debugging and testing during two different phases, the design and the development phases.

During the design phase, a mockup of the GUI has been continuously reviewed by the partners of the project. In each iteration, different aspects about the tool content have been discussed such as, number of inputs to be shown in each screen, description texts for each of the inputs etc. The mockup has simplified and speed up the design process ensuring that all the partners agree on the tool aspect before starting with the development of it. The Figure 32, shows the mockup and the final GUI version of Step 2.
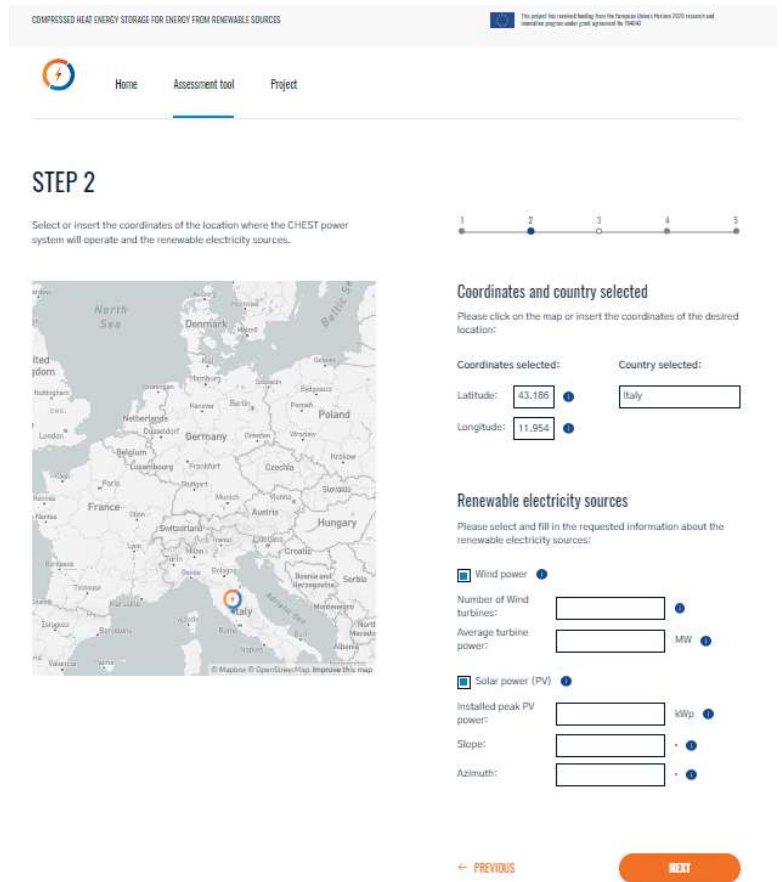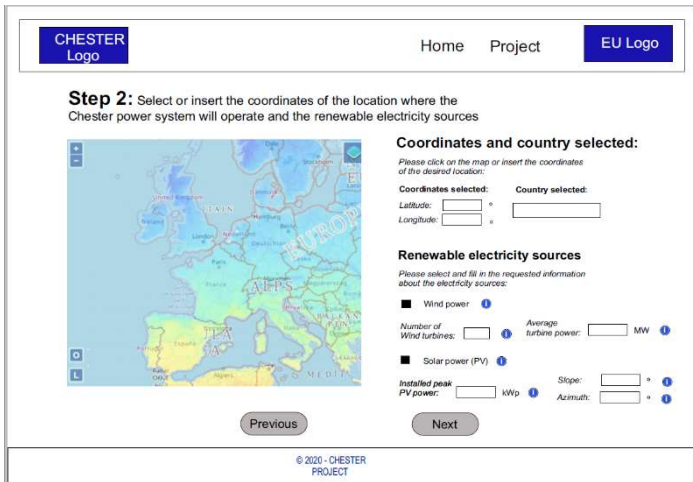
Figure 32 Mockup of CHEST tool Step 2 (left) and final version of Step 2 (right) for the Stand-alone mode.

In order to facilitate, to the user, the definition of input values some checking functions have been implemented in the GUI. These functions validates that the inputs set by the users are properly defined. Some of these validations are: check that the introduced value is inside the allowed range for this input, check if the value fulfills some technical limitation (i.e., the return temperature is lower than the supply one) or check that all the inputs, of the current step, are defined before move to the next step of the tool. The objective of the GUI testing, during the development phase, was to identify that the correct error message was shown when some of the validations were not fulfill. Figure 33, shows the error messages given by the tool when some of the previous validation functions are not satisfied.
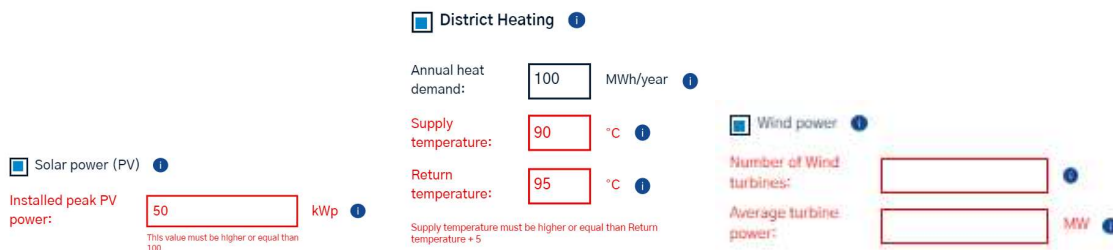
Figure 33 Examples of error messages provided by the validation functions.

As have been already mentioned, some of the errors found during the GUI beta testing process, for both the design and development phases, are included in the Annex III.

7.2. Engine Debugging and beta testing

The beta testing process of the engine has been carried out performing a battery of simulations against the engine. In this battery of simulations, the inputs of the tool have been randomly variated between the defined valid ranges for them. These ranges have been already shown in Table 4 of Section 3 of the current document. The results obtained were analysed to ensure that the engine works correctly and that the values it returns are within the expected ranges. In order to do that, the results of some of the simulated cases in the battery have been compared with the results obtained from the detailed TRNSYS models. Moreover, the results helped to identify and correct some errors in the Engine related with economic calculations of it.

8. Conclusions

The CHEST tool is the outcome of the work done in Tasks 6.4 and 6.5 of the CHESTER project. This tool, is a predesign tool which allows to any interested user to analyze the energetic and economic viability of implement a CHEST system. Two different modes of the CHEST system can be simulated in the tool, the Stand-alone or Grid-connected mode.

The tool is mainly composed by two parts, the Frond End and the Back End. The Frond End is the GUI of the tool where the user defines the necessary inputs, or working conditions, for the calculations. The tool is user friendly, allowing the user to specify with more or less detail his current working conditions, or energy system, where the CHEST system will be integrated. The Back End, or Engine, of the tool is where the calculations are made. The Back End, uses a set of simplified equations in order to estimate the performance of the CHEST system. Additionally, to these equations, the Back End uses a set of predefined information to perform the calculations such as: electrical or price profiles for each EU country, meteorological data from external software (PVGIS) etc. The main results, provided by the engine, are shown in the last step of the tool. Moreover, detailed results can be obtained downloading a report about the simulated case.

An iterative process has been followed in order to design and develop the tool. This process, has allowed to debug and test the tool in a huge variety of scenarios and ensure that the tool works and computes coherent values in each of these cases. Even so, due to the huge number of inputs that can be defined, and the extensive value ranges allowed for each of the inputs, may be possible that a user defines an inconsistent scenario that leads to inconsistent results.

The tool will be hosted in the servers of Aiguasol until the end of the project. The tool is accessible from the "Tool" section of the CHESTER project webpage (https://www.chester-project.eu/).

9. References

[1] ENTSO-E, "ENTSO-E transparency portal," ENTSO-E, [Online]. Available: https://transparency.entsoe.eu/. [Accessed 21 03 2021].

[2] EU, "Photovoltaic Geographical Information System (PVGIS)," 2021.

[3] A. Viti, "DTIE 1.01 Preparacion de agua caliente para usos sanitarios," ATECYR, 1996.

9. References

Appendix I. CHESTER Feasibility Assessment Tool Report

This section describes in detail the contents of the tool report, where all the results from the CHEST simulation as well as the inputs that yield those results are presented to the user. The main results from the simulation are also presented on the tool interface at the end of each simulation, and the description of those contents can be seen in Section 3.7 of this document. The contents of the report are structured according to the following points:

- Introduction
  A brief description of the CHEST system concept and the motivation for use it
- User defined parameters
  All the information of the simulation inputs is listed in this section, which is divided in:
    - Operational mode: Specifies if a stand-alone or grid-connected scenario has been simulated, as well as the location selected and the capacity of the heat pump and ORC (for the grid-connected scenario) or the renewable energy sources included (for the stand-alone power system)
    - Electrical load (only for stand-alone systems): the electricity profile used in the simulation is presented in graphical form. Although the tool generates a profile in hourly basis before the simulation, the graph represents data in monthly basis
    - Electricity price (only for grid-connected systems): in this section, the data for the electricity price is shown, as an average price for the DAM market.
    - Heat source: the characteristics of the heat source used in the simulation, which can be waste heat, solar thermal or biomass. The contents adapt to describe the characteristics according to the type of heat source
    - Heat demand: In case a heat demand was included in the simulation, the parameters are listed here
- Results: here the outcome of the simulation is represented
    - Chest design parameters: the size of the components, as well as the efficiency of the ORC system, the HP COP and the size of the PCM storage are listed, as seen in Figure 34.

CHEST Main Design Parameters

ORC
Nominal power:	0.22 MWel
Efficiency:	13.70 %

Heat pump
Nominal power:	0.66 MWel
COP_{th}:	6.40

PCM Storage
Capacity:	67.94 MWhth
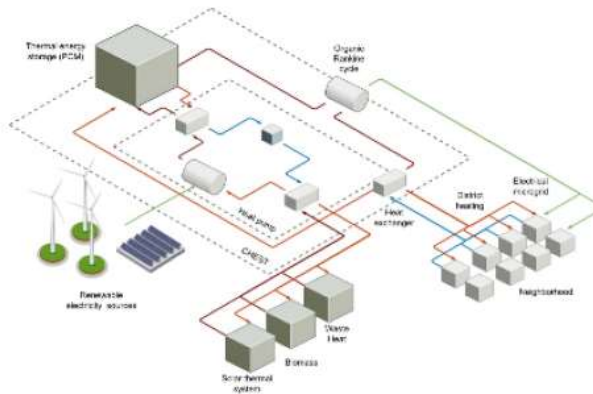
Figure 34: CHEST main design parameters as shown in the simulation report

- Thermal energy results: here the graph shows the monthly distribution of the energy stored at the PCM storage, and the yearly accumulated amount. This is useful to see the degree of use of the PCM storage and the seasonal variations. Figure 35 shows an example of this section of the report

Energy Results

Monthly thermal energy stored by the PCM
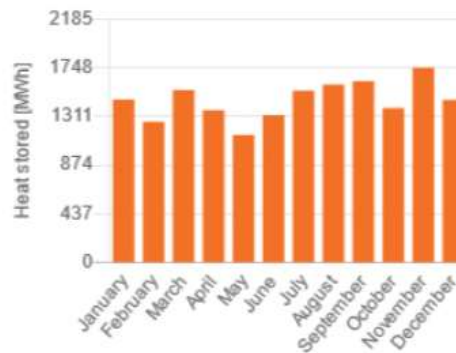
Monthly energy stored by the PCM

Annual energy storage:	17452.58 MWh/ year

Figure 35: Section of the report presenting the energy stored in the PCM in monthly basis

- Capacity factor: this section presents the capacity factor of both the HP and the ORC. As shown in D4.4 of the CHESTER project, the capacity factor is one of the main indicators of a good economic performance of the CHEST system. Here, the user can check if the system has a high capacity factor, which points towards a properly sized system, or in case of a low value, he can try to improve the system changing the inputs to get a better performance. Figure 36 shows the graph of the capacity factor results:
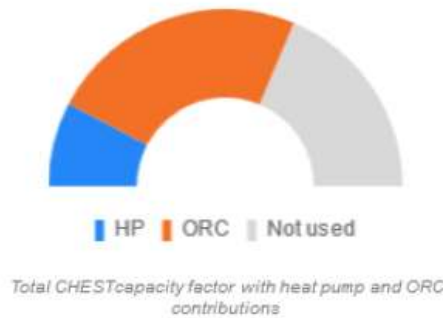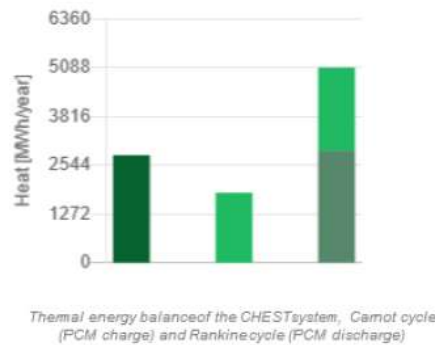
-

Figure 36: Graphical representation of the system capacity factors

- Thermal balance: this section contains all the information of the heat fluxes in the system. Figure 37 shows this section of the report

-

Figure 37: Summary of the system thermal balance on the tool report

Most of the data shown is self-explanatory, but note that the thermal efficiency takes into account only the heat delivered to the heat demand (if any).

- Electrical balance: this section changes depending if the system simulated is a stand-alone power system or a grid-connected system. Figure 38 shows a screenshot of the report in the case of a stand-alone power system:

-
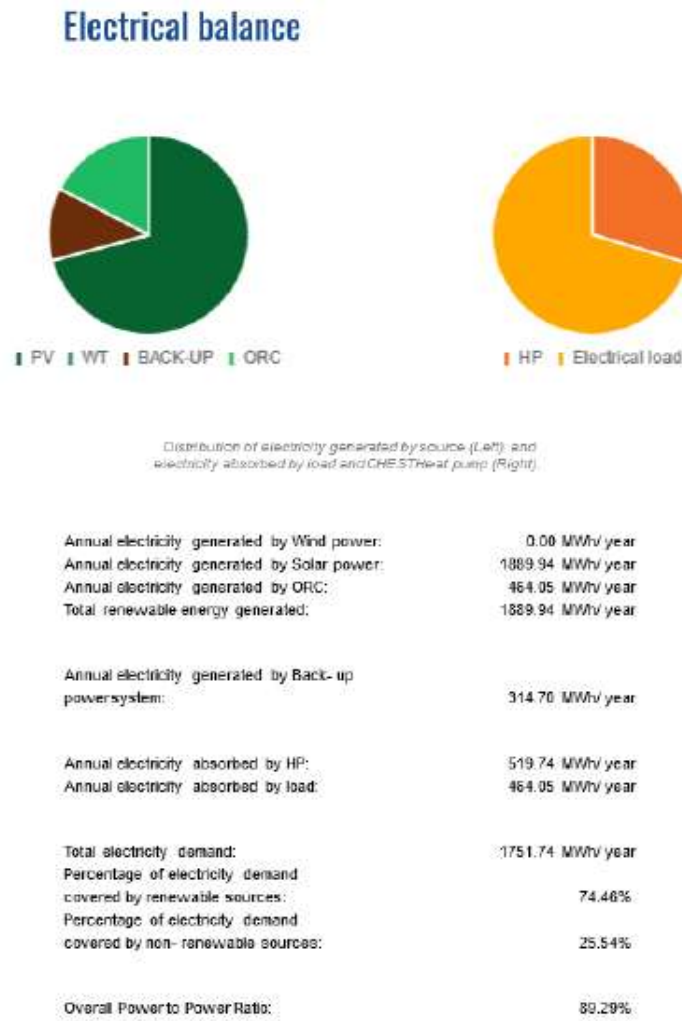
Figure 38: Electrical balance of a stand-alone system as shown in the tool report

First, a breakdown of the energy generated from different sources (PV, wind energy, CHEST ORC) is listed. Then, the electricity consumed by the HP and the amount of electricity consumed directly by the electrical load is shown. Finally, one can find the percentage of renewable energy in the load (note that the simulation considers a backup for the situations where neither the CHEST nor the renewable sources can cope with the demand, and this is assumed to be non-renewable), and the overall power to power ratio of the system is presented.

For the case of a grid-connected system, the results are shorter, an indicate only the electricity consumed from the grid, the electricity generated by the ORC and the system power-to-power ratio.

- Investment costs: in this section the user can see a breakdown of the estimated investment costs for the different elements that build up the CHEST system (ORC, HP, PCM storage and other costs):

Investment Costs

CAPEX distribution [%]
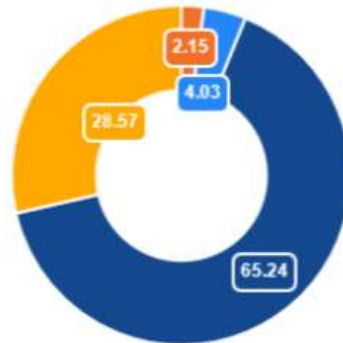
ORC:	101 k€
HP:	189 k€
PCM:	3057 k€
Other costs (*):	1339 k€
Total CAPEX:	4686 k€

Figure 39: Investment costs section of the tool report

The term other costs take into account engineering, procurement and construction management and it's been estimated to be the 40 % of the total costs of the CHEST system components.

- Financial indicators: this section is also quite different in the case of the grid-connected or stand-alone power system. In the case of a stand-alone power system, only the CAPEX, OPEX and TCO (Total Cost of Ownership) are presented, since there is no arbitrage service neither the revenues associated. Total cost of ownership includes all the expenses through the lifetime of the system (assumed to be 20 years) considering a 2% yearly increase of inflation.

    For the grid-connected system, the results are more extensive due to the higher complexity of the economic balance of the arbitrage system. Figure 40 shows an screenshot of the simulation report for the case of the grid-connected system:

Financial Results

Operation profits (**):	436 k€/ year
Maintenance cost (***):	237 k€/ year
Total OPEX (****):	20199 k€
Total Cost of Ownership:	
(Total CAPEX + Total OPEX):	32063 k€
Average electricity purchase price:	0.12 €/ kWh
Average electricity sale price:	0.28 €/ kWh

Monthly revenues [k€]
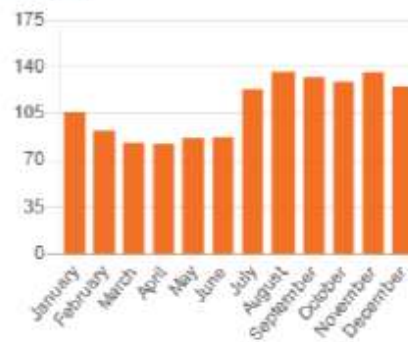
Monthly CHEST revenues from electricity and heat sales.

Annual revenues:	1320 k€/ year
Percentage of annual revenues from electricity sales:	99.97%
Percentage of annual revenues from heat sales:	0.03%
Payback time (*****):	27.06 Years
Internal Return Rate (IRR) (****):	0.79%

Figure 40: Financial results on the simulation report for the grid-connected system

Here, for the case of a grid-connected system, besides the OPEX, CAPEX and TCO previously mentioned for the stand-alone system, the user can find data like the average price for purchased and sold electricity. Finally, the annual revenues, together with more classical financial indicators like payback time or Internal rate of Return are also shown.

Appendix II. General assumptions and limitations

In this section, there are described the main assumptions and limitations found during the development of the Engine of the tool. Due to the fact that, the engine is a simplification of a real CHEST system, which is really complex, some values are fixed to not overwhelm the user with the introduction of too many parameters. Furthermore, some inputs of the tool are limited to a certain value in order to guide the user with the definition of them and to generate favorable scenarios where the CHEST system could be integrated.

General assumptions

The calculation engine receives the input parameters from the interface and selects the default parameters based on the inputs from the user.

Table 1 shows the fixed parameters of the interface.

Table 1 Default fixed parameter for the calculation engine

Parameter	Variable name	Value
Water specific heat capacity	Cp	4.18 kJ/kg·K
Temperature difference between empty and full accumulator	AccAT	75 K
Water density	roW	1000 kg/m^3
Accumulator volume per unit of STS area	volAccRatio	0.07 m^3/m^2
Domestic hot water fraction of district heating demand	demFracDHW	15%
Thermal losses of district heating	lossesDH	10%
PCM volume per meter of HX	ePCM	0.005 m^3/m
PCM phase change enthalpy	ahPCM	200 kJ/kg
PCM HX tube diameter	diHX	0.02 m
Fluid-PCM temperature difference	AT	5 K
Project lifetime	lifetime	30 years

Table 2 shows the tube heat transfer coefficient that depends on the operating mode, stand-alone power system or grid-connected power system.

Table 2: Tube heat transfer coefficient stand-alone system and grid-connected system

Parameter	Variable name	Value
Tube heat transfer coefficient (in stand-alone power system)	hHX	80 W/m^2·K
Tube heat transfer coefficient (in grid-connected power system)	hHX	100 W/m^2·K

Table 3 shows a series of parameters that depend on the heat source temperature selected by the user

Table 3: Default parameters according to heat source temperature

Heat source temperature	PCM material	Melting point	Refrigerant	Coefficient of performance (COP)	Latent-sensitive heat ratio (RLS)	PCM melting enthalpy	PCM density (roPCM)	Condensing temperature (condTemp)	ORC efficiency (effORC)	Power ratio HP/ORC (power Ratio)

$40 \leq T < 55$	LiNO3-NaNO3-KNO3	123 ºC	Butene	3.2	0.54	140 kJ/kg	2068 kg/m³	55 ºC	0.079	2.566
$55 \leq T < 70$	LiNO3-NaNO3-KNO3	123 ºC	Butene	4	0.54	140 kJ/kg	2068 kg/m³	55 ºC	0.079	2.566
$70 \leq T < 80$	LiNO3-NaNO3-KNO3	123 ºC	Butene	5.1	0.54	140 kJ/kg	2068 kg/m³	55 ºC	0.079	2.566
$80 \leq T < 85$	LiNO3-KNO3	133 ºC	R1233zd (E)	5.7	0.58	150 kJ/kg	2018 kg/m³	70 ºC	0.097	2.5
$85 \leq T < 95$	KNO3-NaNO3-NaNO2	142 ºC	R1233zd (E)	5.9	0.55	110 kJ/kg	2006 kg/m³	80 ºC	0.09	2.5
$95 \leq T < 100$	KNO2-NaNO3	149 ºC	R601	5.8	0.5	124 kJ/kg	2080 kg/m³	40 ºC	0.112	1.835
$100 \leq T < 105$	LiNO3-NaNO2	156 ºC	R601	5.9	0.47	233 kJ/kg	2296 kg/m³	40 ºC	0.113	1.686
$105 \leq T$	LiNO3-NaNO3-KCl	160 ºC	Cyclopentane	6.4	0.55	266 kJ/kg	2297 kg/m³	40 ºC	0.137	1.333

Limitations to input values

The interface has some limitations on the user input parameters to ensure that the sizing of the system is done correctly.

In the grid-connected scenario, the relationship between the nominal power of the heat pump and the nominal power of the ORC has to be between 1.5 and 2.5

In both scenarios, the temperature of the heat source can be set between 40ºC and 120ºC in the case of residual heat. If biomass is defined as a heat source, the temperature is 105ºC, and for thermal solar system the temperature is 70ºC.

In case a district heating is included as a heat load, the supply temperature must be at least 5ºC higher than the return temperature; the limits for these temperatures are detailed in Table 4.

Table 4: Maximum and minimum limit of input parameters

Parameter	Minimum	Maximum	Units
Heat pump nominal power (nomHP)	0.1		MW
ORC nominal power (nomORC)	0.1		MW
Latitude	-90.0	90.0	º
Longitude	-180.0	180.0	º
Number of wind turbines	1		-
Turbine power	0.1		MW
Installed peak PV power	100		kWp
Slope	0	90	º
Azimuth	-180	180	º
Forecasted price increment	0	10	%
Annual electrical consumption (annualElecDem)	10		MWh/year
Annual available heat (annualAvHeat)	1		MWh/year
Area of the solar thermal system (STSarea)	2		m2
Heat source temperature	40	120	ºC
Annual heat demand (annualHeatDem)	0.01		MWh/year
Supply temperature (sTemp)	100		ºC
Return temperature (rTemp)	35		ºC