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&

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Student: Oleksandr Husiev

Supervisor: Dr Álvaro Campos Celador, Dr Jon Terés Zubiaga

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Abstract

The necessity to reduce greenhouse gas (GHG) emissions is a world global challenge that is reflected in numerous international, agreements, national and local regulations. Buildings stand out as one of the sectors that require a significant amount of energy, hence building efficiency optimization and incorporation of renewable energy sources (RES) is a constant tendency aimed at leading to the creation of concepts, such as nearly Zero Emission Buildings (nZEB).

In this respect, the potential for reducing energy consumption in the building stock evolving towards districts scale, which can play a significant role in the energy transition of the stock, as its tackle larger scale of projects. To this end, along with passive energy efficiency measures (EEM) district heating (DH) is one of the options for the reduction of energy consumption and emissions from heat production.

The thesis concerns optimization of the district heating network under the cost-effectivity analysis of centralized energy supply systems (ESS) in conjunction with passive EEM, and RES for the Otxarkoaga neighbourhood in Bilbao. For this purpose, based on a simplified model (131 buildings) of the neighbourhood created in the Design Builder program the set of ESS scenarios for the DH network has been designed, described, and simulated. Following that, simulation output has been analysed by energy demand and ESS consumption within a set of applied EEM at the district level. In total 60 combinations have been considered. Also, the DH network topology was proposed, and distribution heat losses were characterized. Finally, the economic study of considered ESS technologies of DH network analyzed under the cost-effectiveness perspective and comparative characteristics of the district to individual building renovation is carried out.

The study showed that centralised heating could be cost-effective for a considered neighbourhood within some technologies. The biomass boiler ESS can have renovation combination with the lowest investment in 10,000 € per building, and geothermal solution, being highly investment, can reach the lowest energy consumption.

Keywords: district heating, cost-effectivity, energy demand, design builder

Oleksandr

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1 Introduction

At the 21st Conference of Parties summit in Paris, held in December 2015, a next step historic agreement was signed regarding climate changes. It was aimed to cut the carbon emissions and to limit the rising global temperatures to “well below 2º C”, aiming for 1.5º C by 2100 [1]. The electricity and heat production sector in European Union leads to about 35 % of CO_2 emissions [2] while building sector heating and cooling in the EU estimated as half of the energy consumption [3]. The EU pursues a consistent policy toward a reduction of GHG emissions by 80–95% before the year 2050 [3]. The heating sector takes a decisive role in such actions. Furthermore, the resolution on European Green Deal places energy efficiency and renewable energies in a prominent place among solutions towards net-zero greenhouse gas emissions objective and outlines the role of district heating in providing affordable energy [4].

The improvements of the demand side, by retrofitting the building stock, being continuously discussed, and already widely implemented. At the same time, it is agreed that energy efficiency improvement is also required on both the supply and demand side, together with the inclusion of renewable energy sources (RES). The Energy Efficiency Directive (EED) followed by the development of National Energy Efficiency Action Plans established a set of actions directed to demand reduction for heating and cooling, building renovation strategies, better framework for investment [1]. Among all, it motivates the Member States to carry out a comprehensive assessment of district heating potential.

Following that, within a discussion about the transition of the building stock, a positive energy district (PED) and positive energy neighbourhoods (PENs) conceptions were introduced as strategic keys for decarbonizing the built environment in Europe [5]. The general idea of concepts is a proceeding with a functional unit on the larger scheme, such as a district that produces more energy from RES than what is needed to fulfil its demand and to be able to export energy surplus to other demand sides. Also, the “Clean Energy for all Europeans package” [6] introduces a concept of energy communities which has one of the goals to provide the local community with environmental, economic and social benefits and among all involves by power production, distribution, and use. At this point approach of heat, production centralization allows using different energy sources, including excess heat from the industry together with combination of RES for the urban communities.

Within EU district heating some of the Nordic countries actively use the benefits of centralized heating systems aimed to decarbonise large shares of heat supply. In Denmark, for example, district heating meets about one-third of total residential energy consumptions and one-third of heat produced from burning fossil fuels, while Sweden reached an even 10% level for heat produced from fossil fuels [7].

Even though the potential benefits, retrofitting measures applied to buildings deal with reduced heating demand. As DH systems have higher efficiency at higher load densities, and energy efficiency measures could influence the heat density due to such improvements [8]. Being a positive trend for the energy system as a whole, it can conflict or have negative impacts on the operation models feasibility of district heating scale systems. In this sense, Rismanchi [9] argued that even if the demand is reduced, District Heating and Cooling will not lose competitiveness if the population density is high.

In this way, the main objective is to analyse the interaction between passive energy efficiency measures and energy supply systems on a district level. It implies, firstly, investigating a methodology that could be applied to centralized ESS analysis within the urban district.

Secondly, to review various technology options and characteristics of district heating networks within a considered case study. In addition, to study how challenges specifically occurring with a chosen tools during modelling of energy supply systems on the district level can be overcome.

Finally, to provide an economic analysis of centralized ESS in conjunction with applied passive measures to identify and characterize cost-efficient scenarios for the district-scale ESS as an alternative to correspondent technologies on individual building scale.

This thesis work organised as follows. Chapter 2 a literature review on district heating generations, and looks at principles considered for sizing, schematic design of some components and parameters for district energy systems. Chapter 3 dedicated to the description of applied methodology within an investigated case study of a neighbourhood located in Bilbao city (Basque Country, Spain), its “digital twin” model. It includes conceptual ideas description applied to the design of ESS technologies, its virtual installations, elements, schemes, and HVAC templates within Design Builder software program interface, and

EnergyPlus simulation engine. In Chapter 5 the simulation output is going to be analysed based on an economic method used to provide a cost-effectivity analysis of investment alternatives in combination with the conception of primary energy consumption. In Chapter 6, the actions at the district level are going to be discussed regarding acting over an individual building level for considered a case study.

2 Literature Review

The term district heating applied to the systems utilized with a principle of the centralized thermal source to provide distribution and delivery of heat services to different customers over an area through the designed and planned distribution system [10]. Generally, a district heating system involves three main components: the heating plant, the transmission and distribution network, and the consumer systems [7].

The system should ensure a wide variety of characteristics and parameters within the design, planning, installation, technologies, distribution of heat, and a heat load density within economic limits of transmission over the area in relation to first cost investment [11].

2.1 District Heating Tecnologies

District heating system can be fed by various heat generation technologies. The type of technologies mainly characterized by energy source utilized to derive required heat energy in form of heat. According to Eurostat electricity and heat statistics, about 75% of heating and cooling is still generated from fossil fuels, whereby derived heat production the highest share produced from natural gas and manufactured gases 37.7 %, solid fossil fuels 23.2 %, while about 28.1% got from renewable energy sources [12]. The central plant (district heating station) may be any type of boiler, heat pump (HP), co-generation, and renewable source technology, taking into account regional specifics. Among DH installations, the predominant role across the majority of EU Member States include fossil-thermal power plants and combined heat and power (CHP) plants [13]. Some studies report that large-scale electric heat pumps already become increasingly important within the EU [14].

2.2 District Heating Networks

Generally, the evolution of district heating systems considered within five generations of networks. The first-generation district heating and cooling (1GDHC) is a steam-based transport system mostly fueled by coal [15]. The second-generation (2GDHC) key difference is a transition from steam to hot water as an energy carrier, however, the supply temperatures mostly maintained higher than 100℃ [16].

The third generation (3GDHC) has the same principle of pressurized water flow with water as heat exchange fluid, but temperatures are usually below 100°C [16]. Sorknæs et al. [17] highlight that temperature levels exceeding 80°C in 3GDHC cause grid losses typically more than 20% [17]. Comparing to the 2nd generation, the 3GDHC has evolved to implementation of pre-manufactured, pre-insulated pipes which are directly buried into the ground, can have a compact substation and use plate stainless steel heat exchangers, and material lean components [18].

The emerging of 4th generation (4GDH) directed to the favour of lower distribution temperatures for space heating and hot water preparation, ensure suitable planning, costs and application of more flexible materials [19]. This generation desired to substitute fossil fuels by integrating RES and various low-temperature heat sources, reduce grid losses, facilitate the integration of grid components into a smart energy system [20]. The most important feature for the 4th generation network is supply temperature level, typically considered below 55-60°C [18].

There are some steps in defining a 5th generation network. Hence, in 2019, Buffa et al. described in [21] the general idea of 5GDHC including a combination of bi-directional and decentralized energy flow capacity that provides new opportunities in comparing to 4GDHC. Also, the authors highlight the utilization of supply water to decentralized Water-Source Heat Pumps (WSHP) at a temperature in the range between -5 ºC to 35 ºC and being capable of working in heating or cooling mode independently of network temperature.

2.3 Methodologies for District Heating Assessment

There are numerous approaches based on versatile methodologies and tools that differ from one to another, as well as the input data applied within each approach. Different case studies that analyze potential energy rehabilitation measures, the feasibility of installing various heat production technologies, renewable energy sources and District Heating and Cooling systems.

The automated modelling of buildings in urban districts is presented by Negeler et al [22] propose a validated methodology for fully automated building modelling within urban districts based on publicly available data. The authors described an approach within

5 key steps such as data acquisition, categorisation, modelling with a JavaScript, dynamic simulation performed in IDA and ICE, and visualisation in the QGIS tool.

One of the latest publication [23] described a district heating networks automatic modelling by existing software CityGML with a description of an algorithm for pipe routing optimization and an empirical logarithmic function for optimized pipe sizing. The authors highlight that with validation for the workflow on the considered case study they have defined, that there is an opportunity to size the inner pipe diameters for an existing district heating network with a deviation of less than 7% from its actual values and with applying of optimization and manual changes in inaccuracies in pipe routing the total pipe length deviated by 8%.

In [24] authors introduced CityBES (City Building Energy Saver) developed as a tool to perform an analysis of pre-selected energy conservation measures in series of buildings in San Francisco. The interesting consumption aimed to support city-scale building energy efficiency analysis by combining urban building energy models (UBEM) on a web-based platform that allows users to quickly set up and run such a model. The GIS data sources used to create a city-building dataset, and the EnergyPlus simulation engine introduced to help with the evaluation of complex energy conservation measures that have an integrated effect on multiple building systems, such as HVAC-related issues, and physics-based dynamic thermal simulation in general.

2.4 District Heating Parameters

Optimization of a District Heating and Cooling (DHC) systems apart of energy station scheme design optimization and energy station location, are mainly related to distribution networks topology, pipe diameter, power system, pipeline insulation thickness, supply and return water temperatures, operation strategy of heat pump units [25].

2.4.1 Pressure regime and mass flow rate

The optimum pressure drop per unit of length (PDPUL) value is a widely discussed topic within numerous publications. Jie et al. [26] highlight three main methods considered for the selection of PDPUL. Firstly, a parameter of PDPUL can be selected on the basics of empirical data, as the theoretical basis of the Darcy-Weisbach equation to model the viscous pressure drop [27]. The numerous PDPUL were considered in various countries and studies. The recommended PDPUL values according to publications regarding the

China design code is 30-70 Pa/m [28]. IEA in its earliest work considered a constant pressure gradient as 150 Pa/m [29].

Secondly, the comparison method often used to select the PDPUL. Pirouti et al. in work [30] pointed that DH networks in Denmark and other European countries quite often have been designed using PDPUL of 100 Pa/m. [27] assumed maximum PDPUL value as 200 Pa/m. Valdimarsson in his study [31], and Yildirim describing a case study [32] of University campus piping network design, mentioned that DH system practice design to PDPUL is in the range of 50–200 Pa/m. Thirdly, the differential methods approach for the selection of PDPUL is described in numerous publications [25, [32–34].

As it can be seen it is important to agree on an optimum PDPUL for a DH piping network. Accepted values of heating load, supply temperature and return temperature allow to determine a mass flow rate. Higher pressure drops result on higher velocity, it means that pipes with smaller diameter could be used to provide the same amount of mass flow when the higher-pressure drop is selected [26]. This scenario leads to a decrease in pipe investment cost and heat loss, while the minimum annual cost (MAC) of a DH piping network can be obtained by selecting the optimum PDPUL [26]**,** however, the pumping costs increase. At the same time, there is a limit for maximum velocity which implies a limit on pipework of velocity before erosion starts to become an issue. Standard BS 6700 recommends that flow velocities should not exceed 3 m/s, while some case studies take this parameter between 0.5 m/s to 2 m/s with a maximum of 3.5 m/s in exceptional circumstances [35].

Conversely, the lower PDPUL leads to an increase in pipe diameters due to the reduction of flow velocity. It results in a decrease in pumping cost, while the pipe investment cost and heat loss cost increases. It can be seen that there must be an optimum PDPUL for a DH piping network.

2.4.2 Pipe sizing and materials

With the development of the third generation of heat distribution, pre-insulated bonded pipes became a widely used solution. It does not introduce significant changes in design except for the thermal barrier covered by the casing pipe around the fluid-carrying pipe. The pipe component materials have been changing over the years. Tendency to chlorofluorocarbons (CFC) phase-out in the 1980s and 1990s has driven the development of polyurethane (PUR) foam. It also was triggered by the intention to reduce carbon footprint and life cycle costs by optimizing thermal performance in the long-term perspective. The high-density polyethene (HDPE) raw material serves for pipe and insulation as a ‘sealing’ high-density polyethene outer casing that forms a protective barrier to external conditions and significantly enhances long-term durability.

There are many different manufacturers on the market that provide sets of pipework types and various materials being investigated by the industry manufacturers, however, completely feasible options remain under continuous development. The pre-insulated steel pipes is a major type on which large DH systems are based [31]. At the same time, manufacturers mention that larger DH schemes often use a hybrid of steel and polymer pre-insulated pipe systems with steel systems forming the main pathways of the distribution network while smaller connections made with flexible plastic systems [36].

2.4.3 Ground conditions and pipework burial

The minimum depth of the trench shall be determined in such a way that the pipes are protected from the effects of traffic and external loads, as well as to preserve them from variations in the temperature of the environment. Thus, the location of the pipe must be considered (road, pedestrian, green zone area), the type of filling, the paving, if any, the shape, and quality of the bed of support, the nature of the lands, etc. In general, under the carriageways or in possible road traffic terrain, the minimum depth will be such that the upper generatrix of the pipe is at least 0.8 m from the surface; sidewalks or places without road traffic, this covering can be reduced to 0.6 m [37].

The daily and seasonal variations of the soil temperature, with respect to the precipitant type that exists on it, are quickly dampened with the depth in which the edaphic environment acts as a buffer against the atmospheric variability of the place [38]. Soil temperature is delegated to both seasonal and diurnal changes, being more insignificant towards the deeper horizons, this dynamically shapes the thermal profile of the soil.

Hence, the soil temperature is closely related to the surface air temperature which is together with solar radiation are the main meteorological parameters for periodic variation in the thermal regime of the soil [39]. However their correlation may be affected by different factors, mainly according to [40] for upper layers (less than 80 cm) the effects of the air temperature may be blocked by the snow cover, and it will result in a decrease in synchronous dependence between the air temperature and soil temperature. The climate profile of Bilbao typically does not have precipitation in form of snow that would remain on the ground for some period.

3 Methodology

In line with the previously mentioned objectives, a case study is selected. Once the case study is selected, the first step conducted within a methodology is its characterization of the case study. It includes a description of the topography of the neighbourhood, buildings, and the composition of the enclosures as input data.

Following that, to specify the possible conceptual topology of the district network. In this context, a described topology scheme for this case study was briefly mentioned in the work [41]. However, at that study, it was introduced to demonstrate the possibility to include several district network alternatives within optimization methodology for drafting integral renovation actions at the district level is presented.

Once the neighbourhood has been characterized, the next is to consider a district model with a description of its input parameters and simplifications. The considered model was validated with in situ measurements and has been used in other publications and oral communications [42]. In addition, a set of passive measures applied on the district level was detailed. Finally, the set of energy supply systems were designed within a detailed HVAC component of Design builder software.

Once the systems are designed, the simulation *.idf files for the EnergyPlus engine created. These file type among all contains a structured parameter for all the envelopes as variables already in machine reading format, so it can be parsed and processed by a script to automatize a process. For that reason, such script was realised on Python language with Geomeppy library that imports a necessary functionality for geometric modifications in the buildings, and Eppy library for manipulation and generation of entry files EnergyPlus. In this part, this technical task is out of the scope and has been taken from an already existed solution.

To specify a piece of information that must be retrieved from series of simulation outputs a working matrix was created. It held data of the different passive scenarios and iterated through the values to insert them as a variable in dependence to the considered scenario. The outputs obtained from the simulations are the DHW and heating demand, designed capacity of installations, final consumption for each fuel type per month of the year and each passive scenario.

3.1 Case Study

The case study is located in the North-West of Spain, in Basque Country. It is the Otxarkoaga neighbourhood placed in the eastern part of Bilbao city. The terrain is a steeply sloping hillside (Figure 1). The Köppen classification map refers climate of Bilbao to Cfb class, which is temperate oceanic climate [43]. It can be described as a climate with relatively moderate summer and winter temperatures as a reflection of the ocean adjacent. In summer seasons the average maximum temperature is between 25 ºC and 26 ºC, while the average minimum in winter is between 6ºC and 7ºC.

Figure 1. Otxarkoaga neighbourhood 3D view

To begin with, the morphological study of buildings points out four different main construction shapes initially described in work [41] and shown in Figure 2. Among all, six of the buildings are classified as square towers (B), seventy-eight buildings are rectangular shape (A), four buildings are comb or E-shaped (E) and fifteen are H-shaped (H). Buildings with different shapes (N) are non-residential buildings, and since the scope of work was directed to residential buildings with remarkably same parameters, these non-residential buildings were excluded from evaluation.

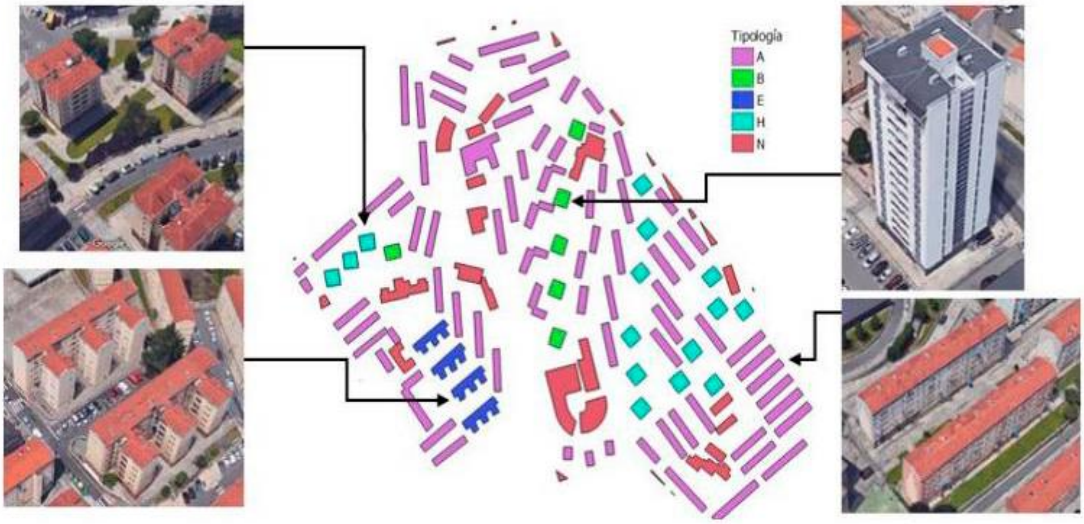

Figure 2. Typology of the buildings in Otxarkoaga [41]

Most of the buildings in the neighbourhood have a North-West/South-East (NW/SE) and North-East/South-West (NE/SW) layout. Still, there are buildings with more unfavourable orientations such as East-West (E/W) or North/South (N/S). The buildings that are considered to have no predominant orientation are marked with a T, which are the buildings with morphologies B and H.

As can be seen, a significant portion of all building stock is a rectangular type A building. Most of them were built in 1961 and they have many similar constructive characteristics. This building type was already described in details by the research group of authors [42] and will be referred to in the next subsection for a description of the district model. At this point, the initial characteristics of the U-values of the enclosure element can be presented as follows: façade 0.74 W/m^{2}K, roof 2.7 W/m^{2}K, ceiling 2.27 W/m^{2}K. The window glass and frame have 3.44 W/m^{2}K and 5.7 W/m^{2}K respectively. In general, all the abovementioned values are out of the values mentioned in the Building Code of Spain [44], where, for example, the facade is specified as 0.49 and the roof 0.4 W/m^{2}K.

3.1.1 Topology of district heating network

Considering the case study on the district level there are three basic topologies, such as radian, ring and meshed, that could be applied for centralized heating and DHW network. The problem of topology optimization is a specific comprehensive optimization problem. In this way, for further assumptions, simplified ring topology for the DH and DHW distribution network has been considered as a possible scenario. Among alternatives, the proposed topology intended to be a balanced type from the point of investment costs, security of supply, integration of multiple heat sources, and extensibility [45]. It serves as a background element for the assumption and choice justification of a set of parameters that are going to be inserted into the further model or analysis.

Particularly, proposed here district heating topology is one big external ring around the district which is divided into "sub-rings" by internal connections (Figure 3). Also, the length of the pipeline system within the loop was additionally contributed by the introduction of interphase connections of a building which are green colour branches from the main red colour distribution pipeline.

The topology and its location on the scheme of the district have been traced as a set of line and polygons geometry types in QGIS - open-source Open Street Map (OSM) based software. The length of pipe for topology was calculated by the QGIS tool for polygon calculation.

Figure 3. District heating network proposal main loop (red) with building interphase connections (green)

The length of the main ring (in red) and building connections (in green) has been considered together with the aim to include a possible extra length of the network that may be required within different options for tracing, installation and civil works within a real-life scenario. The total length of pipes was approached as 9,412 meters.

3.2 Model Definition and Validation

The optimal model of DH system topology is quite complex subject to a set of different challenges. Looking for decisions for optimal design and management solutions, the application of multiple professional software tools for the computation has been applied [46]. Among all, they oriented on mass flows and pressures, energy propagation, economic and environmental aspects and often provide an extreme level of precision to a real-life scenario. However, it makes the modelling process a separate specific comprehensive, expensive, and time-consuming process.

Because of the dynamic operation of the network, transition within its hydraulic and thermal flow regimes, various conversion and storage technologies, it can be easier and convenient and perform some simplifications. In some works, the contribution of the network dynamics is neglected [47]. It is crucial to keep a reasonable level of such simplifications depending on the scope and aim of the work. In this way, in the already mentioned publication [41] authors introduce the concept of District Equivalent Building as a virtual building with a set of energy loads equal to the addition of all the individual load vectors of each building within that district.

Modelling of district heating network within the scope of case study is a critical challenge because of the necessity to balance between express, a simplified solution with acceptable simulation time, and a validated model which correlates with a real-life scenario. Besides, the general scope was closely related to the tools of Design Builder software as the main software applied for detailed analysis of building performance. Design Builder is a software product based on the EnergyPlus simulation engine and oriented to building energy, carbon, lighting, and comfort performance calculations. It allows rapidly compare the function and performance of building designs.

The initial data is an Otxarkoaga neighbourhood model with 131 buildings created in a Design Builder with a digital representation of its 3D model and set simplified parameters for building level simplifications to reduce the simulation initially described by Ms Leire Urien Berrostegieta within a framework of project Annex 75 [48]. For that, a Design Builder model of one of the Otxarkoaga buildings is used as a starting point. As it was spotted before, the given model was validated with the model described in [21].

Within the scope of the district model, certain simplifications have been introduced, to reduce the simulation time. The considered simplifications are grouped into those performed at the building level and those performed at the district level.

3.2.1 Building level simplifications

One of the main conceptual simplifications at the building level includes an approach for each building as an empty block element of Design Builder without partitions or interior floors. To put it more simply, the interior of the building would behave for the program as a single large area. The other parameters, such as orientation, composition of the enclosures, area of the openings, interior volume, etc., are kept the same as the reference to be able to identify the variation in consumption produced by this simplification. It was compared that it has a minimum impact, that is reduction of annual demand on 2,82 % to the annual demand of the validated model.

Following that, a virtual internal thermal mass is proposed with the aim to reduce the effect of a building considered as an empty block. Thus, the effect of floors that have not been introduced in the previous simplification is reproduced, by implying of Design Builder option in the *"internal thermal mass"* box.

It was decided not to implement the option of zoning of a building with a large interior as it also moves the final consumption away from the consumption of the reference building. Thus, as it was desired to simulate the zones in the original building, but without modelling them in their entirety, the effect of the zoning is negligible.

A general approach for windows maintained it the way that, the sum of the window area in each case should be equal to the sum of the area of the original. Initially, it was considered to replace the windows with a single large window which area was the sum of all the windows of the original building. However, one of the parameters that most influence the heat flow through the windows is the glass-to-frame ratio, so for a reliable simulation, it would be convenient to keep this ratio. Due to some of the program limitations, it was not possible to maintain that ratio with a unique big window. For this purpose, the option of modelling the windows in an elongated form was chosen. It is simple to approach compared to the original building and it is possible to maintain the glass-to-frame ratio. This option is not contingently comparing to reference building, as a proportion of the setback and dividers are not maintained. Due to its complexity and 3% impact on the annual final consumption, it was neglected.

3.2.2 District level simplifications

At first, it is important to mention that the composition of the envelopes, the wall-to-window ratio and the area of each dwelling will be considered the same for all buildings in the neighbourhood.

The principal district-level simplification is one of how buildings were defined in Design Builder. Initially, they were modelled as “Building” type but in this way, the simulation time was not reasonable. Therefore, the buildings were modelled as "blocks" inside a big “building” (the whole neighbourhood). Such a decision considerably reduced the simulation time and facilitated data processing. Another considerable simplification of the model is that it does not tackle the height variation of the site (wind speed profile exponent, air temperature gradient, etc.). Another simplification that also must be spotted is that it does not take into account the height variation of the site (wind speed profile exponent, air temperature gradient, etc.).

3.2.3 District model

The district model has a set of parameters that were initially described within project Annex 75 [48]. The applied climate parameters are from the Design Builder programme catalogue and where a default file initially specified for Bilbao city. The detailed composition of the envelopes considered for all the buildings was mentioned in work [42], which originally was provided to the authors by Bilbao Social Housing. Thus, the exterior walls of the dwellings are composed of two layers of hollow bricks separated by an air space, and the interior surfaces of the walls consist of plaster over plaster. The wall-to-window ratio is maintained in all buildings with a value of 23.23 %. More detailed composition of enclosures presented in Appendix A.

As discussed before, Otxarkoaga includes buildings that are quite similar to each other. As it was mentioned before, there are 4 main types of buildings, some of them have a different height or base area, in total 25 base buildings. The rest of the buildings are the same as these base buildings and have been created by copying. The neighbourhood model is depicted in Figure 4.

The building structure is made of reinforced concrete, and horizontal structures consist of hollow tile floors. The U-values for these enclosures are set as calculated by Design Builder.

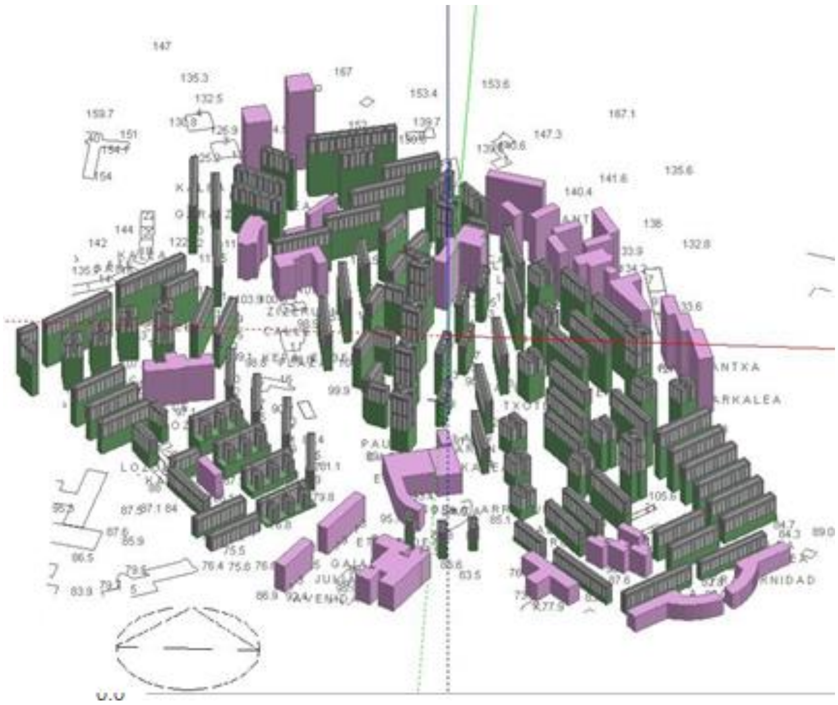

Figure 4. 3D preview of district model in Design Builder

There are single- and double-glazed types of windows considered within the buildings. Both types have aluminium frames without thermal break. The transmittance values of the windows components are shown in Table 1.

Table 1. Composition of the windows

Window composition	**U value (W/m^{2}K)**
Frame (30 %)	5,7
Glass	3,44

The height of the interior of each flat in Otxarkoaga is slightly lower than usual, with 2.47 m high. It is considered with a thickness of the interior floors and ceilings (0.3m) and in total equal 2.7m.

The infiltration value of 0.6 vol/h has been considered in this case, based on literature finding for some of the existing buildings [49]. In addition, manual ventilation parameter set on with a schedule 7 a.m. to 8 a.m., during which the heating is set off. The air renewal during natural ventilation is considered to be 4 vol/h [50].

The setpoint temperatures used in compliance with IDAE [51], such as temperatures 20 ºC set from 8:00 h to 23:00 h and 17 ºC for the rest of hours (except from 7:00 to 8:00 h, when natural ventilation occurs). Also, the data from an already mentioned document from IDAE has been taken for internal loads for lighting, equipment, and occupancy. The occupancy value is set at 0.05 person/m^2 and the sensible occupancy gains are set at 2.15 W/m^2. The DHW consumption defined as 22 l/person per day based on the technical Building Code of Spain guide 2010 edition [52]. From a product of occupancy (person/m^2) and DHW consumption (l/person per day) it was derived a value of 1.1 with the unit (l/m^2 per day) corresponds to the DHW consumption field in the Design builder interface. As the buildings are considered as empty blocks and parameters are per square meter the DHW consumption value must be multiplied per the number of floors. The total area of the building is 2,066.02 m^2. In this way, it is multiplied by 6 floors of the already mentioned building from a case study [42].

For an introduction of steep slope as an area where buildings located and tall buildings shadowing, the effect of the shadows was considered through the introduction of the "terrain component block" program element underneath. It allows characterising a different altitude of buildings. The base heights above which the buildings are located are taken from altitude information from Google Earth.

3.2.4 Distribution pipeline network parameters

The set of assumptions for the model was established based on literature review and simplistic calculations to insert it as a justified parameter for a Design Builder model. This section mainly dedicated to parameters such as pressure drop calculation and thermal transmission value for qualitative thermal losses characteristics of distribution network. Thus, within the study, a heat transfer of fluid flowing through the pipe assumed to be one-dimensional. Following the theoretical equation for specific heat capacity, the heat transfer rate from the system has been considered in equation (1).

$$\dot{Q} = \dot{m} C_p \Delta T \quad (1)$$

Where $\dot{m}$ is the mass flow rate, C_p is the specific heat, and ΔT is the pressure difference

The mass flow rate of a fluid flowing in a pipe or duct was calculated as in equation (2).

$$\dot{m} = V A_c \rho \quad (2)$$

Where ρ is the fluid density, V is the average fluid velocity in the flow direction, and A_c is the cross-sectional area of the pipe.

Hence, the pipe diameter is one of the input contribution parameters for mass flow and heat transfer rate. The calculation performed for a maximum possible velocity limit, which is taken into account following the literature review as 2.9 m^3/sec.

The review on the pressure drop has been considering three main methods considered for the selection of pressure drop: empirical calculations, comparison, and differential approach. In the framework of the assumption as a supplementary to simplified empirical calculation, the comparison approach was also taken into account The Darcy-Weisbach equation is used to calculate the major pressure loss due to friction in pipes. According to the review, the flow conditions of the hot water in DH pipelines could be considered as turbulent flows [28]. Proceeding with the turbulent flow system we also assume a smooth pipe flow and using the Moody chart - non-dimensional graph form that relates the Darcy-Weisbach friction factor *f*, Reynolds number *Re*, and surface roughness **ε** for fully developed flow in a circular pipe, we assign a set of necessary values. The Reynolds number for the flow in a duct or pipe can with the hydraulic diameter expressed in equation (3).

$$Re = \rho \cdot V \cdot \frac{d_h}{\mu} = V \cdot \frac{d_h}{u} \qquad (3)$$

Where d_h - hydraulic diameter (m); V - velocity based on the actual cross section area of the pipe (m/s); u = μ / ρ - kinematic viscosity (m^2/s).

Based on Re the friction factor taken as 0.015. The pressure loss in a pipe, tube, calculated based on the Darcy-Weisbach equation, see equation (4).

$$\Delta p_{major\ loss} = f \cdot \frac{l}{d_h} \cdot \rho_f \cdot \frac{v^2}{2} \qquad (4)$$

Where Δp_{major_loss} - major (friction) pressure loss in fluid flow (Pa (N/m^2)) f - Darcy-Weisbach friction coefficient; l - length of duct or pipe (m); v - velocity of fluid (m/s); d_h - hydraulic diameter (m); ρ_f - density of fluid (kg/m^3). Obtained value 1454471.66 Pa was inserted as the design pump head parameter of a pump.

To consider qualitative characteristics of heat losses for distribution network through heat transfer rate from pipes to ground a generalized conception of UA value, as a multiplication of thermal transmittance (U-value) and area of pipe network (A) is going to be introduced. Thus, thermal conductivity (U-value) of pipes for a pre-insulated pipeline diameter and correspondent insulation value 0.024(W/mK) for U-value taken from one of manufacturing company CPV within its product solution Hiline steel pre-insulated pipe systems [53]. Parameters of pipe applied for calculation presented in

Table 2.

Table 2. Parameters of pipe considered for calculation

Internal diameter (D_1) (mm)	Wall (mm)	External Diameter (D_2) (mm)	Jacket pipe (D_3) (mm)	Insulation (mm)	Insulation Value, (W/mK)	U-value Calculated (W/m^2K)
400	6.3	406.4	560	153.6	0.024	0.2371

Within a calculation of U-value for distinguished pipe, pipeline network considered with a simplification as one insulated pipe using the equation (5). It must be outlined that conductivity through the metal wall of pipe introduced as the second operand in denominator was neglected.

$$U = \frac{1}{\frac{D_3}{D_1 h_{in}} + \frac{D_3 \ln\left(\frac{D_2}{D_1}\right)}{2k_{pipe}} + \frac{D_3 \ln\left(\frac{D_3}{D_2}\right)}{2k_{insulation}} + \frac{1}{h_{GR}}} \quad (5)$$

Where k_{pipe}, $k_{insulation}$ is a thermal conductivity of pipe and insulation. h_{in} is heat transfer coefficient for fluid; h_{GR} is heat transfer coefficient due to the air flowing outside the pipe, D_1 is the internal diameter of the pipe, D_2 – external diameter of the pipe, D_3- diameter of pipe with insulation enclosure.

3.2.5 Distribution losses

The assessment of DH distribution losses is a conceptual aspect within utilized Design Builder software. There was a hypothesis to incorporate distribution losses of buried pipeline network based on available elements of Design Builder within a described case study model.

For that reason, among "Detailed HVAC" components an installation of a water *Water heater Tank* was considered as a buffer installation between heat production components (within ESS scenarios) and consumption components (Zone group and DHW loop). Initially, it was assumed that distribution losses can be interpreted by mass flow through the tank and *Ambient heat transfer* settings can introduce a losses value. The ambient temperature for the tank could be taken as ground temperature. The UA value of the pipeline network described in section 3.2.4 can de be inserted as Heat losses coefficients settings for the water tank. Hence, the key parameters that allow inserting a UA value is a Heat Losses section with a 2 field: *On-cycle loss coefficient* and *Off-cycle loss coefficient (W/K)* (Figure 5).

However, such an approach was rejected. There is a crucial limitation within a program interface such as On-cycle and Off-cycle coefficient must be not higher than 100 W/K. So theoretical implementation of this approach is possible, however, it shrinks implementation only for small-scale systems.

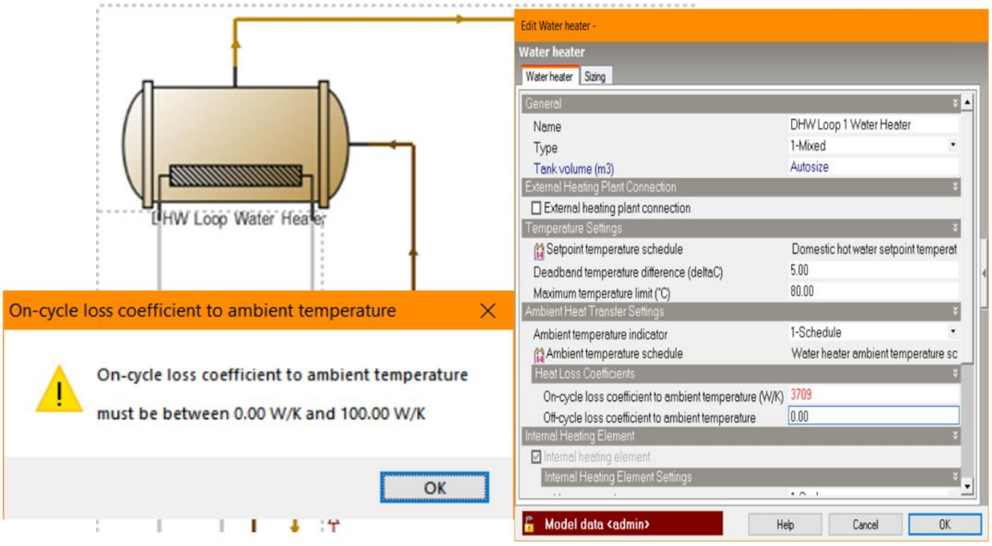

Figure 5.Design Builder interface alert

For that reason, within the scope of work heat losses analysis was shifted rather to a qualitative comparison approach. To perform that, it was decided to introduce a ratio of energy demand to peak power as an equivalent duration (in hours) for a peak load operation, see equation (6).

$$\mathrm{h_{eq}} = \frac{\text{Demand (MWh)}}{\dot{Q}_{peak}} \tag{6}$$

Following that, transmission losses were introduced as a product of overall transfer coefficient U, area of pipeline A, and difference of fluid temperature T_{water} and ground T_{ground}, as presented in equation (7).

$$\dot{Q}_{Trans} = UA(T_{water} - T_{ground}) \tag{7}$$

Finally, as a product of these two values for each scenario heat losses characteristics introduced as am equivalent peak operation heat losses.

3.3 Energy Efficiency Measures

The passive EEM measures were considered for individual building calculation and specified as input data. The passive options were specified for façade, roof, separation from non-habitable spaces and infiltration levels. For each of these elements, 4 options are considered. The first refers to the limitations imposed by the Technical Code of Buildings of Spain [44]. The second refers to the same document, but in this case to the recommendations made in Annex E of this document. The third option is an intermediate between the second and the fourth, the latter being the one used for Passive House Institute certification [54]. The most interesting combinations have been considered for simulation as passive measures scenario by project Annex 75 team and based on logical criteria. Considered scenarios are presented in Figure 6.

Nº	Improvement	Combinations																		
P1	Exterior facade insulation	1	1	1	1	2	2	2	2	2	3	3	3	3	3	3	4	4	4	4
P2	Roof insulation	0	1	1	1	0	2	2	2	2	0	3	3	3	3	3	0	4	4	4
P3	Windows	0	0	0	1	0	0	0	0	2	0	0	0	0	0	3	0	0	0	4
P4	Insulation on non-habitable spaces	0	0	1	1	0	0	1	2	2	0	0	1	2	3	3	0	0	4	4
P5	Infiltrations	-	-	-	-	-	-	-	-	-	-	-	-	-	3	3	-	-	4	4
Considered Scenarios		1.0.0.0.	1.1.0.0.	1.1.0.1	1.1.1.1.	2.0.0.0.	2.2.0.0.	2.2.0.1.	2.2.0.2.	2.2.2.2.	3.0.0.0.	3.3.0.0.	3.3.0.1	3.3.0.2.	3.3.0.3.3.	3.3.3.3.3.	4.0.0.0.	4.4.0.0.	4.4.0.4.4.	4.4.4.4.4.

Figure 6. Considered passive scenarios

Thus, within improvements of enclosure elements, such as wall (Exterior facade insulation), and roof (Roof insulation), each passive scenario includes changing of specified insulation material thickness. In all cases for these elements insulation material considered to be an EPS Expanded Polystyrene with a correspondent standard. The detailed composition of the enclosures with insulation parameters can be found in Appendix B.

3.4 District Heating Energy Supply Systems

Most of the dwellings in Otxarkoaga are equipped with electric heaters, in addition, natural gas boilers are installed in some of them. The reference scenario by means of power load, and energy demand simulations considered within this study include individual electric heaters for the heating demand, and thermo-electrics for the DHW demand, i.e. electric energy consumed for everything.

Table 3. Active scenarios combinations

DISTRICT HEATING		**0. Base case**	**1. Solar PV**
HEATING AND DHW	A. Natural gas boiler	1	1
	B. Biomass boiler	1	
	C. Geothermal Heat Pump	1	
	D. Aerothermal Heat Pump	1	

The set of systems for district heating energy production considered within a combination of space heating and DHW described in Table 3. The ESS on district scale presented by natural gas boiler as typical convenient solutions based on fossil fuel combustion, biomass boiler, and heat pumps technologies is in form geothermal, and aerothermal installations. All these technologies considered within 15 scenarios building retrofitting measures. This is because among the presented 19 scenarios in Figure 6 the insulation of non-habitable spaces is not considered within final scenarios, as it was agreed as an element that hardly affects the demand. To this end, it gives 15 (14 and base case scenario) different combinations per technology, which is 60 scenarios in total. Besides, the additional scenario of RES, in the form of solar PV technology is going to be considered at the district level. It is important to outline that the heating design output provides a *zone sensible heating* and *total design heating capacity* power demand. The *total design heating capacity* is a set of values to which applied a 1.25 security margin coefficient. Consumption savings compared to the base case. The graphic illustration of heating load decrease and energy consumption savings under the reference case (only electricity for heating and DHW) is depicted in Figure 7.

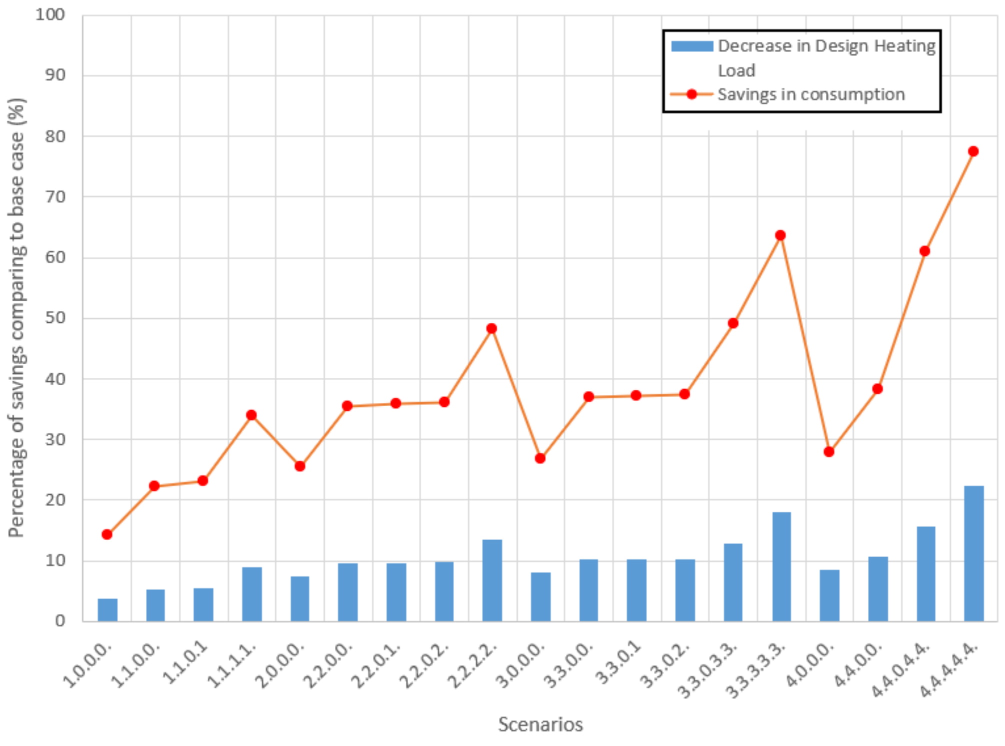

Figure 7. Percentage of consumption savings and decrease of heating load for passive measures scenarios compared to the base case 0.0.0.0

Naturally, more severe passive measures lead to a decrease in energy consumption. The graduate decrease of design heating capacity consequently leads to savings in energy consumption, which are considerably higher order as a percentage compared to the base case. Thus, for the reference case with a base case (0.0.0.0.) passive scenario Design Builder has an output of 23,540.68 kW of zone sensible heating, and 29,425.80 kW of total design heating capacity, with electricity consumption for heating 8,430,814.46 kWh per year. The most severe considered passive option (4.4.4.4.4.) provides a 22.3% in demand decrease comparing to the base case, it results in 77.34 % savings of consumed energy, comparing to the base case.

The facilities are designed with the "Detailed HVAC" option in Design Builder. For the Heating Loop, a setpoint temperature of 65 ºC and ΔT of 20 ºC is established. The temperature parameters have been considered within some basic requirements, such as Legionella-safe temperature of 50-55 °C in circulation line storage and any DHW installations [55]. In addition, design temperatures close to characteristics of 4th generation district heating networks the initial temperature have been chosen as 65 °C for supply and 45 °C for return. The *Waters Main Temperatures* section of the location tab in Design Builder has been scheduled by the average monthly water temperature in Bilbao defined in Table 4 [55].

Table 4. Water temperatures in Bilbao

Month	Water temperature (º C)
January	9
February	10
March	10
April	11
May	13
June	15
July	17
August	17
September	16
October	14
November	11
December	10

The contribution of pumping in the distribution system was also considered. The pressure drop simplification in detail described in section 3.2.2. The obtained pressure drop value of 1,454,471.66 Pa was inserted as a *design pump head* parameter into one of the pumps of the scheme (closest to the demand side), throughout all the ESS schemes.

Finally, the variable mass flow considered preferable over constant mass flow as it is not constantly moving the mass flow. On the other hand, the variable mass flow increases the investment and the complexity of the system. Considering these parameters, the variable mass flow considered within loops.

3.4.1 Heat Generation by Boilers

The hourly demand simulation output data for a reference case scenario with 0.0.0.0 passive measures are considered as initial data for the energy sources sizing approach. By sorting of simulation results it is plotted as the annual load duration curve (Figure 8).

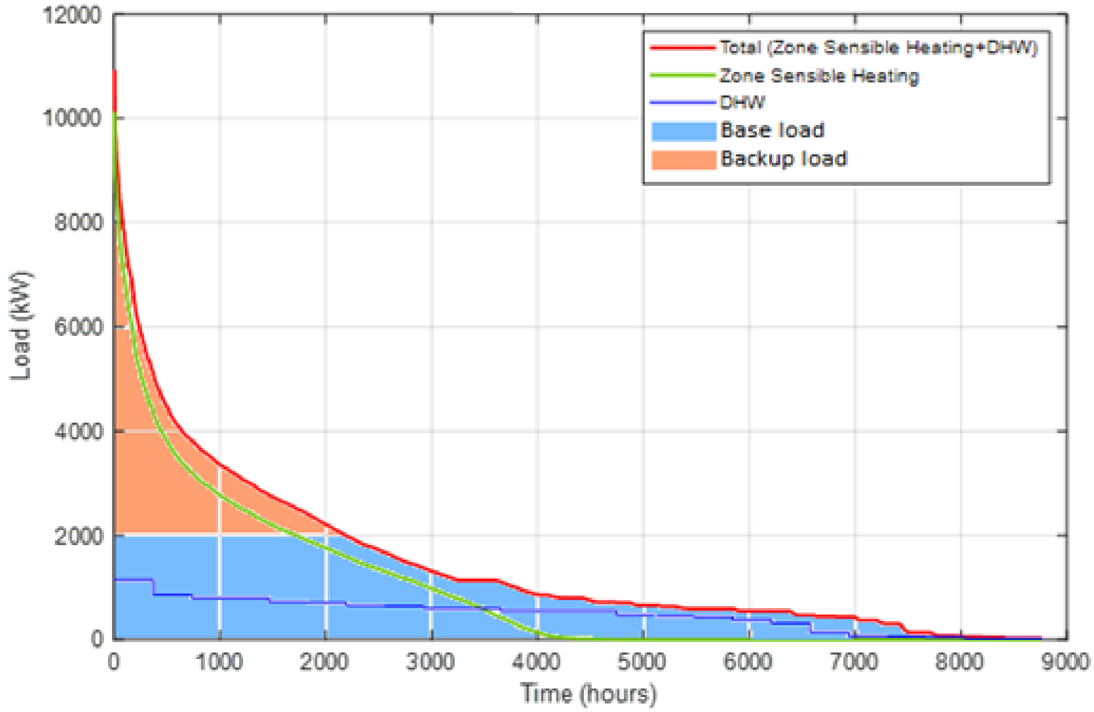

Figure 8. Annual duration cure with load intervals for boiler scenarios

Mainly, the general approach has been formed according to load capacity: *Base load interval* (from 0 to 2,000 kW) – for constant operation within the year mainly to supply DHW*; Backup load interval* (from 2,000 to 8,000 kW) – to cover a high demand based on hourly consumption. These two boilers will work in conjunction and share baseload and backup load capacity, respectively. Finally, *Peak load interval* (from 8,000 to 30,000 kW) installation with the same characteristics and parameters applied throughout all active measures scenarios to maintain a required peak load simulated by the Design Builder total design heating capacity (Figure 7).

There are two different options considered for boilers nominal power capacity design. The first assumes leaving the nominal capacity parameter *'Autosize'* while changing a sizing factor. The common use of the sizing factor is for sizing boilers to meet only part of the design load, so the program will split the design nominal capacity between installed boilers. The second approach includes manual changing of *nominal capacity* parameter for each boiler as half of the heating demand calculated by the software *Heating design* section. It is important to ensure that the overall installed power for any case is equal to the power determined by the heating design which varies depending on passive measures applied. Therefore, the first approach with sizing factors provided in Table 5 has been chosen for boilers nominal capacity.

Table 5. Boiler nominal power capacity sizing

Name of the interval	**Boiler name**	**Ratio (MW)**	**Sizing factor**
Base load (BL)	Boiler 1: Main	2:30	0.07
Backup load (BU)	Boiler 2: Backup	8:30	0.27
Peak load (PL)	Boiler 3: Peak	(30-2-8):30	0.66

The nominal power boilers are set as a ratio of accepted load bands to total design heating capacity generated by the program for a 0.0.0.0 passive measure scenario (Table 3). For ratio presentation, the output value 29,425.8 kW of 0.0.0.0 passive scenario was rounded to 30 MW.

The set of approaches is going to be introduced for each scenario to keep the assumptions of a simplified model feasible. All scenarios will have a main according to main heating technology applied, and a backup system, to cover a peak energy demand of heating and DHW.

Scenario A: Natural gas boiler

The work [56] discussed the efficiency of the district solution taking into account heating and domestic hot water supply. The group of authors highlights that yearly efficiency drops both when the domestic hot water share rises, and when the heat demand drops, considering systems with energy demand 4,900-13,800 kWh. In addition, not many manufacturers of natural gas boilers inform of the efficiency of the domestic hot water part.

For natural gas boilers, the solution proposed in the work is described in the way that the most efficient of boilers have efficiency for space heating of 94% and efficiency for domestic hot water of 87% [57]. In the authors` case, domestic hot water assumed to be 30% of the total heat demand, the resulting total efficiency of the boilers was 91.9%. In our case, according to Design Builder simulation data for reference case, domestic hot water is about 40% of hot water demand. In addition, the standard Design Builder template for Condensing boiler was considered, therefore the resulting of natural gas boilers considered as 89%.

To control the operation of the equipment desired to be available under specific conditions the special operation scheme for boilers applied. The first power range from 0 to 2,000 kW is designed for Boiler 1 and covers mainly the DHW demand. The second range from 2,000 to 10,000 kW is designed for Heating and DHW and assumes operation of the main and backup boiler. Finally, the third range from 10,000 kW up to the upper possible demand limit also includes a peak consumption boiler. The designed scheme of the natural fas boiler scenario in the Design Builder interface depicted in Figure 9.

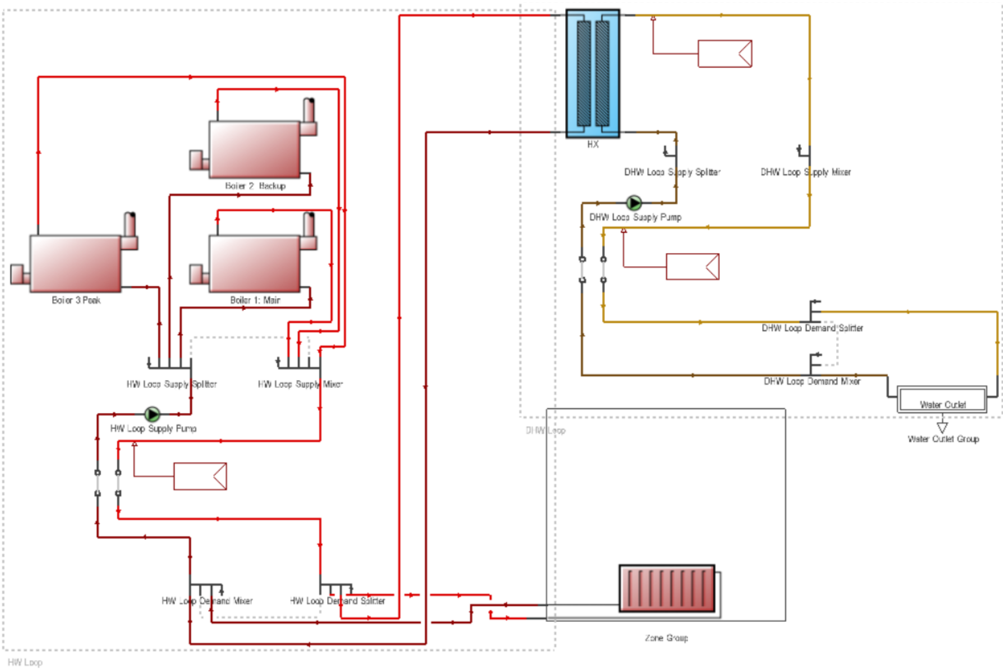

Figure 9. Scheme of Natural Gas Boiler scenario in Design Builder

Hence, Scenario A consists of 3 main components designed with the "Detailed HVAC" option in Design-Builder. It includes such main components, as:

- Hot Water Loop with a standard demand and supply side (HW Loop): Natural Gas boiler (Boiler 1: Main; Boiler 2: Backup, Boiler 3: Peak); Setpoint Manager; Pump.
- Domestic Hot Water Loop (DHW Loop): Heat Exchanger; Heat Exchanger Setpoint Manager; Water Outlet Group.
- Zone Group: Water Convector

In line with assumptions made for a study, the natural gas boiler in the HW loop generates hot water at 65 ºC and delta T of 20 ºC for heating demand. The DHW Loop is presented by DHW template with the swapped water heater to heat exchanger installation. By this decision, the centralized domestic hot water supply is going to be simulated. Few main parameters were modified. The *Design loop exit temperature* set to 55 ºC, *Loop design Temperature difference* - 5 ºC. The Zone group has a water convector to reach the comfort temperature with a defined setpoint temperature. These two are elements kept the same for all models within different scenarios. Modified parameters presented in Table 6.

Table 6. Modified parameters of Natural Gas boiler scenario

Loop	Component	Parameter	Type	Value
HW Loop	Plant Loop Sizing	Design Loop Exit Temperature		65 ºC
		Loop design Temperature Difference		20 ºC
	Boilers	Boiler Template	Gas-fired condensing boiler	65 ºC
		Nominal Thermal Efficiency		0.890
	Setpoint Manager	Setpoint Variable Schedule	Hot Water flow setpoint temperature: Always 65.0 C	65 ºC
	Pump	Design Pump Head		1454471.66 Pa
DHW loop	Plant Loop Sizing	Design Loop Exit Temperature		55 ºC
		Loop design Temperature difference		5 ºC
	HX Setpoint Manager	Setpoint Variable Schedule	Domestic hot water setpoint temperature: Always 55.00	55 ºC
		Heat exchanger model type		Counter Flow

Through a heat exchanger, the water flow at 65 ºC generates hot water at 55 ºC to supply the DHW demand. The heat exchanger is established as "counter-flow" and is modulated with the heating setpoint. Boilers' template has been chosen as "*Condensing Natural Gas Boiler*". The chosen boiler has a performance of 0.89 for the HHV.

Scenario B: Biomass boiler

The biomass boiler scenario based on the same scheme of circuit and parameters with few changes in parameters of boilers. Namely, the boiler based *on a Low-temperature gas-fired non-condensing* template. In line with a Design Builder manual recommendations fuel type, "*9-Other fuel 1"* has been chosen to representing biofuels such as biomass.

The nominal thermal efficiency set to 95% based on an overview of biomass-fired hot water tube boilers [13]. The nominal power sizing implemented in the same way as in the natural gas boiler scenario. The modified parameters of loops and elements for the biomass boiler scheme are given in Table 7.

Table 7. Modified parameters of Biomass boiler scenario

Loop	Component	Parameter	Type	Value
HW Loop	Plant Loop Sizing	Design Loop Exit Temperature		65 ºC
		Loop design Temperature Difference		20 ºC
	Boiler	Boiler Template	Low-temperature gas-fired boilers (non-condensing)	
		Nominal Thermal Efficiency		0.950
	Setpoint Manager	Setpoint Variable Schedule	Hot Water flow setpoint temperature: Always 65.0 C	65 ºC
	Pump	Design Pump Head		1454471.66 Pa
DHW loop	Plant Loop Sizing	Design Loop Exit Temperature		55 ºC
		Loop design Temperature difference		5 ºC
	HX Setpoint Manager	Setpoint Variable Schedule	Domestic hot water setpoint temperature: Always 55.00	55 ºC
		Heat exchanger model type		Counter Flow

3.4.2 Heat Generation by Heat Pumps

The large heat pump solutions are widely discussed, and tested option for district heating [58]. Currently, large-scale heat pumps mostly can supply heating temperatures, which is especially actual for ground source heat pumps of around 80 °C [13]. For the integration into district heating networks, this maximum supply temperature or required power load in many cases are insufficient so that the operation of large heat pumps seems not appropriate. It is a typically described approach that if the flow temperature of the heat pump is not sufficient, there is an option of post-heating with auxiliary systems. For such auxiliary systems, boiler installations are widely applied [13].

The sizing approach for heat pump scenarios C and D is based on HP installation, and a thermal storage system in form of a water storage tank to provide an additional heat buffer for the system. There are two basic intervals for sizing of installations illustrated in Figure 10.

The *Base load interval* (from 0 to 4,000 kW) - for constant operation within the year covered by the heat pump. The *Backup and Peak load interval* (4,000 kW to a maximum limit of a particular passive measure application) – includes the operation of a Backup boiler together with an installed HP. Table 8 includes sizing factors considered for Backup boiler, and heat pump installations.

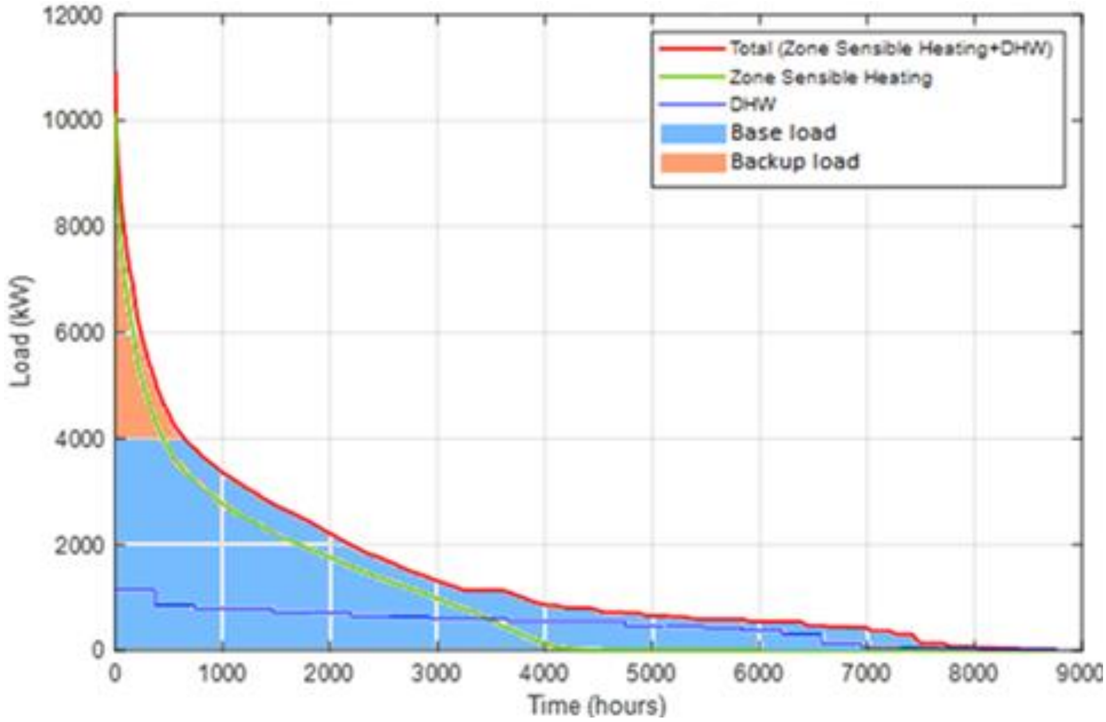

Figure 10. Annual duration cure with load intervals for heat pumps scenario

The Design Builder has the option of authorizing a water tank. Among methods of EnergyPlus engine for sizing the default is *1-Peak draw* method. This design method uses the design flow rates of all the different demands placed on the water heater. The tank size is based on how long it can meet the demand and how quickly it can recover. The user enters the time in hours that the water heater can meet the demands. Only the hot water uses connected to an individual water heater are included in that water heater's peak draw. However, the water tank desired volume design performed manually. The water tank volume inserted into the system is 437 m^3, s*etpoint temperature* parameter set as 65ºC. It is sized to satisfy a 4,000 kW power load, the desired duration has been set 2.5 hours and comes from the energy balance equation (equation 8).

$$V = P_{m.t} \cdot t \cdot \frac{3600}{\rho \cdot C_p \cdot (T_{out} - T_{in})} \quad (8)$$

Where V is a volume of the tank; $P_{m.t}$ is the desired power load to satisfy, t load time; ρ water density; C_p water specific heat; T_{out} outlet temperature; T_{in} inlet temperature.

Table 8. Nominal power capacity sizing for heat pump scenarios

Name of the interval	**Boiler name**	**Ratio (MW)**	**Sizing factor**
Base load (BL)	HP 1 Main	4:30	0.14
Backup and Peak load (BPL)	Boiler: Backup	26:30	0.86

Scenario C: Geothermal heat pump

The ground type considered for Otxarkoaga is a marl rock with a parameter inserted into a simulation file such as thermal conductivity of 2.1 (W/m-K) and a heat capacity of 1347 (kJ/m^3-K). The geothermal resource of the region can be described as predominantly very low (<25 ºC) and low enthalpy (25-90 ºC) with some medium enthalpy (90-150 ºC) temperature heating schemes [59]. According to the Atlas of geothermal resources in Europe, 2002 [60] Geothermal Heat flow density of the Basque country region predominantly in a range of 50-80 mW/m^2.

At this point, there is a milestone that must be clarified for feasibility purpose. As Design Builder parameters for boreholes is limited by a small-scale power, following this approach is barely mean that to cover the desired share of the power demand of the district it would require thousands of boreholes to cover a demand of the Otxarkoaga district.

Based on Design Builder simple sizing data for ground vertical heat exchangers the necessary number of boreholes has been assumed based on trendline extrapolation of plotted Design Builder vertical boreholes simple sizing data (Figure 11).

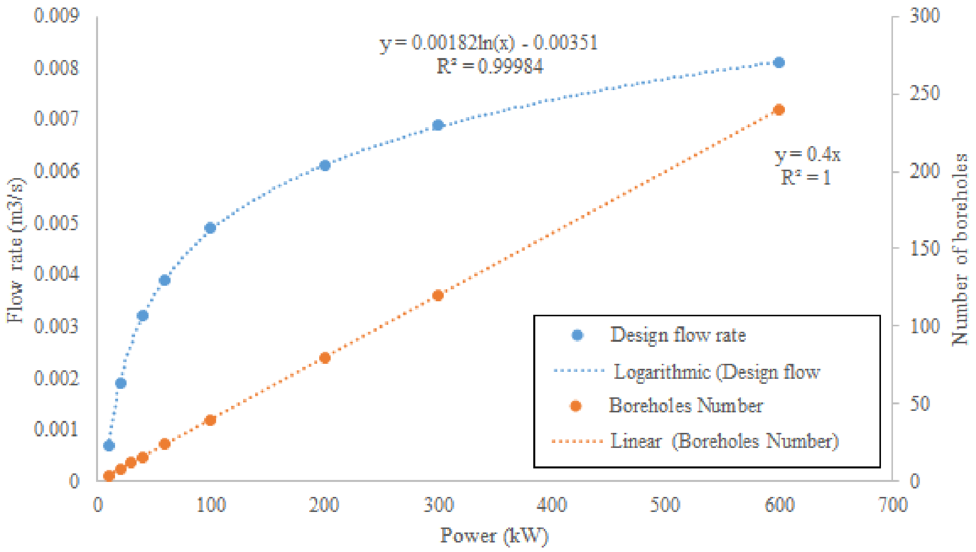

Figure 11. Boreholes number and flow rate extrapolation equations

For the required heat capacity, the estimated number of boreholes is 533. Such assumption implies a "grey box" approach to the ground heat exchanger as there is limited provided details about internal functionality and we deal with an output from the point of inlet and outlet temperatures. design of heat exchanger considered as component out of the scope. This implies the theoretical possibility of implementation of geothermal installation with a capacity required to cover an area with better geothermal resource and significant transmission system length.

However, it has feasibility issues that taken out of scope for the given system as it considered within one of the large borehole heat exchangers fields in Europe, such as Lund Chemical institute (Lund, Sweden), IKEA Dänischburg (Lübeck, Denmark) [61]. In addition, depending on the nature of the measures for boreholes, an environmental impact assessment (EIA) or strategic impact assessment may be required.

The chosen geothermal heat pump has a capacity of 12,464.33 kW for Heat Pump based on the heat pump from the Design Builder catalogue. The scheme of the circuit illustrated in Figure 12.

The ground heat exchanger type accepted as *Vertical*. According to the technical guide "Design of closed-circuit geothermal exchange systems"[55] in the case of vertical heat-exchangers of geothermal installation, the soil temperature can be established as the average annual temperature, which in Bilbao is 14.1° C. The Otxarkoaga district mainly located on the ground which composed of marl rocks [62]. The set of parameters were inserted into the ground heat exchanger, as the value of thermal conductivity for such type of rock is equal to 2.1 (W/m K) and a heat capacity of 1,347 (kJ/m^{3}K) [55]. The set of modified parameters is presented in Table 9.

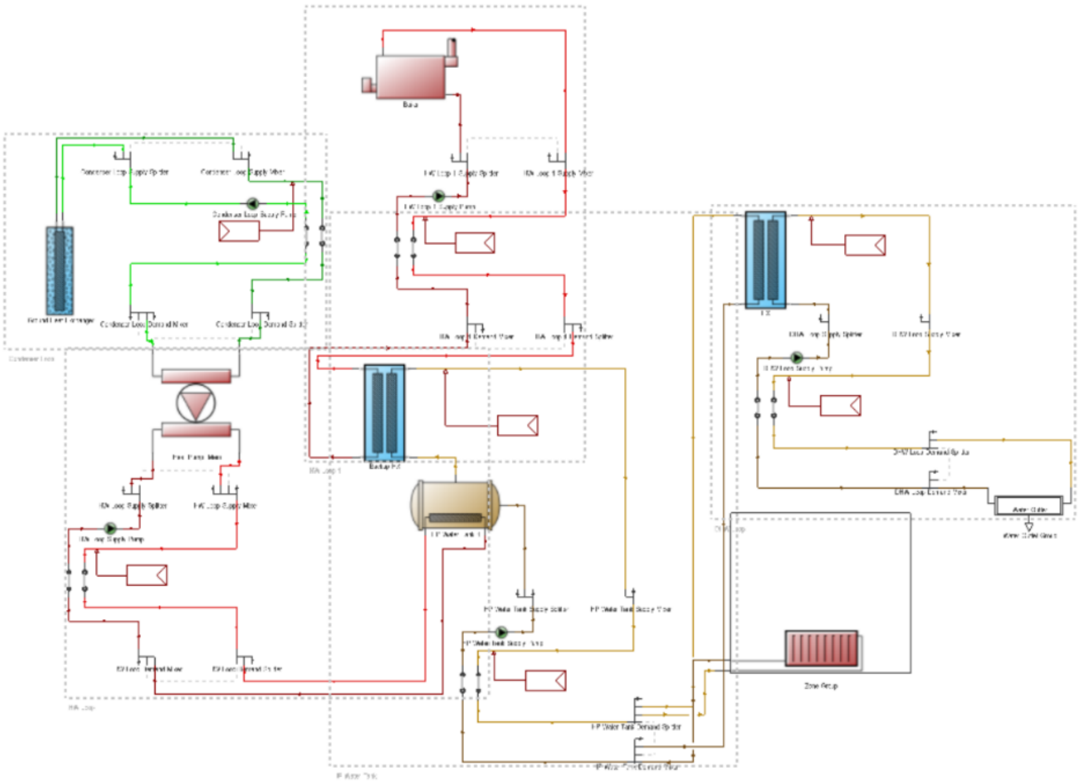

Figure 12. Scheme of Geothermal HP scenario in Design Builder

The scheme of the circuit presented in Figure 12 and consists of 6 main components:

- Condenser Loop Supply: Ground Heat Exchanger; Condenser Loop Setpoint manager; Pump.
- Heat Pump Hot Water loop: Heat Pump; Setpoint Manager; Pump.
- Hot Water Loop (Backup HW Loop) with demand-side connected to Backup heat exchanger (Backup HX): Natural Gas boiler (Boiler: Peak); Setpoint Manager, Pump.
- Water Tank Loop: Water Tank; Backup HX; Aux HW Loop Setpoint Manager; Overall Temperature Setpoint Manager, Pump
- Domestic Hot Water Loop (DHW Loop): Heat Exchanger; Heat Exchanger Set-point Manager; Water Outlet Group.
- Zone Group: Water Convector.

The calculated ratio of satisfied demand (heating and DHW) by ground source heat pump (GSHP) per annum to total input electricity per annum presented as a SPF value, and for the base case scenario considered as 4.07. This value does not include the electricity used by the auxiliary pumps.

Table 9. Modified parameters of Geothermal heat pump scenario

Loop	Component	Parameter	Type	Value
Condenser Loop	Ground Heat Exchanger	G-Function Borehole template	Template	U-tube 76m 120-boreholes
		Ground properties	Ground thermal conductivity (W/mK)	2.1
			Ground temperature	14.1 ºC
		Borehole and pipe geometry	Number of boreholes	533
		Flow rate	Design flow rate (m^3/s)	0.66
HP Loop	Heat Pump: Main	General	Template	ClimateMaster TMW840
		Rated flow rate and capacity	Rated heating capacity	12464.33 kW
			Rated heating power consumption	1081.08 kW
	Setpoint Manager	Setpoint Variable Schedule	Hot Water flow setpoint temperature: Always 65.0 C	65 ºC
	Pump	Design Pump Head		1454471.66 Pa
Water tank loop	Heat exchanger	Minimum temperature difference to activate heat exchanger		2ºC

Scenario D: Aerothermal heat pump

The large-scale heat pumps application in DH systems has been analyzed within multiple works from different perspectives [13], [14], [19]. So far, numerous works operational integration with other technologies. The key aspect for this scenario includes proper hypothesis for information on the heat sources, refrigerants used, capacities, COP, input and output temperatures. David et al. in [14] analyze a numerous heat pump unit across Europe and highlights some of their parameters, such as capacities and market development, heat sources, refrigerants, COP, output temperatures and types of operation. Mainly, authors outline that for the heat pumps in their research, minimal data was provided on the operating hours and the share of production in DH, hence the role of installations in the DH networks could not be established, as this is a parameter that fluctuates from year to year.

The parameters of the DH aerothermal heat pump have been based on previous studies within Annex 75 [48]. The proposed scheme for the aerothermal heat pump scenario illustrated in Figure 13.

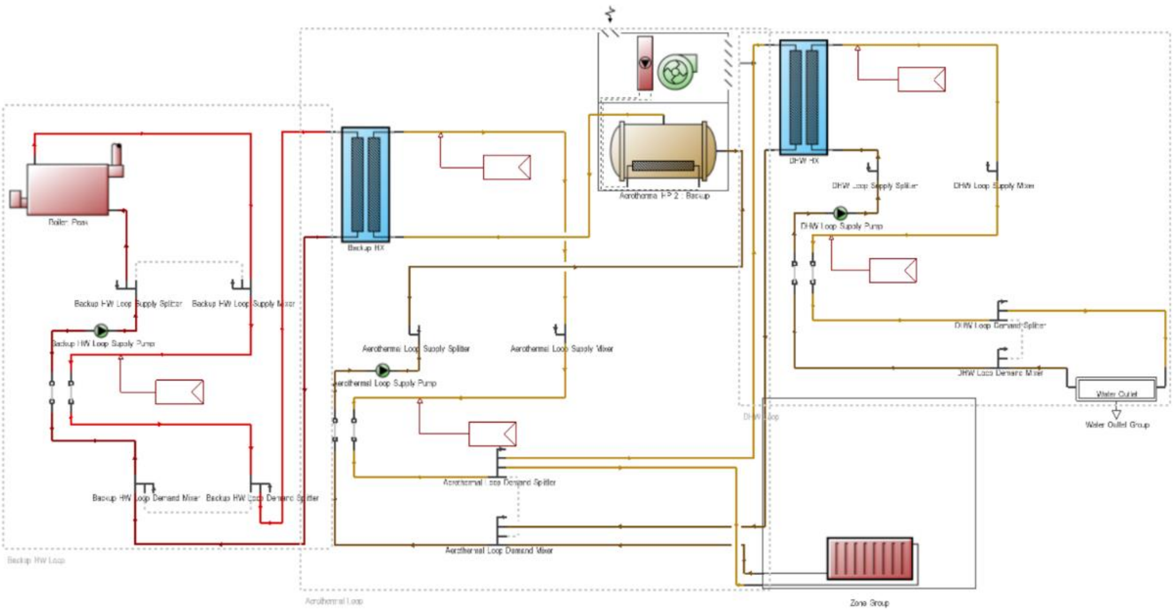

Figure 13. Scheme of Aerothermal HP scenario in Design Builder

The given scheme based on air-source heat pump (ASHP) HVAC Design Builder template, and consists of 4 main components:

- Hot Water Loop (Backup HW Loop) with demand-side connected to Backup heat exchanger (Backup HX): Natural Gas boiler (Boiler: Peak); Setpoint Manager.
- Aerothermal Loop: Aerothermal HP 1: Main; Backup HX; Aux HW Loop Setpoint Manager; Overall Temperature Setpoint Manager.
- Domestic Hot Water Loop (DHW Loop): Heat Exchanger; Heat Exchanger Setpoint Manager; Water Outlet Group.
- Zone Group: Water Convector.

The air-to-water heat pumps have a nominal COP of 3.7 and capacity of Aerothermal HP 1: Main 4,000 kW for the following conditions: 7 ºC for the air at the evaporator inlet and 40 ºC for the water at the condenser inlet. The compressor setpoint temperature is set at 65 ºC and the dead-band temperature is 5 ºC. For considered aerothermal heat pumps the curves of capacity (CAP) and COP were modified as a function of outside temperature and condenser inlet temperature. That correlation is defined with a biquadratic equation. The capacity and COP curves for the individual air-to-water heat pumps are shown in Figure 14.

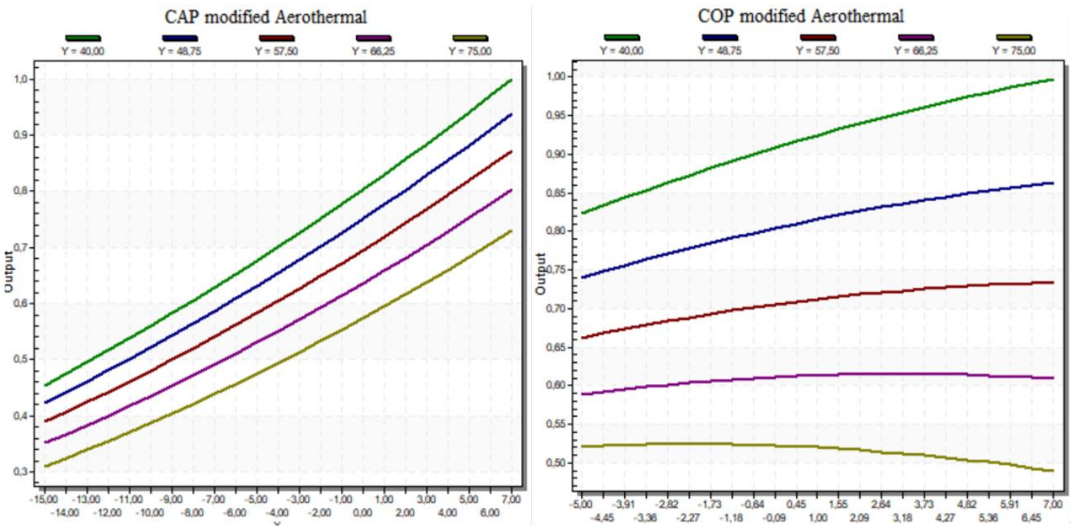

Figure 14. COP and capacity curves of the individual air-to-water heat pump

Like previous scenarios, the aerothermal heat pump (HP) includes a peak natural gas boiler which has identical to scenario A, with a nominal power capacity '*Autosize'* and sizing factor of 0.86. The aerothermal HP aimed to provide main heating, and a hot water loop with the boiler is used to provide additional heat required to meet the overall supply setpoint via 'Backup HX'. The set of modified parameters is presented in Table 10.

To ensure that the setpoint and inlet temperatures for the heat exchanger are such that it could transfer heat from the Loop Demand Side to the Loop Supply Side to meet the heating setpoint, then the heat exchanger will be activated. Therefore, the setpoint manager of Backup HW Loop has been set to '*Hot Water flow setpoint temperature: Always 65.0ºC'* and the *Overall Temperature Setpoint Manager* is set to *'Hot Water flow setpoint temperature: Always 65.0ºC'*. The inlet temperatures from Backup HW Loop side to Backup HX Aerothermal Loop side must differ by more than the value set in *Minimum temperature difference to activate heat exchanger* for the heat exchanger to operate. The heat exchanger model type has been left as proposed by default '*1-Counter flow'*.

Also, to provide heat to the water heater tank from the heat pump an overall heat pump compressor temperature (which is a difference of *Compressor setpoint temperature schedule* and *dead band temperature difference*) must be greater than the *Water Heater Setpoint temperature* schedule. For this reason, *Compressor setpoint temperature schedule* has been set to *'Hot Water flow set point temperature: Always 70.1ºC'* to keep a nominal difference 0.1 ºC of temperature for a correct procession.

Table 10. Modified parameters of aerothermal HP scenario

<table>
<tr><th>Loop</th><th>Component</th><th>Parameter</th><th>Type</th><th>Value</th></tr>
<tr><td rowspan="6">Aerothermal Loop</td><td rowspan="2">Air to Water Heat Pump Coil</td><td rowspan="2">General</td><td>Rated Heating Capacity</td><td>4000 kW</td></tr>
<tr><td>Gross COP</td><td>3,7</td></tr>
<tr><td>Aerothermal HP Water Heater</td><td>Compressor setpoint temperature schedule</td><td>HW flow set point temperature: Always 70.1 C</td><td>70.1 ºC</td></tr>
<tr><td rowspan="2">Backup HX</td><td colspan="2">Minimum temperature difference to activate heat exchanger</td><td>2ºC</td></tr>
<tr><td colspan="2">Heat exchanger model type</td><td>Counter flow</td></tr>
<tr><td>Pump</td><td colspan="2">Design Pump Head</td><td>1454471.66</td></tr>
<tr><td>Backup HW Loop</td><td>Setpoint Manager</td><td>Setpoint Variable Schedule</td><td>HW flow set point temperature: Always 65.0ºC</td><td>65.0ºC</td></tr>
</table>

3.5 Renewable Energy Integration

The choice for complementary RES technology for introduction within analysis initially fall on solar PV panel as the most popular power generation source among European citizens and at the same time versatile, easy and quick to install, and often lowest-cost share of renewables. Initially, within Annex 75, the solar potential of the district was already characterized, and solar PV system investment per building type considered as an input calculated based on types of roofs, and their orientation. This data has been taken as input for applying on the district level.

The installations were designed utilizing characteristics of the panel that were inserted into the PVSyst program. For this, 9 roof types were classified according to the roof shape and the available area according to the previously described topology of the building. The functional unit is a mono-crystalline module of the brand ERA [63] that has been considered.

The panel spacing, optimum pitch angle for horizontal roofs was calculated by online tools, such as PVGIS online tool [64]. For pitched roofs, the panel inclination angle taken the same as a slope of the roof (20º), for other buildings program considered as 35º inclination angle. For performed simulation, the program calculated the energy produced for on-site consumption and the energy fed into the grid. The usable area of each building for the installation of panels is entered into the program. The exception was made for the flat roof, whereas the number of panels calculated manually. By entering an available area for installation, the program outputs the number of installed panels. It also determined the number of required inverters and the power of each unit. Thus, data considered as input for the further analysis presented in Table 11.

Table 11. The photovoltaic potential of the neighbourhood

Typology	**Installable panels (per building)**	**Number of buildings**	**Orientation**	**Produced electricity (kWh/y)**	**Investment (€)**
1	44	15	T	14,629	19,862
2	45	6	T	14,629	20,313
3	60	4	SE	20,813	27,085
4	85	13	SE	26,804	38,370
		12	SO	26,429	
		15	E/O	23,755	
		3	S	27,651	
5	90	4	SE	28,381	40,627
		1	S	29,276	
		1	E/O	25,144	
6	42	6	SO	13,059	18,959
		12	E	12,004	
		2	SE	13,244	
		1	S	13,662	
8	60	2	SO	18,656	27,085
9	20	3	E/O	5,716	9,028
		6	SO	6,219	
		1	SE	6,307	
		1	S	6,506	

4 Results

The economic study of district heating considered within different energy systems for heating and DHW options includes investment costs (CAPEX), operational costs (OPEX), fuel costs and expected lifetime of the units [65]. In this study, the investment costs of each ESS will be calculated together with costs of correspondent EEM scenario, taking into account maintenance cost, and DH distribution network cost. The cost-efficiency study based on Equivalent Uniform Annual Cost Method and total primary energy (PE) conversion to provide a comparative analysis between all available scenarios.

4.1 Economic Analysis

Following economic analysis dedicated to preliminary study for district heating network and among all aimed to consider how district heating, cost-wise, compares to other heating technologies available. Thus, it covers expenditures for energy supply system, district heating network. Also, the distribution energy losses evaluation considered by means of equivalent peak operation.

For the cost-effectiveness analysis, the price for energy sources, such as gas and electricity prices (including taxes) used are from Eurostat report household consumers [66], [67]. At this point between household and non-household prices for electricity and gas, the choice was made towards a higher price. The price of energy sources can be found in Table 12.

Table 12. Energy sources price

Type of energy source	€ /kWh final energy
Electricity [66]	0,2298
Natural Gas [67]	0,089
Wood pellets [68]	0,0514

For further analysis per unit of energy, total primary energy has been considered by means of conversion factors in the building sector of Spain [69] which is given in Table 13.

Table 13. Total primary energy factors (kWh/kWh of final energy)

Energy type	Factor
Electricity	2.403
Wood pellets	1.113
Natural gas	1.195

Investment costs for different heat generation technologies are taken from various sources. The approach for energy supply systems cost analysis includes an introduction of nonlinearities of technologies performed in one of the previous studies [70]. Namely, the investment cost calculations based on specific cost equations applied for a natural gas boiler, biomass boiler and aerothermal heat pump are presented in Table 14. These equations built based on a cost model obtained from the authors' self-tailored top-down analysis of the Spanish market [70].

Table 14. ESS technologies specific cost equations

Technology	Specific cost
Conventional natural gas boiler [70]	$c = 1.589 \cdot P^{-0.475} (€/\mathrm{kWth})$
Biomass boiler [70]	$c = 1.584 \cdot P^{-0.305} (€/\mathrm{kWth})$
Air-to-water heat pump [70]	$c = 381.99 \cdot P^{-0.144} (€/\mathrm{kWth})$
Geothermal heat pump [13]	$c = 1600 \cdot P^{-0.11} (€/\mathrm{kWth})$
Water Tank [13]	$c = (-64 \cdot V + 184000) \cdot 10^{-3} (€/\mathrm{kWth})$

Heat plant costs vary between plants and case studies, moreover especially in the case of a geothermal heat plant. it should be noted that there are a lot of other possible heat sources for DH that are not mentioned here due to the lack of available cost data. As the biggest contributor to the cost of ground source heat pump compared with conventional HVAC systems, installation of ground heat exchangers used for ground source heat pump takes for more than 30% to the total cost of ground source heat pumps [71]. It considered being the biggest contributor to the cost of GSHPs compared with conventional HVAC systems. Cost for drilling can vary from 14-40 €/m [71], geological formations encountered during drilling is one of the factors that determine the costs of drilling. The labour contributes the most, about 46% to the overall cost followed by equipment 30% and material 24%. In this way, the specific investment cost for a geothermal system varies within considered values 1.2-1.9 M€/MW, based on literature fixed values [56, 13, 65, 72].

The annual maintenance and operating costs for energy supply system technologies were included as a percentage of CAPEX per year and equal to 2.5%, a discount factor taken as 2.5% per year, and a lifetime of 20 years, and 25 years for PV and geothermal. Despite that fixed operational costs independent from how the plant is operated and do not vary with a technology energy generation or consumption, it is considered that all the technologies can regulate their load capacity.

The investment for DH piping work breaks down on main equipment, balance of plant, civil and structural works development cost, interconnection costs [13]. In this study, the cost analysis of pipework was performed with a preliminary evaluation purpose. The components of investment have been considered, civil engineering works costs which account between 40 to 50 %, another major share of costs is caused by the pipes themselves [13].

The pipe investment cost is associated with pipe diameters, materials, insulation, construction, installation, length, etc. Pipes per unit length can be expressed using the linear regression method, however, it is suggested when pipe materials, insulation, construction and installation are determined [26]. Prices for materials and work are constantly changing, so a set of adjustments to the costs were considered during implementation. It should be noted that expenditures also depend on the necessary level of modification within the heat interfaces of each building within the district and the cost of the building where the thermal production is going to be located. These types of cost were not considered in this study.

The ground-buried plastic sheath pipes are considered as a predominant solution for district heating, however, steel pipes have a much wider variety of diameters [56]. This kind of pipes typically consists of the steel medium pipe, the polyurethane thermal insulation, and the plastic sheath. The simplified formula in equation (9) is used to predict possible preliminary costs of DH piping networks in euro per route meter considering pipe diameter, pipe material and construction.

$$c = (270 + 2.2 \cdot DN_{pipe}) \cdot (1 + f_{GroundCondition)}) \cdot (1 + f_{PipingSyst}) \qquad (9)$$

The considered formula was built on published cost data from the listed references, aggregated and analysed in the report “Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU” [13]. The ground formula is based on ground condition "inner-city area". The given factors $f_{GroundCondition}$ and $f_{PipingSystem}$ describes correction factors that reflect different construction areas and pipe materials.

The factors were adapted as follow $f_{GroundCondition}$: inner-city areas = +25 %, and $f_{PipingSystem}$: steel jacket pipe = +40 %; plastic casing pipe = 0%.

To provide a comparative analysis of investment alternatives the Equivalent Uniform Annual Cost Method (EUAC) was applied. The EUAC method represented in equation (11) allows expressing cost for different reference lifetime of a project within its different study period as it expresses costs as an annualized estimate of cash flow instead of a simple estimation of present value. For that reason, at first, we calculate the present value of the cost of capital investment at a particular point in time, calculated based on the accepted above 2.5% in equation (10).

$$P = I + A \cdot \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \tag{10}$$

Where A - annual cost, I-investment; i-interest rate; n- project lifetime

$$EUAC = P \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{11}$$

In addition, the investment cost of passive renovation measures has been taken for each dwelling and scaled for the whole neighbourhood. Within Annex 75 these costs were included per dwelling employing calculation via online tool "Price Generator" to get a price of insulation materials. The investment for the total number of buildings in the district is given in Table 15. Data per dwelling considered within Annex 75 has been taken for comparative characteristics of scenarios on the district level.

Table 15. Investment cost of district passive renovation scenarios

Passive scenario	**Investment (€)**	**Maintenance (A) (€/year)**	**Total (€)**
1.0.0.0	2,825,355.60	5,753.52	2,940,426.00
1.1.0.0	3,309,924.60	6,743.88	3,444,802.20
1.1.1.1	4,269,960.72	25,890.84	4,787,777.52
2.0.0.0	5,362,940.88	10,941.12	5,581,763.28
2.2.0.0	6,105,710.88	12,497.40	6,355,658.88
2.2.2.2	7,341,633.00	30,748.32	7,956,599.40
3.0.0.0	5,850,763.92	12,072.96	6,092,223.12
3.3.0.0	6,662,529.00	13,676.40	6,936,057.00
3.3.0.3.3	8,577,932.40	32,776.20	9,233,456.40
3.3.3.3.3	8,577,932.40	32,776.20	9,233,456.40
4.0.0.0	6,341,275.08	12,874.68	6,598,768.68
4.4.0.0.	7,221,563.64	14,666.76	7,514,898.84
4.4.0.4.4.	7,852,611.60	20,467.44	8,261,960.40
4.4.4.4.4.	9,730,381.32	34,756.92	10,425,519.72

As already mentioned, within Annex 75 the solar potential of the district was already characterised, and solar PV system investment was calculated based on types of roofs, and their orientation. In this way, the amount of investment was taken for whole available calculated buildings on the district level and presented in Table 16.

Table 16. Economic data for the photovoltaic installations

Number of buildings	Total production (kWh)	Total investments (€)	Annual savings (€)	Simple average payback (years)
108	2,030,419.90	2,973,437.67	575,727.2	5.2

4.2 Cost-Effectiveness

At first, the investment required for implementing the proposed distribution grid was calculated and presented in Table 17. It is considered as a constant element within a calculation of CAPEX for all ESS scenarios.

Table 17. Distribution network investment

Elements	Cost function (€/m)	Subtotal (€)	Total investment (€)
Main ring	474	3652952.24	4,461,664.48
Connections		808712.24	

The specific cost (M€/MW) for each technology was calculated separately. In the case of scenario A and B with 3 boilers, it was separately made for each installation. The same referred to heat pump installation and separate price of peak boiler investment in scenario C and D. The cost of fuel grouped as main technology fuel cost (i.e., gas for scenario A, biomass for B and electricity for scenario C and D), and backup technology fuel cost considered for heat pump scenarios, for gas. Also, for all scenarios, a secondary consumption of electricity (as consumption of pumps) was included, and renovation investment costs were included. After all, considered scenarios are grouped and plotted in Figure 15.

Within all scenarios, the tendency for EUAC costs and PE for some technologies can be characterized as close to linear. As can be expected for all the ESS scenarios the most severe measures (4.4.4.0.4) provided a most significant reduction of cost per unit of PE equivalent, while base case (0.0.0.0.) always the least favourable option. The most cost-efficient scenarios are meant to be the most severe passive measures that despite a higher investment into renovation can provide higher annual energy savings. In this way decrease in annual expenditures compensate for a passive renovation investment. Also, all scenarios similarly grouped by their tendency to increase within PE and EUAC. Thus, the most cost-efficient scenario for all ESS technologies is 4.4.4.0.4 which in all cases much more efficient comparing to the closes option 3.3.3.0.3.

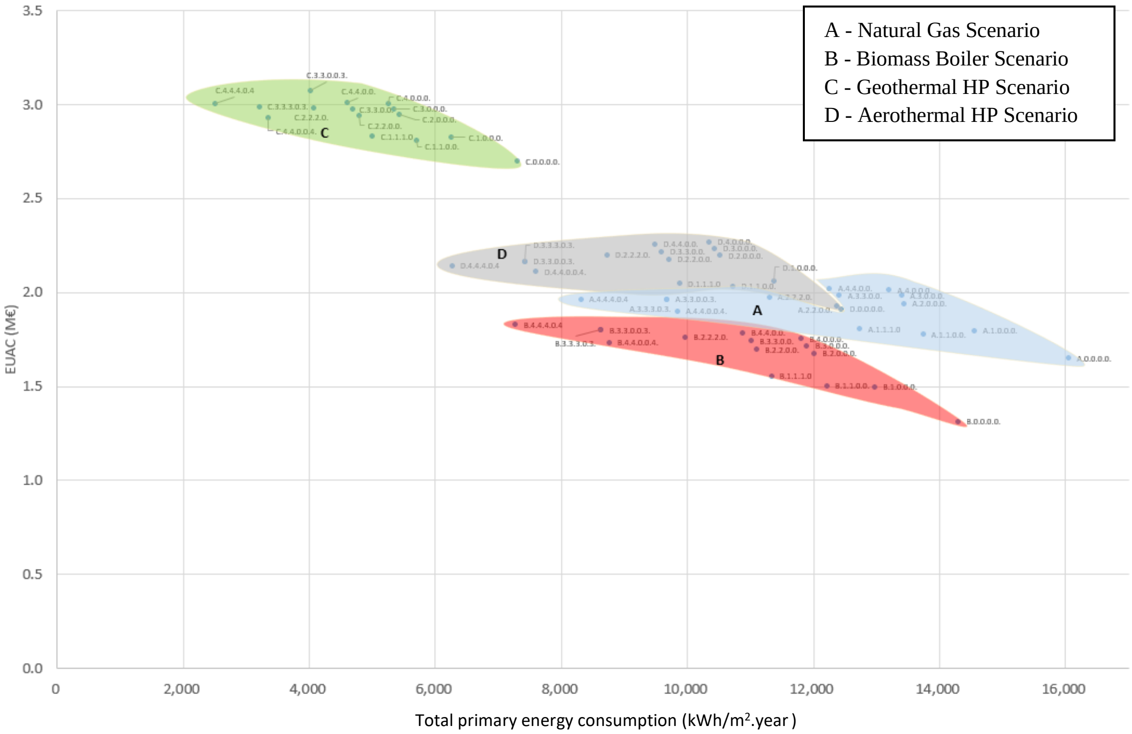

Figure 15. Plotted data of all ESS scenarios

Within a graph analysis, it must be mentioned that considering a total renewable energy consumption by each technology a geothermal heat pump provides the most cost-effective option. Thus, for a heat pump scenario, being more costly technologies, combined with the high price of electricity, results in high EUAC values for this installation, have significantly higher EUAC at the same time being the lowest total PE consumers. Here the geothermal heat pump scenario leads with a close to 2,000 MWh of PE consumption, after that an aerothermal pump comes, biomass, and the least acceptable natural gas boiler. Also, it must be mentioned that an aerothermal heat pump does not achieve high-efficiency values in a climate like Bilbao [14].

Even though that, it can be stated that boilers are highly competitive. If we from the point of investment costs opposite alternative can be observed. The most beneficial scenario is a biomass boiler ESS with a severe measure (4.4.4.0.4). After that comes a natural gas boiler technology which follows by aerothermal HP, and finally a geothermal HP scenario. The capital investment of a natural boiler is 1.5-2 times lower comparing to biomass, however at the same time condensing boiler has a higher efficiency than the biomass boiler. But as fuel cost per kilowatt of biomass is cheaper than that of natural gas it makes the biomass scenario more competitive to natural gas.

When the different proposed combinations were evaluated, the analysis was directed to the thermal needs of buildings. Thus, the electricity consumption of dwellings, as well as interior equipment consumption was not included within the calculation of EUAC and PE for the district.

As it can be seen from Figure 16, the introduction of PV installation for all scenarios significantly shifts considered plotted data. The installation PV with maximum calculated capacity for a whole neighbourhood in conjunction with considered ESS combination can significantly enhance characteristics of the neighbourhood for total primary energy consumption.

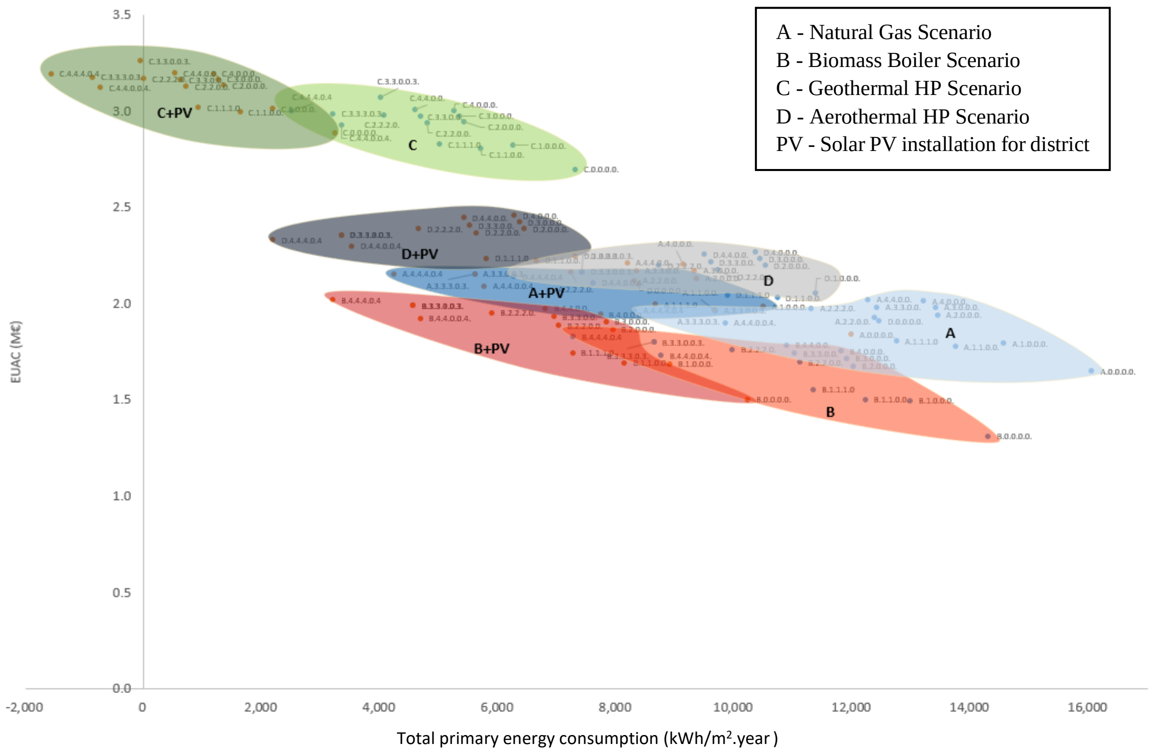

Figure 16. Summary graph of considered scenarios and calculated PV installation for Otxarkoaga neighbourhood

With relatively modest additional investment costs into specified PV installation that does not rise significantly a uniform annual cost for scenarios, the neighbourhood, within studied scope, can be transformed towards PED, PEN conceptions. In this way, the data sample for the most severe, cost-effective scenarios (4.4.4.0.4, 4.4.0.0.4, 3.3.3.0.3.) a negative consumption of PE for a few geothermal heat pump scenarios, that reach up to -1,930.75 MWh, -1,125.97 MWh, and -970.09 MWh of PE, respectively. However, this surplus of energy obtained because the electricity consumption from inhabitants was not taken into consideration, and it will dramatically affect a final value.

The SPF factor considered for heat pumps calculated as a total heat energy output per annum to the total electricity consumed per annum. The total heat energy per annum was characterised based on a percentage of fuel savings that heat pump provides for consumption of gas fuel, comparing to natural gas boilers respective scenario. After that, this percentage applied to the final demand in this way share of demand met by HP has been taken. The SPF graph for considered heat pumps from scenario C and D presented in Figure 17.

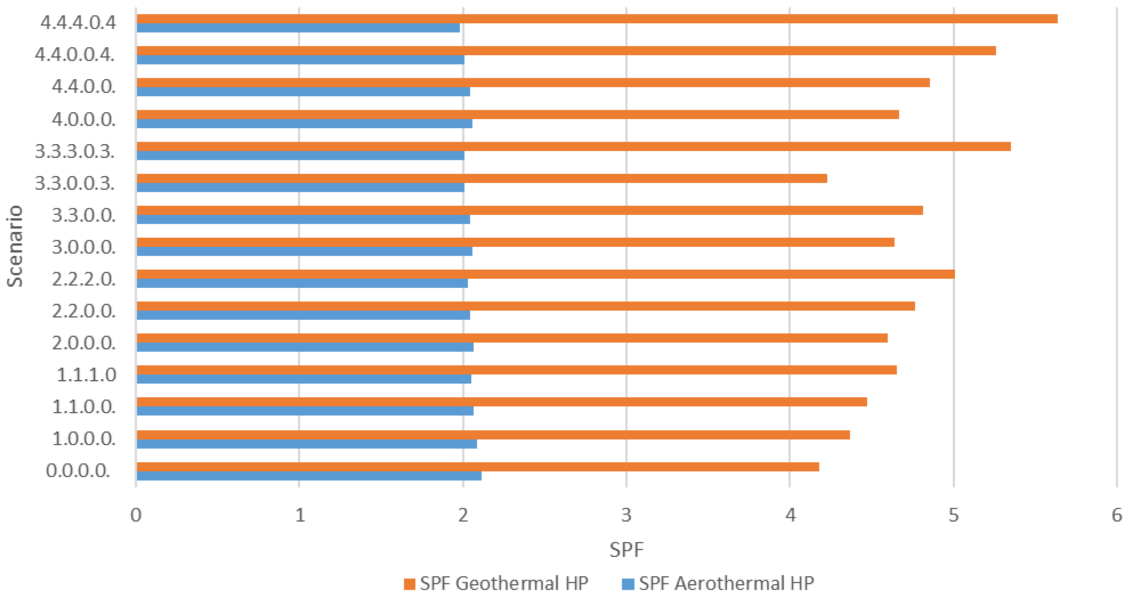

Figure 17. SPF factors of geothermal and aerothermal HP

As it can be seen the SPF factor of geothermal installation supposed to be quite high, varying from SPF 4 to SPF 5.6, which is within discussed values from the literature [14]. At the same time, the aerothermal solution has a much lower SPF of around 2 that in general can be considered as such low value is not enough for the heat pump to be feasible.

The heat losses were characterized in relation to the base scenario and depicted in Figure 18. The general tendency is in conjunction with fuel consumption savings comparing to the base case. Thus, gradual improvement of façade, which is the lowest savings within each option, of 1.0.0.0 scenario is equal to about 6%. After that typically follows façade and roof (1.1.0.0.), and façade, roof, and windows (1.1.1.0). This tendency kept the same regardless of the degree of renovation measures severeness. The introduction of infiltration within options 3 and 4 slightly change a tendency and puts a combination of façade, roof, and infiltration over façade, roof, infiltration, and window.

For qualitative characteristics of the cost of heat losses, they must consider the different weights of electricity and natural gas fuel prices total consumption. Thus, losses cost calculated as weighted value for consumption of gas and electricity within ESS technologies. This is because the consumption of electricity for heat pumps dominates, and the weight of electricity price over natural gas price within consumption is higher.

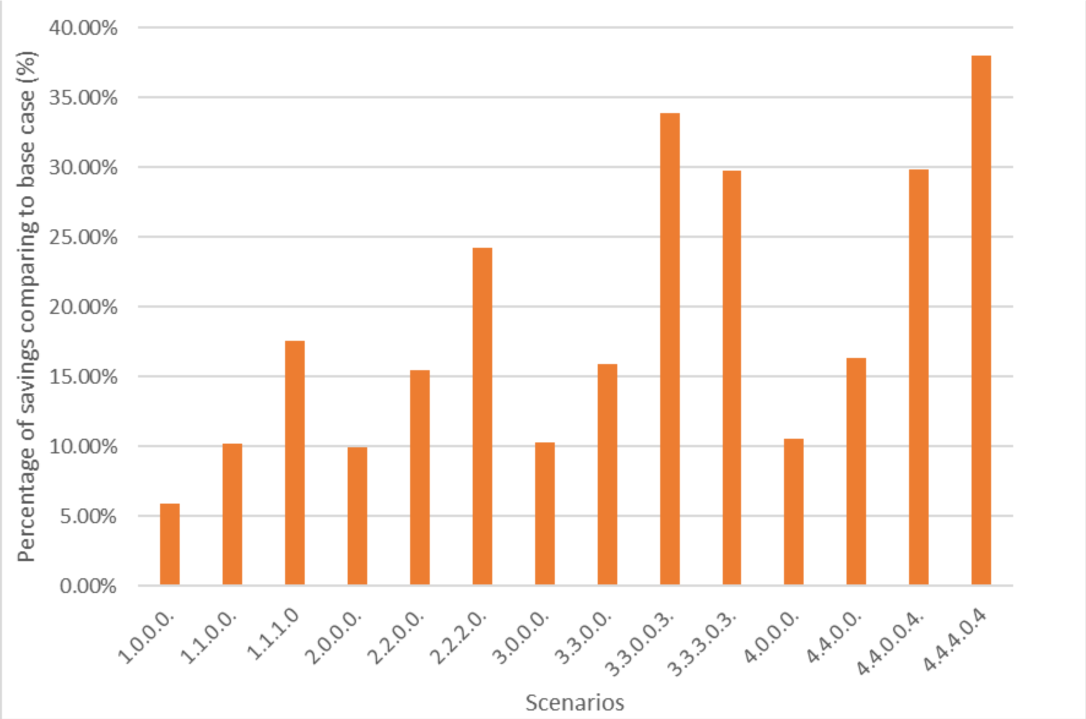

Figure 18. Heat losses cost decrease comparing to base case scenario

With the installation of a solar PV system with a life period of at least 25 years, LCOE for the abovementioned investments is equal to 0.085 €/kWh. Conducted sensitivity analysis (Figure 19) carried out to measure the impact of key factors on the LCOE and provide a contribution element within considered simple payback period. It shows that, naturally, having a low operational cost for a solar system slightly affects an LCOE value, while project lifetime and amount of investments have the biggest contribution. Thus, in case of a 50% increase in lifetime, the final LCOE can be roughly equal to 0.067 €/kWh, and in case of investment decrease, LCOE demonstrates a linear two times decrease up to 0.042 €/kWh.

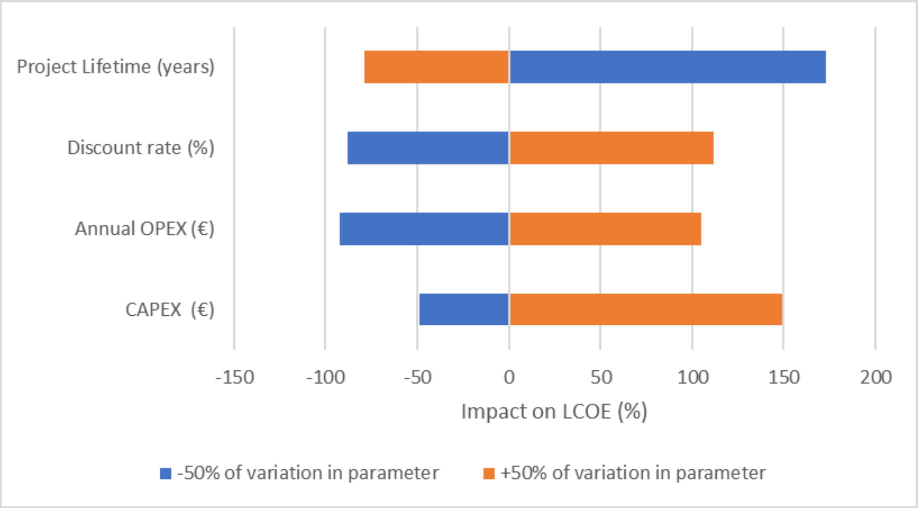

Figure 19. Sensitivity analysis of LCOE of solar PV on district level

LCOE helps to make the final decision on the choice of system and provides a quick and effective assessment of the various alternatives. However, the average cost can also simplify and erroneously provide comparative figures due to many different assumptions (service life, system failure rate, warranty period, loan rate, discounts, etc.) involved in the calculation. The LCOE also does not consider differences related to seasonal and daily long-term use. Finally, this method is not able to take into account such vital factors as personal income and expenses.

5 Discussion

To analyse a characteristic for the district-level approach comparing to improvements considered on the building level, the final diagram is illustrated in Figure 20. In this way, district calculations plotted together with calculations made for an individual building within the same 15 passive EEM, and 4 types of ESS. It is presented per square metre of building conditioned floor area. The area of the building considered in line with the abovementioned reference building and equal to 2,066.02 m^2. Among plotted 240 scenarios that include in equal share a district calculation per building with PV (in blue) and without PV (in yellow), individual building calculation with PV (in orange) and without PV (in grey), the predominant portion of data allocated along oy axis in a way that district heating solutions have a lower investment EUAC per building area.

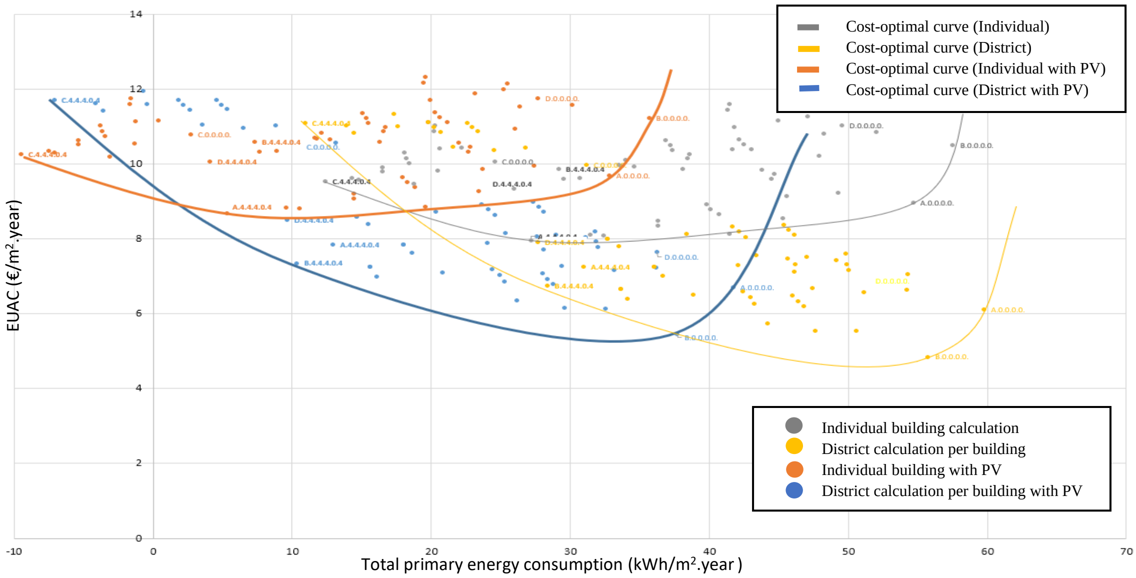

Figure 20. Cost-effectiveness for individual building and district level

The basic scenario and the most cost-effective scenario for energy consumption were specially named on the graph. It can be seen that district heating can provide a lower consumption for biomass boiler and aerothermal HP solution for the base case of renovation (0.0.0.0). But, when we consider natural gas scenarios, district heating can provide a lower cost of investment per building, however, the consumption of energy is preferable towards an individual solution. At the same time realisation of a geothermal heat pump on a district level with the most severe (4.4.4.0.4) potentially results in the cost-effective solution that can significantly reduce PE consumption to provide the lowest energy consumption.

The reduction in demand for geothermal scenario leads to an increase in demand met by this main technology. Thus, with the reduction of heating demand by the introduction of severe passive measures, it can be seen in the example of geothermal HP that centralised solution investment cost rise dramatically to 22,950 €, while individual building solution can be even cheaper, roughly 19,000 €. The centralised technology also includes capital expenditures on the distribution network, and with a decrease of heating demand EUAC rise significantly, making considerable project extremely dubious from feasibility purpose. In this way, individual heat pump able to meet a larger portion of demand having less cost for annual expenditures.

By tracing a schematic cost-optimal curve through the scenarios for individual building and district calculation per building we can outline a set of tendencies. Firstly, the cost-optimal curve for building goes down more steadily, in this way, to consider a reduction in PE consumption, the individual building scenarios are a beneficial option. At the same time, looking at the district level cost-optimal curve, the centralised heating could provide a lower value of investment within a considered neighbourhood. Thus, if the measures for reduction of energy demand applied, the district heating solution is less interesting than acting at the building level.

Secondly, to achieve lower primary energy consumption with convenient boiler solutions, natural gas installation for individual building able to reach lower energy consumption comparing to corresponding technology on the district level. At the same time, distinct heating installation could have lower investments per building.

Finally, biomass boiler installed on a district level is more beneficial solution compared to the same technology installed on the building level, either from the point of investment cost and lower total PE consumption of 5.55 €/m^2.year with 37.75 kWh/m^2.year , to 11.36 €/ m^2.year with 39.25 kWh/m^2.year respectively for base case scenario with PV. With a decrease in energy demand, we observe that the district solution becomes less effective from PE consumtion in this way values are equal to 10.31 kWh/m^2.year and 7.35 €/ m^2.year compared to individual buildng 7.28 kWh/m^2.year and 10.59 €/ m^2.year. At the same time, a biomass boiler solution can not be considered as an undoubtedly optimal solution for the district, as several logistical and investment features must be outlined as it can significantly affect the feasibility of such an option.

6 Conclusion and future work

To conclude, based on a set of input data of the model with a reduced simulation time possible district energy supply system schemes were successfully addressed. Based on the model and designed heating systems for a district heating scale energy characteristic of the neighbourhood has been obtained and analysed.

The optimisation of district heating was considered within passive energy efficiency measures applied for considered buildings of the district. Thus, the design of district energy supply systems was adopted to each specific scenario of renovation and referred to load design for the neighbourhood, as well as analysis in the form of annual duration curve for heating and DHW demand. The integration of RES was performed by solar PV technology considered on a district scale within a cost-effectivity analysis.

Finally, the objectives initially set for the study have been fulfilled. Firstly, the ESS scenarios have been designed, described, and introduced into the digital model within the set of justified simplifications. Interaction of ESS and EEM measures was characterised based on simulated energy demand and consumption within considered scenarios.

Secondly, an interaction between passive and active measures has been investigated within a methodology based on a district model performed in the Design Builder program. The constraints within an ESS design were defined, described, and overcome via study and introduction set of simplifications and assumption justified in the work. Within the study of the modelling tool, the design of nominal capacity for installed technologies was adopted taking into account changing demand for each scenario. independence to using economic analysis.

Finally, based on the equivalent annualized cost method and total primary energy conception cost-effectiveness analysis has been done. It was investigated that energy supply systems on a district scale can reach a lower amount of cost per unit of energy for particular technology comparing to individual building level within a case study.

It was investigated that the most cost-efficient scenarios are reachable with a severe passive measure, such as scenario 4.4.4.0.4, 3.3.3.3.0.3 and 4.4.0.0.0.4. The district-scale solution can provide slightly lower investment costs per building for the majority of scenarios. However, individual building renovation within a considered case study has lower PE consumption for some of the conventional technologies, such as individual building gas boiler installation. As the individual solution does not require investments into the distribution network, it plays an immense role in the feasibility of district heating with reduction of heat demand using a fossil fuel combustion technology for heat production.

District-level heating can be considered for different energy sources. In this way, the implementation of combined heat and power (CHP) installation as a prominent option for PED and energy community conceptions was not included in the final report and could be a matter of further research in line with the already considered model and alternative energy sources. The specific analysis for distribution network design for a case study within a pipeline network feasibility study, qualitative characteristic of distribution heat losses is also a prominent direction within future research within a case study scope.

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Appendix A

Composition of the building enclosures

	e(m)	Conductance (W/m·k)	Capaci-tance (J/kg·K)	Density (kg/m^3)	Thermal resistance (m2·K/W)
Exterior wall					
Gypsum	0,01	0,5	1000	900	
Hollow brick	0,045	0,488888889	900	1200	
Vertical Air gap (NoVent)	0,04	-	-	-	0,1692
Hollow brick	0,125	0,488888889	900	1200	
Fibre glass	0,02	0,04	840	12	
Hollow brick	0,045	0,488888889	900	1200	
Cement mortar	0,035	1,4	1100	2000	
Façade U-value (W/m^2K)	**0,75**				
Exterior roof					
Cement and sand mortar	0,01	1	1000	1800	
Hollow brick	0,045	0,488888889	900	1200	
Cement and sand mortar	0,01	1	1000	1800	
Horiz. Air Gap	0,02	-	-	-	0,0792
Roof tile	0,01	1	800	2000	
Roof U-value (W/m^2K)	**2,842**				
Floors and ceilings					
Conifer wood flooring	0,01	0,14	2800	600	
Horiz. Air Gap	0,01	-	-	-	0,1512
Hollow tilled Floor (20+4)	0,24	1,041666667	1000	1500	
Gypsum covering	0,01	0,4	1000	1000	
Floors and ceilings U value (W/m^2K)	**1,453**				
Indoor walls					
Cement and sand mortar	0,01	1	1000	1800	
Hollow brick	0,125	0,488888889	900	1200	
Cement and sand mortar	0,01	1	1000	1800	
Indoor walls U value (W/m^2K)	1,453				

Appendix B

Composition of the enclosures

	OBJECTIVE	CONSIDERED CLIMATIC ZONE	VALUE ACCORDING TO CERTIFICATE	ACHIEVED VALUES	MEASURES
FAÇADE	**CTE HE**	Zona C1 (Bilbao)	U = 0,49 W/m^2 K	U = 0,49 W/m^2 K	2,83 cm EPS
	CTE HE-E ANNEX	Zona C1 (Bilbao)	U = 0,29 W/m^2 K	U = 0,29 W/m^2 K	8,46 cm EPS
	-	Zona C1 (Bilbao)	-	U = 0,27 W/m^2 K	9,48 cm EPS
	Reach Enerphit	Warm-Temperate	U ≤ 0,30 W/m^2 K	U = 0,25 W/m^2 K	10,66 cm EPS
ROOF	**CTE HE**	Zona C1 (Bilbao)	U = 0,4 W/m^2 K	U = 0,40 W/m^2 K	8,59 cm EPS
	CTE HE-E ANNEX	Zona C1 (Bilbao)	U = 0,23 W/m^2 K	U = 0,23 W/m^2 K	15,98 cm EPS
	-	Zona C1 (Bilbao)	-	U = 0,201 W/m^2 K	18,10 cm EPS
	Reach Enerphit	Warm-Temperate	U ≤ 0,30 W/m^2 K	U = 0,18 W/m^2 K	20 cm EPS
WINDOWS	**CTE HE**	Zona C1 (Bilbao)	U = 2,1 W/m^2 K	U = 2,1 W/m^2 K	-
	CTE HE-E ANNEX	Zona C1 (Bilbao)	U = 2 W/m^2 K	U = 2 W/m^2 K	-
	-	Zona C1 (Bilbao)	-	U = 1,52 W/m^2 K	-
	Reach Enerphit	Warm-Temperate	U ≤ 1,05 W/m^2 K	U = 1,05 W/m^2 K	-

SEPARATION FROM NON-HABITABLE SPACES	**CTE HE**	Zona C1 (Bilbao)	U = 0,7 W/m^2 K	U = 0,70 W/m^2 K	3,12 cm EPS
	CTE HE-E ANNEX	Zona C1 (Bilbao)	U = 0,48 W/m^2 K	U = 0,48 W/m^2 K	5,74 cm EPS
	-	Zona C1 (Bilbao)	-	U = 0,39 W/m^2 K	7,66 cm EPS
	Reach Enerphit	Warm-Temperate	U ≤ 0,30 W/m^2 K	U =0,30 W/m^2 K	10,74 cm EPS
INFILTRATIONS	**CTE HE**	Zona C1 (Bilbao)	-	-	-
	CTE HE-E ANNEX	Zona C1 (Bilbao)	-	-	-
	-	Zona C1 (Bilbao)	-	0,45 h-1	-
	Reach Enerphit	Warm-Temperate	< 0,6 h-1 (n50)	0,3 h-1	-