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D2.7 – REWARDHeat predesign tool validation

Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

REWARDHeat

Project Title: Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

Project Acronym: REWARDHeat

Deliverable Title: REWARDHeat predesign tool validation

Lead beneficiary: CARTIF

Ismael Lozano, CARTIF

Iván Ramos, CARTIF

Rafael Delgado, CARTIF

Alvar de la Calle, CARTIF

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Table of Contents

1 Summary

This deliverable reports the main outcome of REWARDHeat activities focused on the development of an open source, GIS-based tool for the predesign of District Heating and Cooling Networks (DHCNs) under neutral-temperature design and operation premises promoted by the project.

This document reports on the main functions, architecture and exemplary results obtained with the predesign tool, after the further improvements implemented in the interfaces and main capabilities.

Moreover, the structure of the development activities as well as the most relevant aspects of the works are presented. These currently focus on the perspective of the user working with the tool and the main results the tool is capable of provide, but also including the backend development of the software both addressing the definition of the database structure and the improvement of the different calculation modules.

Finally, a use case of the tool has been carried out using the information provided by the partner SAMPOL with the aim of validating the usability and effectiveness of the tool. The case studies the feasibility of the refurbishment of an old pneumatic waste recovering system, which is not being used at this moment, in order to convert it into a low temperature district heating and cooling network in Palma de Mallorca (Spain). CARTIF carried out the whole predesign process while SAMPOL analysed the output information from the tool to check the coherence.

2 Introduction

The main and final purpose of REWARDHeat activity on the design of district heating and cooling networks (DHCNs) with multiple energy sources is the development of an open-source, GIS-based tool for the predesign of such networks, focusing on supporting the increased integration of low-temperature renewable (RE) and waste heat (WH) sources at urban level into thermal grids conceived under the neutral-temperature design and operation premises developed by the project.

Related to this main objective, several tools have been (or currently are) developed to support planning and design of district heating networks (e.g. PLANHEAT [1], THERMOS [2], Hotmaps [3], City Energy Analyst [4], SimStadt [5], INDIGO [6])

The development of REWARDHeat predesign tool benefits from the available background knowledge and fundamental modules offered by these existing software applications and linked open EU research in order to provide a dedicated, complete tool oriented to the specific challenge addressed by the project. In these sense, unique features developed are focused on:

- Preliminary techno-economic evaluation of neutral-temperature bidirectional networks based on yearly calculations with hourly resolution accounting for the impact of network temperature levels. Specific network topologies, centralised and distributed energy assets, design guidelines and operational constraints for these networks are considered.
- Mapping of energy resource potential from low-temperature RE/WH sources in cities
- Combination of GIS-based information for energy demand and resource estimation together with the above-mentioned dedicated modelling approach

In this sense the predesign tool is fed with the outcomes of preliminary activities carried out along the project elaboration:

- structured database with available information from best practice examples on neutral-temperature DHCNs
- GIS-based assessment of low-temperature RES and waste heat sources at urban level
- Design requirements collected from DHC experts and potential end users of the tool

Within this context, the present deliverable will first describe the REWARDHeat predesign tool general concept and detailed interface that constitute the final development to enable the interaction with the user as well as the actual (predesign) calculation workflows. Then, in order to validate the tool, a feasibility study of the refurbishment of an old pneumatic waste recovering system, which is not being used at this moment, in order to convert it in a low temperature district heating and cooling network in Palma de Mallorca (Spain) is carried out, showing the whole calculation process from the input of the data to the generation of results.

3 Predesign tool concept and interfaces

The general concept of the REWARDHeat predesign tool regarding the software architecture is distributed into 3 main layers, as shown in Figure 1: (i) Data layer; (ii) Business Logic Layer; and (iii) Application Layer. The first two layers comprise the tool backend, while the Application Layer represents the tool frontend or Graphical User Interface (GUI).

- The Data Layer contains the data repositories where the general project information, GIS data of the target urban areas (buildings, sources, roads, etc.), technology data and other contextual information (e.g. weather data, economic and environmental reference indicators, etc.) are be stored.
- The Business Logic Layer connects the data layer to the application layer and controls the overall functionality of the tool by performing the main calculations and data processing. Different scripts implement the core services/modules dedicated to energy demand calculation, network route design and energy modelling and KPIs calculation.
- The Application Layer acts as the point of interaction between the REWARDHeat predesign tool and the user. It is used for data insertion and results visualization, including the supporting warnings and guidance to the user across the tool workflow.

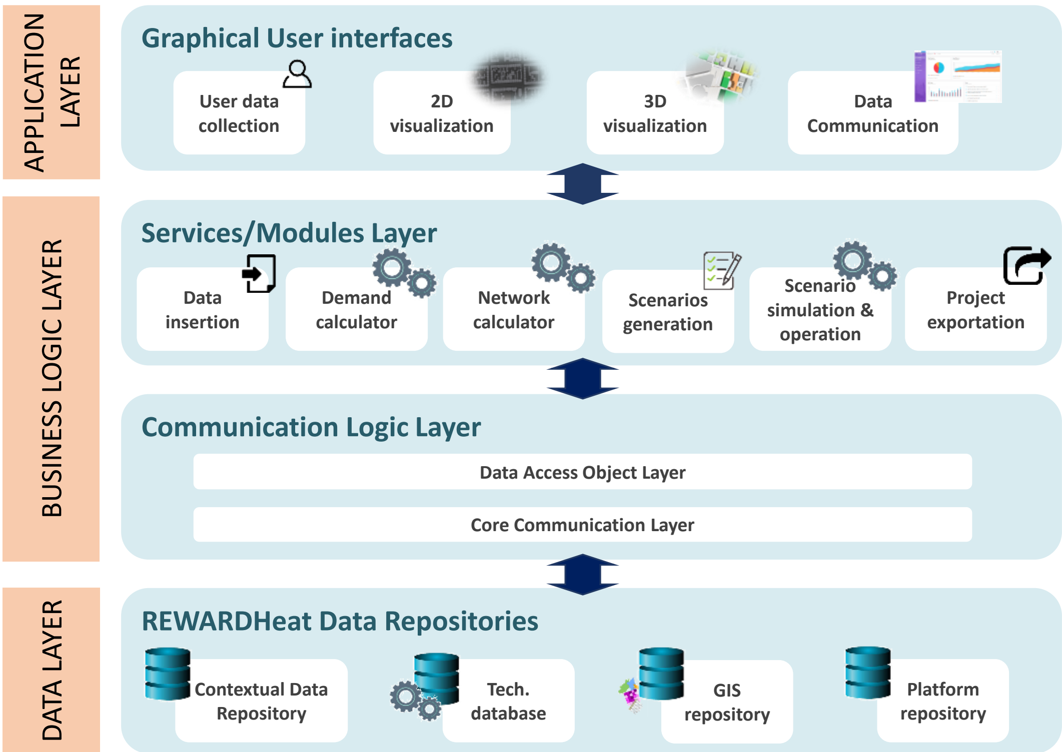


Figure 1 - General architecture of the REWARDHeat Predesign Tool.

The calculation flow of the tool is organized in a tree structure over 3 levels (Baseline, Scenario and Option), as showed in Figure 2. In each level the user must include information, configuring the use case to analyse, to produce an output which is, at the same time, input information for the next level. Finally, information calculated in all the levels is used to calculate Key Performance Indicators for the user to compare the use cases, allowing them to select the best solution.

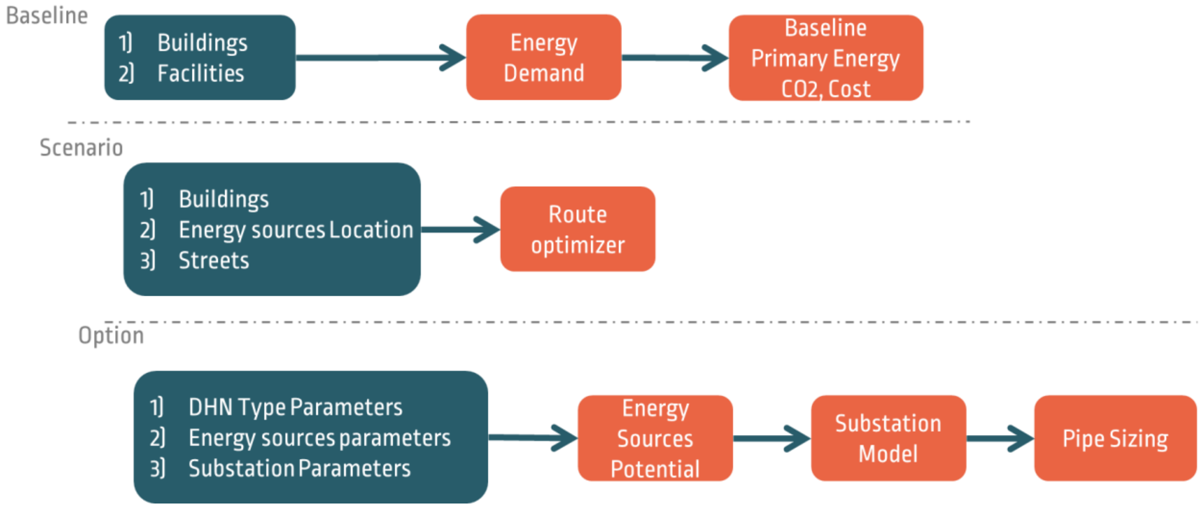


Figure 2 - Calculation flow of the REWARDHeat Predesign Tool

4 Predesign tool development

The development of the REWARDHeat predesign tool started in February 2021 once the tool requirements and functionalities were defined (deliverable D2.4 [7]), reporting a first version of the tool in March 2022 including the description of the capabilities implemented in that moment (deliverable D2.6 [8]).

4.1 Organization of the development process

The development process continued from the last version deployed (deliverable D2.6 [8]). Thus, the work has been organized into the following topics:

- Network router – REWARDHeat tool integrates existing libraries for what concerns the network router to optimize the path to interconnect all the nodes involved.
- Network overall energy modelling – This is the core part of the tool calculation engine. A general model approach is being defined to account for the impact of different network temperature levels and different system configurations for neutral-temperature bidirectional thermal grids including appropriate capture of the effects produced by different sizing of central and decentral production units. In this case, the energy calculation is divided in different steps organized in calculation modules interconnected between them. More details about the energy modelling is described below in this document.
- Pipe sizing – The tool includes a preselection of the pipe size of each section of the network based on the results of the overall energy modelling and a selection method based on the maximum water flow the pipe is expected to allocate.
- KPIs calculation – For each system calculated a series of Key Performance Indicators are calculated based on the information used internally during the calculation process. A dedicated window to compare the KPIs evolution during the year is included in this version.
- Database structure and contents – As already mentioned, the REWARDHeat tool will rely on a specific Data Layer with several databases dedicatedly defined to deal with all the information derived from the required inputs, interim internal calculations and produced outputs. This mainly includes general project information, GIS data, technical data for the different involved technologies, as well as other contextual data.
- Backend connections – The Communication Logic Layer (represented in Figure 1) is a hidden, but fundamental, part of the development. The software integration of the tool databases, the calculation engine and the Graphical User Interface (GUI) will be dealt with in a parallel development thread.
- GUI / frontend development – This comprises the creation of the visual interfaces required to collect the necessary information to be entered by the user and to represent the results obtained.

The development has been organized in order to work in parallel on the different services/modules of the calculation engine, as well as on the enrichment of input information, while the supporting database structure and communication features are extended and improved. This is being addressed in an iterative development process where different development threads feed each other as the definition of the calculation modules evolve.

Besides the integration of new modules and features, special attention has been paid in optimizing the algorithms to reduce the computation time at the minimum value, including the evaluation of different scripting approaches and the organization of the information flows.

Once the first consolidated versions of the backend are ready, the full development of the GUI has been undertaking, improving the existing windows and creating new ones.

4.2 Tool frontend developments

The pre-design tool is built under client-server architecture to provide user the functionality of implement their own analysis without installing some applications and software. The last version of the tool includes the following interfaces:

- Main page
- Project management area
- Selection of an Area of Interest (AOI)
- Baseline definition
- Scenarios management area
- Scenario configuration and network route visualization
- Options management area
- Option configuration and pipe size visualization
- KPIs comparison

These interfaces including the main functions and functionalities of each step will be described below considering the user interaction in each interface. The first developed interface corresponds to the main page of the tool. Figure 3 shows the design of the REWARDHeat pre-design tool main webpage with a brief description of the project and tool objectives while enabling the user registration (creation of a new user, not available at the moment) or login process through the corresponding username and password information. These two options (Figure 4) for user interaction are included with two buttons. The scroll-down function in this main page gives user the opportunity to find more information about REWARDHeat project.

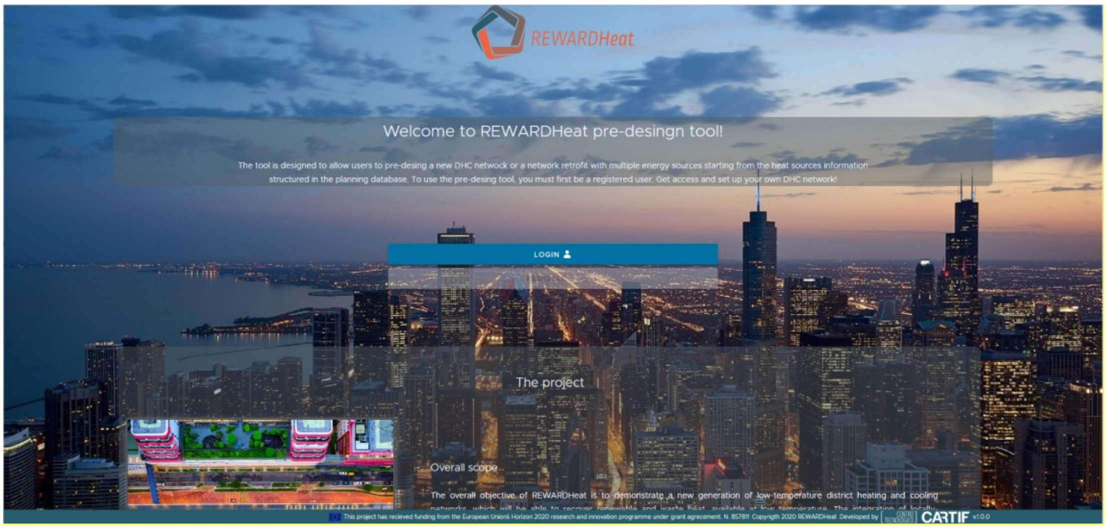


Figure 3 - Home page of the REWARDHeat pre-design tool

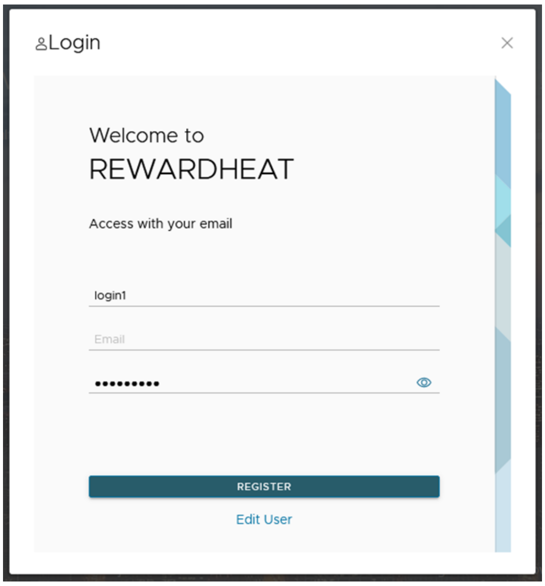


Figure 4 - Application form for the login (left) and register (right) in the pre-design tool

The second developed interface provides users the opportunity to create and manage new projects (Figure 5). Once the user is registered as a tool user and logged in the tool, users need to create a new project to start using the calculation algorithms for district heating design. For this, a project name and a description will be provided (Figure 6).

Figure 5 - List of projects in the project management area of the REWARDHeat pre-design tool

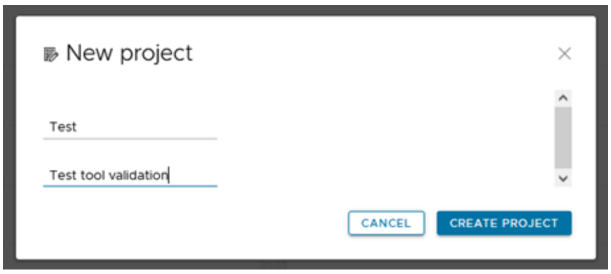


Figure 6 - Application form for the definition of a new project using the pre-design tool

The third interface included in the tool is the selection of an Area of Interest (AOI) (Figure 7). This interface provides user the following functions and functionalities: (i) upload your own shapefile, (ii) use OpenStreetMaps (OSM) buildings and (iii) select building geometries from a demosite. Each functionality is explained below.

Figure 7 - Area of interest (AOI) interface included in the pre-design tool.

- Upload your own shapefile: this function gives user the opportunity to upload a shapefile of the buildings as starting point for baseline definition. The shapefile must be uploaded using a zip file in which all the files required in a shapefile are stored. At least .shp, .dbf, .prj are included in the zip file. The shapefile needs to include these attributes: year of construction (year), building height (height), building area (area), building use (use) and a numerical identifier (id) for each building (Figure 8). If a shapefile is provided, the attributes of each building parameter will be provided. Otherwise, the tool will estimate it as detailed in the information coming from OSM or will allow the user to edit the attributes of his building to choose the most appropriate. Otherwise, the tool will estimate it as detailed in the use of OSM or will allow the user to edit the attributes of his building to choose the most appropriate. A document about how to obtain the shapefile is included in the tool, giving the user guidance about the process (Figure 8).

Figure 8 - Shapefile generation user guide location

- OpenStreetMaps buildings: this function uses the API service of OpenStreetMaps (OSM) to collect the building geometries and its attributes that are collected by this initiative. The tool allows to build a polyline to call the OSM database and collect the required data for the project (Figure 9). Some of the attributes are empty in OSM and default functions were developed to give a value based on estimations as height-area ratio, residential as default value for building use or 1980 as default value for the year of construction. At certain level of zoom, the location of potential waste heat sources is depicted in the map, giving the user the option to design the district heating network close to these points (Figure 10). The building area is calculated by the tool backend. As explained before, the tool allows the user to edit the attributes of each building or a group of buildings to choose the most appropriate value of each attribute.

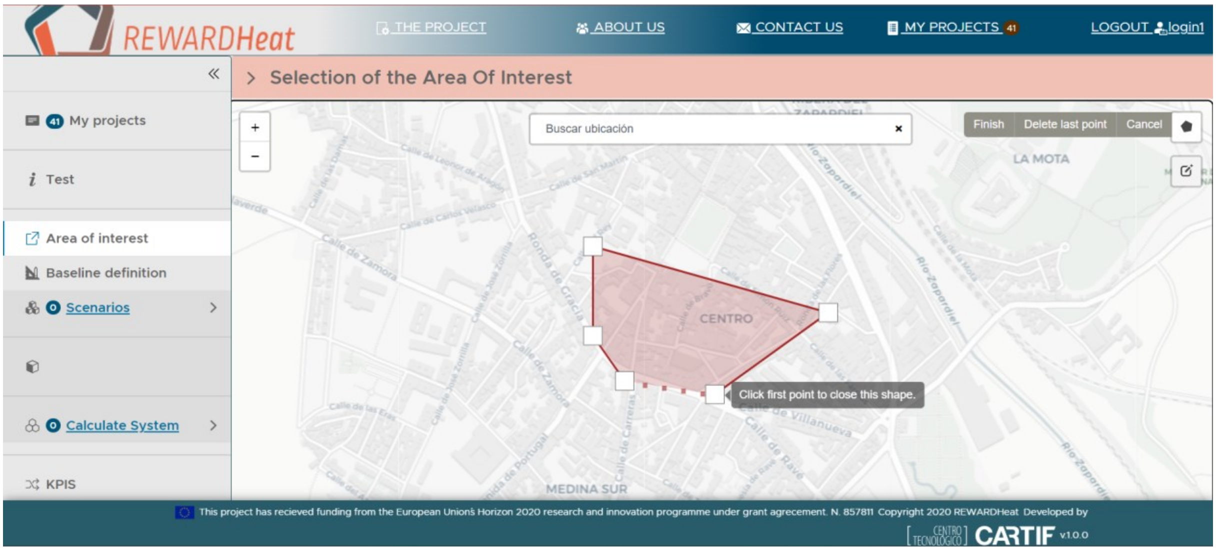


Figure 9 - Selection of an Area of Interest to collect data from OpenStreetMaps

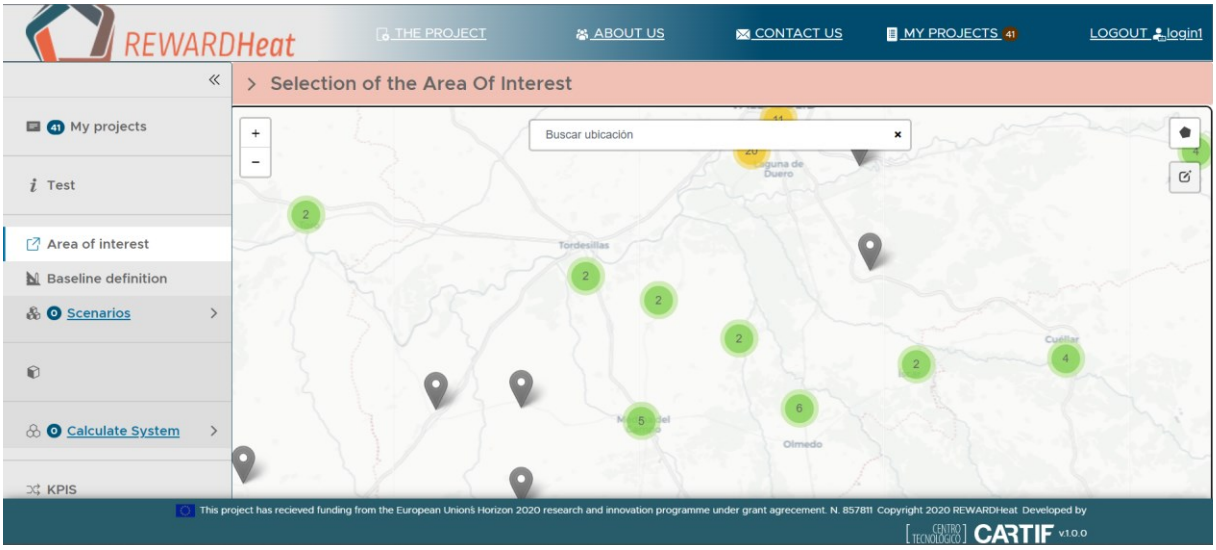


Figure 10 - Area of interest selection including waste heat mapping

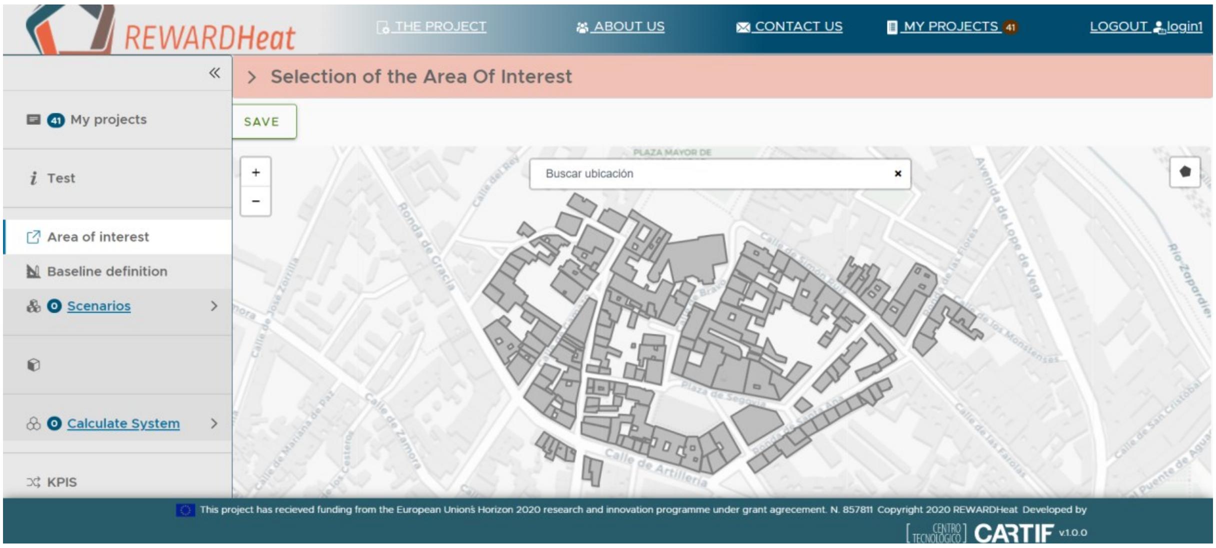


Figure 11 - Data collected from OpenStreetMaps using the defined Area of Interest

- Select shapefile from a demo site. This option loads pre-defined shapefiles for the demosites including in REWARDHeat project (buildings and their attributes). This feature will be included in the tool once data from demosites will be available.

Once the buildings are collected or updated in the tool, the user will select the final buildings to work and save them so that they can be stored in the database being available during the project baseline definition.

The fourth interface covers the project baseline definition (Figure 12). At the end, this use case will provide as outputs the energy demand calculation (heating, cooling and domestic hot water), the primary energy to cover this demand, the cost and the associated emissions. To obtain these results, the user has four different alternatives for calculation: (i) demand algorithm, (ii) monthly demand disaggregation, (iii) yearly demand disaggregation and (iv) upload your own demand file.

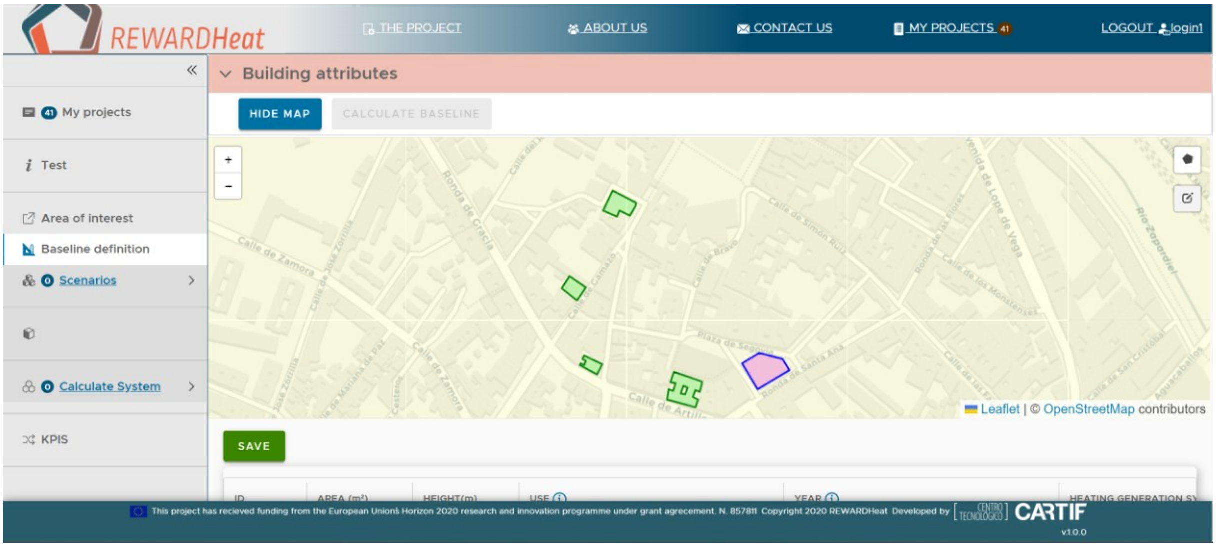


Figure 12 - Main interface of project baseline definition.

The first item for the energy demand calculation is to evaluate if all buildings have filled the required attributes (id, area, height, use and year) to set up the process. The user has the opportunity to modify building attributes by selecting and editing each building or a group of them. After editing the user need to save to upload the data in the project database (Figure 13). For primary energy calculation, cost and emissions, the user needs to select for each building the heating and cooling generation system as well as the heating and cooling distribution system. If this data were not provided, a default value will be included considering the year of construction of each building and the typology. If all required data were provided a green validation element will be included in the "is fulfilled" attribute. In addition, when a building is selected the tool includes an option to upload your own energy demand profile (hourly, monthly or yearly) based on real measured data (bottom box in Figure 13). If this data is provided in one or more buildings, the tool backend excludes them for the complete energy demand calculation selecting the disaggregation methods or in a simpler way, storing the hourly data profile.

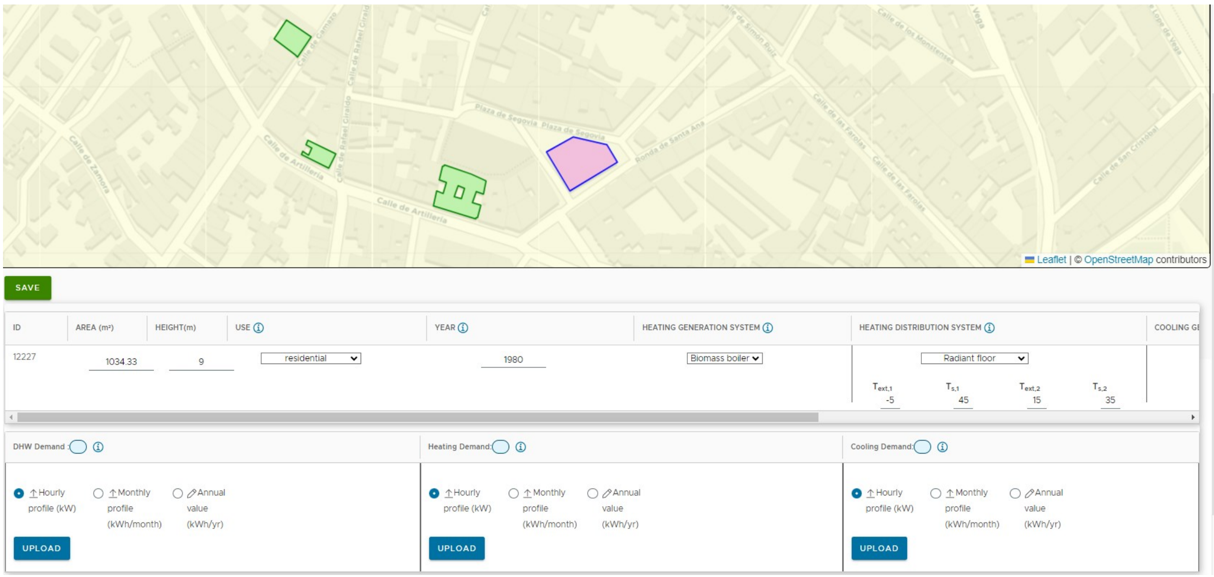
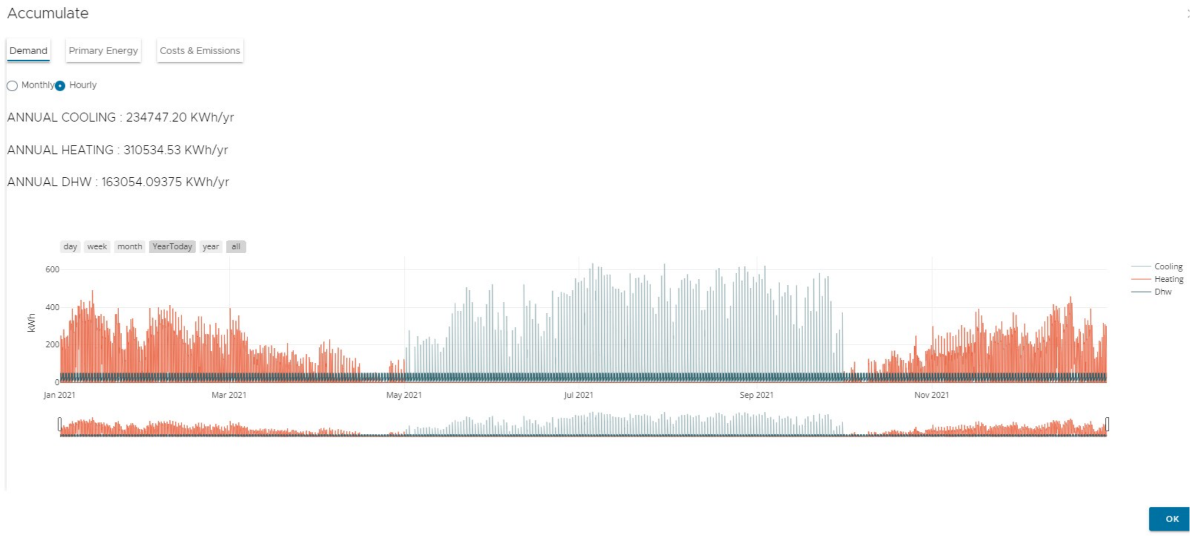


Figure 13 - Building selection to modify attributes.

Once the user has completed all the building attributes that allow the calculation of the energy demand, the user can activate the "calculate baseline" button to start the execution of the energy demand calculation algorithm and the primary energy, cost and emissions transformation algorithm. A progress bar will appear showing the user the progress of the calculation and an estimation of the remaining processes for its completion. When the calculation is finished, a new button will appear to see the results graphically for each of the evaluated buildings (Figure 14). The graph library used by the tool gives users the opportunity to evaluate the results in a yearly, monthly and hourly basis for each evaluated building. In the graph visualization, three different alternatives are provided: demand, primary energy and costs-emissions. In case one or more buildings are selected, the information showed in the graphics is that related to the selection. Additionally, the results and the meteorological information used in the calculations can be exported to CSV files (Figure 15).



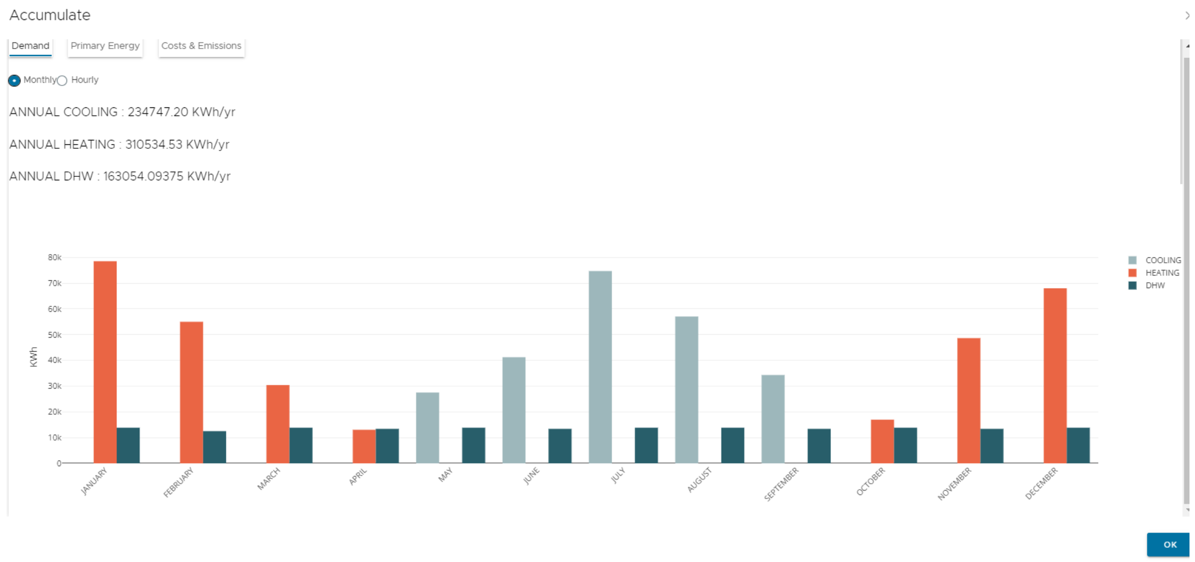


Figure 14 - Graphical visualization of the energy demand calculation in yearly, monthly and hourly basis

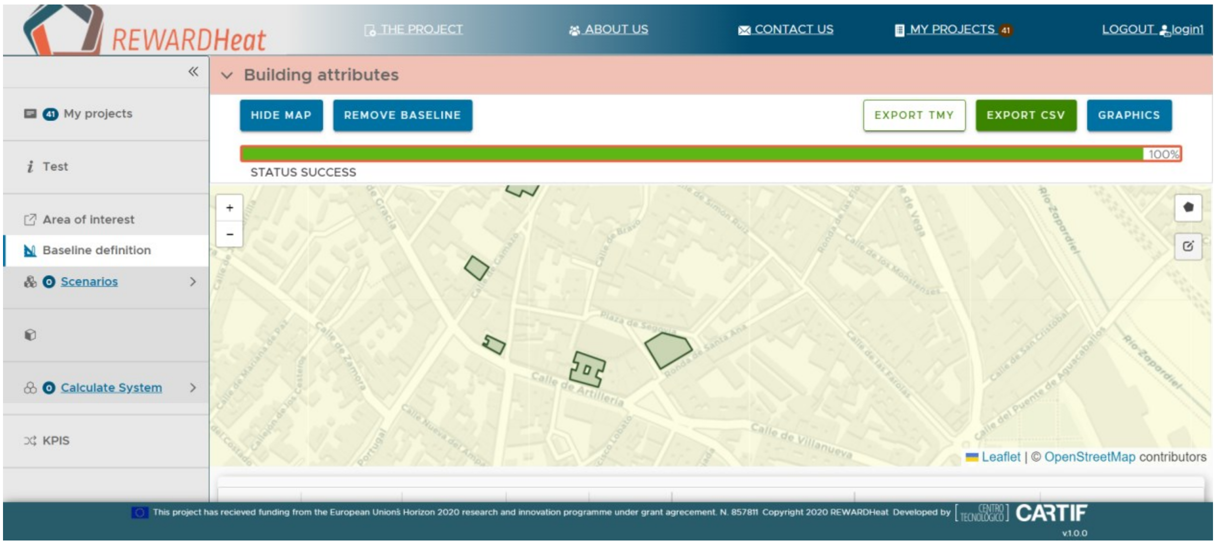


Figure 15 - Baseline interface after calculation finishes

At this point, as mentioned above in Figure 2, a new level of information is generated called Scenario, with the optimized network route as main output of this level. Thus, the user must include the selected set of buildings to interconnect with the network, the type and location of the producers and the available streets to be used by the route optimization script. To configure the scenario, a step-by-step input form has been set up in order to allow the user to reflect the specific conditions of the project.

1. Buildings, allowing the user not to include in the district heating network some of the buildings included in the baseline calculation. The deactivated buildings are depicted in grey colour. Figure 16a.

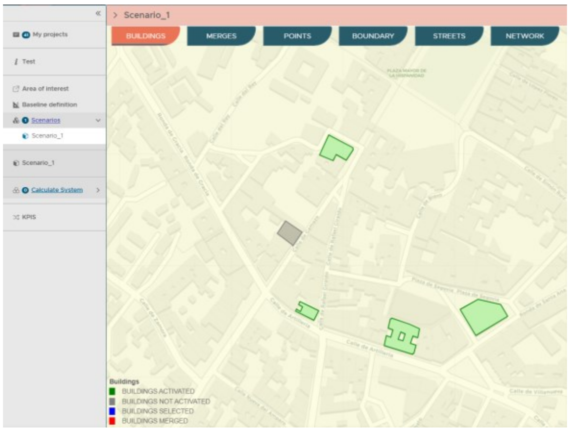
2. Merges, allowing the user to join several buildings in a summed demand. This option especially applies in the case where several buildings share a central energy station or when the user wants to only place one substation for them. The merged buildings are depicted in red colour. Figure 16b.

3. Points. This interface is intended to include the heat producer systems among the potential waste heat database points that are located in the map, or the producer facilities that the location can be selected by the user. The producers included in this version are geothermal and solar thermal systems. To be able to continue with next steps, the selection of a balancing node is mandatory. This node acts as a central system to balance the energy in the network. Figure 16c y Figure 16d.

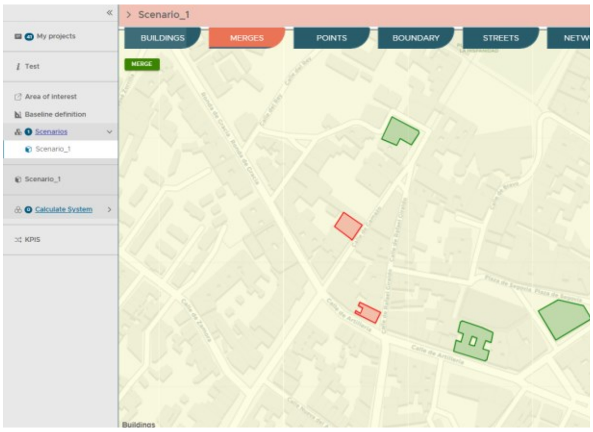
4. Boundary. In this window the user must create a polygon within which the information of the streets will be obtained from OSM. This step has been implemented to reduce the unnecessary streets processing to reduce the computation time of the optimum route calculation script. Figure 16e.

5. Streets. This interface uses the streets information obtained in the last step allowing the user to exclude streets from the route calculation in case some constraint is applied to them, such as the impossibility to dig in some parts of the city, presence of underground facilities, etc. The included streets are depicted in blue colour, while the excluded ones are depicted in grey colour. Figure 16f.

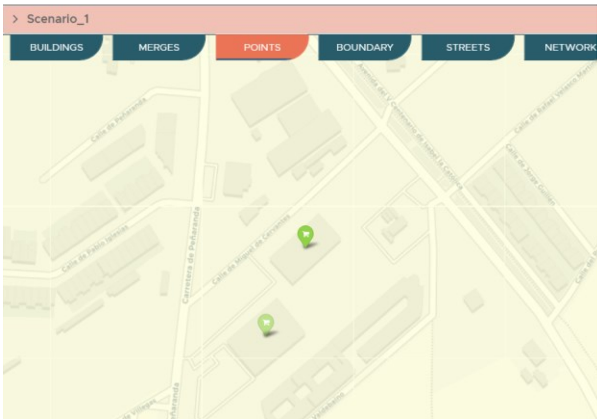
6. Network. After all the above steps have been fulfilled, the tool activates the option to calculate the optimized route. A progress bar will appear showing the user the progress of the calculation. When the calculation is finished, the route will be shown. Figure 16g.



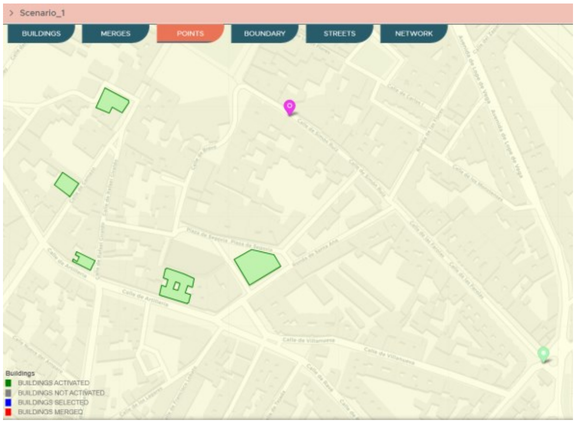
a) Scenario inputs. "Buildings"



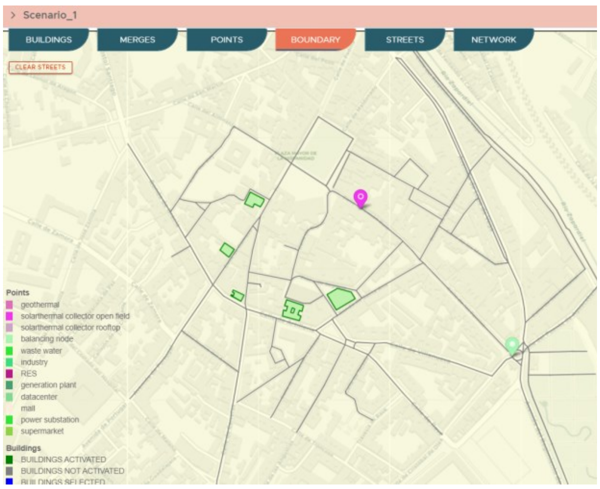
b) Scenario inputs. "Merges"



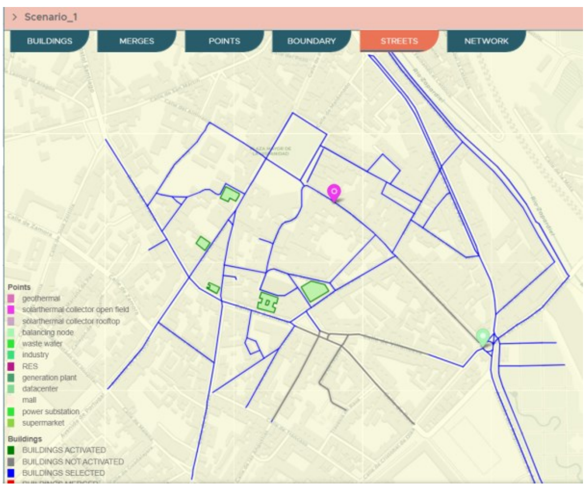
c) Scenario inputs. "Points" from database



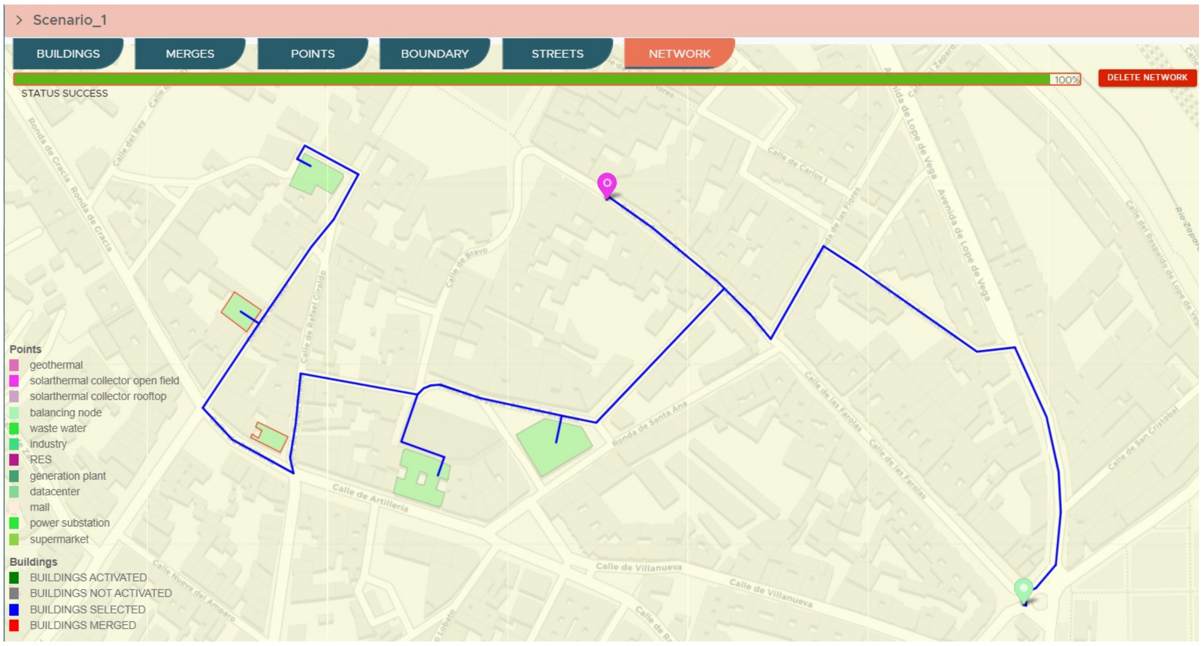
d) Scenario inputs. "Points" from user



e) Scenario inputs. "Boundary"



f) Scenario inputs. "Streets"



g) Optimized network result

Figure 16 - Scenario interfaces

One the network route is calculated, a new level of information is generated, called Option, with the pipe size calculation as main output. In this step, needed internal calculations such as the energy generated by the producers, the energy coming to or from the network using a substation model, the calculation of the hourly mass flow in each section of the network and the KPIs are done. In this step, the user must include the parameters of the producers to calculate the energy generated and the type of network to be considered by the substation model.

First, the user must select the district heating type to be calculated using a dropdown among the following options:

- Conventional: Supply temperature, 80°C. Return temperature, 40°C. The network cannot cover cooling loads, so the systems included in baseline selection are assumed to cover that load.
- 4^{th} Generation: Supply temperature, 50°C. Return temperature, 30°C.
- 5^{th} Generation: Supply temperature, 35°C. Return temperature, 25°C.

After that, all the producers included in the scenario are listed with a thumbs up or down symbol depending whether the information has been provided or not. The parameter to include are different depending on the type of producer, in the Figure 17 an example for a solar thermal collector producer is shown.

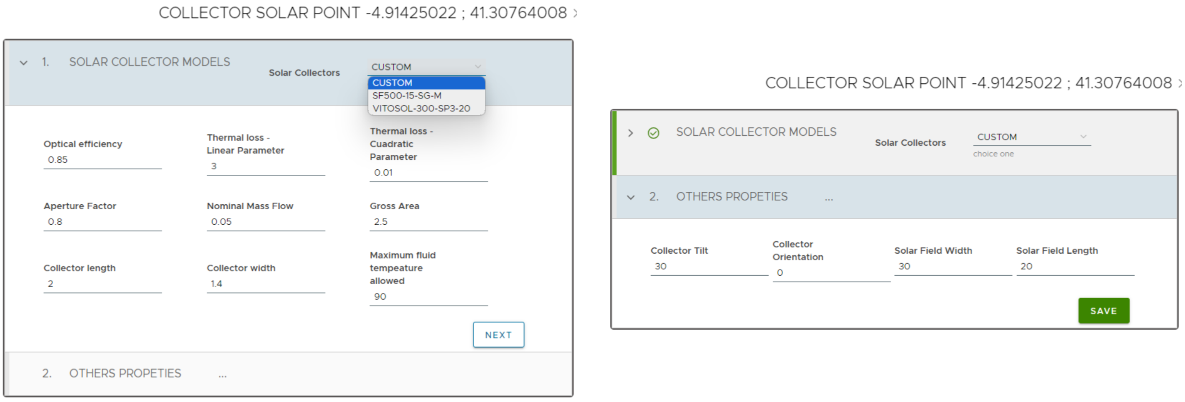


Figure 17 - Parameters of solar thermal collectors

After all the above steps have been fulfilled, the tool activates the button to calculate the option. A progress bar will appear showing the user the progress of the calculation. When the calculation is finished, the pipe size will be shown with a colour legend. The corresponding sizing for the example project is showed in Figure 18, together with other project result to notice the different sizes of the sections.

At this point, all the information regarding the district heating network has been calculated. Then, the last interface developed is dedicated to compare the results obtained by the option calculation and the baseline scenario, or the results obtained in two different options. In order to do that, a selection window with two dropdown lists has been place in the interface to allow the user to select what options to compare (Figure 19).

Once the user clicks “Compare” button, new panels will show including different information. First, in the bottom-left part, the user will be a summary table including the annual value obtained. Then, in the upper-right part of the window, a new dropdown list with all the calculated KPIs (Figure 20) allow the user to see the monthly evolution of each one, overlapping the two options the user selected firstly (Figure 21).

Figure 18 - Pipe size calculated for two different projects

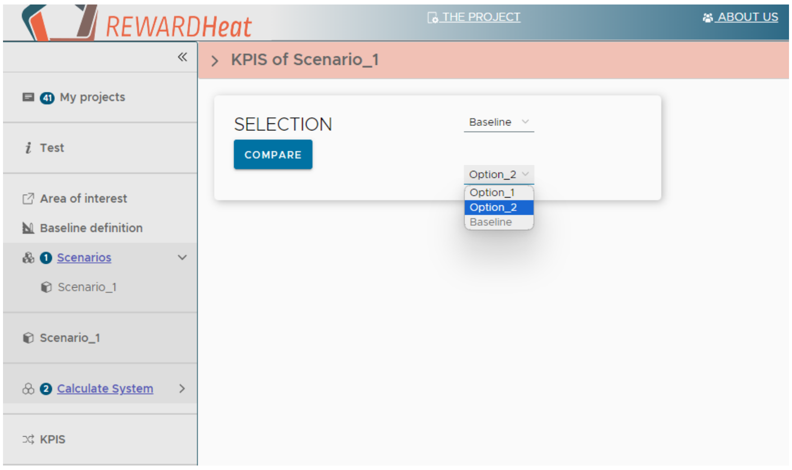


Figure 19 - KPIs interface. Options selection

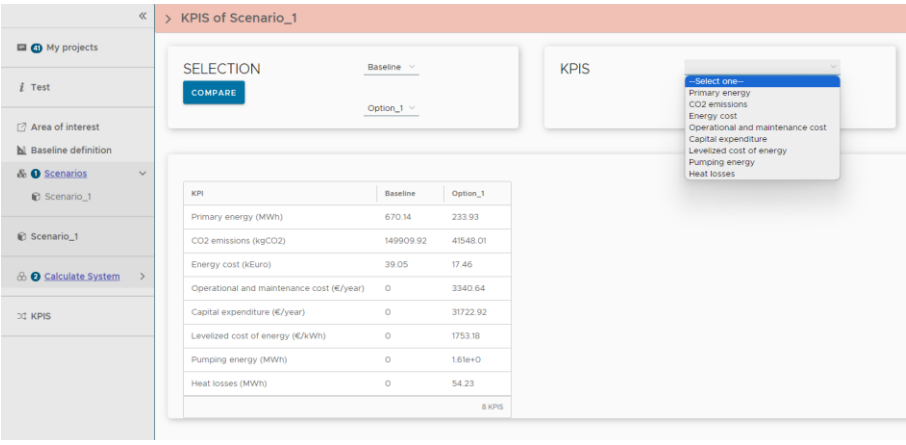


Figure 20 - KPIs interface. KPIs selection

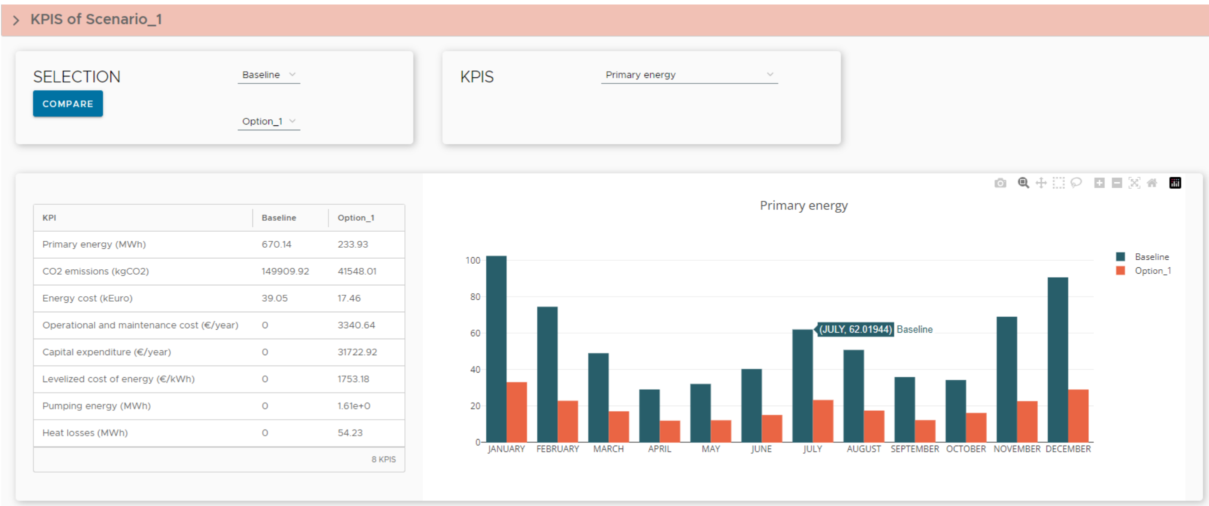


Figure 21 - KPIs interface. Monthly KPIs visualization

4.3 Database, computation modules and backend integration

This section includes a description of the tool database (architecture and stored data), the different computation modules developed during the tool implementation after the description of D2.6 and a brief description of how the database and the modules are connected to be functional in the tool.

4.3.1 Pre-design tool database

The definition of the structure of databases capable of storing and serving all the information required at each step of the predesign tool workflow has evolved since the beginning of the project in order to adapt the new scripts and relations included.

The most recent version of the database includes new tables that allow storing new data generated by the calculation scripts, such as the disaggregated energy from the producers, the final energy exchange between the substations and the network, the pipe size of each section of the DHN or the calculated KPIs, as well as other data needed to perform the calculation properly (see Figure 22).

The database is an open task throughout the development of the tool that will incorporate data according to the needs established by the different calculation algorithms. It is feasible that the implementation of data on new energy sources as well as the energy calculations associated with the network will establish additional needs and as consequence it will be necessary to create new tables and relate them to the existing ones.

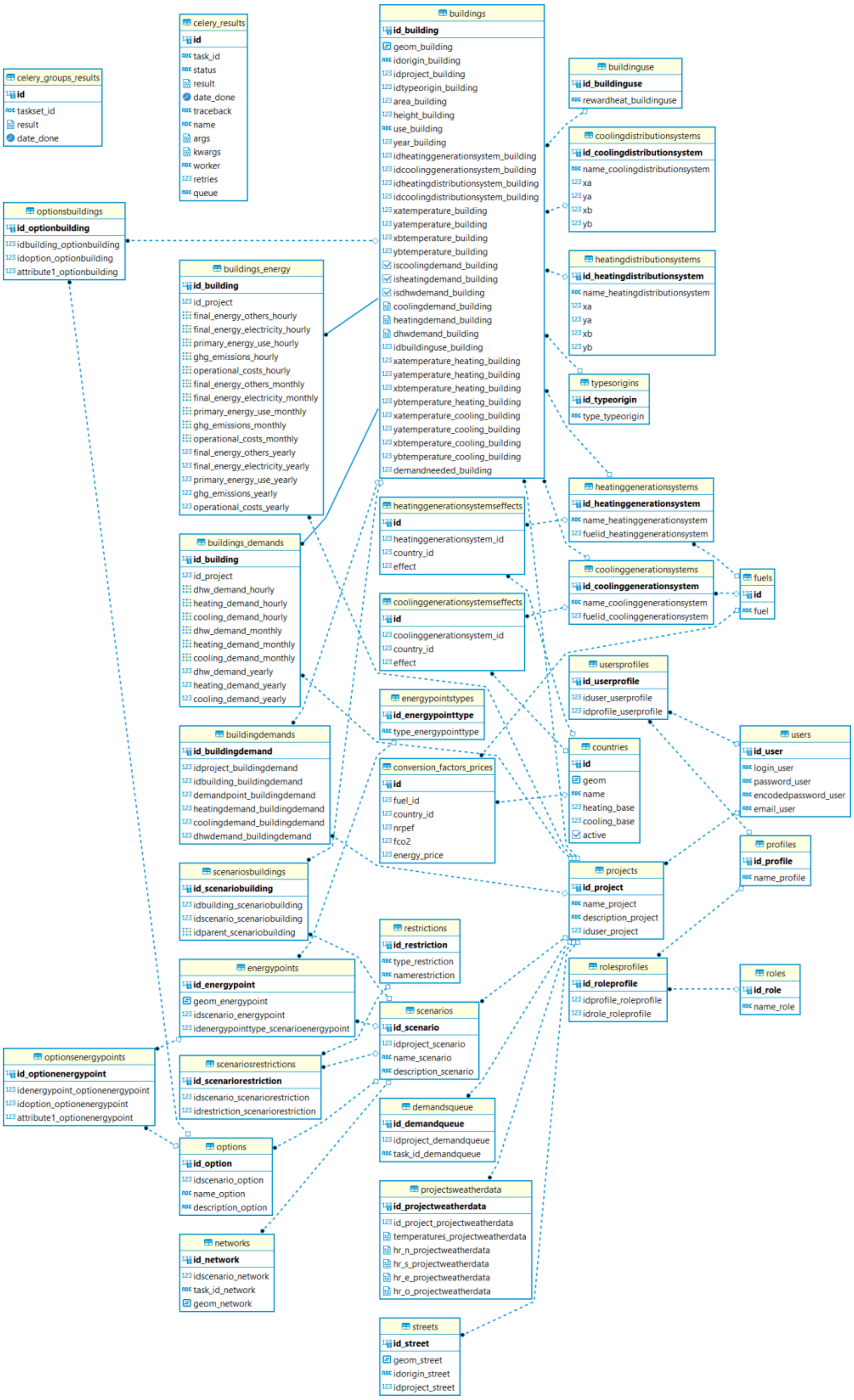


Figure 22 – Current REWARDHeat database

4.3.2 Energy demand calculation

Energy demand estimation algorithm is one of the first and core calculations to be solved. REWARDHeat is inspired on the Demand Mapping Module (DMM) approach used during PLANHEAT project to conduct the demand calculations [9]. This DMM is built as a QGIS plugin, which is quite different from the requirements needed for implementation within the REWARDHeat predesign tool following a client-server architecture, so the methodology has been adapted, modified and improved. The hypotheses and main considerations within the reference method are summarized below[1].

In order to simplify the assessment, static equations are used to determine hourly demands following the Energy Performance of Buildings Directive (see equation 1, 2 and 3). The static calculation is considered suitable and preferable for a pre-design tool in the early stages of a DHC project conception. Full dynamic modelling would be used for advanced stages of design when a big amount of input data and higher levels of detail and accuracy on the technical analyses are required, which is out of the scope of the tool developed in this project.

The wall heat transfer hourly loads for each building is determined multiplying the number of heating/cooling degree hours (HDH/CDH) at the particular location, the heat transfer coefficient (U) of the envelope areas (A) and the heating schedule of each hour. The annual heating and cooling demand results are obtained as the sum of their corresponding hourly values. In order to calculate the HDH and CDH values, reference heating set point of 21ºC and cooling set point of 25ºC respectively are considered. Night setback effects can be accounted for by the corresponding schedules. Losses through the ground are neglected, but might have an impact on the overall heating demand. Different internal gains related to occupancy, lighting, appliances and solar gains are included. Finally, ventilation heating/cooling loads (calculated for the different base temperatures for heating-h or cooling-c) are assumed. If a mechanical ventilation system with heat recovery is installed, ventilation heating/cooling loads are reduced by the heat recovery system efficiency (nHR). The hourly domestic hot water demand is determined by multiplying the annual DWH demand per square meter, the gross floor area of the building and the normalized utilization factor of the DHW (see equation 3).

$$AHD_k = \sum_{i,j=1}^{8760} \left(HDH_{i,j} \times A_k \times U_k - Gains_{i,j} + hventilation\ losses_{i,j} \times (1 - n_{HR}) \right) \cdot heating\ schedule_{i,j}$$

(Eq.1)

$$ACD_k = \sum_{i,j=1}^{8760} \left(CDH_{i,j} \times A_k \times U_k + Gains_{i,j} + cventilation\ gains_{i,j} \times (1 - n_{HR}) \right) \cdot cooling\ schedule_{i,j}$$

(Eq.2)

$$DHWD_k = \sum_{i,j=1}^{8760} DHW\ demand_k \times GFA_k \times \frac{Hourly\ usage\ factor_{DHW_{i,j}}}{\sum_{i,j=1}^{8760} Hourly\ usage\ factor_{DHW_{i,j}}}$$

(Eq.3)

[1] The information included in this section was developed originally in D2.6 [8], but also included in this report in the sake of clarity for the user

These equations require an important amount of input data related to building geometries and constructive characteristics, weather conditions along the year, as well as to static information dependant on the specific building use. The used data will be explained below.

The energy demand calculation engine that is implemented in the tool includes weather (hourly temperature and hourly solar radiation) data from two different alternatives: The first one is the PVGIS initiative [10] which is connected to the tool by means of an API, collecting temperature and solar radiation in four orientations (N, S, E, W) using a slope of 90 degrees (vertical wall). Both datasets are in an hourly basis. The second alternative is only available if PVGIS API is not working. This alternative uses Copernicus C3S datasets [11] to obtain hourly temperature and hourly radiation data in each project location. Solar radiation data (global component) are transformed in the four orientations following distribution patterns built with downloaded PVGIS data. Static information or static data was collected from PLANHEAT database in order to cover the required data for heating, cooling and domestic hot water demand calculation considering the specific use of each building.

The first collected values are the heat transfer coefficients or thermal transmittances (U-values) that are used to measure how effective elements of a building's fabric are as insulators. These values are used to estimate how effective the different building elements are at preventing heat from transmitting between the inside and the outside of a building. Calculation also requires air leakage data per building use considering it year of construction. The database includes values covering the 27 European countries and 3 non-European countries. An example of this data is presented in Table 1.

Table 1 - Example of the U-value data (roof, wall and window)) of PLANHEAT for Spain by different types of buildings and period of construction

Country	Period	Type	Roof	Wall	Window	Air leakage
Spain	<1945	Residential	1.8	2.5	5.7	1.2
Spain	1945-1969	Residential	1.4	2.1	5.7	1.2
Spain	1970-1979	Residential	1.4	2.1	5.7	0.9
Spain	1980-1989	Residential	1	1.6	3.3	0.9
Spain	1990-1999	Residential	1	1.6	3.3	0.9
Spain	2000-2010	Residential	0.5	0.8	3.1	0.9
Spain	>2010	Residential	0.5	0.8	3.1	0.6
Spain	<1945	Others	1.4	2.5	5.8	1.2
Spain	1945-1969	Others	1.4	2.2	5.8	1.2
Spain	1970-1979	Others	1.4	2.2	6.1	0.9
Spain	1980-1989	Others	1	1.8	3.3	0.9
Spain	1990-1999	Others	0.9	1.7	3.3	0.9
Spain	2000-2010	Others	0.6	0.9	2.8	0.9
Spain	>2010	Others	0.6	0.9	2.8	0.6

Other relevant data for energy demand calculation, are the equipment internal gains, internal gains that are related to the developed activities in the building and the gains due to lighting. Our calculation approach works with different values and schedule per building use (Table 2 and Table 3) but differences at country level in both parameters are not provided.

Table 2 - Equipment internal gains, occupancy internal gains, lighting gains and glazing values by different building use collected from PLANHEAT database

id	Building use	Equipment internal gains	Occupancy internal gains	Lighting gains	Glazing
1	Residential	4.4	1.755	6.46	0.27
2	Office	11.77	70.485	15	0.50
3	Education	4.7	298.242	10.66	0.28
4	Health care	3.58	7.329	13.02	0.23
5	Commerce	5.2	8.183	15.07	0.20
6	Hotel	0.945	4.72	10.76	0.17
7	Public	5.48	5.94	9.69	0.50
8	Restaurant	18.88	11	9.69	0.30
9	Sport	16.02	25.5	10.76	0.20

Table 3 - Hourly building schedule for residential buildings in the day one of the year

id	Day of year	Hour of day	Season	Building use	Heating	Cooling	Lighting	Equipment	Occupancy	DHW
1	1	0	W	Residential	0	0	0.1	0.1	1	0.25
2	1	1	W	Residential	0	0	0.1	0.1	1	0.1
3	1	2	W	Residential	0	0	0.1	0.1	1	0.1
4	1	3	W	Residential	0	0	0.1	0.1	1	0.1
5	1	4	W	Residential	0	0	0.1	0.1	1	0.1
6	1	5	W	Residential	0	0	0.1	0.1	1	0.1
7	1	6	W	Residential	0	0	0.1	0.1	1	1
8	1	7	W	Residential	1	0	0.3	0.3	0	0.5
9	1	8	W	Residential	1	0	0.3	0.3	0	0.25
10	1	9	W	Residential	1	0	0.3	0.3	0	0.25
11	1	10	W	Residential	1	0	0.3	0.3	0	0.25
12	1	11	W	Residential	1	0	0.3	0.3	0	0.25
13	1	12	W	Residential	1	0	0.3	0.3	0	0.25
14	1	13	W	Residential	1	0	0.3	0.3	0	0.25
15	1	14	W	Residential	1	0	0.3	0.3	0	0.25
16	1	15	W	Residential	1	0	0.3	0.3	0	0.5
17	1	16	W	Residential	1	0	0.3	0.3	0	0.5
18	1	17	W	Residential	1	0	0.3	0.3	0	0.5
19	1	18	W	Residential	1	0	0.5	0.5	0	0.5
20	1	19	W	Residential	1	0	1	1	0	0.5
21	1	20	W	Residential	1	0	1	1	0	0.5
22	1	21	W	Residential	1	0	1	1	0	0.5
23	1	22	W	Residential	1	0	1	1	0	0.5
24	1	23	W	Residential	0	0	0.5	0.5	1	1

Finally, data for each building type on domestic hot water demand by building use per unit area (Table 4) is embedded. These data are distributed to determine the hourly DHW demand.

Table 4 - Domestic hot water demand by building use per unit area

id	Building use	DHW demand
1	Residential	13.9
2	Office	3.2
3	Education	57.2
4	Health care	133.4
5	Commerce	3.2
6	Hotel	126.4
7	Public administration	3.2
8	Restaurant	35.3
9	Sport	256

In order to calculate the energy demand adequately, it is necessary to have the height of the buildings being able to quantify their envelope and area exposed to the different weather conditions. Height can be obtained using LiDAR data or calculating them be using the number of floors in that are stored as part of the building attributes in the national cadasters. But this height attribute is not always available, as is the case of OSM or the geometries generated by the user himself. To cover this lack of data, an analysis of more than 150,000 building using Copernicus Urban Atlas [12] and building boundaries was developed. to evaluate the relationship between building height and area. The obtained results are presented in Figure 23. For Hotel and Sport buildings a pattern similar to Office and Education respectively is assumed.

Finally, as referred before in this document, some modifications to the PLANHEAT calculation algorithms are required for proper integration into the whole REWARDHeat tool concept, but also, they are being addressed to facilitate and improve the data extraction from data sources (such as the buildings geometries contained in the shapefile or the hourly values from representative weather files). In particular, a dedicated GIS process developed in Python was created to extract representative building envelope areas for each of the four main orientations (N, S, E and W). These will be used later to apply the corresponding hourly radiation values and thus, properly consider solar gains into the balance equation excluding adjacent walls. The process decomposes the building envelope into its constituent walls and determines if they correspond to external (free) walls and assign its main orientation based on the wall azimuth. The accuracy of the calculation can be improved by predefining a larger set of main orientations, better calculation of glazing values per building type or the application of more specific glazing transmittance values.

The demand calculation includes other two algorithms that are useful if the user has real data of buildings in the case study. Following a similar approach than the DHW demand calculation, these algorithms work with the yearly or monthly value disaggregating them by means of the HDH and CDH values.

Figure 23 - Building height-area analysis that is integrated in the tool for energy demand calculation

4.3.3 Route optimizer

The building of the network route is based on a minimum distance optimization algorithm based on graph theory. The configured algorithm works with the selected buildings as energy consumers, the energy producers (waste heat from industries, supermarkets, datacentres, substations, or sources inserted by the user) and the streets (collected from OSM) as an axis for the route layout. The developed algorithm uses the DHNx library [13] for geometry managing before the network optimization to prepare the streets, buildings and energy points in the correct geometry format to be optimized. After that, the script uses the capabilities of the NetworkX library [14] to obtain the optimized route connecting the corresponding points (producers and consumer) using the selected streets.

NetworkX is a Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks. Specifically, the tool uses the Steiner Tree approximation to return an approximation to the minimum Steiner tree of a graph, with the minimum cost tree that spans all the nodes in the network (consumers/buildings and producers). A graph example of the algorithm implementation is presented in Figure 24.

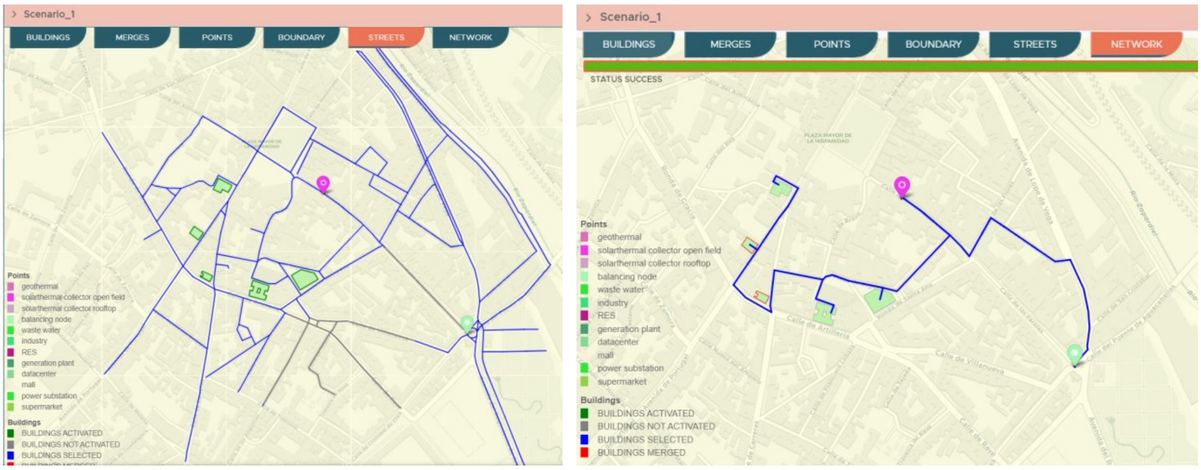


Figure 24 - Route optimization algorithm implementation

It is necessary to highlight that the optimization algorithm based on graph theory includes a function to evaluate if graphs are connected or not. This function was included due to the interface was designed to delete streets that are not user will be able to that are not feasible to implement the network, such as streets with a subway installed underneath or with surface installations that prevent the installation of the network. When two graphs are not connected, the implemented algorithm is able to provide the minimum distance route connecting all the producers and consumers, deleting the graph that is not connected with this main graph.

4.3.4 Energy producers disaggregation methods

For the energy producers, an hourly disaggregation method for the annual energy production is needed. The method used depends on the type of producer.

Solar Thermal Collectors Field

The Solar Thermal Collectors Field disaggregation method uses information introduced by the user regarding the characteristics of the collectors, tilt, orientation and the available area of the field, and weather information used in the project.

First, considering the available dimensions of the field inserted by the user and the dimensions of the solar collector selected, an estimation of the number of rows and collectors per row is made. This is needed to calculate the estimated outlet temperature of the energy generated by the solar field, which depends on the configuration of the collectors.

After that, the model used to calculate the energy generation and its temperature is the one implemented in the City Energy Analyst (CEA) software [15], which uses the following equations:

$$\dot{Q}_{pot} = Area \cdot \left[\eta_0 \cdot Irradiation - a_1 \cdot (T_{avg} - T_{Amb}) - a_2 \cdot (T_{avg} - T_{Amb})^2\right]$$

$$T_{out} = T_{in} + \frac{Irradiation - (a_1 + 0.5) \cdot (T_{in} - T_{Amb})}{\dot{m} \cdot Cp} \cdot Area$$

Where:

- $\dot{Q}_{pot}$ is the energy generated by the solar collector
- η_0 is zero loss efficiency at normal incidence.
- a_1 is the collector heat loss coefficient at zero temperature difference and wind speed [W/m²·K].
- a_2 is the temperature difference dependency of the heat loss coefficient [W/m²·K²].
- T_{avg} is the mean fluid temperature.
- T_Amb is the ambient temperature.
- T_{in} is the inlet temperature.
- T_{out} is the outlet temperature.
- $\dot{m}$ is the nominal mass flow though the collector.
- This model generates the estimation of the solar generation for a year in an hourly basis that will be used in different calculation steps of the tool.

Geothermal Heat

Geothermal Heat potential estimation model is based in a method called G.POT (Geothermal POTential) for determining the shallow geothermal potential of a site [16]. The shallow geothermal potential is the thermal power that can be efficiently exchanged by a Borehole Heat Exchanger (BHE) with the ground. The method considers various factors such as the thermal properties of the ground, the thermal properties of the BHE, and the operational and design parameters of the plant as depicted in Figure 25. The G.POT method provides a simple and flexible method for calculating the geothermal potential and can be applied in different scenarios. The method is included in the tool as a script to characterize geothermal producers using the following equation to estimate the annual geothermal potential:

$$\bar{Q}_{BHE} = \frac{a \cdot (T_0 - T_{\lim}) \cdot \lambda \cdot L \cdot t'_c}{-0.619 \cdot t'_c \cdot \log(u'_s) + (0.532 \cdot t'_c - 0.962) \cdot \log(u'_c) - 0.455 \cdot t'_c - 1.619 + 4\pi\lambda \cdot R_b}$$

Where:

- $\bar{Q}_{BHE}$ is the annual geothermal potential.
- $a = 7.01 \cdot 10^{-2}$ if the potential is expressed in MWh/y.
- T_0 is the soil temperature in °C.
- $T_{\lim}$ is -2°C in winter and 40°C in summer.
- λ is the thermal conductivity of the ground obtained from Hotmaps database [17] in W/m/K.
- L is the borehole length in meters.
- R_b is the thermal resistance of the borehole.
- t_s is the simulation time. In this case, it is 365 days.
- $t_c' = t_c/t_y$, t_y is 365 days and t_c is the length of the load cycle in days.
- $u_s' = r_b^2/4\alpha t_s$, α is calculated using the thermal diffusivity of the ground.
- $u_c' = r_b^2/4\alpha t_c$

Soil temperature (T_0) is calculated based on an empirical equation ($T_0 = 15.23 - 1.08 \cdot 10^{-2} \cdot Z + 5.61 \cdot 10^{-6} \cdot Z^2 - 1.5 \cdot 10^{-9} \cdot Z^{-3}$) based on the land elevation [18]. This equation is valid up to an elevation of 1500 meters above sea level over which the soil temperature is highly influenced by the snow dynamics. The elevation is obtained from Open Topo Data REST API server using the location coordinates of the area where the DH network is under development.

After the yearly potential is estimated, it is dissaggregated in hourly values using the Heating and Cooling Degree Hours determined with a reference meteorological year and a set point of 21°C for heating and 25°C for cooling.

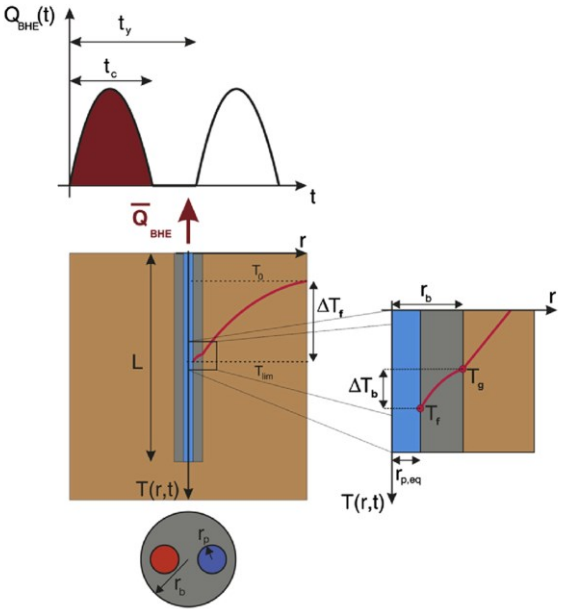


Figure 25 - Input parameters for the estimation of the shallow geothermal potential ($\bar{Q}_{BHE}$) with the G.POT method [16]

Industries

The creation of a general script to disaggregate WH coming from industries would not be representative of the reality due to the fact that WH depends on a diverse set of factors that are not possible to be integrated in a general database, such as special considerations in the manufacturing process, number of working shifts and working schedules, holiday periods among others. In this case, an estimation of the available amount of WH is obtained from an open-source database [19] that includes a yearly value for the recoverable energy for each geolocated industry. Using that value, the method to disaggregate it in hourly values that has been integrated in the tool is based on the user input about the working days along the week within it is considered the WH is produced constantly. Thus, the annual potential energy is divided during the days that the user selects for the whole year. In this iteration, the generation temperature is fixed at 90°C.

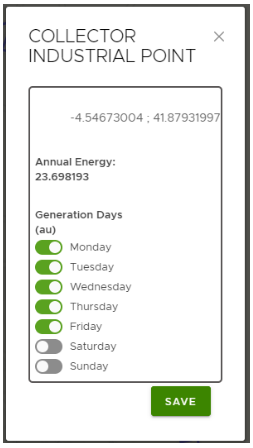


Figure 26 - Disaggregation inputs for industry database values

Data centres

The number of data centres (DC) in recent years is growing rapidly, and with that, the share in total consumption of electricity is growing too. A significant amount of electricity is transformed into heat energy which increases the optimal temperature in DC for component operation. This heat needs to be removed and usually, it doesn't have any further application.

Today it is recognized that waste heat can be integrated into district heating (DH) and by using it reduce the usage of conventional heat fuels.

Integration of waste heat is possible in three ways: with a heat exchanger (HEX), with a booster heat pump, or with the combination of the HEX and heat pump. Although those utilizations are examined and implemented, there is a lack of research on the optimization of the integration of waste heat into the district heating network (DHN). To perform optimization, a thermodynamic model of the DC and a pinch analysis model were developed. In this study, a method for evaluating the economic feasibility of DC waste heat integration into DH systems is proposed. The most suitable integration technology of waste heat into DH systems by using the hourly merit order of waste heat utilization technologies based on pinch analysis is found. The connection pipe between DC and DHN is optimized, and the ideal diameter is determined considering different temperature regimes of the network: low-temperature, ultralow temperature, and neutral temperature networks. The methodology was tested using a case study of a DC in the City of Zagreb.

The script integrated in the predesign tool is based on the methodology used to perform that study [20].

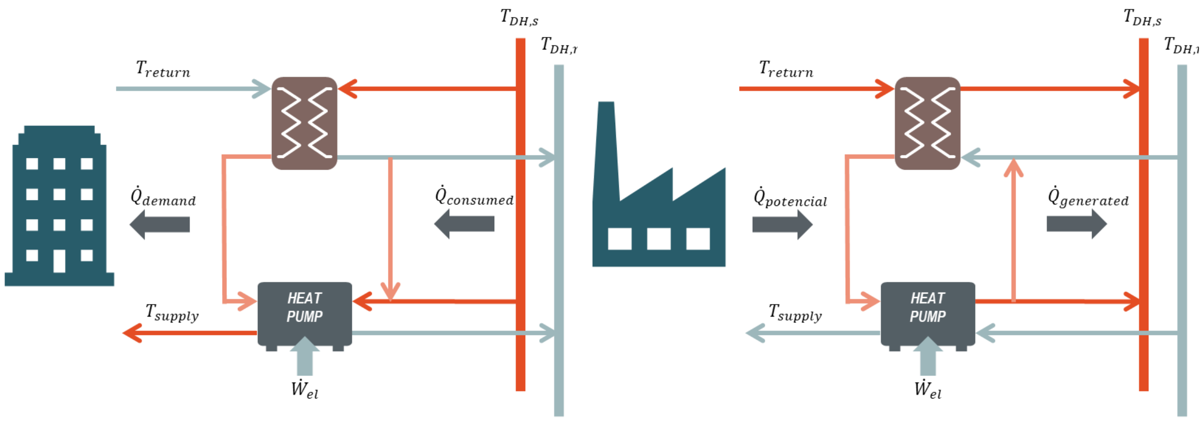
Supermarkets, Shopping malls and Power substations

District heating systems are almost always located in densely populated urban areas where various heat sources are available, such as cooling and refrigeration systems in supermarkets, shopping malls, and power transformers. These urban sources often have a large share of waste heat, which is usually emitted into the environment. This waste heat could be used to partially cover the thermal load in district heating systems. In this case, University of Zagreb have developed an economic assessment model for the integration of urban heat sources into existing district heating systems. By the hourly merit order of waste heat utilization technologies based on pinch analysis, we have defined the most suitable integration of urban heat sources into existing district heating systems. Different temperature regimes of the urban source and the existing heat network have been considered. Finally, the method was tested on the case study of a supermarket and power substation located in Zagreb, while the sensitivity analysis was carried out with a focus on various technical and economic boundary conditions. The script integrated in the predesign tool is based on the methodology used to perform that study [21].

4.3.5 Substation model

Once the demand of the buildings corresponding to heating and cooling and the energy produced is calculated and disaggregated hourly, and the temperature of the network is selected by the user, the energy coming to or from the DHN and the water flow is needed to calculate the water flowing through each section of the network to, finally, estimate the size of the pipes to be installed.

In order to do that, a model of a substation has been made including the use of a heat exchanger (HX) and/or a heat pump (HP) depending on, firstly, the supply and return temperature of the DHN (linked implicitly to the type of network to be calculated) and, secondly, to the supply temperature need of the buildings (linked to the type of heating/cooling distribution system included in the baseline definition) and to the temperature level considered in the waste heat calculation described in the section above. The model considers a different configuration depending on energy flow to or from the network as shown in Figure 27.



a) Configuration when consuming energy from the DHN (eg. heating of buildings)

b) Configuration when producing energy to the DHN (eg. producers or cooling of buildings)

Figure 27 - Substation configuration considered by substation model

After identifying if a point is a consumer or a producer from the point of view of the network, the model prioritizes the use of the HX in case the temperature level allows to use it. If this is not the case, the model analyses the feasibility of using the HP or a combination of HX and HP to match the temperature levels, assuring the supply of the demand and the harvesting of the WH potential, to calculate the real consumed and generated energy from the grid and the electricity used in the process by the HP. The COP of the HP is estimated considering the temperature levels as well. Finally, the script calculates the volumetric flow used to or from the grid and the primary energy, CO2 emissions and cost of the energy associated to the operation of the substation.

4.3.6 Pipe sizing calculation

The goal of the pipe sizing script is the estimation of the diameters of the pipes for each section of the calculated network. Then, the script is divided in three parts:

1. Adaptation of the inputs. The script groups the information of the energy consumed or generated by the buildings and producers estimated in previous calculation steps and reorder them to allow a proper flow calculation.
2. Calculation of the hourly flow in each section of the network. The script processes the nodes and edges of the network, creating a relation matrix based on the principle of energy balancing in each node. Then, considering that the flow is known in the boundaries of the network, i.e. nodes associated to buildings or producers calculated using the substation model described above, the flow in each section is obtained directly from a simple matrix mathematical operation. This calculation is done hourly, so the result is the hourly flow in each section of the network which is useful for the analysis done in next steps.
3. Pipe sizing. Once the flow passing through each section is calculated, the yearly maximum flow obtained is selected to dimension the associated pipe with the possibility of having different pipe sizes in each section according to the calculated maximum flow. Each pipe section is associated with a maximum flow based on previous estimates, making it straightforward to identify the pipe section with the maximum design flow (Table 5). The association between flow and diameter can be easily changed according new estimations or calculation methods.

Table 5 - Maximum flow associated to each pipe diameter

DN [mm]	Flow [m3/s]
50	0.001119192
100	0.007147123
150	0.02120575
200	0.045553093
250	0.082957681
300	0.135009944
350	0.203967903
400	0.291539798
450	0.400788683
500	0.53014376
550	0.68423888

4.3.7 KPIs definition

The selection of the Key Performance Indicators (KPIs) has been carried out according to the most used parameters considered in DHN network design, and in the calculation simplicity according the available information generated by the tool.

Primary Energy, CO2 and Cost Estimation

The methodology to calculate the Primary Energy, CO2 and Cost for the DHN is the same as used in the Baseline calculation and described in [8]. This time, the country selected to get the proper conversion factors is the same as identified during baseline calculation. However, for the substations the fuel used is the electricity consumed by the HPs or, in the case of certain combination of DHN types and distribution systems for the buildings, the original cooling generation system (Table 6 to Table 7). Contrary to the case of the baseline calculation where the energy consumed is estimated through a general efficiency for the generation system, in this case, the electricity consumed is estimated using the substation model described in Section 4.3.5 which includes a more detailed COP calculation.

Table 6 - Country IDs used by REWARDHEAT predesign tool.

id	country	id	country	id	country
1	Austria	11	Germany	21	Poland
2	Belgium	12	Greece	22	Portugal
3	Bulgaria	13	Hungary	23	Romania
4	Croatia	14	Ireland	24	Serbia
5	Cyprus	15	Italy	25	Slovakia
6	Czech Rep.	16	Latvia	26	Slovenia
7	Denmark	17	Lithuania	27	Spain
8	Estonia	18	Luxembourg	28	Sweden
9	Finland	19	Malta	29	UK
10	France	20	Netherlands	30	Norway

Table 7 - Heating and Cooling Generation systems and fuel IDs used by REWARDHEAT predesign tool.

id	HGS
1	Biomass boiler
2	Gas boiler
3	Oil boiler
4	WWHP
5	AWHP
6	Electric Boiler
7	District Heating
8	None

id	CGS
1	None
2	WC-chiller
3	AC-chiller
4	GF-ABS-chiller
5	SF-ABS-chiller

id	Fuel
1	Wood
2	Gas
3	Oil
4	Elect
5	DH
6	Sun

Similar to the tables shown above, the conversion factors to calculate the non-renewable primary energy, green-house gases emissions and operation costs are defined depending on the fuel and the country (Table 8). The value of the conversion factors depends on the country for those that the information is available but, in case there is no information included in the database, the tool uses a default value for the calculation.

Table 8 - Conversion factors used by REWARDHeat predesign tool

fuel_id	fuel	nrPEF [$kWh_{primary}$/kWh]	fCO2 [gCO2/kWh]	EnerPrice [€/kWh]
1	wood	0.1	20	0.05
2	gas	1.1	210	0.04
3	oil	1.15	260	0.06
4	elect	2.5	300	0.15
5	DH	1.6	150	0.1
6	sun	0	0	0

OPEX, CAPEX and LCOE

OPEX (Operational Expenditure), CAPEX (Capital Expenditure), and Levelized Cost of Energy (LCOE) are commonly used as indicators in the energy sector to evaluate and compare renewable energy and power generation projects. The connection between the different concepts is presented in Figure 28.

OPEX refers to the operational costs incurred during the lifespan of a project. These costs are associated with day-to-day operations, maintenance, and management of the facility (e.g. labour costs, maintenance expenses, insurance, taxes, and other recurring operational costs). CAPEX represents the initial capital investment required to design, build, and commission a project. It includes the costs of acquiring land, construction, equipment, and other assets necessary to establish the project. Finally, the LCOE is a metric used to evaluate the lifetime cost of generating electricity from a particular source, usually expressed in economic terms per kilowatt-hour (€/kWh). It provides a way to assess the overall cost-effectiveness of an energy generation project over its lifetime. LCOE is usually calculated by dividing the total cost of the project (CAPEX + OPEX) by the total electricity generated over its lifetime. This indicator is very useful to compare different energy sources and technologies on a standardized basis.

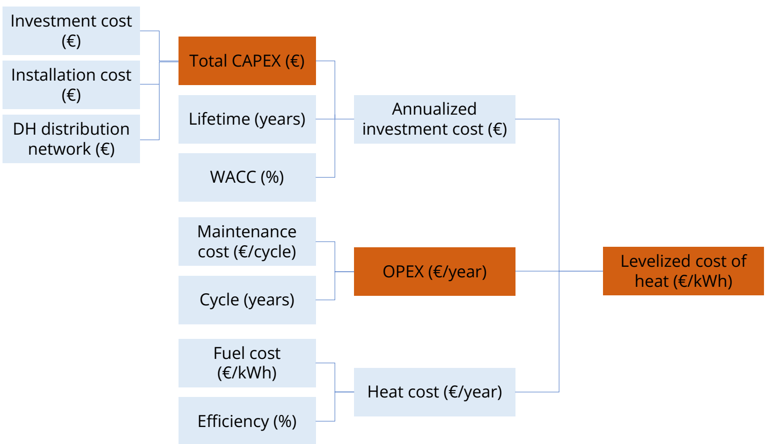


Figure 28 – Interlinkages between CAPEX, OPEX and LCOE.

In order to provide the values of the OPEX, CAPEX and LCOE the calculation algorithm is based on the Technology Data for power and heat production plants (version 12, 2022/06/21) from the Danish Energy Agency (Table 9). The cost of the pipes was collected from the Sustainable Energy Authority of Ireland for a two-pipe system, considering outer and inner-city conditions (

Table 10).

Table 9 – Investment, operational and maintenance cost, efficiency and lifetime for the energy producers' types used in the pre-design tool.

ID	Type	Investment (€/kW)	Variable O&M (€/kWh)	Fixed O&M (€/kW)	Efficiency (%)	Lifetime (years)
1	generation plant electric	150	0.0009	1.07	0.99	20
2	generation plant gas	60	0.0011	1.95	1.05	25
3	generation plant biomass	3.28	3.18	136.50	0.285	25
4	seasonal storage	-	-	-	-	-
5	connection with existing DH	670	0.00169	2.00	5.2	25
6	geothermal	1300	0.002	18.26	3.74	25
7	Solar thermal collectors open field	310	0.00021	0.61	0.45	30
8	Solar thermal collectors' rooftop	310	0.00021	0.61	0.45	30
9	supermarkets	1080	0.0022	2.00	3.37	25
10	industry	670	0.00169	2.00	5.2	25
11	datacentres	1080	0.0022	2.00	3.37	25
12	waste water treatment	9020	0.026	262.00	0.22	25
13	balancing node	1080	0.0022	2.00	3.37	25
14	malls	1080	0.0022	2.00	3.37	25
15	power substations	1080	0.0022	2.00	3.37	25

Table 10 – Nominal diameter and pipe cost for a two pipe DH system.

DN	Max Capacity	Outer city cost	Inner city cost
50	434	626	782
100	2792	695	869
150	7506	695	869
200	15044	834	1043
250	21300	1113	1391
300	30672	1252	1565
350	41748	1391	1738
400	54528	1599	1999
450	69012	1738	2173
500	85200	1947	2434
550	103092	2303	2879

Considering these previous data, the CAPEX, OPEX and LCOE indicators are calculated in the tool using the following equations, that are based on the results of the data collected during the tool workflow:

$$CAPEX = Investment\ cost\ Producers + Total\ pipe\ cost + Investment\ cost\ substations$$

$$OPEX = O\&M\ cost\ producers\ (fixed\ and\ variable) + O\&M\ cost\ substations\ (fixed\ and\ variable)$$

$$LCOE = \left(CAPEX(year) + OPEX(year)\right)\ /\ Annual\ Energy\ Production$$

Pumping Energy

The pumping energy used in the DHN is calculated in several steps:

1. The inputs for the scripts are adapted to the proper format to apply the calculation equations.
2. The pressures losses in each section of the DHN are estimated using the following equation obtained from the experimental experience of companies dedicated to the design and operation of this kind of networks. The difference between the results obtained using this simple equation and more complex ones included in the literature [22] has been calculated with a result of less than 4%, so the equation is selected in the sake of simplicity and computation time. The pressure losses are calculated for each section and for each hour of the year.

$$\Delta P = \frac{0.55 \cdot \rho \cdot v^{0.13} \cdot Q^{1.87}}{0.101972 \cdot D^{5.01}} \cdot L$$

   Where:

   ΔP is the pressure losses of the pipe in Pa

   ρ is the density of the fluid in kg/m^3

   v is the kinematic viscosity of the fluid in mm^2/s

   Q is the volumetric flow through the pipe in l/h

   D is the internal diameter of the pipe in mm

   L is the length of the pipe in m

3. Once the pressure losses are calculates, the pumping energy is calculated considering the flow through the pipe and a pumping performance of 0.9 using the following equation [22] for each section of the DHN and each hour of the year, accumulated in a monthly and yearly value to be shown to the user.

$$PE\ [Wh] = \frac{\Delta P \cdot Q}{\eta_{pump}}$$

Heat Losses

The Heat Losses of the system depends on several factors. First, the most important are the temperature of the network, which is linked to the kind of network the user wants to design and selected prior to the option calculation, and the temperature of the soil where the pipe is installed. Other important factor considered is the pipe diameter of each section of the DHN, used to estimate the heat Thermal Conductance of the pipe. In order to do that, in this version of the tool, some considerations have been taken into account:

- The properties of the soil are uniform in all the Area of Interest.
- The temperature of the soil is equal to the ambient temperature.
- The soil conductivity is constant with a value of 1,2 W/mK
- The distance from the surface of the ground to the upper part of the buried pipe is 0,6 meters.
- The distance between the surfaces of the pipes is 0,2 meters.
- The thickness of the isolation layer of the pipes is 0,1 meters.
- The thermal conductivity of the isolation material is 0,03 W/mK

Finally, the calculation model described in [23] is used to estimate the thermal losses in each section of the DHN during the year (Figure 27) and accumulated in a monthly and yearly value to be shown to the user.

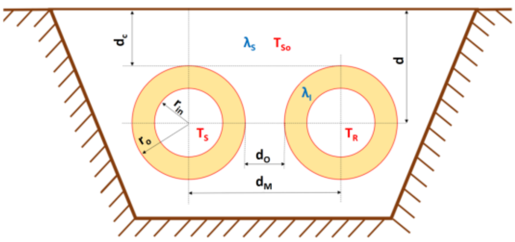


Figure 29 - Scheme of two underground district heating pipes [23]

If a comparison of the obtained values of the Heat Losses is performed for two calculated options using the tool, it can be seen that the losses are about 40% lower in the case of 5th generation DHNs (Option_1 in Figure 30) than the conventional ones (Option_2 in Figure 30), as expected.

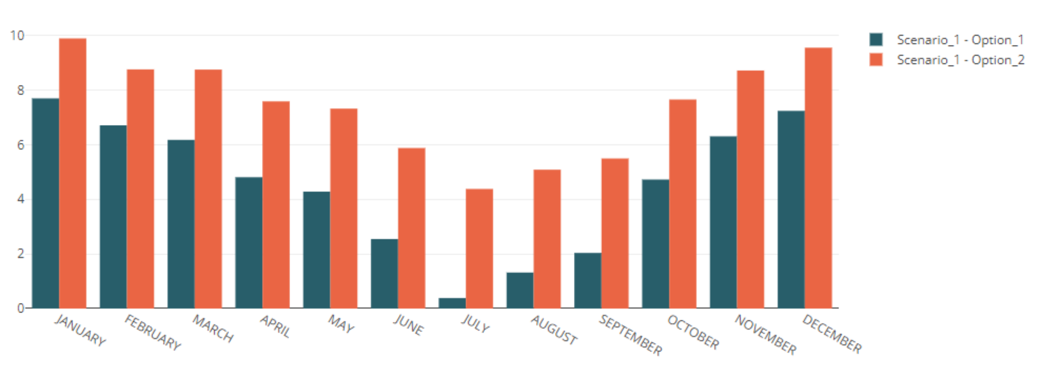


Figure 30 - Comparison of Heat Losses calculated for a 5th generation and a Conventional DHN

4.3.8 Architecture and backend development and integration

The general architecture of the Predesign tool is conceptually the same and that described in D2.6 [8] with slight modifications. Figure 31 shows the general architecture of the REWARDHeat platform, with two main blocks, the frontend or user interface and the backend. For the development of the frontend, the Angular Web development platform has has continued to be used. In the case of the backend, and given its complexity, different technologies have been used to adapt in the best possible way to the different needs of the platform development.

The platform API enables the communication between the frontend and the database, which uses Spring Boot technology (based on Java) both for authentication and authorization, as well as for the CRUD (create, read, update, and delete) operations with the different tables of the database.

The database is based on Postgres/Postgis. The main reason to work with this object-relational database is the power of its geometric/geographic functions, which greatly facilitate common tasks in platform development.

For the calculation and communication of the scripts described in sections above, different technologies have been used, with the aim of allowing the user of the platform to work on different projects, while waiting for the completion of the calculations required during the different steps. A small API has been developed in Flask, which allows communication with the main API of the platform, responsible for queuing the different calculation tasks, adding them to a table in Redis memory, and managing the different calculations through Celery.

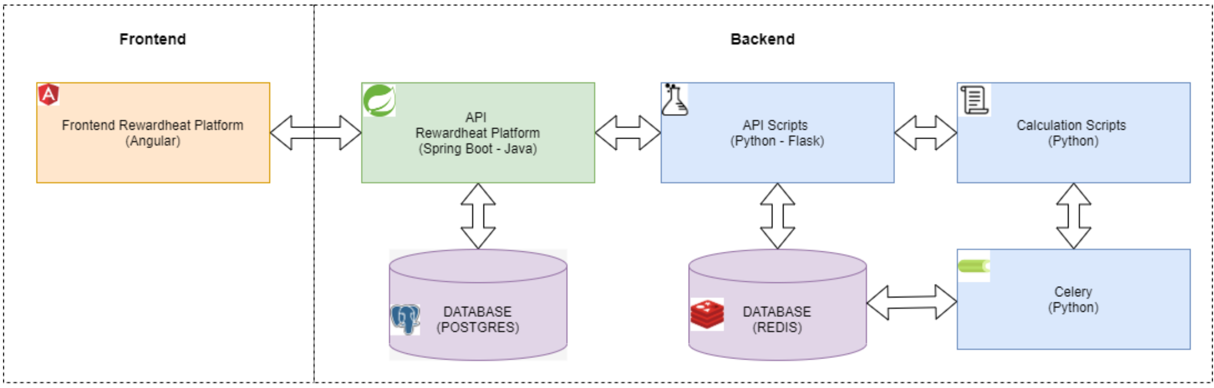


Figure 31 – REWARDHeat Predesign Tool backend architecture

4.4 Tool deployment and access to the last version

The REWARDHeat predesign tool is deployed in a web-based application allocated in the servers of CARTIF. The Access Release, in a first step, has been accessible by the WP2 partners and now the last release is accessible by all REWARDHeat partners.

The URL to access the REWARDHeat predesign tool is:

https://tools.cartif.es/rewardheat/#/TheProject

For this version, there is only one predefined user accessible using the following login information:

- Login: rewardheat
- Password: #xk16BV%B

It should be noted that the tool, at this stage of development, presents the limitation of 5 buildings allowed to be included in the project. This number should be sufficient to allow the user to have relevant information to explore the potential of the tool and extract enough information for a possible DHN design.

5 Validation of the tool. Feasibility study in Palma de Mallorca

5.1 Location and motivation of the study

Palma, the capital of the Balearic Islands in Spain, is located in Mallorca (Figure 32). Its historic center is characterized by ancient buildings not well-designed to accommodate chillers or heat pumps properly. This has led to outdoor units (condensers for cooling or evaporators for heating) being placed in non-adequate locations, such as areas exposed to direct sunlight or with poor ventilation, significantly reducing their efficiency and increasing electricity consumption.

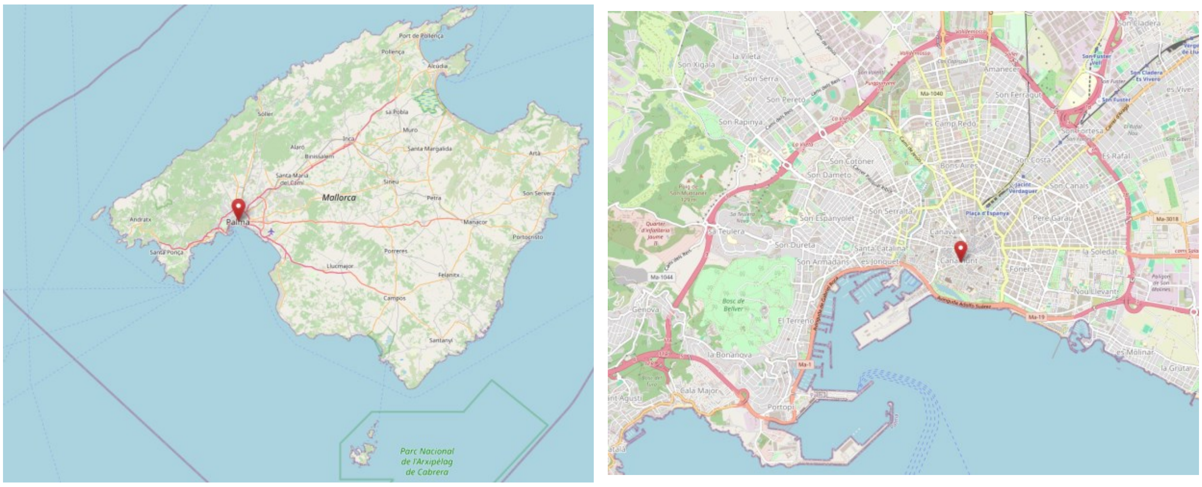


Figure 32 - Location of replication site in Palma (Spain). Source: Open Street Maps

Implementing a low-temperature District Heating and Cooling network would greatly improve the performance of air conditioning systems in the city centre, particularly in large buildings. Additionally, this solution would allow owners to make better use of terraces, where the outdoor units are currently placed, a particularly relevant aspect in buildings with limited space. Considering the last, the REWARDHeat pre-design tool presented in this document has been used to assess the refurbishment of an old pneumatic waste recovering system which is not being used at this moment, in order to convert it in a low temperature District Heating and Cooling network. In the following sections the pipe layout of the pneumatic network and a list of building addresses that would be connected to the DHC network will be shown. After that, the use of the tool will be analysed to validate it and assess the feasibility of the refurbishment.

5.2 General description of the pneumatic system and location

In October of 2002, the city of Palma installed a pneumatic waste recovering system within the historical city centre in order to avoid the use of rubbish containers. That system collected the waste deposited in specific bins and takes it to the central processing station. However, due to premature failure of pipelines, the waste management system ceased operation in 2005 without any use currently.

The main challenge in implementing a district network is the cost associated with excavations and trenching, especially in a historic area like the centre of Palma. The proposal presented in this document suggests using the existing pipelines of the obsolete pneumatic waste network.

The network, consisting of 12 kilometres of pipes with 500 mm of diameter running through the historic centre (Figure 33), could be repurposed to be used in a heating and cooling network, supplying energy to numerous hotels and large administrative buildings in the area, including several office buildings owned by the Palma City Council.

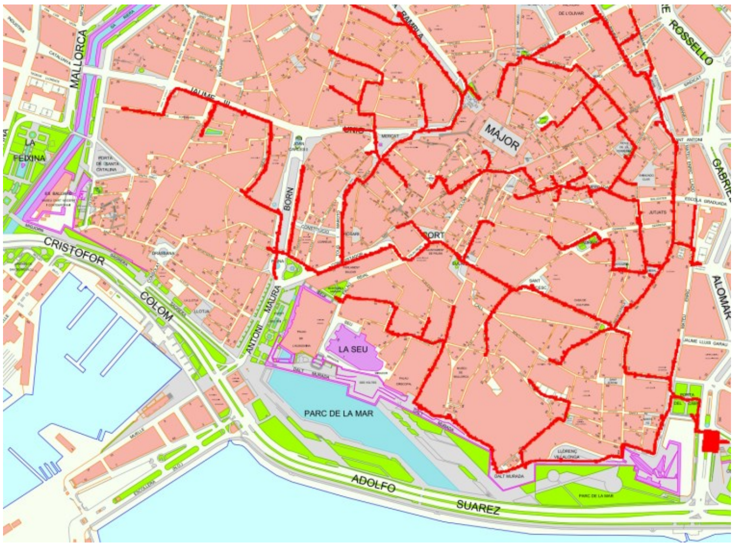


Figure 33 - Extension of pneumatic piping network. Source: SAMPOL

5.3 Thermal demand calculation

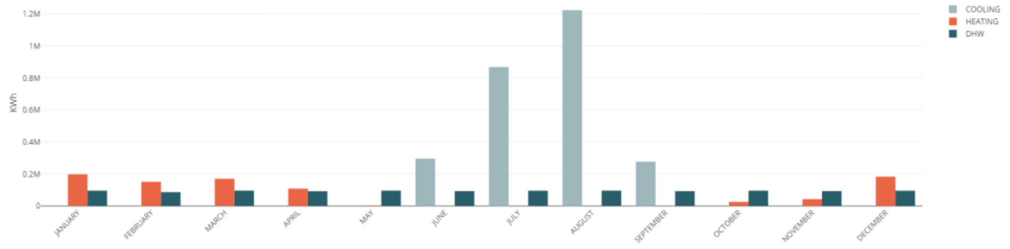
The list of buildings and their characteristics collected by SAMPOL, are represented in Figure 34 and summarized in Table 11. The energy demand of the buildings has been included in the tool using different sources. For most of the buildings the demand is estimated using the method integrated in the tool, while for four buildings the annual demand is introduced by the user and disaggregated in hourly values internally by the tool. Using that information, the total demand of the buildings, the primary energy consumed, the CO_2 emissions and the cost is calculated and represented in Figure 35. It is worth to mention that the main energy demand in Palma de Mallorca comes from the needs of cooling of the buildings with 2,666,576 kWh/year, representing 75% of the total, contrasting with the heating demand of 884,084 kWh/year. The total primary energy consumed by the buildings is 3,654.8 MWh/year, the total CO_2 emissions are 692,144.2 $KgCO_2$/year and the total operational costs are 221,090 €/year.

Figure 34 - Picture of the set of buildings included in the DHCN of Palma de Mallorca

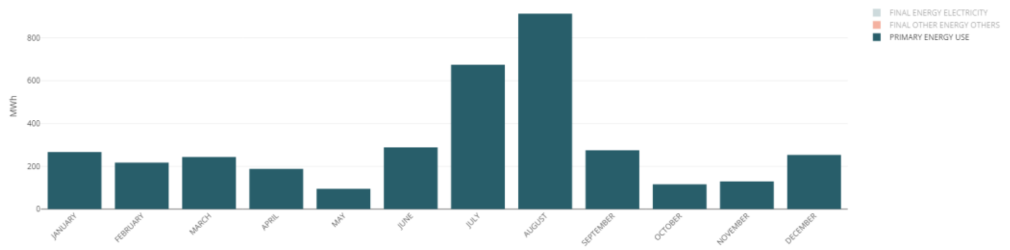
Table 11 - List of buildings to be included in the DHCN of Palma

Building Name	Area	Height	Use	Year	AHD[2]	ACD[2]	ADHWD[2]	HGS[2]	HDS[2]	CGS[2]	CDS[2]
Sa Gerreria	220.8	15	Residential	1980	29870[3]	34401[4]	15334	AWHP	Fancoils	AC-	Fancoils
Flassaders	684.7	20	Residential[5]	1900	310760[3]	829584[4]	6695	Gas	Conv.	AC-	Fancoils
La Calatrava -	315.2	12	Residential	1995	12293[3]	27674[4]	17525	Gas	Conv.	None	None
Casa Balager	808.5	12	Residential[5]	1910	222989[3]	599628[4]	48053	AWHP	Fancoils	AC-	Fancoils
PM. S'ESTEL	1408.6	15	Sport	2002	35920	157428	360606	Gas	Fancoils	AC-	Fancoils
La Calatrava –	558	15	Health Care	1996	16326	133662	372132	AWHP	Fancoils	AC-	Fancoils
Edifici	1576	18	Office	1989	33185	417161	30256	AWHP	Fancoils	AC-	Fancoils
Teatre Xesc	853	12	Commerce[5]	2003	6405	112516	10922	AWHP	Fancoils	AC-	Fancoils
Casal Solleric	894.6	12	Residential[5]	1900	15852	40730	61417	AWHP	Fancoils	AC-	Fancoils
Escola	1246	6	Education	2001	9723	90913	142557	Gas	Conv.	AC-	Fancoils
Quarter	935	6	Public	1960	24308	73972	5982	AWHP	Fancoils	AC-	Fancoils
Cort	1596	9	Public	1886	57662	165299	15320	AWHP	Fancoils	AC-	Fancoils

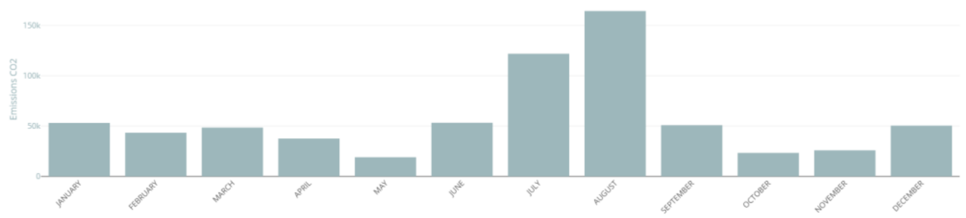
[2] AHD = Annual Heating Demand; ACD = Annual Cooling Demand; ADHWD = Annual DHW Demand; HGS = Heating Generation System; HDS = Heating Distribution System; CGS = Cooling Generation System; CDS = Cooling Distribution System
[3] Indicated by the user in annual basis
[4] Approximated based on heating demand indicated by the user
[5] Different real use but construction similar to indicated



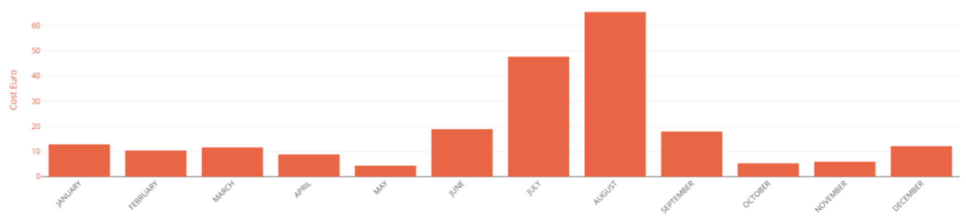
a) *Energy demand of the set of buildings included in the analysis*



b) *Primary energy consumed by the set of buildings included in the analysis*



c) *CO2 emissions by the set of buildings included in the analysis*



d) *Cost generated by the set of buildings included in the analysis*

Figure 35 - Baseline calculation for the selected buildings in Palma

5.4 Network route calculation and pipe sizing

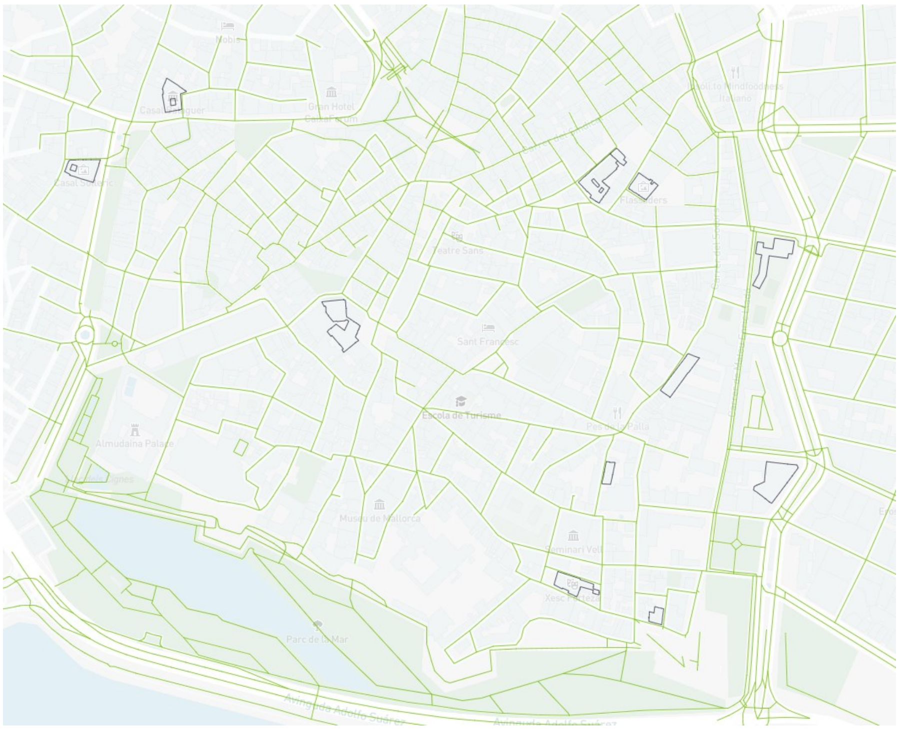
Once the buildings have been selected, included in the tool and its demand calculated, the next step is the generation of the scenario. In this case, the tool is not prepared to upload a predefined route, so the process to create it, is including in the calculation only the streets used by the pneumatic waste management network. For the created Scenarios, only one producer or Balancing Node has been included and placed in the location of the central waste management station of the former network (red rectangle in Figure 36), working as main producer to supply the heating and cooling to the network.

Figure 36 - Location of balancing node of the DHCN of Palma

Regarding the scenario creation, the available streets obtained directly from OSM and the streets used to force the route to be similar to the pneumatic one is show in Figure 37.

If the superposition of the pictures of the pneumatic network and the obtained route is represented, it can be observed that they shared most of the street for their connection (Figure 38). Considering that the pneumatic network connected much more points than only the buildings included in this study, that fact validates the calculation of the optimal route for the connection of the points, giving results quite similar to real cases.

After the route is obtained, the project is prepared to calculate the pipe size in each section of the network configuring the parameters in the Option level. For all the options calculated, the network type selected is 5th Generation DHCN in order to provide heating and cooling to the buildings, including in the balancing node a AC-Heat Pump for heating and an AC-chiller for cooling. After calculating the option including all the identified buildings, the resulting maximum pipe diameter of 550 mm (Figure 39a) exceeds the existing diameter of the pneumatic network of 500 mm. Due to that, alternative networks removing the most demanding buildings have been calculated until obtaining pipe diameters below that threshold also considering that the DHCN is made of two pipes (Figure 39b and Figure 39c). Finally, the selected scenario is that where two buildings were removed from the calculation (Figure 39c), and the balancing node is made of an AC-Heat Pump for heating and an AC-Chiller for cooling.



Streets available for the calculation of the route

Streets used to force the route calculation

Figure 37 - Streets available for the calculation of route for DHCN of Palma

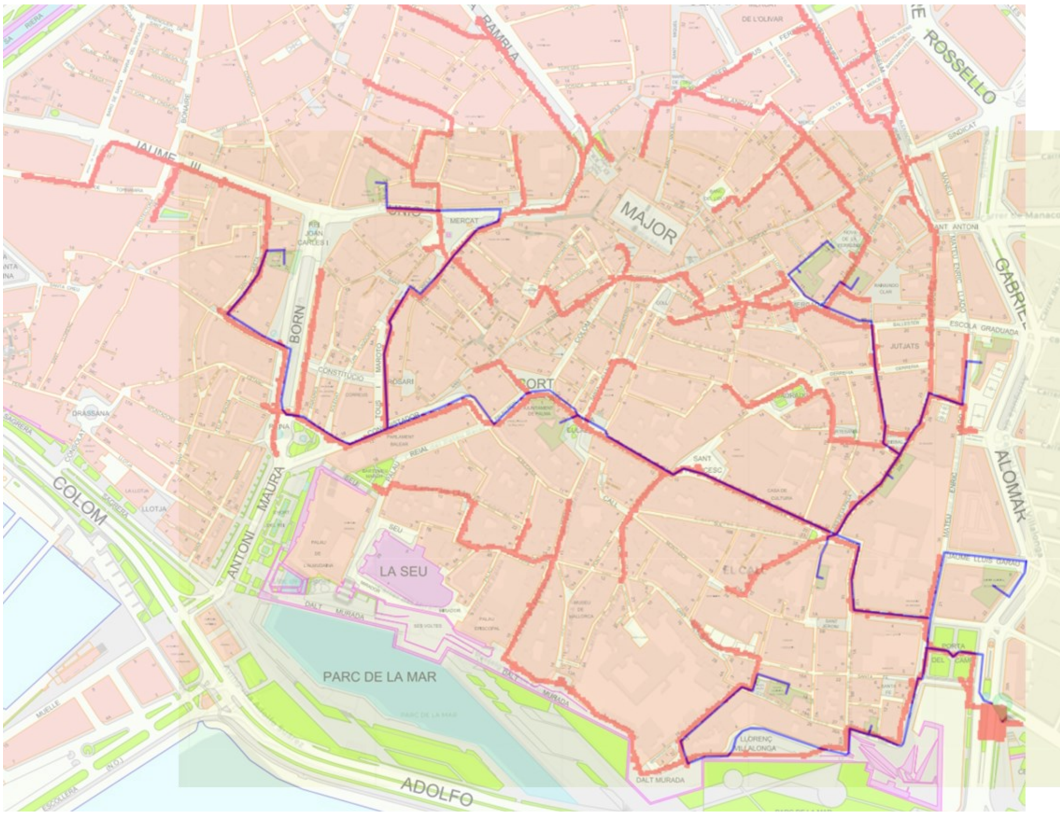
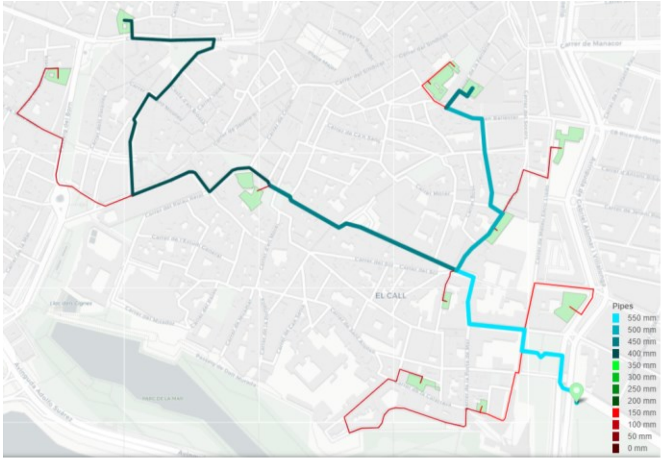
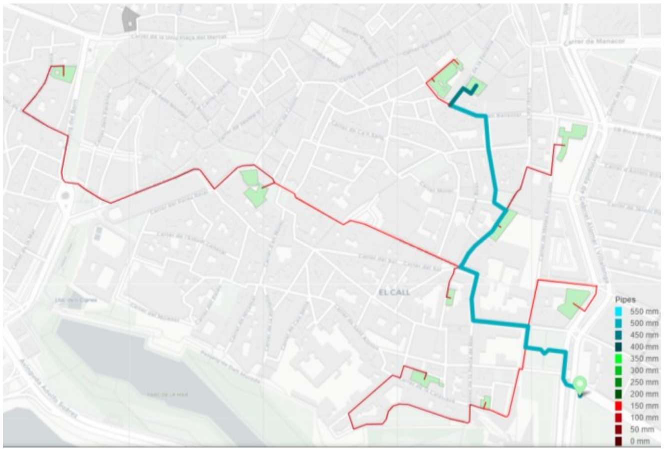


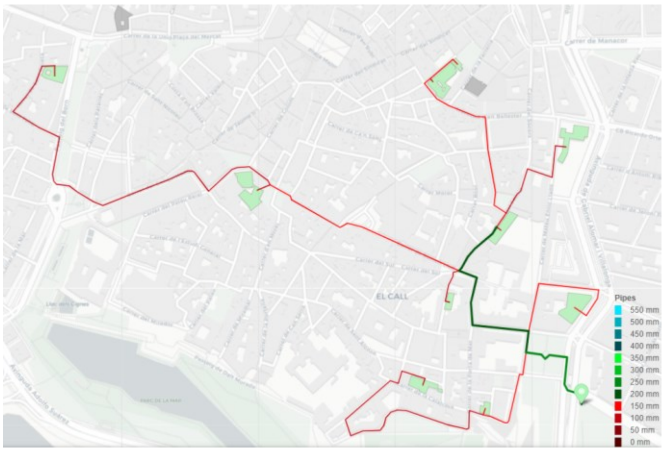
Figure 38 - Superposition of the pictures of the pneumatic network and the obtained route for DHCN of Palma



Scenario including all the buildings



Scenario including one building (grey)



Scenario including all the streets without two buildings (grey)

Figure 39 - Calculated DHCN routes including different set of buildings

5.5 KPIs calculation and analysis

In this section, the KPIs of the selected network have been calculated using the pre-design tool and summarized in Table 12. The data associated to the buildings not included in the network calculation have been subtracted from the Baseline in order to show comparable figures. As shown, the reduction in the Primary Energy and CO_2 Emissions is in the range of 20%, mainly due to the use of a fuel with lower emissions for heating generation as the HP is. However, the same fact has a reduced impact in the energy cost due to the similar price associated to electricity in comparison to gas.

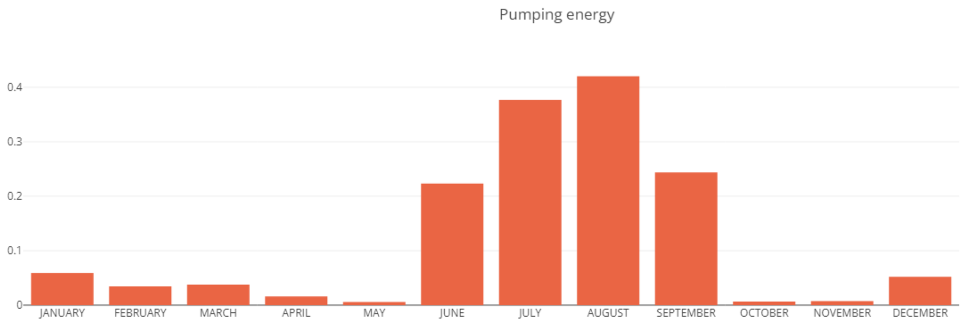
Table 12 - Comparison of KPIs between Baseline and DHCN

KPI	Baseline total	Buildings removed	Baseline to compare	Penumatic_Net_3 5G_Net_AC	Difference
Total demand (MWh)	3551	1963	1588	1588	0%
Primary energy (MWh)	3655	1606	2049	1701	-17%
CO2 emissions (kgCO2)	692144	302184	389960	302110	-23%
Energy cost (kEuro)	221	100	122	127	+4%

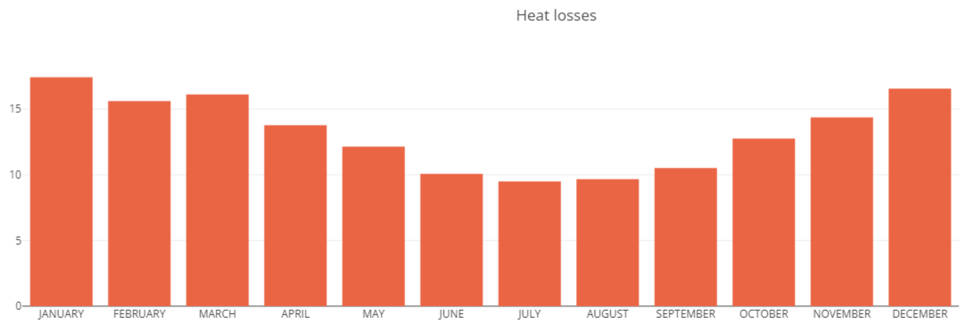
The rest of the calculated KPIs associated to the operation of the DHCN are shown in Table 13. Additionally, the Pumping Energy and the Heat Losses of the DHCN are depicted in Figure 40. It must the noted that those indicators are not included in the calculation of the total primary energy, CO_2 emissions and costs generated by the network, but that energy must be provided usually through the use of additional electricity in the case of pumping energy or through and additional heating demand for the balancing node in the case of the heat losses. The highest pumping energy occurs during the summer season when the highest energy demand in the buildings is required, reaching a maximum value of around 420 kWh during August and a minimum of around 5 kWh during May and October. Pumping Energy in this case is negligible since it represents 0,09% of the annual energy demand of the DHCN. Heat Losses vary along the year together with the estimation of the ground temperature, finding a minimum value of around 9,5 MWh during June to September, and a maximum value of around 17 MWh during January and December. The Heat Losses represents the 10% of annual energy demand of the DHCN, that could be reduced through the optimization of the kind and amount of thermal insulation of the pipes and the depth to which they are buried although considering that the installation costs could increase.

Table 13 - KPIs associated to DHCN

KPI	Penumatic_Net_3 5G_Net_AC
Operational and maintenance cost (€/year)	134291
Capital expenditure (€/year)	95101
Levelized cost of energy (€/MWh)	88
Pumping energy (MWh)	1.48
Heat losses (MWh)	158.57



Pumping energy of the DHCN in MWh



Heat losses of the DHCN

Figure 40 - Pumping Energy and Heat Losses of the DHCN in MWh

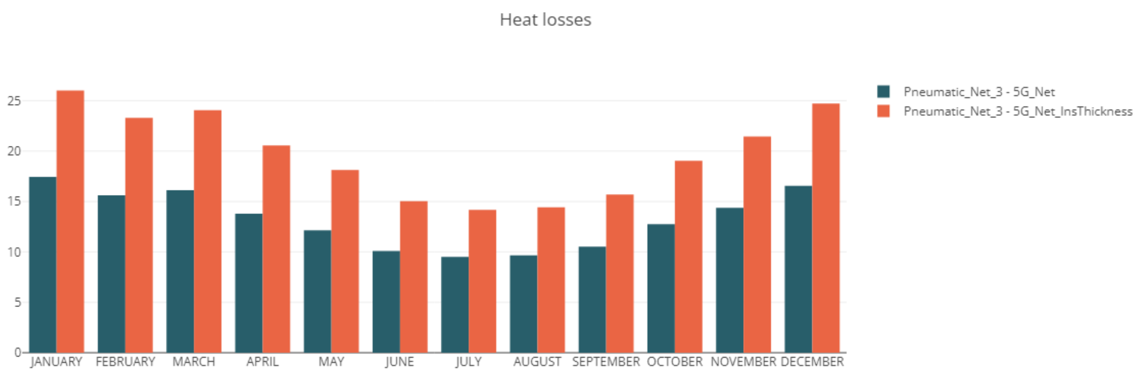


Figure 41 - Comparison of Heat Losses with 10 cm (orange) and 5cm (blue) of insulation thickness

A test in order to try to optimize the insulation thickness of the pipes has been done. The system was calculated reducing the insulation thickness to 5 centimeters, instead the initial 10 centimeters. As expected, the CAPEX of the installation is reduced in around 7% due to the decrease in the cost associated to the pipe installation and the LCOE is reduced in around 3% to a value of 85.24 €/MWh. However, the total heat losses increase in almost 50%, representing an additional load to be covered by the system (Figure 41). In conclusion, the reduction in the insulation thickness is considered to be best option in terms of economic indicators, with low impact in the environmental aspect.

After the last process, the inclusion of a geothermal producer is studied. For that, a new scenario including a geothermal point located next to the balancing node is generated as shown in Figure 42. After that, the Option is generated including the default values for the geothermal parameters and an insulation thickness of the network pipes of 10 cm. The results after including the geothermal producer show that it does not have any effect in the reduction of the primary energy or emissions nor in the economic KPIs (Table 14), possibly due to the fact the power generation is low compared to the total demand of the buildings.

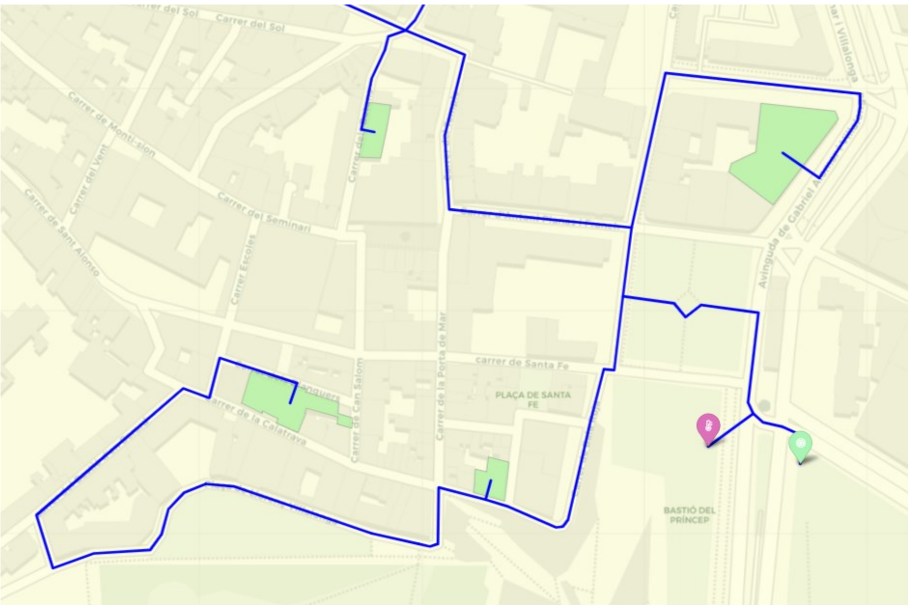


Figure 42 - Scenario including geothermal producer in DHCN of Palma

Table 14 - KPIs comparison after including a geothermal producer

KPI	Penumatic_Net_3 5G_Net_AC	Penumatic_Net_4 5G_Net_AC	Difference
Total demand (MWh)	1588	1588	0%
Primary energy (MWh)	1701	1677	-1.4%
CO2 emissions (kgCO2)	302110	297832	-1.4%
Energy cost (kEuro)	127	125	-1.6%
OPEX (€/year)	134291	135190	+0.6%
CAPEX (€/year)	95101	96029	+0.9%
LCOE (€/MWh)	88	89	+1.1%

As an alternative, a reduced network with lower CAPEX is proposed as well. In order to do that, only the closest buildings that provide a calculated pipe diameter equal to 250 mm or less are included. In Figure 43, both the route and the calculated diameter is shown. In this case, the balancing node is made of an AC-Heat Pump for heating and a AC-Chiller for cooling and the insulation thickness of the pipes is 5 cm. The corresponding KPIs are calculated and included in Table 15 and Table 16, showing higher reductions in the environmental indicators than the initially proposed network.

Similarly, the highest pumping energy occurs during the summer season when the highest energy demand in the buildings is required, reaching a maximum value of around 300 kWh during August and a minimum of around 5 kWh during May and October. Pumping Energy in this case is also negligible since it represents 0,06% of the annual energy demand of the DHCN. Regarding Heat Losses a minimum value of around 9,5 MWh during June to September, and a maximum value of around 17 MWh during January and December. The Heat Losses represents the 10% of annual energy demand of the DHCN.

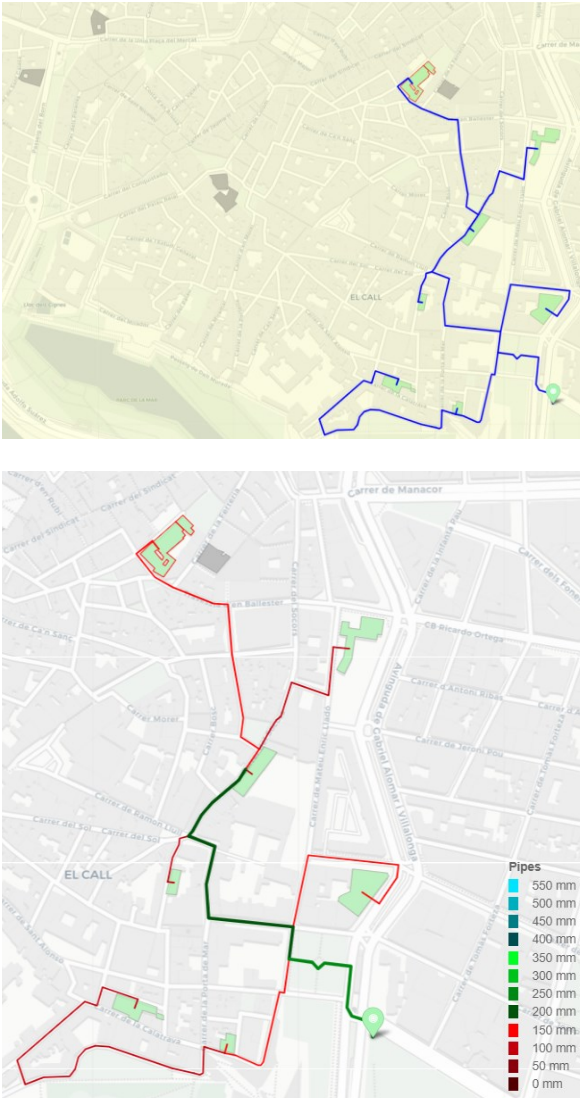


Figure 43 - Alternative reduced CAPEX DHCN route

Table 15 - Comparison of KPIs between Baseline and reduced CAPEX DHCN

KPI	Baseline total	Buildings removed	Baseline to compare	Pneumatic_Net_ CAPEX 5G_Net_AC_Thic kness	Differe nce
Total demand (MWh)	3551	2509	1042	1042	0%
Primary energy (MWh)	3655	1876	1779	1369	-23%
CO2 emissions (kgCO2)	692144	350056	342088	243214	-29%
Energy cost (kEuro)	221	120	101	102	+1%

Table 16 - KPIs associated to reduced CAPEX DHCN

KPI	Penumatic_Net_3 5G_Net_AC
Operational and maintenance cost (€/year)	108533
Capital expenditure (€/year)	58501
Levelized cost of energy (€/MWh)	77
Pumping energy (MWh)	1.0
Heat losses (MWh)	160

6 Conclusions and next steps

The development of the REWARDHeat predesign tool has been continued starting from the alpha version (see REWARDHeat D2.4 [8]) which implemented some of the expected features collected during the first year of the project. However, not all those features have been integrated within the tool due to technical and deadline restrictions of REWARDHeat project, representing a deck of developments to be explored in the future.

A complete definition of the tool capabilities included in the last version and their integration with a dedicated design of interface has been presented in this report, enabling a proper interaction with the user and the operative execution of the tool workflows.

The validation of the tool has been carried out in parallel to the deployment of each feature to assure the functionalities.

Besides, the predesign tool has been used to assess the refurbishment of an old pneumatic waste recovering system in order to convert it in a low temperature district heating and cooling network. The procedure followed during the assessment has represented a valuable mechanism to identify and solve bugs present in the tool, and improve some parts of it.

Some of the available possibilities of the tool have been proven, letting the designer proceeding with different types of calculations to get the best possible configuration in terms of both energy efficiency and economics and representing a great tool in the identification of profitable use cases in terms of money and emissions reduction.

It is planned to continue developing new functionalities or improve existing ones through own funds or the possible inclusion of the tool in new research projects.

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