Master's thesis

Master's degree on Energy Engineering

Implementation of methodologies for calculating vertical Borehole Heat Exchangers (BHE) lengths for Ground source heat pumps (GSHP) systems in MATLAB: Design of an App

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Abstract

The exponential exploitation of fossil fuels in the XX century, despite its positive benefits in terms of life quality and macroeconomic indicators, has brought what some consider the biggest challenge in the history of human era, being Global Warming and the consequent Climate Change.

Citizens are bombed everyday with information and press notes regarding the need to change the old, traditional fuels for new, renewable, sustainable energy sources, that joins technological advances with the sensitivity for environmental preservation, in a secondary transition from centralized to distributed generation and auto consumption.

In this process, very low enthalpy geothermal installations can be a suitable option to air condition facilities and residences thanks to its flexibility and operability as thermal resources for both heating and cooling, coping with one of the most important energy consumption needs of buildings, and becoming an investment that would save money to its users. However, the lack of tools to assist professionals and citizens in the sizing of these installations hides the potential of this technology for the future.

To assist the solution for this inconvenience, this project has been devoted to the conception of GeoHPEX-design tool© (v1.0), a standalone application to allow users (both professionals and citizens) to design very low enthalpy geothermal installations with vertical borehole heat exchangers.

In this document, the reader will firstly understand the potential of this technology in the territory of Catalunya and the justification for constructing this application, after which it will be possible to study the theoretical design, the graphical user interface design and the mathematical models implemented in the program, finishing with its validation and calibration. The final product will be available at a resource dependant on the Institut Cartogràfic I Geològic de Catalunya, open to all users willing to try GeoHPEX.

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Contents

List of figures

List of tables

1. Introduction. Theoretical bases

1.1 On Engineering and its social responsibility

The History and development of Human kind as a species is inevitably linked to that of the evolution and development of Technology. Since the beginning of human consciousness and cognitive development, human species has been able to transform and adapt the environment to its needs through new, innovative creations and tools, as it is the only animal on Earth capable to develop complex novel concepts, previously inexistent, by the use of the available resources [51].

On the early era of Human race, the civilization with the most advanced technological and engineering skills had the better chances to dominate the rest of them, as a consequence of the predominant war culture. The invention of bows and arrows, in this sense, would suppose a decisive development on military engineering that would drastically decrease the resistance of opposing civilizations that did not control this technology, while the design of channelling, roads and new construction methodologies would enable the growth of cities, improve the salubrity and allow the increase of the population, as in the case of Greek and Roman civilizations.

Through years after, the ongoing findings on the different technological fields threw positive results on life quality and allowed possibilities hardly conceived. Let it serve as an example the creation of Juanelo Turriano [10] for the city of Toledo (Spain) called '*Artificio de Turriano*', an engineering system to pump water from the river Tajo (flowing beside the city) to the highest part of the capital. This Italian-Spaniard engineer designed and supervised in the XVI century the construction of a mechanism that would pump water from the river by saving the approximately 100 meters difference in height from the shore to the town hall, outperforming the Archimedes screw installed in Augsburg (highest water jump known by that time) by 60 meters.

Fig 1.1. Model of the 'Artificio de Juanelo' exposed at the Fundación Juanelo Turriano (Madrid) [11]

Forwarding to modern engineering, from the epistemological perspective the development has focused primarily on the solution of technological challenges, and has encountered up to what has been named as five 'innovative waves' [40]. The first recognized wave is the design of water – powered mechanisms, followed by the second wave with the steam – powered machines, the railroad growth and the use of steel as a material for construction.

On the third wave, electricity and chemical innovations (with the internal combustion engine as the main achievement) supposed the main challenges to scientists, with further improvements in the fourth wave on petrochemicals and electronics, plus aerospace engineering. The latest wave, and the one in which the society is currently at, is the innovation on digital networks and information technology.

Coming to the end of this fifth wave, the future of engineering is likely to pursue the success of the 17 goals of Sustainable Development [45], especially in the goals for good health and well-being (3), clean water and sanitation (6), affordable and clean energy (7), industry, innovation and infrastructure (9) and climate action (13). Further future relies, however, on mere speculations for the relationship of technology and humans [13].

As it may be noticed, this future innovation wave has a great distinction from the rest of them, highlighting concepts such as 'sustainable' or 'clean', stating that not only the technological perspective is considered, but what is sought is to combine it with the optimization in the use of resources and a sensitivity for environmental preservation.

Whether if it was explicit or not, the development of new technologies has had an enormous impact on society besides if the motive was to resolve a technological challenge or to improve the life quality of society, endowing the profession of engineering with a social responsibility towards the rest of the population coming from their ability to transform society.

This duty, however, has been forgotten by some, just as Gerard van Oortmerssen (president of the International Council of Academies of Engineering and Technological Science) points out at the United Nations Educational, Scientific and Cultural Organization (UNESCO) report for Engineering published in 2010, where he claims that although technological innovations have created wealth, facilitated our life and provided comfort, only a few have had access to it [40].

This report emphasizes the role of engineering to end with social inequalities, pointing out the main challenges in the different fields of engineering. Under this framework, the present work has set its main goal to develop an open tool that can be accessed by all users and whose property is a public entity, ensuring that there is no other purpose of this work different from sharing it with anyone willing to make use of it.

The construction of this application is hopped to bring renewable energy technologies to the different users that can be found, and show them that the transition to sustainable energies is no longer a dream for the future but a reality of today, whose feasibility is proven.

Together with this hope, the main motive of this project is to share the knowledge of engineering with as many as it can be, as a response of the social responsibility that, as an engineer, the author thinks to possess. Being aware of its limitations, it is his desire to build a useful tool that can enable a sustainable future for society, as far as possible.

1.2 Definition of the project. Objective

The purpose to which this project is dedicated is the development of an application of public access that enables users to perform a theoretical calculation of the length of vertical Borehole Heat Exchangers (BHE) for Ground Source Heat Pumps (GSHP), by following the methodology described by the International Ground Source Heat Pump Association (IGSHPA) [42], recommended for installations with thermal loads below 120 kW. The ownership of the application has been granted to the Institut Cartogràfic I Geològic de Catalunya (ICGC) by the author of this project, both interface and code. The name of the program is GeoHPEX-design tool© v1.0 (from this point, GeoHPEX).

The methodology described by IGSHPA is standard and has been adapted to the different requirements of other associations around the globe. In this sense, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) published in 2015 the adaptation of this methodology to the American standards, creating a guide for the design of Ground-Coupled, Groundwater and Surface-Water Systems for Commercial and Institutional Buildings [26], while the Instituto para la Diversificación y Ahorro de la Energía (IDAE) adapted the methodology followed in this project to the Spanish regulation, adjusting minor details on the work of IGSHPA [3].

As some of the modifications performed by these two entities enhances the performance of the calculation methodology originally described by IGSHPA, either by improving the approximation of the heating and cooling demand of installations or by reducing execution time, the final methodology used for the development of this project has implemented the improvements mentioned from both adaptations, and ensures the application to follow the current Spanish regulation regarding geothermal installations.

To design this application, the tool *App Designer* of Matlab® 2020a is chosen as for a request of the ICGC, under whose environment the methodology selected is implemented. Therefore, the application design not only will consist on the implementation of the methodology in a script, but also in the design of a Graphical User Interface (GUI) through Matlab® to assist the user in the handling of the application.

The program is intended to evaluate the length of vertical BHE for facilities, by introducing the necessary information (dependent of the use the user is willing to have for it) through the GUI. Although it is conceived for all users, the technicity of the information that the app handles might not be suitable for all publics, leaving its main use to technicians or professionals.

The design will be able to perform the calculation for the length of the BHE distinguishing between newly built constructions and installations already built, although the selection of each criteria is open to the user. Consequently, in case the user already knows the heating and cooling load of the facility, together with the annual energy consumptions for both conditioning modes, he will not be required to introduce in the program the information regarding the constructive characteristics of the building.

In case of newly built constructions (or for those that lack from the information of the facility), the application will perform the calculation by estimating first the thermal load for cooling and heating of that facility, based on the constructive characteristics of the building and the type of use, then following the mentioned methodology.

The type of use of the facility determines the methodology followed to calculate the thermal load for heating and cooling. Consequently, a broad display of uses is intended to be offered for the user to select. With this characteristic, the application is able to perform the calculation of the thermal demand for any kind of service and surface.

To perform this design, the user will be required to introduce the geographical position at which the facility or installation is located. The territory under which the calculation is limited corresponds to that of Catalunya, as for a request of the ICGC due to the ownership of the maps containing the necessary information for the calculation.

By introducing the coordinates in the system through the GUI, the program will automatically read the thermal design conditions and weather in accordance to the Spanish 'Documento Básico HE' [32]. Once the user has entered the mentioned information, the system will be able to acquire the required data to complete the thermal model, thus avoiding the user to seek information regarding the climate at their locations.

After the comfort temperature and the geometry is set, the user is open whether to use the information of the heat pumps stored in the application, or to introduce to information of a heat pump of their own. Apart from that, in case the user already had information of the terrain in which the location is set (cases where a Thermal Response Test [TRT] was previously made, for example), the application will offer the possibility to use those results as inputs to the program, in exchange of those stored by ICGC in its maps. With this last input, the user will be now ready to execute the program and get the results.

The application will be in the format of an executable file (.exe) that will contain the required information for the correct functioning of the application, being the intention for this project that the user will only have to download this executable, being able to run in all operative systems.

As a summary, the goals for this application should fulfil the following requirements:

- Easy for its use. The program has to assist in case the user does not understand how it works.
- The information demanded to the user should balance the detailing of the installation and the excess in information requirement. As this is an

approximation to a real installation, the increase of the degree of detail may not achieve an improvement in the results, and it may confuse other users.

- Optimal response. The solution offered should be the optimum, reducing the chance of oversizing an under sizing, thus minimizing environmental impact and engaging the optimum point of operation for the Heat Pumps.
- Fast calculation. Although the amount of information required for the modelling is large, the program should not take long to perform the calculation and offer the response.
- Offer reliable results. The model has to be calibrated to improve the performance of it.

Taking into account the objectives exposed above, the building of the application is being developed and corrected by ICGC, applying the necessary modifications and adding convenient suggestions from the 'use-and-feel' perspective.

1.3 Review of the State-of-the-Art

Though the methodology established by IGSHPA is been described and revised in several occasions, and being studied by other associations to adapt the methodology to their standards, very few have attempted to develop a program that could automatically implement the system, fewer have designed a GUI to assist the process.

There can be two main reasons to this fact, according to this findings: on one hand, the first applications for geothermal energy where driven towards electricity generation, focussing the efforts into finding adequate spots for the installation of these type of plants, the adaptation of Brayton and Rankine cycles towards the energy range of the thermal heat resource (by the selection of organic fluids, for instance), and the selection of proper materials that could withstand the conditions under which the heat exchangers would operate.

This fact is also driven by economic factors. From the economical perspective, a power plant results more profitable than small installations as the ones planned to be addressed in the project, in which case the efforts of professionals would be directed to enabling the operability of the most profitable option. The greater the thermal resource is, the better profitability it shows, under a framework of positive policy measures [5] [38].

After this option was broached, other different possible applications had been taken into consideration, arriving to the actual use for lower enthalpy systems (revise *1.5 The soil of Catalunya. Evaluation of geothermal potential in the territory of Catalunya*).

On the other hand, the few uses for low energy systems and the existence of the available methodology drove to the individual application of the mentioned, not using special tools for it. Hence, each individual project was designed following the steps described in the literature without using any special tool for it, which could become a tedious process when it came to predefine some operating conditions and adjusting the thermal response of the location to the previous calculations.

Although geothermal energy is below the evolution proposed by the European Commission for the future of the Zone [8][9], the possible application of low enthalpy thermal systems for thermal conditioning of facilities and residencies is handled nowadays as the way-out to fulfil the objectives imposed from Europe regarding geothermal energy.

Coming back to the State-of-the-Art, two different tools have been found that could relate to the application developed in this project, namely GEO2D [12] and RETScreen® International [39].

GEO2D consists on an open script for Matlab® that executes the calculation of vertical and horizontal BHE considering a 2D model of the ground, by approaching the performance of the ground heat exchanger and the heat pump from the thermodynamic point of view.

It makes use of finite elements to evaluate the differential heat transferred by every successive infinitesimal section of the tube (taking advantage from the symmetry of the tubular ground heat exchanger), and calculates both the number of boreholes and the length of the heat exchangers with accurate precision.

This tool, however, requires the user to mandatorily know the thermal load and the energy demand to calculate the length of the exchangers, and does not consider the availability of commercial ground heat exchangers, that could alter the results.

On the other hand, RETScreen® was designed by the Minister of Natural Resources of Canada between the years 2001 and 2005, conceived to become a standard tool to execute energy efficiency analysis of facilities and implement renewable energy projects for both big and small installations. Its constitution is the result of the collaboration of the Canadian CANMET Energy Technology Centre – Varenness (CETC), the National Aeronautics and Space Administration (NASA) and the Global Environment Facility (GEF).

Its scope is broader than GEO2D or the project explained in this document, as it performs calculations for any kind of renewable source existent, focused however on wind and solar energy. A screenshot of the program is attached below.

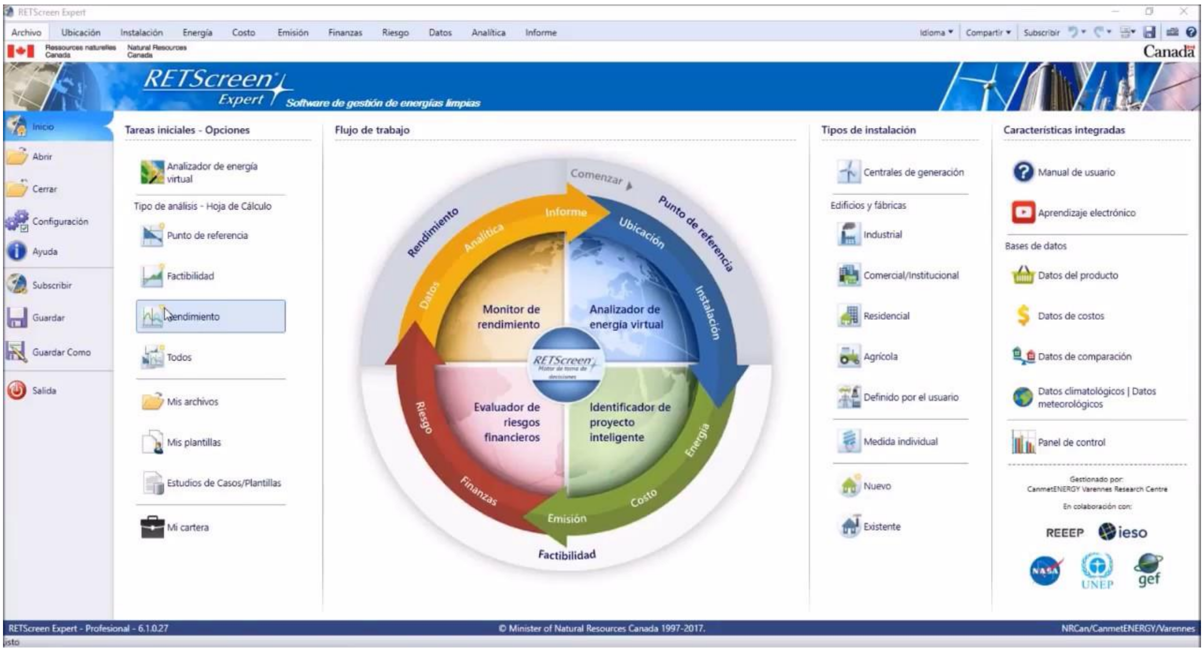

Fig 1.2 Screenshot of the application RETScreen® [39]

As it looks, the feel of the GUI corresponds of a professional design with a broad set of options to choose, in which it is possible to find the option for the design of a geothermal installation.

By means of the ICGC, it had been possible to access the manual regarding the computation of geothermal installations that RETScreen® counts with, in order to analyse the newness included from the original work from IGSHPA.

From the study of the procedure of IGSHPA, IDAE and RETScreen®, the methodology used to compute the thermal demand and the length of vertical BHE was developed. Hence, it is worth mentioning that a part of the methodology implemented in the project is inspired on the systems from the theoretical perspective, as the programming of them is either inexistent or secret and has been designed and implemented entirely by the author of this project.

To understand the strengths and weaknesses of RETScreen®, an analysis is performed to detect the sections that could be taken into consideration, from those that could be improved or replaced, or that did not fulfil the requirements set by the 'Código Técnico de la Edificación' (CTE) in the document 'Documento Básico HE' [32].

Several improvements were detected and were suitable to be replaced:

- The amount of information demanded to the user was excessive compared to the precision showed by RETScreen®. Along the calculation of the geothermal installation, the user was urged to introduce numerous parameters regarding the climate at the location of the facility, average temperature ranges experienced at the location or other inputs regarding the soil characterization, while the error of the result following the methodology for calculating the demand exceeded the precision of the inputs.
- Linked to the previous point, the user was demanded to introduce parameters to the GUI that could sound strange to one unless it is used to deal with such language, and that is not usually found easily when looked at any search motor. The user can become confuse when they are asked for the Heating Degree Days at their location, when it could be automatically acquired with the location of the facility (this is in fact the procedure followed by GeoHPEX).
- Low options in the uses of the building. RETScreen® considers up to 4 different types of use of the location, which are the industrial use, the use as office building, and the residential usage, in case of having or not having basement. The user does not have further choices to make.
- Wrong interpretation of the fresh air latent load (see *2.4 Heating and cooling load estimation*). In the Canadian application, the computation of this load is performed by relating it to the sensible load previously calculated, through a

linear interpolation showed below, constituting an unprecise method to establish the latent load from this source.

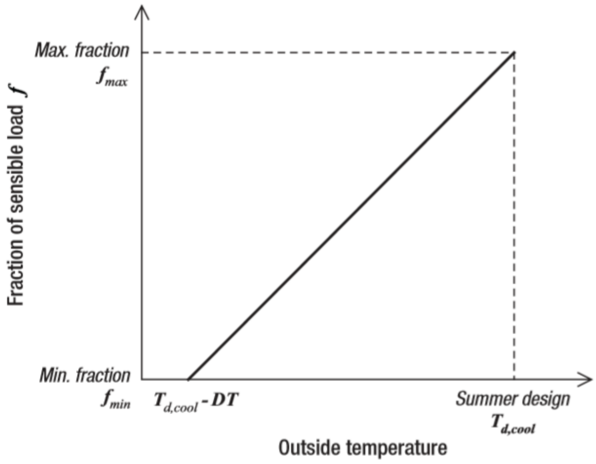

Fig 1.3 Theoretical concept of the latent to sensible fresh air load. The variable $T_{d,cool}$ stands for the temperature set for cooling design, while DT is the design day temperature range. F_{max} and F_{min} are tabulated values of the relationship between latent and sensible load, ranging from 2.5 to 0.5 [39]

- Poor validation of the models. Along the description of the methodology for the calculation of the geothermal systems, there is an evident lack of referencing explaining the precedence of the information used.

Having seen the possibilities of improvement of the systems, there was defined a list of future developments that could be implemented in GeoHPEX, in accordance with the opinions of ICGC:

- The possible uses for the facilities should be increased, requiring to establish a method to differentiate each use and to be justified.
- There is no reference in any of the projects to the definition of the geometry of the building. Further in the project it will be seen that RETScreen® system defines a squared geometry, which could be improved by defining other different geometries.
- Reduce the number of inputs to the GUI. The application should automatically load as much information as it could be, especially in the case of climatic parameters and soil characterization.
- Modify the methodology to perform a more realistic calculation of the thermal load, especially in the case of the latent fresh air thermal load.
- Validate the application with the results gathered by ICGC, that will help to calibrate the model and distinguish possible bugs in the building of the program.

The following sections in this document will cover the development of the application and the methodology followed, preceded by the justification and the potential of geothermal energy installations in the territory of Catalunya.

1.4 Renewables in the World and Catalunya. Role of geothermal energy

Since the discovery of oil and its derivatives, the World has seen an exponential growth in its energy consumption derived from the possibility of having a fuel with high energy density and high security of transportation and availability, that has led to both positive and negative impacts been studied in the Master on Energy Engineering (under which this project is developed) and whose final conclusion points towards Renewable energies as a solution for a sustainable progress, defined as energetic resources that are constantly replenished or that are virtually inexhaustible, and whose impact on the environment is presumably low.

In 1900s, the annual global primary energy consumption according to statistics was of 12,500 TWh. Nowadays, the latest statistics (2015) according to the International Energy Agency (IEA) establishes the annual global primary energy consumption at 158,490,6 TWh, which is above 12 times greater than that of the beginning of the XX century [22]. This unprecedent evolution is showed in the figure below, where it is observable the strong influence of crude oil and natural gas in the increase of energy consumption:

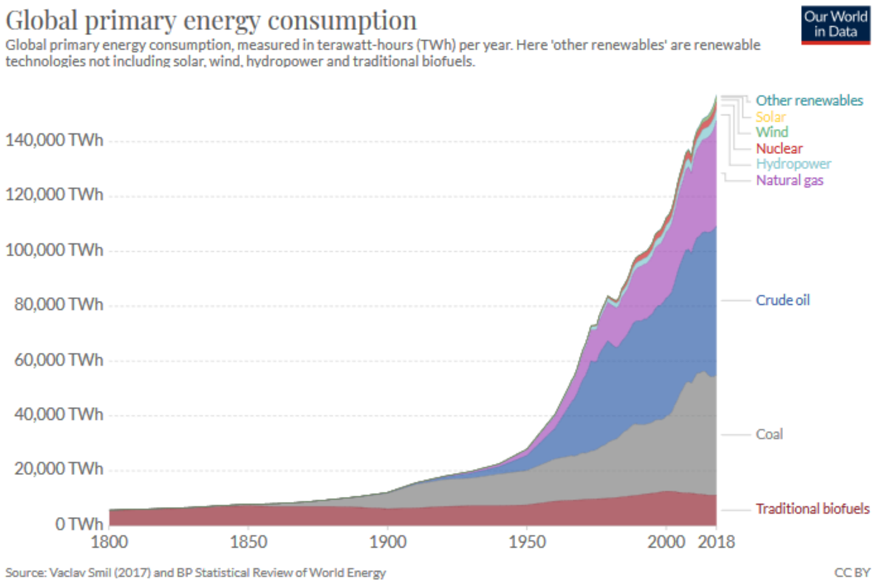

Fig 1.4 Annual global primary energy consumption, from 1800 to 2018. Though the image is extracted from Our World in Data [36], the source of the information comes from the BP Statistical Review of World Energy and Vaclav Smil (2017)

This increase in the energy consumption has brought those who had the access to it a greater standard of life quality, established by a direct relationship between both factors: the greater the energy consumption (related to any index, such as energy per capita, per Gross Domestic Product or by population), the higher is the life quality index, though there is a point in which further energy consumption does not result in any increase of the life quality [37].

Quality index is a non-measurable concept that evaluates statistics such as life expectancy, coverage of the Healthcare system, Gross Domestic Product (GDP), etc. An example of this relationship is shown below this text, where the relationship mentioned is justified.

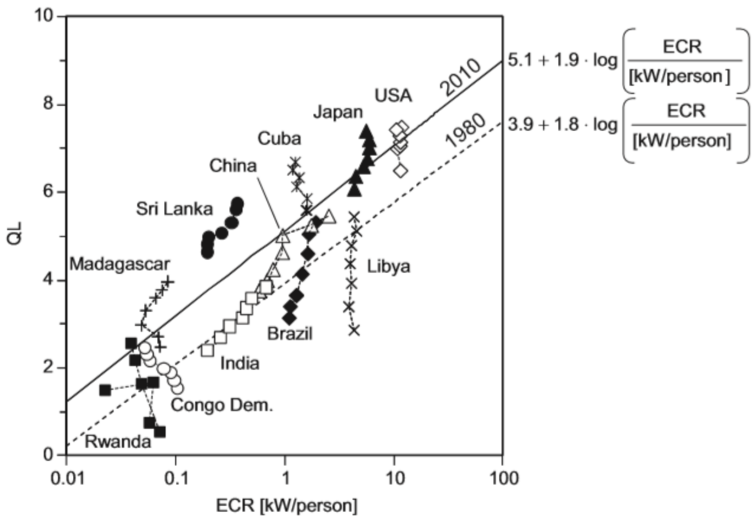

Fig 1.5 Life quality (QL) related to the energy consumption worldwide (ECR) [37]

These evident benefits have not come without a cost, as the main energy sources that provide the final energy consumed come from fossil (traditional) fuels, which after its combustion there is a significant level of emissions of CO_2, CH_4, NO_x, particulate matter and other compounds, main agents of the phenomena known as Climate Change and Global Warming [2][28][29] [33].

As a consequence, the opportunities demonstrated by renewable sources to provide the required energy (mainly electricity) demand by accounting the sustainability of the environment has brought an increase in the installed capacity of this sources worldwide. Thus, the irruption of Solar PV technology and Wind power has increased the share of the installed capacity of renewables, as seen in the following chart:

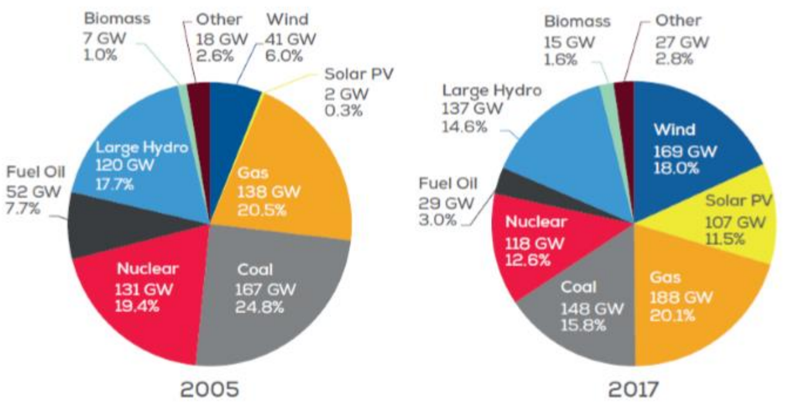

Fig 1.6. World installed capacity, by sources [50]

Despite the important presence of renewables in the installed capacity, the reality is that only the 34% of the electricity produced worldwide come from renewables (considering Hydro power and nuclear power as renewables), and just a 18.36% of the total energy consumption comes from renewables [22].

In the case of the European Union (EU), the share of electricity generation coming for renewables ascends to 46.45% (considering Hydro power and nuclear power as renewables for being 'clean' sources), while the annual primary energy supply has its origin mainly from non-renewable sources (71.74%). The European Union and the European commission have stablished, consequently, the necessary measures to reconduct the situation [6] [8] [9], with high levels of investments from the Commission.

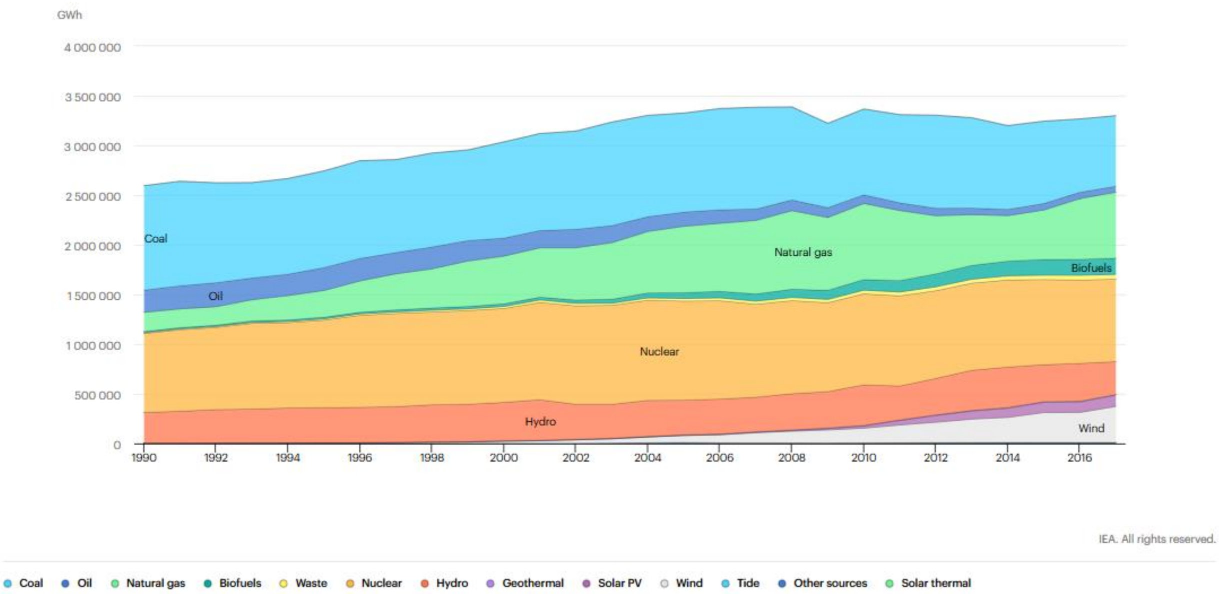

Fig 1.7 Electricity generation worldwide, by source [22]

Geothermal energy, for its part, has experienced a positive evolution in the supply of electricity worldwide from 1990 to nowadays, coming from 36,426 GWh annual to 85,348 GWh in 2017. This share, however, only accounts for the 8.2% of the worldwide electricity supply, while in Europe the share falls to a poor 0.15%.

This value is a consequence of the specific requirements for the implementation of high enthalpy geothermal power plants (revise *1.5 The soil of Catalunya. Evaluation of geothermal potential in the territory of Catalunya*) by the type of soil, the presence of geothermal resources and the availability of access to the geothermal source. In fact, Iceland produced in 2018 6,010 GWh of electricity from geothermal sources, which corresponds to a total of 30.3% of the total electricity consumption of that country.

As it is seen, the role of geothermal energy as an electricity supplier is not further developed compared to the rest of the sources, with a worldwide installed capacity of

13,931 MW [25]. However, the possibility of implementing this technology as a thermal heating and cooling supply has renewed the interest in this renewable source and has promoted new European strategic plans for the promotion of renewables in this way [7].

As for what accounts for Catalunya, the gross distribution of the installed capacity and the electricity production is shared between renewable sources and nuclear power plants, as it is seen below [19].

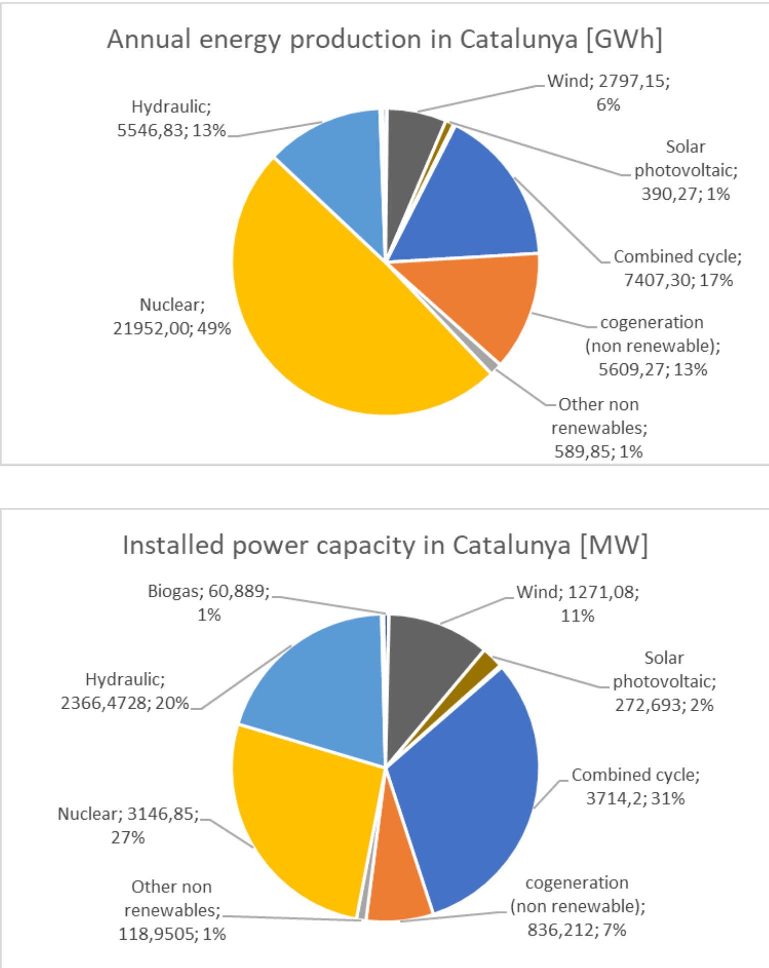

Fig 1.8 Installed power capacity and annual energy production in Catalunya for the year 2018. Own image, generated from the information available at [19]

The figures above show that the electricity production in Catalunya depends mainly on nuclear power, cogeneration, hydraulic energy and combined cycle power plants. If nuclear energy is included in the renewables for being 'clean', it would mean that Catalunya produces almost the 70% (69.6%) of the demanded electricity from renewable sources. Excluding the electricity produced at nuclear power plants (namely Ascó, Valdellós II) from either renewables or non-renewables, approximately 40% of the rest of the electricity comes from renewables.

Relating the installed capacity with the final energy generation along the year through the Capacity Factor $CF = \frac{E}{P \cdot 8760}$, being E the energy production along the year, and P

the nominal power capacity of the plant, it is seen that the source of energy with greater CF is Nuclear (0.796) followed by non-renewable cogeneration power plants (0.766). The energy source with less CF is solar photovoltaics, with an estimated value of 0.164.

Geothermal energy has not any presence yet neither for the production of electricity, nor for industrial installations registered in the energetic balance of Catalunya [20]. However, the geological constitution of Catalunya can open the door for the implementation of low enthalpy installation in its territory. The following chapters will address this possibility, that justifies the development of this project.

1.5 The soil of Catalunya. Evaluation of geothermal potential in the territory of Catalunya

Geothermal energy is an energetic resource that englobes a wide set of concepts, some of which are required to be introduced for the complete understanding of the potential of this technology in the territory of Catalunya. Hence, this chapter of the present document is dedicated to briefly introduce the reader to Geothermal energy, specifically to low enthalpy geothermal installations, and the possibility of its application in this territory regarding the soil conditions presented.

Geothermal energy is defined as the energy stored in the form of heat below the solid surface of Earth, originally absorbed from the incoming energy of the Sun in the form of light [44] and the heat released by the radioactive disintegration of the rocks. The energy that is able to be stored flows on the outer layers of the planet (crust) through conduction, while convection is the principal method of energy transference at the mantle.

Consequently, the term 'geothermal resource' is referred to express the concentration of heat existent at Earth's crust in form or quantity such that its extraction is potentially feasible and economically affordable. Economic feasibility is usually linked to the difficulty to access the geothermal resource, dependent of the soil type, the presence of underground water sources susceptible to be used (or, on the contrary, necessary to leave apart to avoid possible contamination of the resource) and the access to perforation technologies.

The types of geothermal resources can be classified by the geological context, the temperature level, the exploitation technologies and the type of deposit. The most popular system to classify resources is to segregate each of them by the temperature level, also known as enthalpic level, which classifies the exploitation methods into four different uses:

- Geothermal resources of very low enthalpy (very low temperatures): less than 30ºC. These resources are addressed in this project.
- Geothermal resources of low enthalpy (low temperatures): between 30 and 90ºC.
- Geothermal resources of medium enthalpy (medium temperature): between 90 and 150ºC.
- Geothermal resources of high enthalpy (high temperature): above 150ºC

Note: the referred temperatures respond to the maximum temperature difference experienced compared to ground temperature.

Geothermal resources of medium and high enthalpy are used primarily for electric generation, and the installation of these type of facilities require locations in which the deposits of geothermal fluids possess extraordinarily high thermal gradient (usually placed in regions with intense volcanic and seismic activity), usually aquifers separated from magmatic intrusions by an impermeable layer in sedimentary basins.

Low and very low enthalpy installations imply, however, fewer requirements compared to the above. Low enthalpy installations require locations with above-average (30ºC) thermal gradient, located at permeable sediment basins that allow the heat extraction through thermal fluids (water), and its main use is to supply heat to installations of considerable size (perforations between 100 – 150 m).

Finally, geothermal resources of very low enthalpy do not require much conditions, except the avoidance of continental and marine waters, since its use is to provide heat and cooling to small facilities. The soil, in this sense, acts as a buffer for the heat transfer, maintaining approximately a constant temperature along the year for layers below the mere surface (10 m).

In fact, this behaviour results favourable for providing heat and cool for a heat exchanger to air condition facilities: average ground temperature during winter is above outside temperature on the surface, while ground temperature during summer is below the outside temperature. Almost Earth's whole surface fits the requirements for applying this technology, existing two different configurations to access this resource: horizontal heat exchangers and vertical heat exchangers.

Heat and cool is extracted, as said, from a heat exchanger system, which consists on a piping structure in whose interior flows a thermal fluid, in charge of transporting the absorbed heat (or cool) to the heat pump installed at each facility (see *1.6 Commercial heat pumps and heat exchangers*). However, each display of the heat exchangers has its pros and cons, as will be observed.

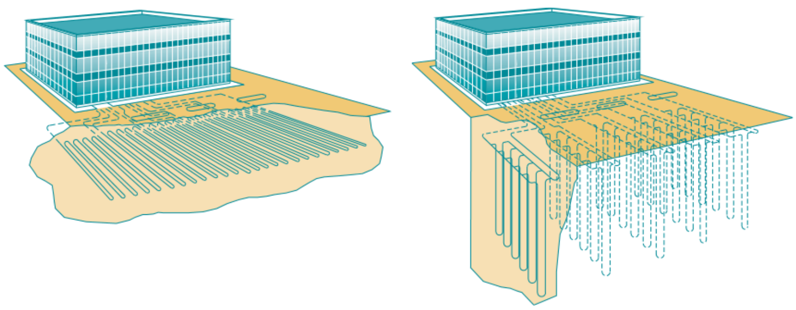

Fig 1.9 Horizontal (left) and vertical (right) arrangement of ground heat exchangers. Adapted from [39]

The implementation of horizontal ground heat exchangers results, due to the depths at which the piping system is buried compared to the vertical arrangement, in a less expensive investment in comparison. However, the performance of the exchanger system is not as efficient as the one showed by the vertical configuration, making necessary to install longer exchangers. Moreover, the horizontal display requires a greater horizontal space for its installations, which is some cases can be a limitation.

Vertical exchangers, for its nature and the requirement of drilling, result a more expensive option compared to horizontal arrangements, but the stability of the temperature of the strata increases the performance of the heat exchange between the piping system and the ground, requiring fewer drilling depths for the facility. The use of horizontal ground is optimized, as the limitation for new vertical boreholes comes only from the interaction of each one towards the others.

Comparing both technologies and considering the conditions presented in Catalunya, the vertical configuration of the BHE appears to be the most attractive option, besides the economical counterpart, and is in fact the configuration selected by ICGC to perform the calculations for GeoHPEX. Despite this, characteristics such as the thermal properties of the terrain and the hardness of the soils strongly influence the costs of drilling and exchanger systems, which would be worth to be evaluated for the territory of Catalunya.

Both characteristics are strictly dependent on the constitution of the ground and the geological strata found at each location. Consequently, in order to justify the potential of very low installations a research on the soil of Catalunya has been carried out to evaluate the thermal properties and the hardness presented in representative points.

To do so, the geological columns of up to 7 points of the territory, spread through the four provinces, have been revised, whose results are contrasted to those of the data stored by ICGC.

A geological column is a vertical sample of the terrain, used for its geological and paleontological characterization, whose length (depth, or 'potential' in geological terms) depends on each location. For obvious reasons, the strata found at deeper depths corresponds to older geological ages than those more proximate to the surface, converting each sample a proof for the geological phenomena occurred at each location, helping to understand the orography and events, and enabling the possibility to date those phenomena.

The columns are extracted from the data stored at the Instituto Geológico y Minero de España (IGME) [24], the geological map of Spain at a scale 1:50,000. As said, to sustain the findings on these columns, the information was compared with those given by ICGC [17].

The findings of the literature studied is presented below in the form of a table, including the location, the type of strata found at each column and the paleontological era to which each stratum belongs.

Location	Tremp (Lleida)	Torroella de Montgrí (Girona)	Alcoletge (Lleida)	Igualada (Barcelona)	Barcelona (Barcelona)	Tarragona (Tarragona)	Mora de ebro (Tarragona)
Geological description	Gravels, slimes, marls and clays	Sandstone and slimes	Clays, sandstone and slimes	Sandstones, limestones and marls	Clays and sandstones	Limestone, marls and diatomites	Marls, clays and sandstones
Proximate chronostratigraphic characterization	Quaternary	Biarritz eocene	Oligocene, (suevionian-arverniense)	Superior biarritz Eocene, inferior priabonian	Helvecian - Tortonian	Superior and inferior cretaceous	Inferior and médium Triassic

Table 1.1 Geological description of the inspected columns from IGME [17] [24]

The strata that conforms the territory of Catalunya is mainly constituted by clays, sandstones and marls, which are considered as soft, unstable grounds. In terms of drilling, the mentioned strata are ones of the cheapest as the technique to perform boreholes only requires rotary equipment (hard strata would require, on the contrary, pneumatic percussion), and hence the economic impact on geothermal installations is lowered down.

While the material is favourable for very low enthalpy vertical BHE considering the difficulty to drill, the thermal properties of each strata also speak in favour for these installations.

Thermal characterization of the soil is, on average, performed by the evaluation of its thermal conductivity, volumetric capacity and diffusivity. Being its conductivity the ability to transmit heat through the material, and its volumetric capacity the energy required by a unit volume to increase its temperature by a degree, the diffusivity is the relationship between the two of them, usually understood as the ability of heat to 'flow' through the strata.

To optimize the performance of vertical BHE there must exist an equilibrium between the thermal conductivity of the soil and its diffusivity; while high values of diffusivity amplifies the thermal range of the soil, the 'freedom' with which heat flows disables an optimal absorption from the exchangers, requiring longer boreholes. On the contrary, low diffusivities and low thermal conductions endows a higher thermal stability, but the temperature range of the soil is reduced. The reduction in the temperature gradient, consequently, would require longer exchangers to fulfil with the requested thermal loads of installations.

The ICGC has evaluated the three parameters named above, stablishing an average diffusivity of $0.77\ \frac{mm^2}{s}$, thermal conductivity of $2.8319\ \frac{W}{m\,K}$ and thermal volumetric capacity of $2.6864\ \frac{MJ}{m^3K}$, with minimum values of 0.2, 0.45 and 1.7 and maximum values of 2.53, 5.5 and 4.08, respectively [18]. According to literature [16], the thermal parameters found in Catalunya result suitable for very low enthalpy installations.

Both researches demonstrate that Catalunya, for its ground definition, has a great opportunity to implement geothermal installations for heating and cooling. GeoHPEX would suppose, in this sense, a proper tool to enhance the number of installations of this type in the territory, increasing the share of renewables and providing a sustainable method to air condition residences and industries.

1.6 Commercial heat pumps and heat exchangers. Main considerations

Though it is open to modifications, regular installations of very low enthalpy geothermal systems for heating and cooling will consist on three major units: the heat pump, the earth connection (from now, heat exchanger system) and the interior heating and cooling distribution system.

From the perspective of this project, the interior heating and cooling distribution system is excluded, focusing on the heat pump size design and the heat exchanger system since ICGC is only interested on developing an app to evaluate these two, regardless of the distribution system (although for sizing both units it is necessary to address the thermal load of each facility).

The functioning of the installation is straight forward and does not differentiate from other conditioning systems on its theoretical bases. During cool seasons, when there exists a heating thermal load to reach a comfortable temperature in the interior of the house, heat is extracted from the ground through the heat exchanger system (in the case of GeoHPEX, from the vertical BHE), by the thermal fluid circulating in the interior of the piping system, pumped by heat pumps.

This circulation can be usually performed in an open or closed circuit, though it all depends on whether the installation possesses an underground water reservoir at permeable basins. In case of being affirmative, it is possible to use the present water as the thermal fluid for the geothermal installation, which after the heat exchange would be returned to the reservoir.

As this is not the usual case, GeoHPEX implements the calculation of closed loops, Ground Coupled Heat Exchangers (GCHE), in which the thermal fluid is never in contact with the rocks, avoiding the possibility for poisoning water reservoirs and opening the geothermal installation to make use of other thermal fluids different from water (though for economic reasons water is generally used).

The heat pump unit, for its part, results as decisive as the GCHE system regarding its implication towards the coverage of the thermal load of the facility, and the posterior sizing of the heat exchanger system. This unit couples the ground capturing system with the interior distribution system, by an air-water heat exchanger. It also counts with pumps for both air and water circulating the device, to recover the pressure drop after the exchange. After it, air is pumped back to the interior of the facility, while the thermal fluid of the GCHE is pumped back to the ground.

As for hot seasons, the process occurs in the reverse direction. The heated air flows to the heat pump and transfers its energy to the thermal fluid in the GCHE system, after which this heat is injected in the ground, having the thermal fluid cooled down through the pipes.

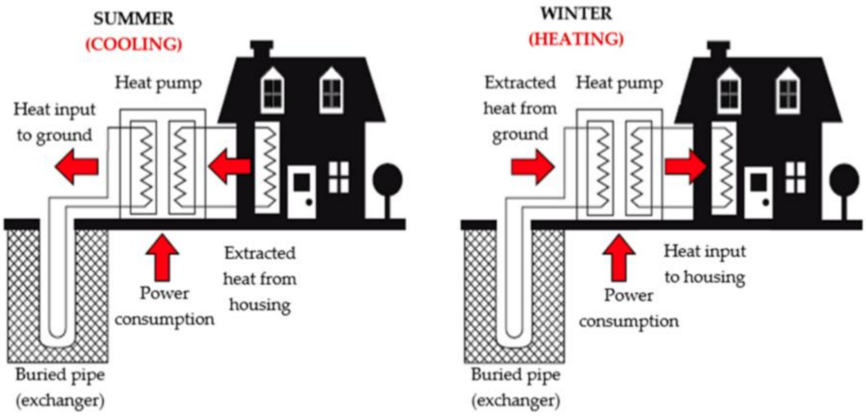

Fig 1.10 Traditional functioning of very low enthalpy geothermal installations [30]

Depending on the climate at which each installation is located, there could exist an imbalance between the energy extracted from the ground during winter seasons and the injected during summer, though the heat extracted or injected to the building does not correspond with the injected or extracted from the ground, as there exists the work of the compressor entering the system. In this sense, the expressions regarding this phenomenon is shown:

$$E_{gh} + W_{ph} = E_{hh} \ (eq\ 1.1) \qquad E_{gc} = E_{hc} + W_{pc} \ (eq\ 1.2)$$

$$COP_h = \frac{E_{hh}}{W_{ph}} \ (\ eq\ 1.3) \qquad COP_c = \frac{E_{hc}}{W_{pc}} \ (eq\ 1.4)$$

where E represents the energy evacuated or injected to the ground or house, and W the energy consumption of the heat pump. The sub-indexes gh, ph and hh (eq. 1.1 and 1.3) correspond to the ground heat extracted, the energy consumption of the heat exchanger in heating mode and the house heat received from the geothermal installation, respectively. On the other hand, gc, pc and hc apply for the same concepts but in cooling mode. The expression COP is the Coefficient of Performance, a value used in conditioning systems to evaluate the efficiency of each systems, by establishing the amount of thermal energy extracted or given by unit of electric energy (in heating and cooling modes, the same heat pump might not have the same COP, hence the addition of the sub-indexes c and h).

Combining expressions (eq. 1.1) and (eq. 1.3) (heating mode), and (eq. 1.2) and (eq. 1.4) (cooling mode) it is obtained the following expressions:

$$E_{gh} = E_{hh} \cdot \left(\frac{COP_h - 1}{COP_h}\right) \quad (eq\ 1.5) \qquad E_{gc} = E_{hc} \cdot \left(\frac{COP_c + 1}{COP_c}\right) \quad (eq\ 1.6)$$

Which would imply that in cooling mode, the system is injecting more heat to the ground than the extracted from the facility, while in heating more the extracted quantity from the ground is less than the injected to the building.

Keeping a low thermal imbalance (thermal balance between the injected heat and the extracted heat is virtually impossible) is important for the correct functioning of the geothermal installation, as if it was the case of excessive heating or cooling of the ground, the thermal gradient that served as reference for sizing the installation would no longer be valid and extinguishing the geothermal resource.

As vertical BHE have been selected to be applied in GeoHPEX, the research on commercial heat exchangers has been limited for this configuration in accordance with the ICGC. Moreover, the exchangers selected end at the bottom of the borehole in a U-bend to avoid geometrical pressure losses, as showed in the following figure.

Fig 1.11 U-bend of vertical BHE [1]

Commercial heat exchangers for very low enthalpy geothermal systems have two standard nominal diameters, with a range of lengths between 80 and 165 meters. ICGC has decided to set the available database of GeoHPEX in accordance with the products offered by ALB Sistemas, a company stablished in Catalunya that has collaborated in numerous occasions with ICGC. Consequently, the following configurations will be available at GeoHPEX:

- Nominal diameter: 32 x 2.9 mm (outer diameter = 32 mm; inner diameter = 29 mm). Available lengths: 80, 90, 100, 110, 120, 140, 165 m.
- Nominal diameter: 40 x 3.7 mm (outer diameter = 40 mm; inner diameter = 37 mm). Available lengths: 80, 90, 100, 110, 120, 140, 165 m.

The material of the heat exchangers is polybutylene 5-10, with thermal conductivity of $0.38\ \frac{W}{m\,K}$. As for heat pumps, ICGC has set a database of eleven models to be selected, that GeoHPEX will consider in the sizing of the geothermal installation. The database is based on the products of TRANE [43], an American company that usually collaborates with the ICGC (Eurovent certified). The information is presented below.

Model	Heating load (W)	Heating COP	Mass flow rate (l/s)	Cooling load (W)	Cooling COP
1	**7,040**	3.23	1.49	5,770	3.22
2	**8,390**	3.25	1.79	6,840	3.24
3	**9,830**	3.24	2.09	8,020	3.25
4	**12,060**	3.32	2.61	9,680	3.32
5	**14,490**	3.37	3.14	12,200	3.28
6	**17,240**	3.45	3.75	14,500	3.38
7	**19,420**	3.43	4.23	16,300	3.37
8	**25,850**	3.45	5.66	21,600	3.35
9	**29,900**	3.48	6.55	25,000	3.4
10	**37,000**	3.46	8.09	30,500	3.32
11	**45,000**	3.46	9.84	37,500	3.41

Table 1.2 Available heat pump database in GeoHPEX. Courtesy of ICGC

As it is seen in Table 1.2, each model is able to cope with higher thermal loads in heating mode than in cooling mode, by the nature exposed previously. Though this database is used by GeoHPEX, it is conceived to be expanded in future versions.

Through the revision of the State-of-the-Art and the properties of the soil in Catalunya, it has been proved the potential of very low geothermal installations in the territory and the justification of this project. Hereinafter, the conception of the program and its functioning (equations and algorithms) will be explained, together with the development of the GUI.

2. Performance and building of GeoHPEX

The contents of the previous chapter stated, through its development, the justification on the design of GeoHPEX and the possibilities and implications that it could carry. As a continuation to this document, the current chapter will go through the theoretical design planned for building GeoHPEX, explaining its contents and mathematical models behind the results shown in the app.

There will be a special attention to the information requested to the user, justifying the reasons for introducing any parameter as an input or automatically loading it from the databases. Furthermore, there is a section dedicated entirely to the explanation on how Matlab® can load the necessary information, and how it is stored, treated and accessed.

Afterwards, the mathematical model of the thermal load (depending on the user selection) will be explained, together with the algorithms used for it, as it results in the main issue regarding the calculation of the vertical BHE length. As a consequence, the methodology to size the heat pump system and the length of the exchangers is exposed, addressing the assumptions and information generated. Finally, the chapter will focus on the results generated by GeoHPEX, how are they presented, and the possibility to be stored and transferred.

The code used for GeoHPEX cannot be shown, as it has been granted to ICGC and its size exceeds 3400 lines, impossible to be attached to this Master's thesis file. To review the implemented code, please send an e-mail to the following mail:

j.ariza.zapero@gmail.com

2.1 Theoretical design of GeoHPEX

As exposed in previous sections, GeoHPEX is conceived as a tool to design vertical BHE for geothermal installations, to be used by all willing to. However, performing such calculation usually requires a set of information that, though technicians and professional are used to its terminology and would not find problems to know the values, would mislead some other users.

In order to avoid such event, the GUI of GeoHPEX has been designed thinking on an everyday user that is not familiar with the terminology treated in air conditioning or geothermal installations, but also thinking on opening the tool to professionals that can make a deeper use of it.

The best solution to combine both necessities was to organize the GUI in different tabs, each one dedicated to gather the information required to operate, connecting each of them by buttons to change between tabs. The tabs are designed for being completed from top to bottom, and each button has been programmed to evaluate the information imputed by the user and detect any misinformation, offering warning and error messages to inform him.

Before deepening into the content of each tab, it is at least necessary to establish the mechanism to calculate the length of vertical BHE from the theoretical point of view (the technical perspective is explained later in the chapter), which will provide the justification on the number of tabs selected for GeoHPEX and its content.

The calculation of the BHE is dependent on four factors: the thermal load for design [kW], dependent also on the thermal necessities imposed by the user; heat pump system required, namely the part load factor and the COP showed (which is dependent, on the other hand, on the thermal load for design); ground thermal conditions, that define the ground temperature through the year and the design entering water temperature; and the calculation criteria, which would establish the season to which the design is done, the type of BHE selected and other possibilities taken into account, as limiting the load to design or selecting different properties for the heat pumps and ground characterization.

As seen, all of them are linked and reciprocatively affect each other when there is a variation on one of them, requiring as a need to identify the primary data from the exposed and automatize the rest of the information by its use.

Ground thermal conditions is entirely dependent on the location of the facility, requiring for its characterization the thermal properties of the soil and climatic information. Thus, the location must be an input to the application and has been introduced as a request in the GUI. The climatic information is not only used for the ground definition, but is also necessary for the application of the methodology to estimate the thermal load when it is not known.

To complete the calculation of the thermal load in case of unawareness, there should be a space at the GUI to request the desired comfort temperature and the definition of the building, in terms of type of use, planar geometry, built surface area, number of floors, occupation, and window surface. For those that know the thermal load for summer, winter, or both seasons, there should also be a space to introduce those inputs.

As the inputs required to define the thermal demand are large, it is worthy to dedicate one tab entirely to it. In GeoHPEX, this tab is called 'Thermal demand' to be consistent with the input of this section of the GUI. The location is also included in this tab, as a matter of space optimization.

Back to the methodology, once the system has calculated the design thermal load, it is necessary to calculate the heat pump system required, considering the calculation criteria that the user desires. This is because, on average, the thermal load for winter does not match the summer load, so the heat pump sizing for the same building notoriously differs from selecting one season or the other as sizing criteria.

Moreover, there has been implemented a functionality to curtail the thermal load to design, so both the design criteria and the curtail option should be included. Beyond that, however, is the heat pump database or heat pump selected to design the heat pump system. The user should be allowed to decide whether to use the database available at GeoHPEX or user their own, so there should be a space for the user to make such decision and introduce, if it is the case, the parameters of other heat pump.

Finally, the user should decide the type of BHE that he wants, together with an estimation of the length of each borehole. As well as this, the user would, in case of knowing, introduce its own data for the definition of the ground thermal condition. All the exposed parameters are included in another tab, named 'GSHP selection and geothermal field'.

Therefore, defining the above conditions will enable the calculation of the vertical BHE, as the four main factors have been defined and imputed. To navigate, 'GSHP selection and geothermal field' tab has a button to retreat to 'Thermal demand', and a button to run the calculations and proceed to the results tab 'Results'.

As explained before, the navigation buttons offer tips, warnings and error messages to help the user to properly use the application. In the case of the tab 'Thermal demand', the button to access 'GSHP selection and geothermal field' has been programmed to check that the information introduced in that tab is correct, while the 'run' button set on 'GSHP selection and geothermal field' not only has been programmed to evaluate the information on its tab, but to check also the information on 'Thermal demand', in case the user changed tab not by clicking the navigation buttons.

Therefore, it is justified to have, at least, three tabs: 'Thermal demand', 'GSHP selection and geothermal field' and 'Results'. As a request from ICGC two more tabs are included, which are a front page to serve as a welcome, and other tab to explain the procedure to use the app, named 'Workflow' in GeoHPEX.

Back to the 'Results' tab, the user will obtain the following information:

- Thermal load as a function of the external temperature
- Annual energy consumption as a function of the external temperature
- Number of boreholes and length of the vertical BHEs
- Thermal imbalance of the ground (net energy injected or extracted from the ground by the end of the year)
- ID model of the heat pump and its characteristics (thermal capacity and COP for both summer and winter)
- Recommendation on the design criteria that the user should select, depending on the energy demand along the year
- Report generation, to store the mentioned information and other parameters, that enables the exportation of the generated data.

The experience that has been prepared for the user will begin when loading the app, as there is a splash image with the commercial name of the program, the name of the authors and the entities that promoted the app. When the app is finally loaded, the front page is firstly showed, that contains the overview of the program and two buttons: one directs the user to 'Workflow', the tab that explains briefly the functioning of GeoHPEX; the other directly drives to 'Thermal demand', as the user may not require to read the workflow (might have used the app before or might have read the manual that would be published at ICGC).

In case that the user accessed 'Workflow', he will read the process to use the application. Additionally, there will be a button to download the manual, attached to the program. By the end of this tab, the user will proceed to 'Thermal demand'.

In 'Thermal demand', the user will provide the location of the facility and the thermal description of the building (either by knowing the thermal load or imputing the characteristics of the facility). By clicking the button 'Next', the GUI will change to the tab 'GSHP selection and geothermal field', on which the user selects the parameters to define the calculation of the vertical BHE. Finally, the user is ready to click the 'Run' button and proceed to 'Results'.

A message confirming the correct input will show on the screen, where he will obtain the thermal load and energy consumed along the year, the number and length of the vertical

BHE, the heat pump system modelled, the recommendation on the sizing criteria and the option to generate a report.

To assist the understanding on how the user is supposed to make use of GeoHPEX, the following flow diagram is presented on the next page. After the theoretical design has been exposed, it will be proceeded to define the structure of the GUI and how GeoHPEX helps the user to go through it.

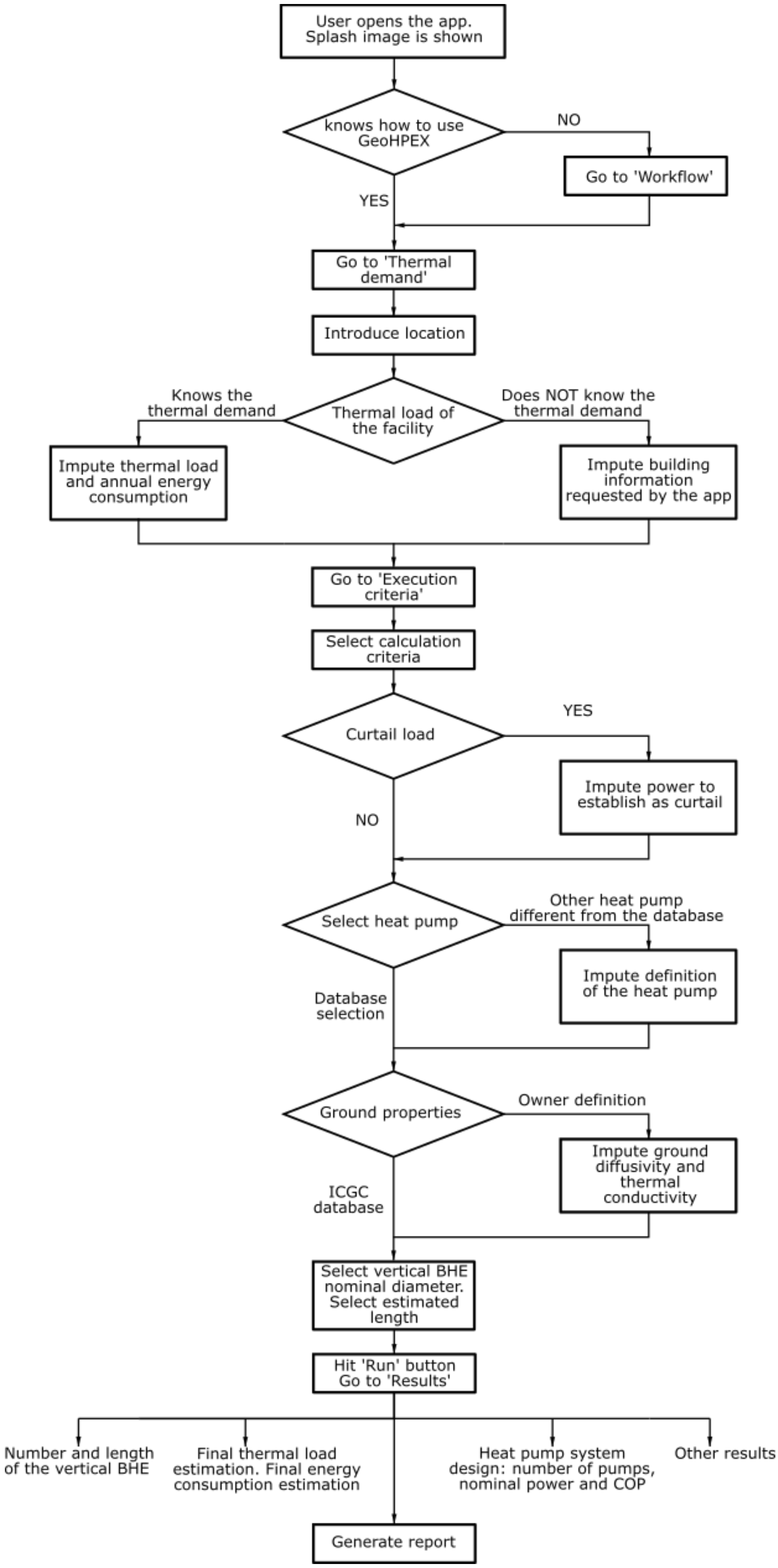

Fig 2.1 Theoretical usage of GeoHPEX. Source: own elaboration

2.2 User requirements. Graphical User Interface construction

The previous section exposed the theoretical design of GeoHPEX and the information required for the calculation of vertical BHE. On this section of the document, it will be possible to analyse how the GUI has been designed to assist the user in the use of the tool, how to navigate through the application and the assists programmed for the user.

To organize the program, the GUI has been divided into five different tabs, as explained before, being the first two a front page and a workflow on how to use GeoHPEX. But before getting to that part, a splash image has been designed to appear while the app is loading. The credits of this Image correspond to Ignasi Herms, Georgina Arnó and José Juan de Felipe, who established the contents of the following image.

Fig 2.2 Splash image, appearing during loading time of GeoHPEX

When GeoHPEX is completely loaded, the splash image vanishes to show the front page of the GUI, a short presentation of the program. It contains a briefing on the application, explaining the uses that it can perform, together with the authors and the signatures of the entities participating in the program. To give a geothermal 'environment', it has been decided to introduce an image of the piping of a heat pump system, placed on the up-right part of the GUI, serving as framework for the overview of GeoHPEX without keeping away the focus on it. To start the navigation, as exposed on Fig 2.1, two buttons are added to move to the workflow or to the 'Thermal demand' tab. The front page or 'Main menu' is shown in Fig 2.3.

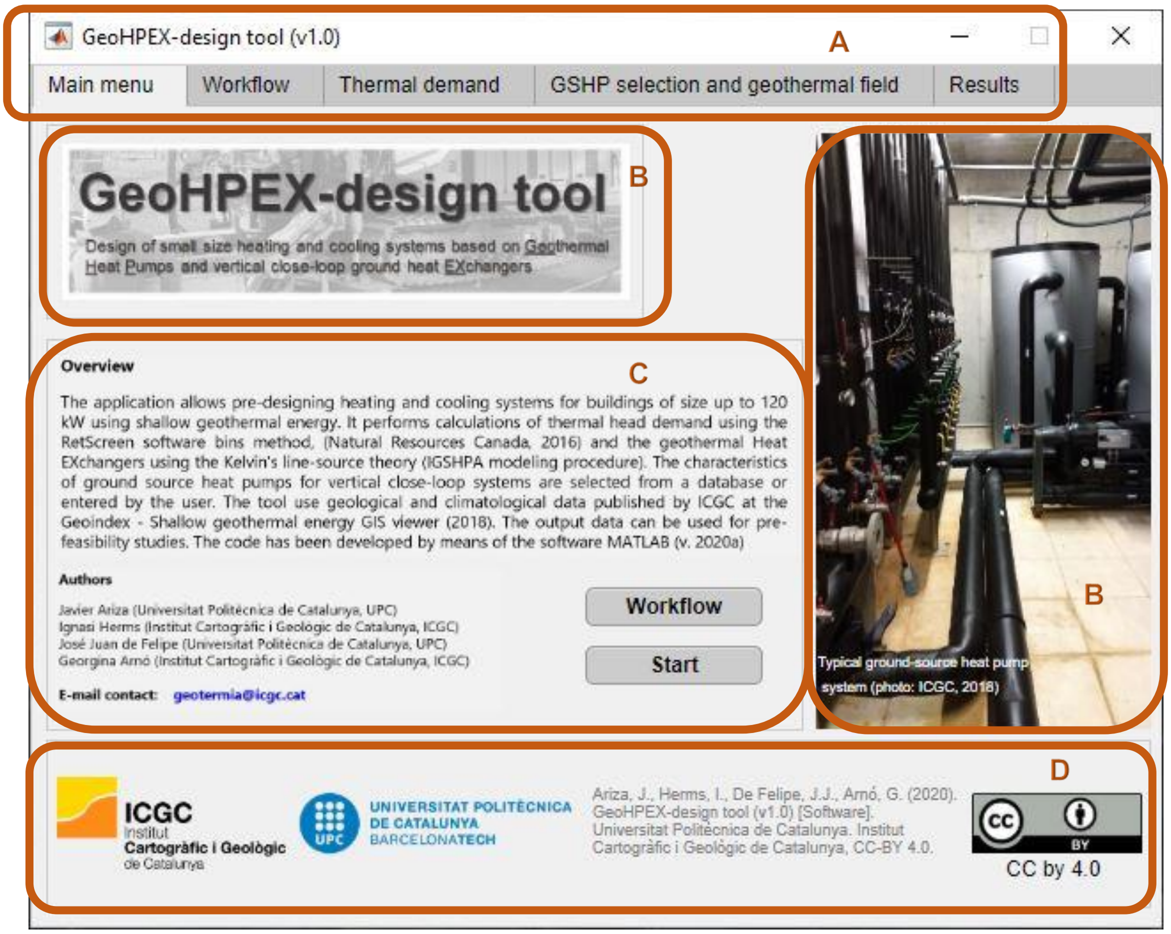

Fig 2.3 Front page (named 'Main menu' on GeoHPEX) of the tool.

In part A, the user finds the name of the application, and is able to select the tab that he prefers, showing the tab selected with a lighter grey colour (notice that the rest of the available tabs are in a darker grey tone). Part B presents the logo of the application, and the mentioned image to apport the necessary geothermal 'environment', in such size enough to be important without reducing the value of the overview and the rest of the components.

Part C of this front page contains the overview of the tool and the authors, plus the e-mail contact of ICGC in case of requiring any assistance. As a convenience of space, the buttons to navigate and continue are set in this space. Finally, part D contains the logos of the two entities participating in GeoHPEX, the authors and the Creative Commons signature, imposed by the ICGC.

If the user decides to see the workflow, the user will push the button 'Workflow', that will redirect him to the referred tab. Otherwise, the user will click on 'Start' and will skip the tab 'Workflow' to directly go to 'Thermal demand'. In the first case, the GUI tab showed is the following.

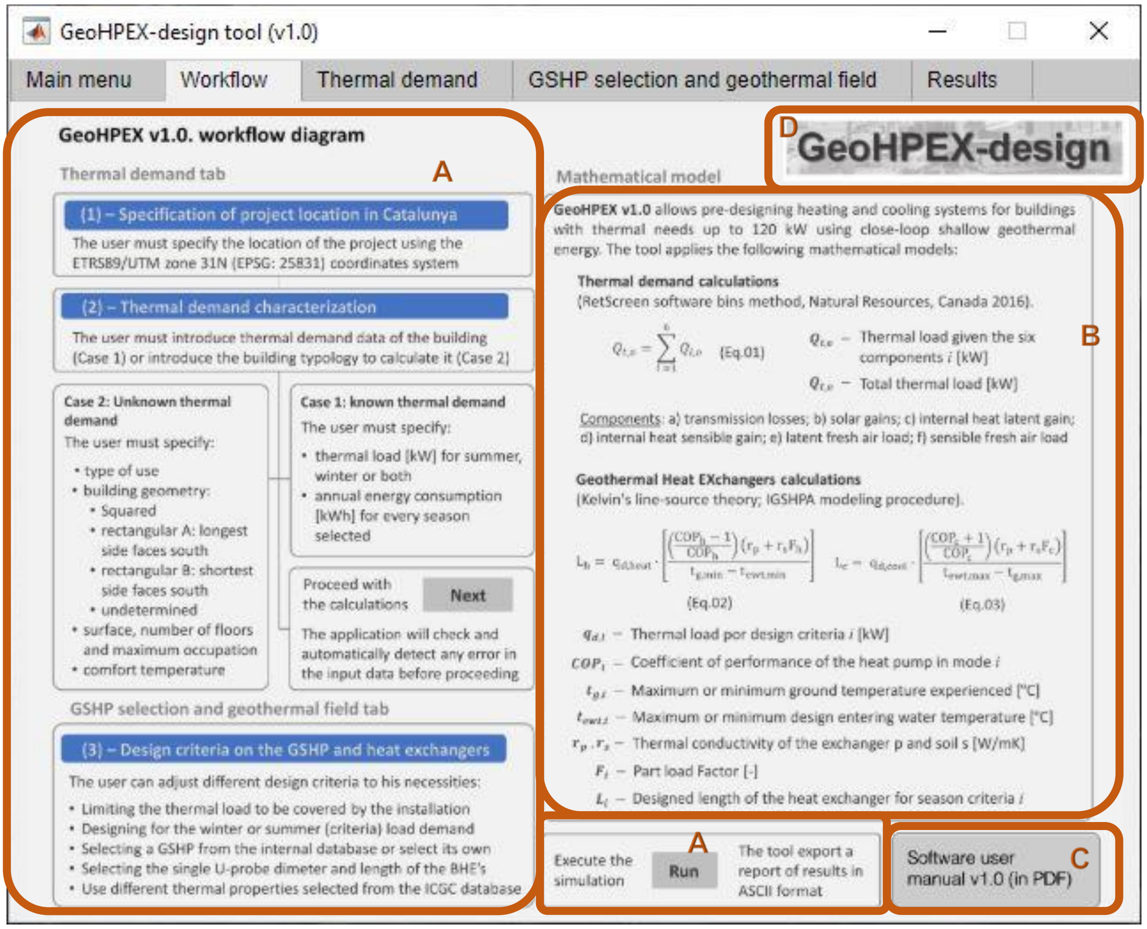

Fig 2.4 'Workflow' content on GeoHPEX

Though the space is reduced, the workflow includes the enough piece of information to use the application without getting lost. However, to deepen on the instruction, there has been set a button on the down-right part of the GUI (part C, 'Software user manual v1.0 (in PDF)') that will download the manual attached to the program.

Part A consists on the verbal interpretation of Fig 2.1, explaining the possibilities that the user can have in its experience with GeoHPEX. On part B, the user can find the mathematical models GeoHPEX applies, as a justification on the results shown (in case any user is interested).

Part D represents a difference with respect to the previous GUI, as a different icon has been placed on that section. Except for the front page, all the tabs have that image on the same spot, in order to give value to the application and provide a professional look and feel. To change to the following tab, ICGC had stablished on other works that the user would click on it, although it would have been better to have enough space to proceed to 'Thermal demand' by means of a button.

'Thermal demand' is vital for the calculation of the heat pump system and the BHEs, and constitutes, perhaps, the most important tab in GeoHPEX regarding the weight of this section in the code of the app. As said before, this tab contains the location selection and the thermal definition of the facility, which can be carried out in two methods. This condition has been taken into account in the building of this tab, where there are two separate zones in the GUI to use, depending on the case of each user. As a way to avoid confusion, the user is forced to choose one or the other, and depending on the choice the unused section of the tab is disabled.

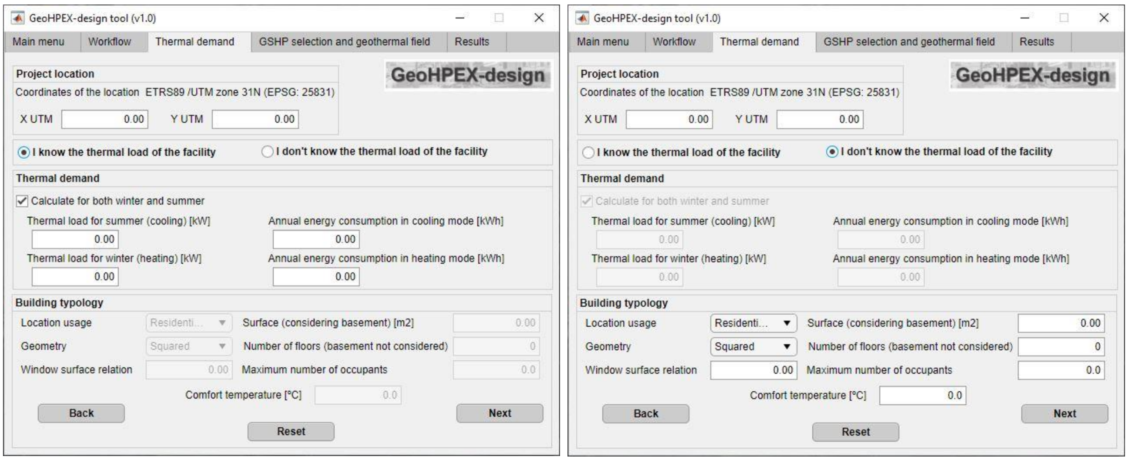

Fig 2.5 Enable and disable ability on 'Thermal demand' tab of GeoHPEX

The default option that users find is the case in which the thermal demand is known, finding the section of the building typology firstly disabled. When the user selects the other case, the section for the thermal definition is disabled while enabling the section on the building description.

In Fig 2.6 it is possible to see the functionalities available in this tab. In part A, the user will introduce the coordinates of his location using the ETRS89/ UTM zone 31N system, with horizontal and vertical coordinates. Using the GUI from top to bottom, the user will encounter part B, which offers the possibility to select either the case of knowing the thermal demand, or knowing the building typology. The selection of one of them disables the section of the contrary (parts implied are C and D): in part C, the user can specify the thermal load and the annual energy consumption of winter, summer or both seasons. In case the check box for calculating both seasons is selected, the program will detect any missing or wrong information when clicking on the button 'Next', having a similar behaviour when deselected.

On part D, the user has to specify the following information:

- Location usage and geometry
- Built surface area and number of floors
- Window surface relation [m2 window / m2 surface] and maximum number of occupants
- Comfort temperature

There has been set up to ten different usages and four different geometries, displayed with two scroll buttons. The type of uses available are the following:

- Residential (without basement)
- Residential (with basement)
- Residential (flat)
- Educational institution
- Office
- Industrial
- Hotel and catering
- Wholesale and retail
- Hospital
- Sport facility

While the geometries defined for GeoHPEX are:

- Squared
- Rectangular (Case A)
- Rectangular (Case B)
- Undetermined

Notice the presence of Rectangular (Case A) and Rectangular (Case B) as available geometries for the user. The difference comes in the south-oriented wall of the residence, which in Catalunya receives most of the solar gains: while in Case A, the longest side is south-oriented, Case B presents the longest side facing East and West, having less solar gains than in Case A for the same location.

By this information, the program has the enough data to perform the thermal evaluation to later size the heat pump system, and consequently the length and number of BHEs. Finally, in part E the user can go back to 'Workflow', reset the information to zero (original state) or continue to the next tab.

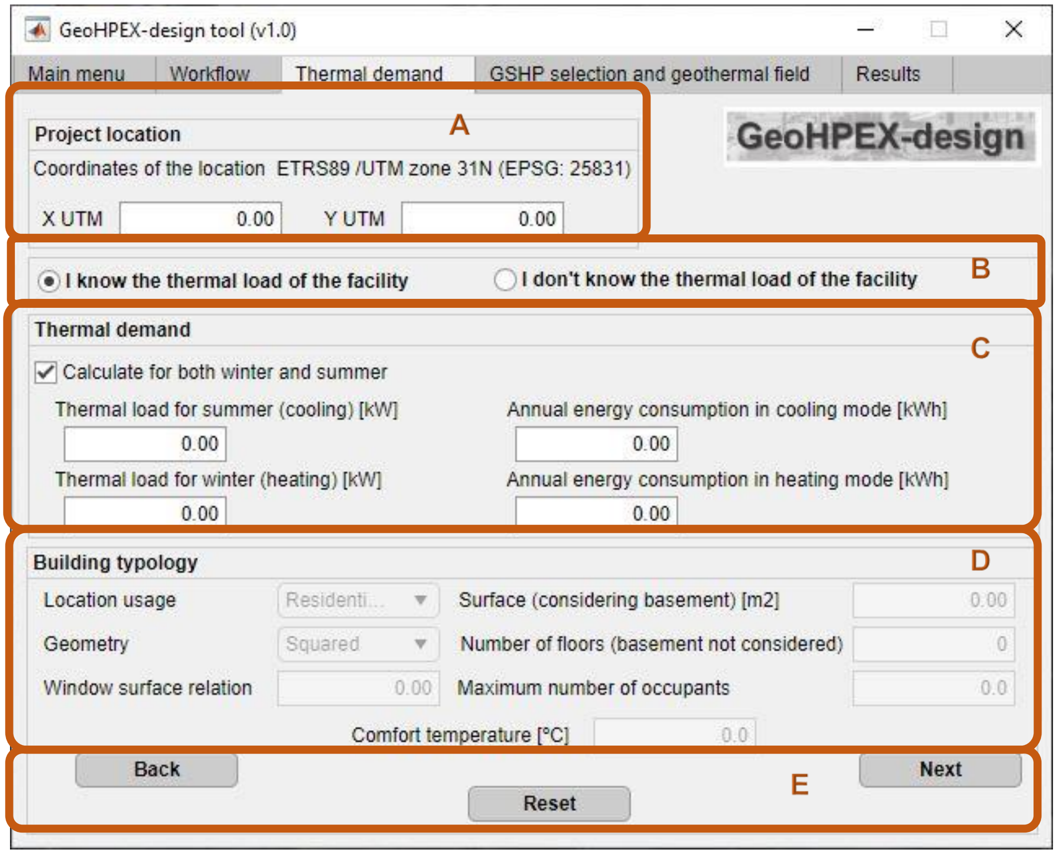

Fig 2.6 GUI design for 'Thermal demand'

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As said, to assist the user there has been implemented automatic error messages that appear when the user hits the button ‘Next’. This programming has also been introduced in the ‘Run’ button on tab ‘GSHP selection and geothermal field’, for the case in which the user changes tab without using the navigation buttons.

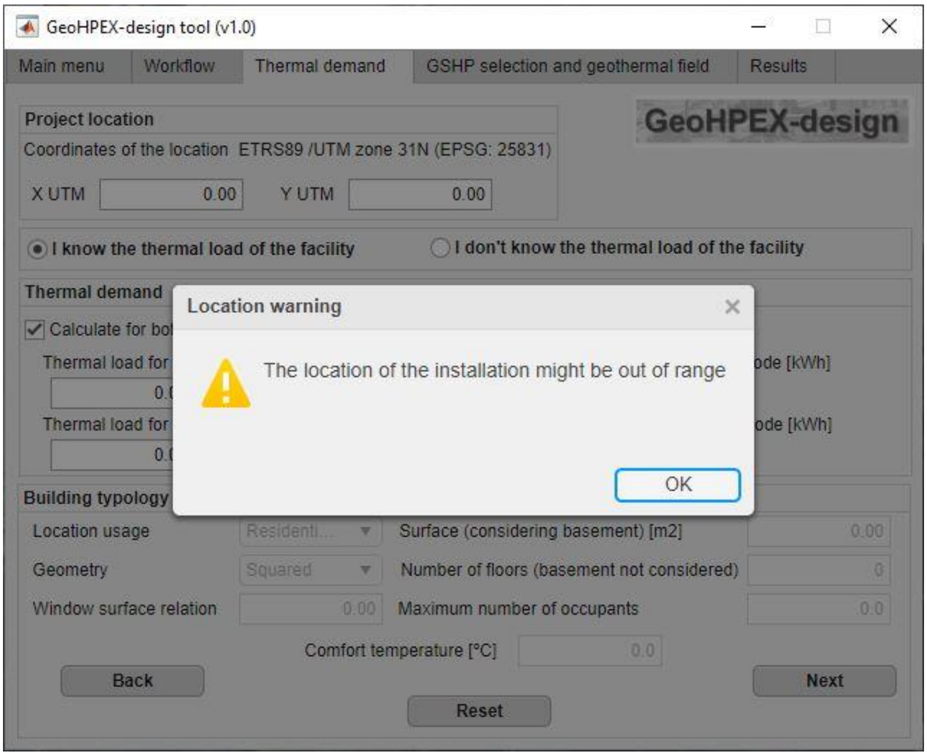


Fig 2.7 Warning message appearing in case of wrong location input

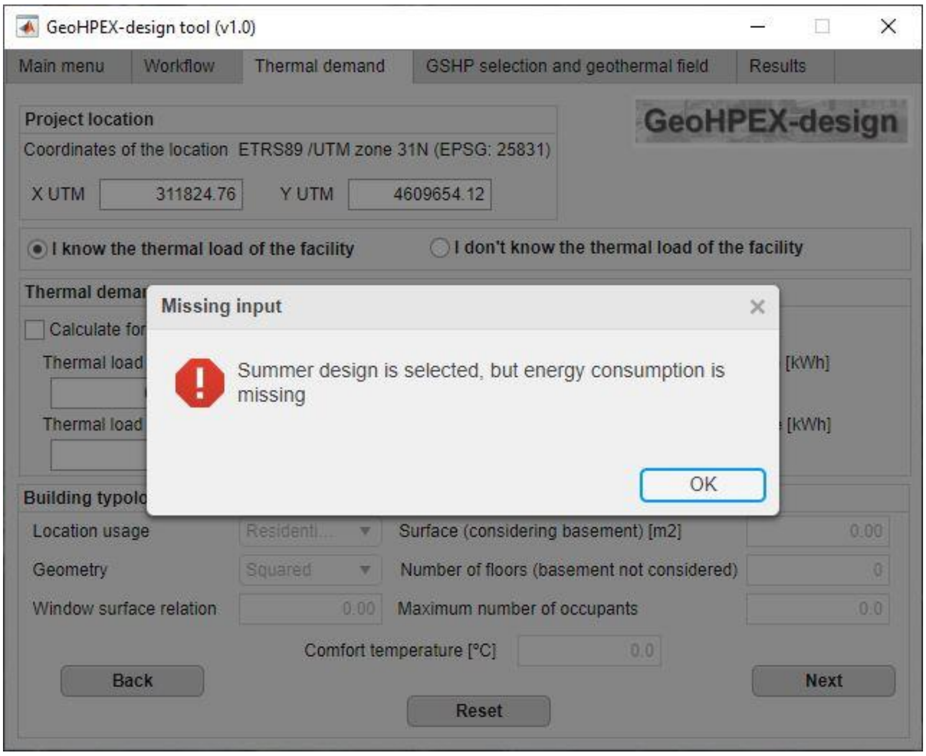


Fig 2.8 Error message for wrong thermal input

Clicking 'Next' button serves as a tool to check the information offered by the user, and has been programmed to evaluate the necessities depending on the selection of each case (see more in *2.3 Loading information. Bin method requirements and secondary data generated*). If everything is correct, the tab is changed towards 'GSHP selection and geothermal field' (see possible error messages on *ANNEX I*. Graphical User Interface of GeoHPEX-design tool© (v1.0) and error messages programmed

This tab, as explained again before, selects the criteria to size the geothermal heat pump, curtail the thermal load to cover, select the BHEs and choose heat pumps and thermal properties of the ground different from the databases. The methodology to size the heat pump system requires defining firstly the season design criteria and whether the user prefers to curtail the load, therefore seems reasonable to place this section at the top of the tab. After that, the heat pump for the heat pump system can be selected, thus including this information below the design criteria. The rest of the parameters to select are placed at the bottom, guarded on left and right by the navigation buttons 'Back' and 'Run', and 'Reset on the lowest section of the GUI.

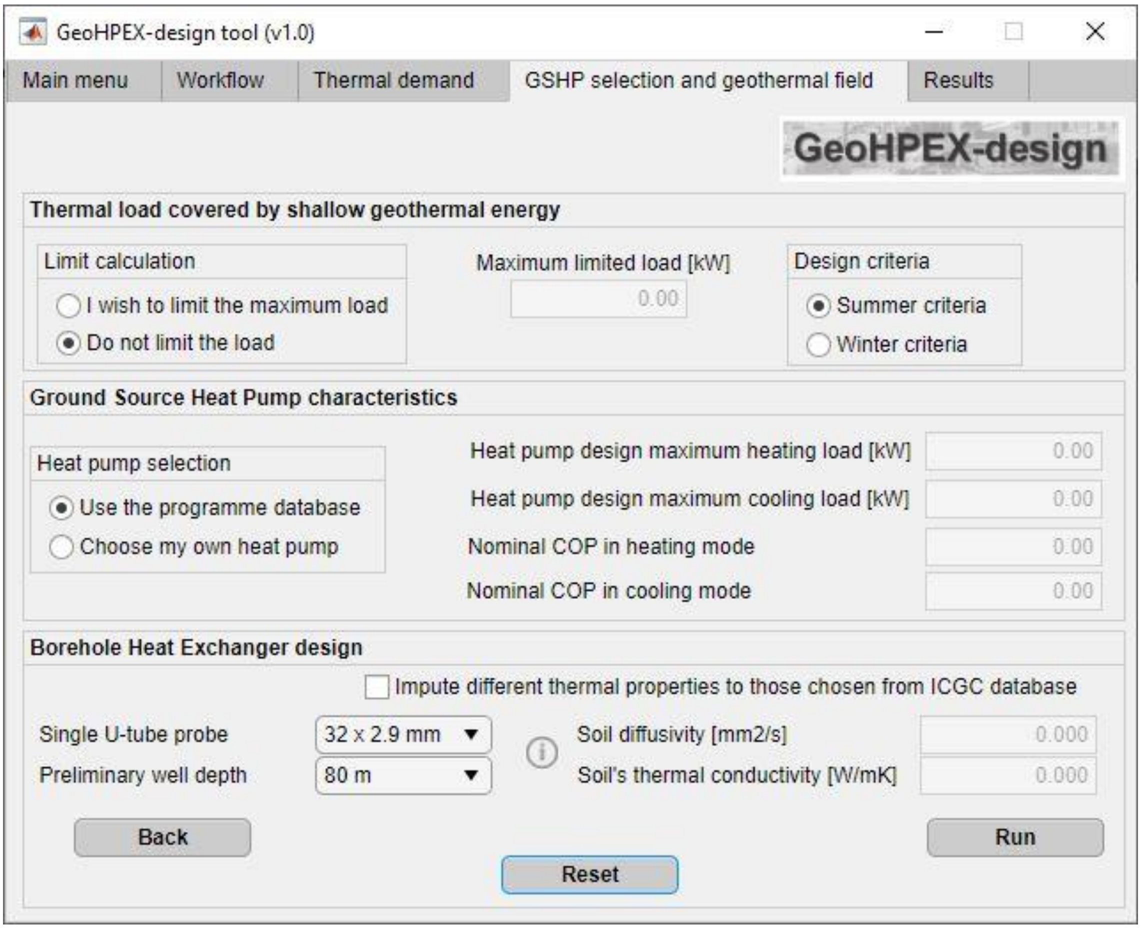


Fig 2.9 GUI design for 'GSHP selection and geothermal field'

As it happened on the previous tab, the user is open to select different values for the heat pump and thermal properties, although the preferred values are the store on the app. To avoid confusion, the fields to impute other values are disabled, and only enabled when the user specifically selects the radio buttons or the check button placed for this.

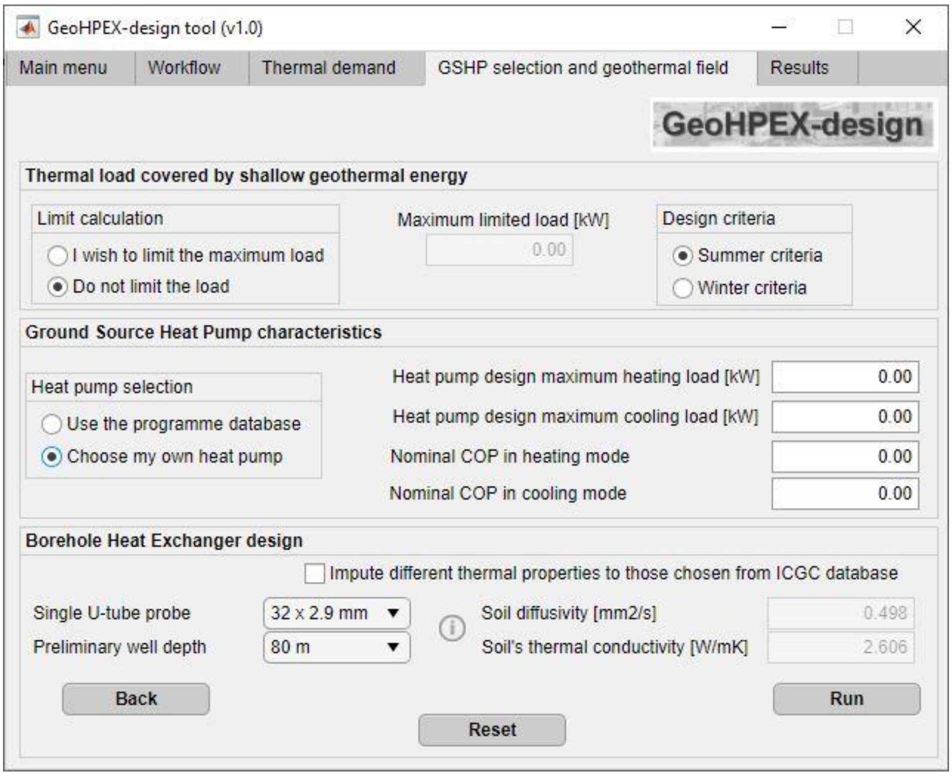


Fig 2.10 Example of enabling the section for the selection of other GSHP. The radio button is selected on 'Choose my own heat pump, making GeoHPEX to enable the desired section.

When all the information is imputed, the user will click on 'Run' to execute the case and obtain the results. The button will firstly evaluate the correctness of the information imputed on the previous tab, after which will perform the same for the current tab.

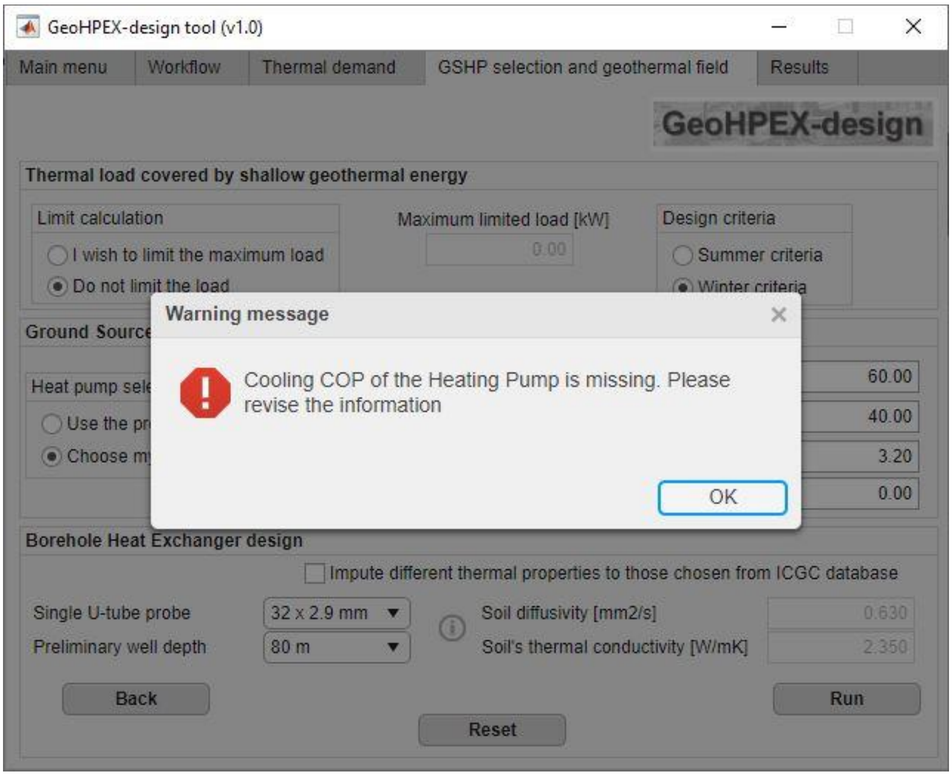


Fig 2.11 Error message appearing when 'Run' is pushed and there exists a mistake in the information

Otherwise, a message adverting the user on the valid information will appear on the GUI. The tab will automatically change to 'Results', where the user is finally able to check the findings of the simulation.

As there is a numerous quantity of results that can be of interest for the user, the space in the tab is reduced and requires a proper organization, giving birth to a GUI design that has been able to contain all the results intended to show in this tab (see *2.1 Theoretical design of GeoHPEX*). In Fig 2.12 it is displayed the built GUI for 'Results'.

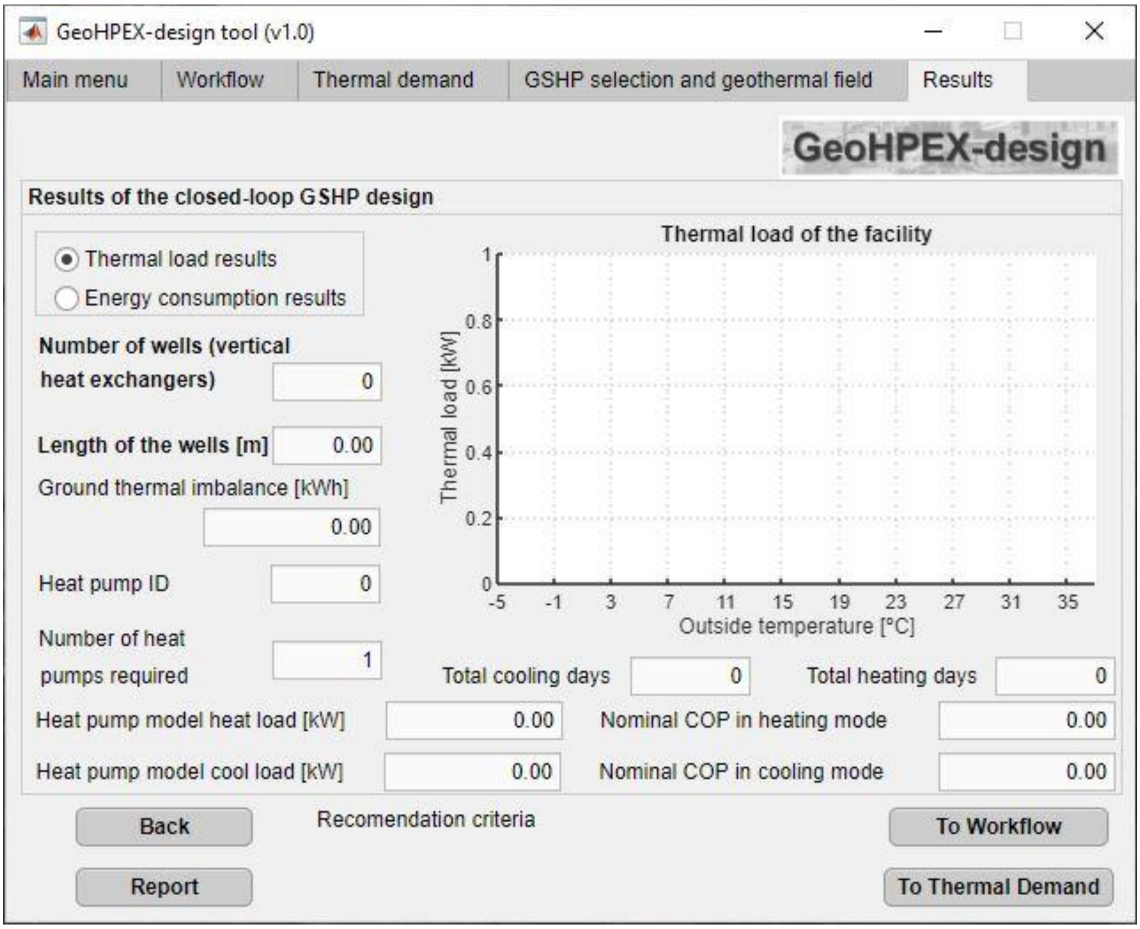


Fig 2.12 GUI design for results

On the top-right section of the tab there is displayed a graph, to check the thermal load and energy consumption of the facility depending on the radio button selected on the top-left part. Below this radio button, the user will find the number of wells and the length of the vertical BHEs, and below it, the ground thermal imbalance.

As for the GSHP system sized, the user will find:

- Model ID of the heat pump selected and number of pumps required
- Operative conditions of the heat pump selected, for heating and cooling
- Number of days requiring heating and cooling at the facility

Finally, the user can either go back to the rest of the tabs (except to the front page), or generate a report with the results coming from the simulation. However, the user can only see the graphs on the GUI, exporting in the report only the values for each outside temperature.

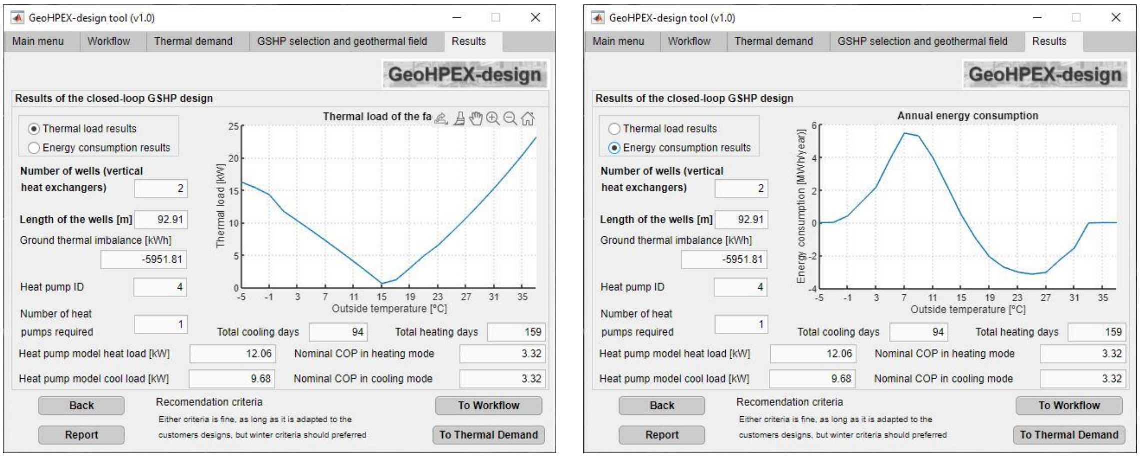


Fig 2.13 Results on the thermal load (left) and annual energy consumption (right) depending on the radio button selected

By the revision of this feature, the design of the GUI and the information that the user has to impute has been presented, revised and justified. In the following section of the chapter, it is possible to analyse the logic behind the button ‘Next’ and ‘Run’ of GeoHPEX that detects errors in the information imputed, while learning the secondary information obtained by the primary data included in the different tabs available.

2.3 Loading information. Bin method requirements and secondary data generated

In the previous chapter, the Graphical User Interface, the components and the information imputed by the user were exposed. This section of the document is intended to explain the secondary data generated from the inputs of the user, as well as the sources of the assumptions made by GeoHPEX and the programming implemented in the buttons 'Next' and 'Run' to assist the user experience. But before this, it is basic to introduce the reader to the *modified Bin Method* [42], used in GeoHPEX for designing the geothermal installation.

The behaviour of a GSHE geothermal system is time and temperature dependent, as the optimal operation point is shifted depending on the time of the day (modifying the solar gains), outside temperature (shifting the thermal gradient between the defined comfort temperature of the interior and the external temperature) and the day of the year (modifying the average temperature of the soil).

Consequently, IGSHPA designed a methodology (applied in GeoHPEX) in order to be only temperature dependent, valid for first approximations on geothermal systems, main goal of this application.

The main characteristic of this system is that it organises yearly temperature frequencies into discrete blocks (named bins). Each block applies for a discrete set of temperatures, and the content of the bin is the number of hours in the year that the temperature was between the temperature range of the bin.

Let is serve as an example the case of a location in which the temperature is between 2 and 4 ºC for 86 hours in the year. The temperature assigned to this bin would be the mean of the range (in this case, 3 ºC), and the content of the bin is 86 hours. As an approximation, it would be said therefore that along the year, the temperature of the location is equal to 3 ºC around 86 hours.

To perform such method, it is necessary to have an hourly measured value of the outside temperature for the whole year. The same thing done in the example is applied to the rest of the temperatures, defining a finite number of bins with the number of hours of that temperature along the year. For obvious reasons, the sum of all the bins sum 8760 hours, and the size of the bin, in general, is 2 ºC (bin values of -5 , -3 , -1 , 1 , … , 35, 37 are, for instance, used in GeoHPEX, covering temperature ranges from -6ºC to 38ºC). The use of each bin will be exposed in later sections of the document (see *2.4 Heating and cooling load estimation*).

The source of this information, however, is often not easy to be found, and the programs in the State-of-the-Art left it to the user to impute the information of the bins (in reality, these bins are a histogram of the temperatures of the location), which can result in a major inconvenience for the user and a reason to quit using the app.

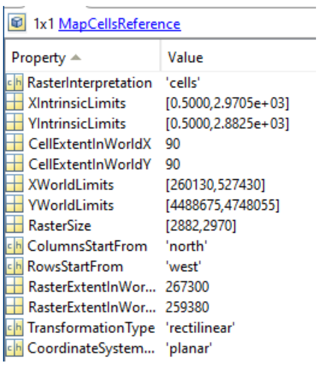
On the contrary to other countries, the Spanish *'Código Técnico de la Edificatión*' [32] counts with a database that defines the climate of each location in the territory, in .txt files with hourly values of the ambient temperature, humidity, irradiation, wind direction and magnitude, etc., which are perfect to be applied to this method. This database is recommended to be used to define the thermal demand of facilities, and the number of bins and the temperatures to represent them have been established as for the climatic data for Catalunya (no temperature below -6ºC is considered according to this literature).

The cited literature classifies the climate in Catalunya depending on the province of the location and the height above sea level, existing up to seven different climate typologies. This directs to the need of evaluating the height above sea level and the province in which the location is placed in GeoHPEX to design the geothermal system, if the intention is to load this information automatically when introducing the location.

To do so, the ICGC prepared two raster maps (among others that will be seen in this section) that contain the information of the province and the height above sea level in Catalunya. The raster file (.tif in the case of GeoHPEX) implementation on Matlab is crucial, as a wrong interpretation of the location (by the inputs of the user) would lead to a wrong climate selection to apply the bin method, and the results would be useless.

Matlab2020a® included in the latest version a toolbox to load raster files on the command window, inexistent in previous versions. The program loads the raster file by creating two different objects: a matrix, containing in each cell the values of the raster; and a MapCellsReference object that defines the conditions of the raster map.

Each object is linked to each other, and cannot be understood one without the other. The MapCellsReference object contains the information of the extents of the map, the vertical and horizontal size of the cells in which the information is divided, the number of cells that contains the maps, and other relevant contents.


1x1 MapCellsReference

Property	Value
RasterInterpretation	'cells'
XIntrinsicLimits	[0.5000,2.9705e+03]
YIntrinsicLimits	[0.5000,2.8825e+03]
CellExtentInWorldX	90
CellExtentInWorldY	90
XWorldLimits	[260130,527430]
YWorldLimits	[4488675,4748055]
RasterSize	[2882,2970]
ColumnsStartFrom	'north'
RowsStartFrom	'west'
RasterExtentInWor...	267300
RasterExtentInWor...	259380
TransformationType	'rectilinear'
CoordinateSystem...	'planar'

Fig 2.14 MapCellsReference example of a raster object loaded in Matlab2020a®

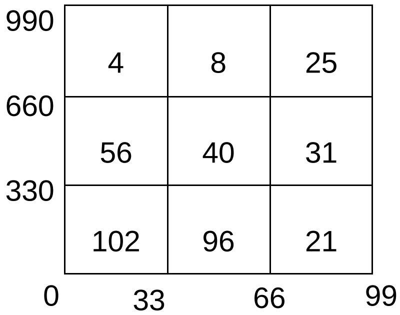
The matrix, on the other hand, contains the values of the map for each position. In the case of the province, ICGC defined numbers to represent each province (1: Barcelona, 2: Girona, 3: Lleida, 4: Tarragona). If a cell contained a number 1, it would mean that the cell represents a point in the province of Barcelona.

The most important characteristic of the objects is the X and Y WorldLimits of the MapCellsReference, and the X and Y intrinsic limits. The values of the intrinsic limits are those that Matlab works with, while the world limits are the representation on the real world of the relative position of the intrinsic cells.

This is better explained with an example. Let us imagine a 3x3 map such as the following:

4	8	25
56	40	31
102	96	21

The size of the map in the real world goes from 0 to 99 in the horizontal axis, and from 0 to 990 in the vertical axes, as this:



The limits 0-99 and 0-990 would be the X and Y WorldLimits of the raster loaded on Matlab®, with respective cell sizes of 33 and 330. However, Matlab® registers the matrix with different indexes:

3	4	8	25
2	56	40	31
1	102	96	21
	1	2	3

The position [3,2] in the matrix loaded in the program corresponds to the coordinates [99,660] in the world (column, file calling system, used in Matlab), with a value of 31. To access the information, it is necessary to create an imref2D object in Matlab, and apply the world and intrinsic limits of the map loaded to it.

Once the user has introduced the input of the location, the program has acquired the values of the X, Y position in the World limits. After creating the imref2D object for any map and applying the intrinsic and world limits of the struct object loaded, GeoHPEX acquires through the function worldToIntrinsic the relative position of X and Y for the matrix loaded (intrinsic coordinates), and the program reads the value for those intrinsic coordinates evaluating the correct result from the input of the user. It is worth mentioning that the matrix loaded in Matlab® stores the matrix 'correctly' for the horizontal direction (from left to right column, the horizontal value in the world is at the same position as the horizontal value of the matrix), while the vertical coordinate is inverted (y_world position in real world corresponds to [size – y_intrinsic] in Matlab®). See this feature below.

Fig 2.15 Representation of the loading behaviour of the raster maps. On the left, the silhouette of Catalunya is presented. On the right, how Matlab® stores the information. The horizontal coordinate is the same in the World and in the program, but the value of the vertical component is the inverse between maps

To approximate the results, the value read at the matrix is the bilinear interpolation of the surrounding cells. The same mechanism to load data with raster maps is applied to the rest of the raster files used, regardless the contents of them.

Having seen this, the province and height above the sea can be evaluated from the input of the user. This will serve as a filter when the input location is out of range, and will be able to evaluate the correct climatic data corresponding to it. The climatic zones considered in GeoHPEX are presented, where the program automatically selects the one to load depending on the lectures of the province and height [32].

Tabla a-Anejo B. Zonas climáticas

<table>
<tr><th rowspan="2">Provincia</th><th colspan="24">Altitud sobre el nivel del mar (h)</th></tr>
<tr><th>≤ 50 m</th><th>51 - 100 m</th><th>101 - 150 m</th><th>111 - 200 m</th><th>201 - 250 m</th><th>251 - 300 m</th><th>301 - 350 m</th><th>351 - 400 m</th><th>401 - 450 m</th><th>451 - 500 m</th><th>501 - 550 m</th><th>551 - 600 m</th><th>601 - 650 m</th><th>651 - 700 m</th><th>701 - 750 m</th><th>751 - 800 m</th><th>801 - 850 m</th><th>851 - 900 m</th><th>901 - 950 m</th><th>951 - 1000 m</th><th>1001 - 1050 m</th><th>1051 - 1250 m</th><th>251 - 300 m</th><th>≥ 1301 m</th></tr>
<tr><td>Barcelona</td><td colspan="5">C2</td><td colspan="4">D2</td><td colspan="6">D1</td><td colspan="9">E1</td></tr>
<tr><td>Girona</td><td colspan="2">C2</td><td colspan="10">D2</td><td colspan="12">E1</td></tr>
<tr><td>Lleida</td><td colspan="2">C3</td><td colspan="10">D3</td><td colspan="12">E1</td></tr>
<tr><td>Tarragona</td><td colspan="2">B3</td><td colspan="8">C3</td><td colspan="14">D3</td></tr>
</table>

Table 2.1 Tabla a-Anejo B. Zonas Climáticas, for the provinces of Catalunya. Adapted from [32]

The .txt of the seven possible climatic data were loaded in excel files (easier for Matlab to load correctly), to be used by GeoHPEX. A total of four different excel files were generated from the original information, by creating a histogram and generate the temperature bins or by imputing directly the whole, untreated data:

- bin values along the year, in 2 ºC bins, from -5 ºC to 37ºC (22 bins in total)
- bin values for the coldest month of the year
- bin values for the hottest month of the year
- Rough data of the ambient temperature along the year (without treatment)

The potential of the information generated just with the location input of the user goes beyond the presented. IDAE stated in its adaptation of the methodology [3] to define the temperature design conditions for winter and summer as a matter of percentiles from each location.

The temperature design for winter and summer is the reference to which the geothermal system is sized. The selection of those values is done through percentiles, 99% for winter and 0.4% for summer. The meaning of those values refer to the number of hours in the year in which ambient temperature is above them: for winter, the design temperature has to fulfil that in the 99% of the hours in the year (8672 hours approximately), the temperature is above the selected, while for summer the temperature selected is above the rest registered the 99.6% of the time. In the case of the climatic zone B3, the design temperature for winter is equal to 5ºC, while the temperature design for summer is 35 ºC. For E1, however, those percentiles correspond to the temperatures -3 ºC and 29 ºC, respectively. Therefore, an excel file was generated to store the design temperature for summer and winter of every climatic zone, storing also its correspondent number of bin (bin position: -5ºC is equal to 1, -3ºC is 2, … , to 37ºC that represents 22).

The bin method requires, apart from this temperature, the values of the mean daily temperature variation of the location (in magnitude). This value (DR), for instance, for a day in which the temperatures oscillated between 15 and 25 ºC, would be equivalent to 5 ºC, as the mean temperature of that day is equal to 20 ± 5ºC (ASHRAE definition of DR [26]). To improve the performance of GeoHPEX, three different values of DR were calculated, one for the hottest and coldest month, and the yearly average. This was done through an algorithm defined firstly, that took the rough data in a double 'for' loop (one for every day and other one to count the 24 h) and stored the results. As those values were constant for each climate, it was decided to store the results in an excel file, reducing the computational time expended in this.

The definition of the climatic conditions also defines the values of the heat transfer coefficients of the buildings according to the literature [32], that are used to calculate the thermal demand in the geothermal system. The values of the heat transfer coefficient for the different constructive elements are presented below.

Tabla 3.1.1.a - HE1 Valores límite de *transmitancia térmica*, U_{lim} [W/m²K]

Elemento	Zona climática de invierno					
	α	A	B	C	D	E
Muros y suelos en contacto con el aire exterior (U_S, U_M)	0,80	0,70	0,56	0,49	0,41	0,37
Cubiertas en contacto con el aire exterior (U_C)	0,55	0,50	0,44	0,40	0,35	0,33
Muros, suelos y cubiertas en contacto con espacios no habitables o con el terreno (U_T) Medianerías o particiones interiores pertenecientes a la *envolvente térmica* (U_{MD})	0,90	0,80	0,75	0,70	0,65	0,59
Huecos (conjunto de marco, vidrio y, en su caso, cajón de persiana) (U_H)*	3,2	2,7	2,3	2,1	1,8	1,80
Puertas con superficie semitransparente igual o inferior al 50%	5,7					

*Los *huecos* con uso de escaparate en *unidades de uso* con actividad comercial pueden incrementar el valor de U_H en un 50%.

Tabla a-Anejo E. Transmitancia térmica del elemento, U [W/m² K]

	Zona Climática de invierno					
	α	A	B	C	D	E
Muros y suelos en contacto con el aire exterior, U_M, U_S	0,56	0,50	0,38	0,29	0,27	0,23
Cubiertas en contacto con el aire exterior, U_C	0,50	0,44	0,33	0,23	0,22	0,19
Elementos en contacto con espacios no habitables o con el terreno, U_T	0,80	0,80	0,69	0,48	0,48	0,48
Huecos (conjunto de marco, vidrio y, en su caso, cajón de persiana), U_H	2,7	2,7	2,0	2,0	1,6	1,5

Fig 2.16 Thermal transmittance (limit values above, recommended below) in accordance with the Spanish regulation [32]

See the correspondence on the letter in the chart with the climatic zone selected. Finally, the location also defines the ground conditions of the facility. The ICGC prepared a total of ten raster files to be used in GeoHPEX, of coordinates [260130, 527430] in the horizontal component and [4488675, 4748055] in the vertical (size of 90x90 cells), containing the following information:

- Province and height above the sea (function explained before)
- Mean temperature of the surface of the ground
- Temperature of the ground at a depth of 50, 100 and 150 m
- Thermal conductivity and thermal diffusivity of the ground
- Average number of days requiring heating for installations
- Average number of days requiring cooling for installations

The process to load the information of each map follows the same procedure as explained, after which the necessary secondary information that completes the primary inputs of the user in the GUI is finished. The complete set of values is enough to perform the calculation of the thermal demand, size the GSHP system and calculate the number and length of the vertical boreholes, resting the evaluation of the ground temperature for the facility.

It is worth to address this evaluation of the ground temperature carried out by GeoHPEX, as it is further used to size the geothermal installation. The expression that defines the ground temperature for depths smaller than 170 - 180 meters approximately is the following [42]

$$t_g(x,t) = \bar{t_g} - DR_{an} \cdot e^{\left(-x\sqrt{\frac{\pi}{365\cdot\alpha}}\right)} \cdot cos\left(\frac{2\pi}{365} \cdot \left[t - t_{t,min} - \frac{x}{2} \cdot \sqrt{\frac{365}{\pi \cdot \alpha}}\right]\right)$$

t_g – Ground temperature, as a function of the depth and the day of the year [ºC]

$\bar{t_g}$ – Mean temperature of the surface of the ground (secondary, from ICGC raster files) [ºC]

DR_{an} – Yearly mean daily temperature range of the location [ºC]

x – Depth of the ground [m]

$t_{t,min}$ – Julian day when the minimum temperature happens [1-365]

t – Julian day [1-365]

α – Diffusivity of the ground [m^2/day]

Beyond this depth, ground temperature begins to increase around 3ºC per 100 m depth. GeoHPEX creates a vector representing the depth in the soil, from 1 meter to 200 in steps of 10 cm (1991 positions), and stores the evaluation for t_g for the whole year in a 365x1991 matrix. For future calculations, the program stores the following information:

- Average temperature of the soil at a depth of 2 meters, for the hottest month
- Yearly minimum ground temperature registered
- Yearly maximum ground temperature registered

Though this data could have been stored and automatized in an excel file, it was decided to keep it in this way for a future possibility of GeoHPEX v2.0, to enable the possibility of showing the ground temperature for every day of the year. Having solved the process to automatically load the majority of the data, this section is concluded with the logic programmed to the elements and buttons in the GUI to navigate 'forward'. The first breech that helps the user is that all the edit fields placed in the tab are set to admit only positive values, showing a message of error as a tooltip.

The rest of the tools for the user in this tab come in the form of alert messages, appearing in the GUI when there is a wrong input of information. A total of 18 possible messages will appear in case of any defect in the information, with a custom message. The cases conceived are the following:

- Wrong input of the x coordinate of the location (input out of the horizontal range of the raster maps)
- Wrong input of the y coordinate of the location (input out of the vertical range of the raster maps)
- The user knows the thermal demand, desires to calculate the geothermal system for both seasons, but thermal load for summer is missing
- The user knows the thermal demand, desires to calculate the geothermal system for both seasons, but thermal load for winter is missing
- The user knows the thermal demand, desires to calculate the geothermal system for both seasons, but energy consumption for summer is missing
- The user knows the thermal demand, desires to calculate the geothermal system for both seasons, but energy consumption for winter is missing
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, but thermal load for summer and for winter are imputed
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, but energy consumption for summer and for winter are imputed
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, but energy consumption for summer is zero when the thermal load for summer is greater than zero
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, but energy consumption for winter is zero when the thermal load for winter is greater than zero
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, but thermal load for summer is zero when the energy consumption for summer is greater than zero
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, but thermal load for winter is zero when the energy consumption for winter is greater than zero
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, but there is no imputed value

- The user does not know the thermal demand and the built surface is equal to zero
- The user does not know the thermal demand and the number of floors is equal to zero
- The user does not know the thermal demand and the comfort temperature is equal to zero (the program changes tab, but the message appears noticing this error)
- The user does not know the thermal demand and the window surface relation is equal to zero (the program changes tab, but the message appears noticing this error)
- The user does not know the thermal demand and the number of occupants is equal to zero (the program changes tab, but the message appears noticing this error)

If none of the mentioned cases happen, the program will load the diffusivity and thermal conductivity of the ground to appear in part the 'Borehole Heat Exchanger design' block in the tab 'GSHP selection and geothermal field' (see Fig 2.9). If after hitting the button, the values shown for both are zero, it means that although the location imputed is in the range of the maps, the point could be located outside Catalunya (this precise explanation is showed as a tooltip in the GUI).

In this tab, a similar breech to help the user has been designed. The edit fields included in the GUI only admit positive values, while pushing the button 'Run' analyses the values from both tabs. This means that this button executes first the analysis on the 18 cases of the button 'Next', and then evaluates other 10 cases, namely:

- The user knows the thermal demand, desires to calculate the geothermal system for only one season, has imputed the data for summer season, but winter criteria is designed
- The user knows the thermal demand, desires to calculate the geothermal system for only one season, has imputed the data for winter season, but summer criteria is designed
- The user desires to curtail the maximum power of the geothermal installation but the value to curtail is equal to zero
- The user wants to use his own pump, but the nominal heating load is equal to zero
- The user wants to use his own pump, but the nominal cooling load is equal to zero
- The user wants to use his own pump, but the nominal heating COP is equal to zero
- The user wants to use his own pump, but the nominal cooling COP is equal to zero

- The user desires to use a value of the ground diffusivity different from the stablished at the ICGC database, but the input value is zero
- The user desires to use a value of the thermal conductivity of the ground different from the stablished at the ICGC database, but the input value is zero
- The user introduced a location within the range of the raster maps, but it places the facility out of Catalunya

If all the information is correct (this is, for the use selected the information required is correctly imputed), the program is ready to perform the calculations required to estimate the number and length of the vertical BHE. In the following sections of the chapter, the methodology used to calculate the thermal demand and size the GSHP geothermal system will be explained, endowing a meaning to all the information that GeoHPEX has acquired directly through the GUI, and indirectly from the secondary data loaded.

2.4 Heating and cooling load estimation

Once the information has been correctly loaded and imputed, GeoHPEX is ready to perform the estimation of the thermal demand and size the GSHP geothermal system for it. In this section of the chapter, firstly it will be introduced the mathematical model implemented in GeoHPEX for the thermal load estimation, with the different methodologies applied depending on the case of the user, analysing the different components that form the thermal load. As this methodology is explained, it will be presented the list of variables used for the calculation, and the theory of the algorithm implemented to calculate each component for the thermal load. Finally, it is possible to see the format of the results shown by GeoHPEX, and those that are used to size the geothermal system.

The thermal load of a facility refers to the heat transfer required to keep a stable temperature in the interior of a building, and depends on different components who are time and temperature dependent. It is measured in kW, and the value of the thermal load measured at the design temperatures (see section 2.3) will be used to size the geothermal installation. The calculation of this thermal load and energy consumption is performed in different ways depending on the selection of the user on whether he knows or not the thermal demand of its facility.

IGSHPA has defined in the modified Bin Method the two methodologies for the mentioned cases, being the simpler method the one in which it is known the thermal demand. Besides being simpler or not, both methodologies result in a temperature dependent expression that relate the outside temperature with the thermal load required for the facility. The usual shape of this dependency when plotted takes the form of the following graph.

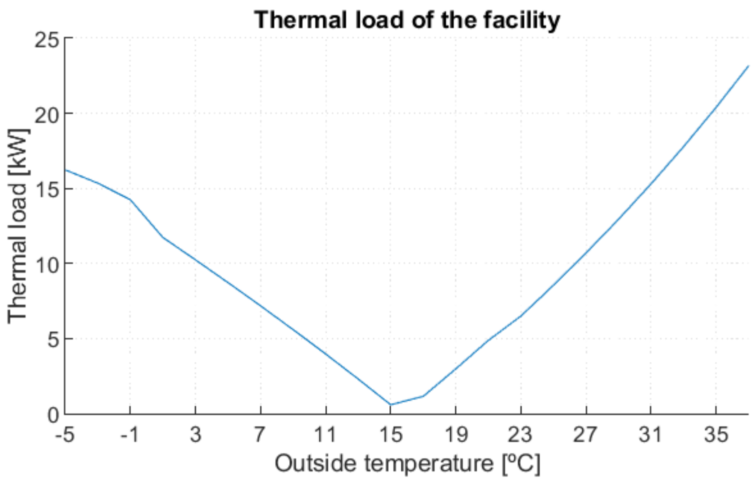


Fig 2.17 Example of a thermal load curve. Taken from GeoHPEX

The graph presented is in absolute value (which is the usual presentation of the results), but in reality, the values below 16 ºC (in this case, where there is a disruption of the graph) are negative, representing a loss of heat and hence, a demand for heat supply (this is the sign criteria that has been selected in GeoHPEX). As the bin method has calculated the average number of hours for every outside temperature, it is possible to obtain the results on the energy demanded by the facility, by multiplying each thermal load to its correspondent number of hours.

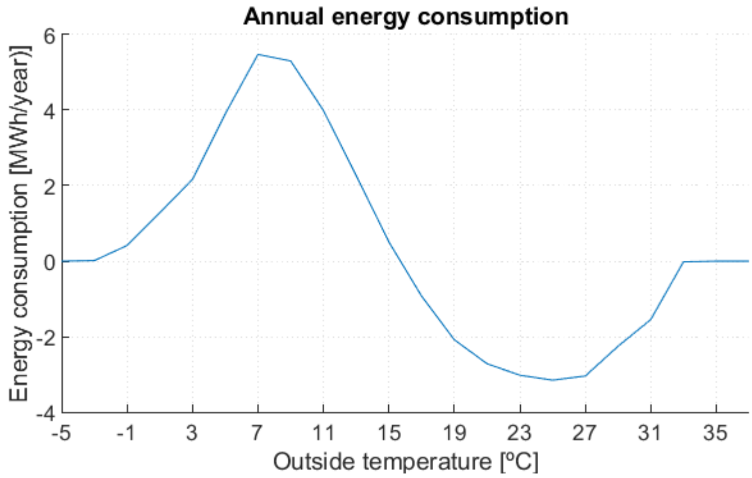


Fig 2.18 Example of an average curve for the annual energy consumption. Taken from GeoHPEX

Though the greatest thermal loads appear, for obvious reasons, on the extreme temperatures, the maximum energy demand for the case of Fig 2.18 happens at 7 ºC for heating, and at 25 ºC for cooling. The graph is conceived for positive values to represent the need to introduce heat to the system (heat), while negative values do it for extracting heat from the facility (cool). Note that the sign criteria match with the established: for negative thermal loads, when heat was lost, an incoming positive heat is required, while the contrary happens for cooling loads. The interpretation of this graph would be that the geothermal system should supply up to 5.2 MWh of heat along the year considering the number of hours that the outside temperature is equal to 7 ºC, while supplying other 2 MWh for the amount of time in the year in which the temperature is equal to 13 ºC. Around 3 MWh of cooling is supplied for the number of hours in the year at a temperature of 25 ºC.

To begin with, the thermal load in cases of knowing the thermal demand will be explained, as it is more direct and uses lesser inputs. To perform the estimation of the load, the following information is demanded. Note that beside the information demanded, it is written if the user has introduced the value directly (primary data) or if it is automatically loaded from those inputs (secondary data), for both methods.

1. Location (primary)
2. Thermal load for summer (primary)
3. Thermal load for winter (primary)
4. Annual energy consumption in cooling (primary)

5. Annual energy consumption in heating (primary)
6. Yearly bin values, and bin values for the hottest and coldest months (secondary, loaded from 1. in the excel files generated)
7. Design temperatures for winter and summer (secondary, loaded from 1. in the excel file generated for the percentiles)
8. Temperature assignation for the values (predefined)

The location is required to analyse the climatic zone where the location is placed, and enables the correct loading of the bin values and the design temperatures. The rest of them, either are primary data or are predefined.

This methodology, known as energy method, consists on generating a first order relation between the outside temperature and the thermal load, for summer and winter, in the form of

$$Q_i = c_0 + c_1 \cdot T_o \qquad (eq\ 2.1)$$

being Q_i the thermal load of the facility for the season i, and c_0, c_1 two coefficients defined by the input values. This methodology places the thermal load for winter and summer in their respective design temperatures, and each coefficient is calculated for both summer and winter, requiring to calculate four different values and generating two lines. To calculate both coefficients, IGSHPA defines the following expressions:

$$c_0 = \left[\frac{q_{d,s} \cdot \sum_{i=1}^{P} T_{o,i} \cdot h(T_{o,i}) - q_{tot,s} \cdot T_{d,s}}{\sum_{i=1}^{P} T_{o,i} \cdot h(T_{o,i}) - T_{d,s} \cdot \sum_{i=1}^{p} h(T_{o,i})}\right] \quad (eq\ 2.2)$$

$$c_1 = \left[\frac{q_{tot,s} - q_{d,s} \cdot \sum_{i=1}^{P} h(T_{o,i})}{\sum_{i=1}^{P} T_{o,i} \cdot h(T_{o,i}) - T_{d,s} \cdot \sum_{i=1}^{p} h(T_{o,i})}\right] \quad (eq\ 2.3)$$

$q_{d,s}$ – Thermal load input for season s [W]

$q_{tot,s}$ – Annual energy consumption for season s [Wh]

$T_{o,i}$ – Outside temperature assigned to the bin value i ([-5,37] for GeoHPEX) [ºC]

$T_{d,s}$ – Design temperature for season s [ºC]

$h(T_{o,i})$ – Number of hours contained in the bin value of temperature $T_{o,i}$ for the hottest/coldest month [h]

The evaluation of both coefficients for both winter and summer seasons build two different lines, that for winter has c_0 > 0 and c_1 < 0, while it happens the contrary to the summer line. When the value of the thermal load is above zero, it would mean that there is a requirement for heat or cool (depending on each curve), but as a nature of the construction of the model, it is required to correct the demand for the temperatures in which both heating and cooling are supposed to be required, solved to set the thermal load as equal to zero as shown in the following example.

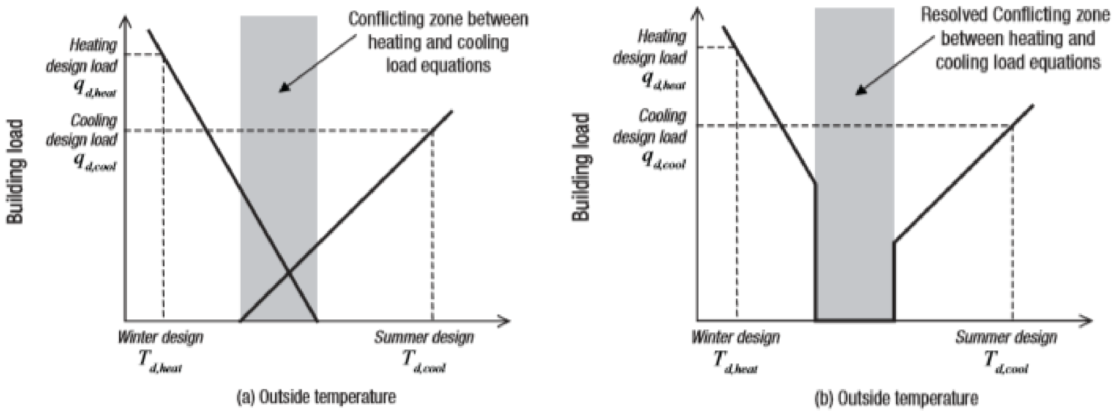


Fig 2.19 Solution on coincidence for the energy method [39]

Once GeoHPEX has detected that the information introduced is correct and has identified the type of use case selected by the user, it calculates the thermal load curves for heating and cooling (in the cases in which the user only introduces the values of one season, there is no conflict to solve, and the coefficients of the season not chosen are null). To construct only one curve from the original two, an algorithm that analyses the values for both curves for every temperature is defined, and stores the correspondent value on a third variable, used to be plotted on the 'Results' tab of GeoHPEX.

- If the curve for heating (decreasing curve) is above zero and the curve for cooling is below zero, the value stored corresponds to the heating curve
- In case both curves are above zero, the value of the variable at that temperature is set as zero
- Finally, in case of values of the heating curve below zero and cooling load above zero, the value of the cooling curve is stored

To implement the option for only one season, the program sets the negative values of each curve as equal to zero, as the algorithm used is no longer required and negative values do not have a physical meaning. The results obtained in Matlab®, as there were defined 22 temperature bins, is a 1x22 vector object containing the values of the thermal load. For a convenience of later algorithms, the values for winter are set as negative, plotting in the GUI the absolute value of that vector.

The methodology to calculate the thermal load when the user only knows the building definition (known as descriptive method) is more complicated, in terms of the number of components used and the existent differences for office and industrial uses, from the residential ones (each one has its own procedure). Both share most of the same theoretical methodology, but there are specifications on each case that drives through separate methodologies.

To use this methodology, the user has had to select the option 'I don't know the thermal load of the facility' in 'Thermal demand' tab, and impute the type of use, the geometry, built surface, number of floors, occupants, window surface relation and comfort temperature. Depending on the type of use selected, GeoHPEX picks one of the two descriptive methods: in case of selecting a residential use (with or without basements, or flat), the descriptive method for residential uses is selected, while for the rest of them the selected method is the descriptive method for industries.

The mathematical model of the descriptive method developed by IGSHPA is rather simple compared to a real estimation of the thermal demand by the use of dedicated software, which could implement finite elements computation or numerical methods. However, for a first estimation of the thermal load of facilities and the posterior evaluation of a GSHP geothermal system, the methodology has proved to be proximate enough to consider the results on the geothermal installation as valid.

The method conceptualizes the facility as a unique block, that computes what IGSHPA calls a 'block thermal load'. Though the thermal load of a building is the summation of the thermal loads of each zone in the building for residential buildings, this does not happen for industries and offices, as the peak loads of each zone might not happen simultaneously. A single zone approach, finally, is defined for all descriptive methods, which imply a single air temperature in the interior of the facility.

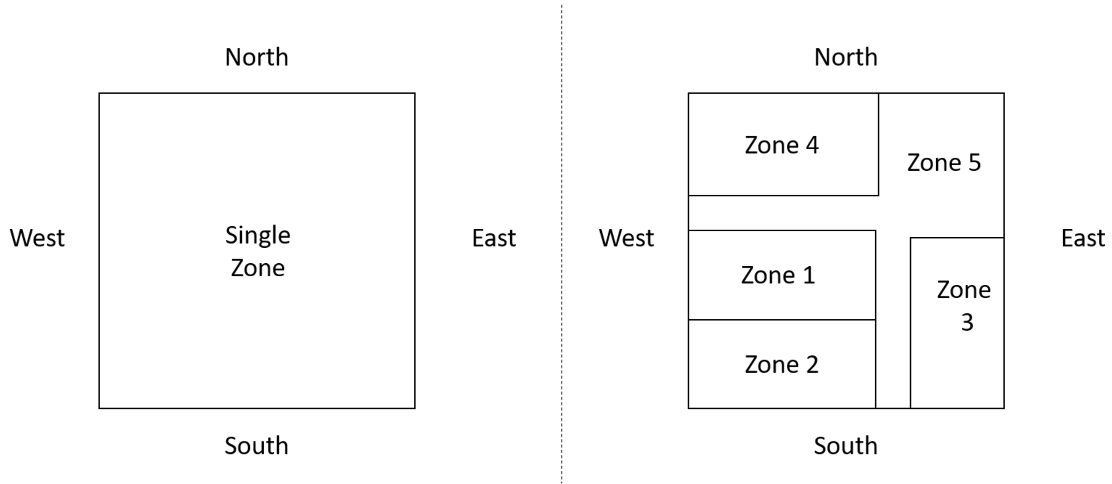


Fig 2.20 Single zone (left) versus zone approach (right). GeoHPEX uses the single zone approach as a recommendation from IGSHPA. Figured inspired from [39]

The definition of the thermal load has been divided into six different components (a matrix variable of 6x22 was created to store the load), calculated separately, which are:

- Transmission losses through the walls of the facility
- Sensible solar gains
- Fresh air load (sensible and latent)
- Internal gains (sensible and latent)

The differences existing between residential and industrial uses are present in the transmission losses (industrial uses do not consider the existence of basements, and the height of the walls are usually higher on industrial buildings), the fresh air load (differences in the volumetric flow rate of entering air) and internal gains (usually much higher in industrial uses). In addition, the heat transfer coefficients used for industrial uses in GeoHPEX are established as limit values, instead of the recommended average values used for residential uses, as a result of the tests performed to validate the model created in the app (Fig 2.16) [32]. The sign criteria selected is to assume outgoing heat (necessity to provide heat from the GSHP system) as negative, while incoming heat is positive, same as before.

The transmission losses account conductive and convective losses from the interior of the facility through the walls (there are no provisions made for opaque surface solar gains). The building environment is considered at constant temperature (equal to the comfort temperature), and by thermal equilibrium it is considered that the inner surface of the walls are at the same temperature as the interior of the room, while also by thermal equilibrium the exterior surface of the walls are at the external temperature. This is not true in real approximations, but is enough close for having valid results. Therefore, the transmission losses are those exchanged though the wall area, defining them as

$$q_{trans}(t_o) = \sum_i (UA)_i \cdot (t_o - t_c) = \sum_i q_i \quad (eq\ 2.4)$$

with q_w the thermal load [kW] for a given outside temperature t_o, t_c as the comfort temperature specified by the user and $(UA)_i$ the global heat transfer coefficient for the element i.

The built surface area, plus the number of floors and the presence or absence of a basement, define the area of exchange in the facility, where the geometry, although it does not affect the results (GeoHPEX keeps the perimeter constant, so even with the changes in the exchange area of the four cardinal directions, the load for the surface of the four walls is kept constant), is used to define the length of the south-oriented wall.

There has been defined five different surfaces of exchange: ceiling, windows, ground, walls and doors. In the cases of residential uses, the heights of the walls have been set to 2.5 meters (except for basements, set to 3 meters), while a height of 3 meters is defined in the rest of the uses.

The area of exchange for the ceiling and ground is obtained diving the built surface area introduced by the user, by the total number of floors (when the user has selected the case with existent basement, GeoHPEX adds an extra floor). For the window surfaces, the area of exchange is as simple as multiplying the built area imputed, by the window surface relation of the user. In the case of flats, there is only one door considered, while for the rest of the cases a number of 3 doors of size 1.5x2.5 are settled. For flats, the temperature gradient set for the ground (in this case, separation to other flats) is equal to 21 ºC minus the comfort temperature.

$$q_{ceiling}(t_o) = U_c \cdot \frac{s}{f} \cdot (t_o - t_c) \quad (eq. 2.5)$$

$$q_{ground}(t_{gm}) = U_g \cdot \frac{s}{f} \cdot (t_{gm} - t_c); \quad q_{ground,flat} = U_g \cdot \frac{s}{f} \cdot (21ºC - t_c) \quad (eq. 2.6)$$

$$q_{window}(t_o) = U_{ww} \cdot s_w \cdot s \cdot (t_o - t_c) \quad (eq. 2.7)$$

$$q_{door}(t_o) = U_d \cdot 1.5 \cdot 2.5 \cdot n_p \cdot (t_o - t_c) \quad (eq. 2.8)$$

U_c – Heat transfer coefficient of the ceiling in contact with the exterior [W/mK] (secondary, obtained from the location of the facility)

U_g – Heat transfer coefficient of the ground in contact with the soil [W/mK] (secondary, obtained from the location of the facility)

U_{ww} – Heat transfer coefficient of windows in contact with the exterior [W/mK] (secondary, obtained from the location of the facility)

U_d – Heat transfer coefficient of doors in contact with the exterior [W/mK] (secondary, obtained from the location of the facility)

f – Number of floors (primary, user input)

s – Built area [m^2] (primary, user input)

s_w – Window surface relation [m^2 window / m^2 built surface] (primary, user input)

n_p – Number of doors (predefined)

t_o – Temperature at the exterior [ºC] (predefined for every bin generated)

t_c – User's comfort temperature [ºC] (primary, user input)

t_{gm} – Mean ground temperature at a depth of 2 m for the hottest month [ºC] (secondary, generated from the ground temperature)

(Same notation as before is used in the future) As for the vertical walls, depending on the case in which the basement is present or not, the system performs as such:

- In case of existing a basement, the thermal load component splits in two, as the thermal gradient for the buried section is calculated with the ground temperature and not with the external temperature. The exchanges are the following

$$q_{wall\_e}(t_o) = U_w \cdot [(f-1) \cdot H_w \cdot (2 \cdot l_{sun} + 2 \cdot l_{side}) + 0.3 \cdot H_f \cdot (2 \cdot l_{sun} + 2 \cdot l_{side})] \cdot (t_o - t_c)$$

$$q_{wall\_b}(t_g) = U_w \cdot [0.7 \cdot H_f \cdot (2 \cdot l_{sun} + 2 \cdot l_{side})] \cdot (t_g - t_c) \quad (eq. 2.9 \ and \ 2.10)$$

U_w – Heat transfer coefficient of walls in contact with the exterior [W/mK] (secondary, obtained from the location of the facility)

H_w – Height of the walls. The values assigned by GeoHPEX are 2.5 m for residential uses, and 3 for industrial or office buildings (predefined)

l_{sun} – South-oriented wall length of the facility [m] (secondary, generated for the built area, the number of floors and the geometry imputed by the user)

l_{side} – West or East oriented wall length of the facility [m] (secondary, generated for the built area, the number of floors and the geometry imputed by the user)

H_f – Height of the basement walls, set as 3 m. (predefined)

Notice that the basement (eq. 2.9) shows the 30% of its area, in contact with the ambient temperature. In case that the user selects a use with no basement (industrial uses included), the expression simplifies to

$$q_{wall\_e}(t_o) = U_w \cdot f \cdot H_w \cdot (2 \cdot l_{sun} + 2 \cdot l_{side}) \cdot (t_o - t_c) \quad (eq. 2.11)$$

Therefore, except for the load at the basement, all the components depend on the external temperature, as requested from IGSHPA. The evaluation for every external temperature set at the bins defines its correspondent thermal load.

As for the sensible solar gains, the expression to calculate the values has been defined by IGSHPA [42] as the following:

$$q_{gain}(t_o) = S_c \cdot [q_{sol,w} + M \cdot (t_o - t_{ph})] \quad (\text{eq. } 2.12)$$

$$S_c = l_{sun} \cdot H_w \cdot f \qquad M = \frac{(q_{sol,s} - q_{sol,w})}{(t_{pc} - t_{ph})}$$

$$t_{ph} = t_{d,heat} + \frac{DR_w}{2} \qquad t_{pc} = t_{d,cool} + \frac{DR_s}{2}$$

S_c – Area of the facility exposed to the sun (in Catalunya, south-oriented) [m²] (secondary, obtained from the location of the facility)

$t_{d,heat}$ – Winter design temperature (see section 2.3) (secondary, loaded from the climatic zone selected, in an excel file) [ºC]

$t_{d,cool}$ – Summer design temperature (see section 2.3) (secondary, loaded from the climatic zone selected, in an excel file) [ºC]

DR_w – Mean daily temperature range of the location for winter (see section 2.3) (secondary, loaded from the climatic zone selected, in an excel file) [ºC]

DR_s – Mean daily temperature range of the location for summer (see section 2.3) (secondary, loaded from the climatic zone selected, in an excel file) [ºC]

And being $q_{sol,i}$ the average solar contribution for summer s and winter w in [w/m²], while M represents the solar heat gain interpolation coefficient. The average solar contribution values are defined through the same expression, but adapted depending on the season calculated.

$$q_{sol,i} = \frac{AG \cdot SC \cdot FPS_i}{4 \cdot nh_i \cdot S_c} \cdot \sum_i x \qquad (eq. 2.13)$$

AG – Glass area exposed to the sun $AG = s_w \cdot s \cdot \left(\frac{l_{sun}}{(2 \cdot l_{sun} + 2 \cdot l_{side})}\right) [m^2]$

SC – Shading coefficient, equal to 0.81 [42]

FPS_i – Fraction of possible sunshine for season i, set to 0.64 for summer and 0.45 for winter [42]

nh_i – Number of operative hours of the air conditioning equipment [h] for season i, set to 13 for summer and 23 for winter [42]

The value of $\sum_i x$ represents in the original formulation of IGSHPA a summation term for the maximum solar heat gain factor for all directions, at summer and winter, multiplied by the 24-hour sum of the cooling/heating load factor for every direction, whose values are tabulated. To prevent loading these tables, the summation term was substituted in RETscreen® [39] by two curves, one for each season, expressed as a function of the latitude (Y coordinate in our system), with enough accuracy to validate this change.

$$\sum_{winter} x = -1.55 \cdot lat^2 + 2.9687 \cdot lat + 12369$$

$$\sum_{summer} x = 0.8586 \cdot lat^2 - 33.9 \cdot lat + 10955$$

The value of the latitude requires the transformation of the coordinate, from UTM 31 to lat-long system. GeoHPEX automatically evaluates the value required. As seen, all the required parameters either were imputed by the user, generated as secondary data or were predefined. The methodology generates a linear function, placing $q_{sol,w}$ at t_{ph}, and $q_{sol,s}$ at t_{pc}. There exists the possibility that, when evaluating the solar gains of very cold temperatures, the values of $q_{gain}(t_o)$ are negative. As this is physically impossible when talking about solar gains, GeoHPEX sets those values to zero (hardly occurs, though).

Moving now to the fresh air charge, this thermal load was divided between the sensible and the latent loads. In the case of the sensible load, IGSHPA [42] defined the thermal load as

$$q_{fr,sens}(t_o) = \rho \cdot c_p \cdot \dot{V} \cdot (t_o - t_c) \quad (eq. 2.14)$$

ρ – Density of air. Set to 1.225 [kg/m^3] [14]

c_p – Specific heat at constant pressure. Set to 1,005 [J/kg K] [14]

$\dot{V}$ – Volumetric flow rate of air entering [m^3/s]

The volumetric flow rate is different for industries and residences. In the case of residences, the volumetric flow is dependent on the insulation levels and the total volume of the facility. GeoHPEX would assume a medium level insulation, and stablishes that every hour there is a replacement of the 25% of the air in the facility by the intrusions of air, while for industries, offices and the rest, the volumetric rate is fixed to 10 litres per second.

Determining the value of the sensible load would only consist on evaluating it for every outside temperature bin. As for the latent load, the humidity of the location and the humidity of the interior are the most important parameters, following this expression:

$$q_{fr,latent}(t_o) = \rho \cdot \dot{V} \cdot \left(W_o h_{s,o} - W_c h_{s,c}\right) \quad (eq. 2.15)$$

W_o – Water content (relative humidity) of the exterior air [kg water/kg dry air]

W_c – Water content (relative humidity) of the interior air [kg water/kg dry air]

$h_{s,o}$ – Enthalpy of saturated water vapor at 1 atm, and t = t_o [J/kg water]

$h_{s,c}$ – Enthalpy of saturated water vapor at 1 atm, and t = t_c [J/kg water]

Although the expression (eq. 2.15), IGSHPA recommends a linear interpolation to obtain the latent load from the sensible load previously calculated, because using eq. 2.15 implies the evaluation of the enthalpy of the air, and it can become difficult.

However, GeoHPEX does not follow this methodology, as Matlab can count with CoolProp©, a library to estimate different parameters of a wide range of liquids and, for this case, humid air, by containing psychrometric tables. Therefore, the two expressions for the fresh air load have been implemented in GeoHPEX as just one

$$q_{fr}(t_o) = \rho \cdot \dot{V} \cdot \left(W_o h_{s,o} + (1 - W_o) h_{a,o} - W_c h_{s,c} - (1 - W_c) h_{a,c}\right) \quad (eq. 2.16)$$

$h_{a,o}$ – Enthalpy of dry air at 1 atm, relative humidity W_o and t = t_o [J/kg dry air]

$h_{a,c}$ – Enthalpy of dry air at 1 atm, relative humidity W_c and t = t_c [J/kg dry air]

The optimal calculation would imply to request the relative humidity for the interior of the facility, plus loading the average relative humidity of the location. As ICGC did not have any information related to the annual relative humidity in Catalunya, it was decided to assume the average relative humidity of Catalunya based on the Institut d'Estadística de Catalunya [21], equal to 73.05%. For the interior of the facility, the resources point to values proximate to 50% to maximize comfort [41] [49]. Thus, GeoHPEX performs the evaluation of the parameters assuming those conditions, improving the exactness of the method from previous implementations of IGSHPA's method.

To end with the components of the thermal load, GeoHPEX evaluates the internal gains of the facility, both sensible and latent. In this situation, the methodology followed by the app agrees with IGSHPA, presenting differences for the calculation for residences of industries.

- For residential uses, the gains of the equipment and the occupants are taken into account. For sensible gains, the expression is the following

$$q_{in,s} = k_{in} \cdot s + k_{p,sens} \cdot n_o \quad (eq. 2.17)$$

k_{in} – Sensible gains for the equipment, equal to 14 [42] [W/m^2]

$k_{p,sens}$ – Sensible gains for occupants 74.6 [42] [W/ n occupants]

n_o – Number of occupants (primary)

As for latent gains, the thermal load only considers the action of occupants, with latent gains per occupant equal to 74.6 W, same value as for sensible gains.

- For industrial uses, gains from the lighting system are also considered. In this case, the sensible gains of the facility are obtained as such

$$q_{in,s} = k_{in} \cdot s + k_{light} \cdot s + k_{p,sens} \cdot n_o \quad (eq. 2.18)$$

k_{light} – Sensible gains for lights, equal to 15 [42] [W/m^2]

k_{in} – Sensible gains for the equipment, equal to 10 in industrial uses [42] [W/m^2]

Latent gains are calculated following the same procedure than in residential uses.

As seen, the internal gains are independent of the external temperature, and as a consequence GeoHPEX adds this constant load to every bin generated. Adding the six components together (though it uses one expression, GeoHPEX decided to separate the sensible and latent load of fresh air for the internal evaluation of the results) in one unique variable generates a curve as in Fig 2.17, a line whose cross in the horizontal axes represents the equilibrium temperature, at which there is no need to cool or heat the facility. The evaluation of the thermal load at the design temperatures for winter and summer determines the design load to size the geothermal installation, therefore after this process, GeoHPEX has acquired the enough information to size the GSHP geothermal installation, and consequently, the length and number of boreholes for the facility.

However, the user has the possibility to curtail the thermal load to be covered by the geothermal system, introducing the value of this curtail. In such case, GeoHPEX analyses the values of the thermal load generated: for negative values, if the absolute value of the thermal load is larger than the curtail value, the program saves the negative value of the curtail as the thermal load, happening the same for positive thermal loads, than in case of exceeding the curtail, the value stored is the curtail.

The following section of the chapter will introduce the algorithm implemented to size the geothermal installation, developed for GeoHPEX, understanding the logic and the assumptions made at the program. The results will be exposed later on its correspondent tab.

2.5 Ground Source Heat Pump sizing and added value. Display on 'Results'

The previous section of the chapter followed the methodology used by GeoHPEX to establish the thermal load and energy consumption of facilities, explaining the different alternatives that the program can select depending on the conditions entered by the user. From the results obtained, the program is now prepared to generate a proper sizing on the GSHP demanded, being able to calculate the heat pump required and, finally, the number and length of the vertical BHEs. This section will also explain other results obtained by the program that are showed in 'Results' tab, offered as an added value for the user.

As said, the inputs from the user regarding the thermal demand of the facility has enable GeoHPEX to evaluate the thermal load as a function of the external temperature, which also determines the energy consumption by the contents of the thermal bins. Moreover, by introducing the location of the facility and the design criteria, the app has loaded the information of the design temperature for the installation (see *2.3 Loading information. Bin method requirements and secondary data generated*) that the algorithm has to use.

To serve as a reminder, the program requires the evaluation of the thermal load at the design temperature for the season selected, so that there could be an assignation of the heat pumps to cover this demand at that temperature. The program, as explained before, was programmed in case the user imputed only one season, to detect that the design criteria selected matched with the season introduced, avoiding mistakes in the sizing.

The nominal capacity of the heat pump database (Table 1.2) were positive values. As a matter of nature of the thermal demand, the absolute values of this vector were copied to another variable, to analyse only positive values for both winter and summer criteria.

The construction of that copied variable was as such to get it prepared for the direct evaluation of it. Therefore, the program only requires to access the cell position that corresponds to the temperature design for the season selected, obtaining the reference load to size the system (from now, referred as 'design thermal load').

Users of GeoHPEX has two options regarding the heat pump, either selecting the database of ICGC, or imputing the values of its own heat pump, creating a need to differentiate both cases in the algorithm to select the pumps. Firstly, the app evaluates if one heat pump from the stored is enough, using the values for the design criteria selecting (heating or cooling).

- If the user decides to use the database of ICGC for the design thermal load, GeoHPEX states that, in case this value is higher than the 105% of the nominal capacity of the biggest heat pump for that season, more than one pump is required.
- Analogously to the previous case, when the user has introduced its own heat pump, GeoHPEX checks if the 105% of the nominal capacity of the heat pump for the season criteria is below the design thermal load, where if positive would mean that the system requires more than one pump.

The system now is aware if one heat pump is enough or more than one is required, for the season criteria selected by the user. Consequently, the algorithm splits between the two cases.

- When the user has introduced its own heat pump, and GeoHPEX has determined that only one heat pump is sufficient, the program stores the number of heat pumps required as equal to 1. The characteristics of the heat pump where stored before.
- When the user decided to use the database of ICGC and the program stated that only one pump is sufficient, GeoHPEX performs as such:
  - If the design thermal load is below the nominal capacity of the smallest heat pump (obviously, for the season criteria selected), the number of pumps required is equal to 1, and the characteristics of the heat pump selected are those of the smallest.
  - In case the design thermal load is, on the contrary, equal or higher than the nominal capacity of the biggest heat pump stored in the database, the number of heat pumps required is equal to 1, and the characteristics of the heat pump selected are those of the biggest heat pump stored in the database.
  - If the thermal load does not fulfil neither of the cases above, the program optimizes the selection following this procedure:
    - If the design thermal load is between the range of ± 5% of the nominal capacity of a heat pump, even though it can be larger or smaller, that heat pump is selected.
    - Otherwise, if the design thermal load is larger than the nominal capacity of a heat pump i but smaller than that of the heat pump $i+1$ (bigger), the heat pump $i+1$ is selected (this is done through a while loop, from top to bottom in Table 1.2). The ID of this model is stored.

In case that more than one heat pump was required, it was decided to divide the thermal load between heat pumps of equal characteristics. This is not the optimal solution, but ICGC agreed with this selection. Therefore, the algorithm evaluates the number of heat pumps dividing the design thermal load by integers, until the result of this division could fit the algorithm exposed above.

Let it be as an example a design thermal load of 30.5 kW, and a heat pump model with nominal capacity of 10 kW. A single pump is not enough as the design thermal load is much bigger than that of a single pump. GeoHPEX, in that case, would have noticed that, and has accessed the algorithm for more than one pump required. Then, in a while loop, the first integer to obtain the number of heat pumps is 2, having a new design thermal load of 15.25 kW. As this thermal load is, again, higher than the 105% of the nominal capacity of the heat pump, two heat pumps are still not sufficient for the GSHP system. Consequently, the program tries with 3 heat pumps, having a new design thermal load of 10.17 kW. In this case, as this new thermal load is below the 105% margin stated for a single pump, the solution of using three heat pumps is valid.

Analogously to this example, GeoHPEX evaluated the number of heat pumps required (the reference nominal capacity depends on whether the user selected its own heat pump or not).

- It the user has used the database of ICGC, GeoHPEX compares the new design thermal load to the 105% of the nominal capacity of the biggest heat pump in the database. When the new design thermal load can be covered by that heat pump, GeoHPEX performs the algorithm of one heat pump, using as thermal load the new design thermal load. The number of heat pumps required is the integer that enabled the access to the one-pump algorithm, while the type of heat pump selected is the result of the mentioned algorithm.
- On the other side, when the user has introduced its own heat pump, the characteristics of the heat pump do not change and are those of the user. GeoHPEX only requires to obtain the number of heat pumps that enable the operability of a single heat pump.

The solution of this algorithm results in knowing the number of heat pumps and the characteristics of them, to be shown in their respective areas of the tab 'Results' (Fig 2.12). The justification on selecting equal heat pumps in case of multiple heat pump required is based on the necessity of evaluating the COP of the heat pump system. If the algorithm had selected different models to operate the GSHP system, the overall COP would depend on the part load factor and the definition of the operation model for the system, which has been excluded from GeoHPEX. Selecting equal models ensures a unique value of the COP of the system, equal to the COP of a single heat pump.

With this information, the system can evaluate, finally, the length of the vertical BHEs that are required. According to the literature, the expression to obtain the length of the boreholes depend on the design criteria selecting, having one expression for heating or cooling sizes [42].

$$L_h = q_{des\,(h)} \cdot \left[\frac{\left(\frac{COP_h - 1}{COP_h}\right) \cdot (r_p + r_s \cdot F_h)}{t_{g,min} - t_{ewt,min}}\right]; \; L_c = q_{des\,(c)} \cdot \left[\frac{\left(\frac{COP_c + 1}{COP_c}\right) \cdot (r_p + r_s \cdot F_h)}{t_{ewt,max} - t_{g,max}}\right]$$

$$(eq. 2.19 \; and \; 2.20)$$

Recalling the expressions (eq. 1.5) and (eq. 1.6) from section *1.6 Commercial heat pumps and heat exchangers. Main considerations*, the expression for the length uses the instant thermal load seen from the ground side ($q_{des\,(h)} \cdot \left(\frac{COP_h-1}{COP_h}\right)$ for heating and $q_{des\,(c)} \cdot \left(\frac{COP_c+1}{COP_c}\right)$ for cooling). The requirements to implement the equations (eq. 2.19 and 2.20) are the following:

- $q_{des(i)}$ – Design thermal load for design criteria i (secondary, obtained from the thermal load estimation at the design temperature of the location) [W]
- COP_i – Coefficient of performance of the heat pump system for heating h or cooling c (secondary, obtained from the heat pump system sized) [-]
- r_p – Thermal resistance of the pipe (primary, from the selection of the U-probe in the tab 'GSHP selection and geothermal field') [mK / W]
- r_s – Thermal resistivity of the soil, $r_s = {k_s}^{-1}$; [mK / W]
- k_s – Thermal conductivity of the terrain (secondary, obtained from the raster maps of ICGC by the location) (primary, imputed by the user) [W / mk]
- F_i – Part load factor of the heat pump system for heating h or cooling c (secondary) [-]
- $t_{g,i}$ – Minimum min or maximum max ground temperature registered annually (secondary, obtained from the analysis of ground temperature (see *2.3 Loading information. Bin method requirements and secondary data generated*) [ºC]
- $t_{ewt,i}$ – Minimum min or maximum max design entering water temperature (secondary) [ºC]

Depending on the design criteria, one or the other expression is selected. As for the inputs, the design thermal load and the COP to use were determined earlier (the design thermal load is the overall thermal load, not the one covered by each heat pump when multiple heat pumps are required). The COP is that of the heat pump model selected.

The thermal resistivity of the soil is directly obtained as the inverse of the thermal conductivity. GeoHPEX stored that value either by evaluating the raster maps of ICGC or by reading the input of the user, while the selection of the U-probe defined the internal and external diameters of the exchangers. The thermal resistivity of the U-probe is obtained from

$$r_p = \frac{1}{2 \cdot \pi \cdot k_p} \cdot ln\left(\frac{d_o}{d_i}\right) \quad (eq. 2.21)$$

being k_p the thermal conductivity of the probe (equal to 0.38 W/mK, as seen on section 1.6), and d_o and d_i the external and internal diameters of the probe (same section of the document).

The design entering water temperature refers to the temperature entering the heat pump system (that, as explained in the introduction, counted with a heat exchanger). The maximum and minimum values are obtained as such [39]

$$t_{ewt,min} = t_{g,min} - \frac{5}{9} \cdot 15; \quad t_{ewt,max} = \min\left(t_{g,max} + \frac{5}{9} \cdot 20, (110-32) \cdot \frac{5}{9}\right) \quad (eq. 2.22)$$

Notice that the term $\frac{5}{9}$ and $(110-32) \cdot \frac{5}{9}$ corresponds to the transformation of 15ºF and 110ºF to ºC, because RETScreen®, as a Canadian program, does not use the International Metric System.

As for the partial load F_i, IGSHPA recommends its description for the hottest or coldest month, depending again on the design criteria selected by the user. The evaluation of this parameter required an algorithm to calculate this value, because F_i depends on the criteria selected and the number of pumps that were required for the GSHP system.

- The algorithm only requires the design criteria, the number of pumps and information of the model selected (user's model or database model, depending on the choice made by the user). The algorithm will address the nominal capacity of the design criteria established. Apart from this, the program will access the thermal bins of the hottest or coldest month (again, depending on the location and the design criteria) loaded from the excel files (see *2.3 Loading information. Bin method requirements and secondary data generated*).
- For every temperature bin, the algorithm evaluates if the correspondent thermal load of the facility (only in heating or cooling mode) is below the nominal capacity of the heat pumps, multiplied by the number of heat pumps selected.
    - If the thermal load is below or equal to the heat pump limits, it can be entirely covered by the GSHP system. Therefore, the energy consumed for that temperature is equal to the thermal load of the facility multiplied by the number of hours stored for the correspondent bin

  - In case the thermal load is higher than that of the nominal capacity of the heat pump multiplied by the number of heat pumps, then the thermal load that can be covered by the geothermal system is equal to the limits of the heat pump system. The energy consumed in this case will be equal to the limits of the heat pump, multiplied by the hours of the correspondent temperature bin, and an auxiliary system would be required to complete the thermal demand.
- The energy of every bin is accumulated in a variable. Finally, the part load factor F_i is obtained as such

$$F_i = \frac{E_p}{p_{nom} \cdot n_{pump} \cdot h_m}$$

E_p – Thermal energy able to be provided by the geothermal system for the month selected [Wh]

p_{nom} – Nominal capacity of the heat pump, for the mode selected [W]

n_p – Number of pumps sized for the facility [-]

h_m – Sum of the hours in the hottest or coldest month (usually 744 or 720 hours) [h]

In the end, this partial load factor is, for its definition, equal or less than 1 [0 – 1], as the system will never provide more energy than the limits of the heat pump. Finally, GeoHPEX has obtained all the parameters requires for the evaluation of the length of the vertical BHEs.

GeoHPEX computes this value, which corresponds to the exact depth required for a single well. However, there is a limitation on the depth of the BHEs, reason why the user is requested to introduce the estimation of the length of the probes, based generally on the maximum depth at which it is possible to dig.

Having that value as the reference (recall on section 1.6 that the offered lengths are commercial ones), the number of wells in the solution is equal to the total length calculated in the methodology, divided by the estimation of the depth of the wells. As this number is on most cases a decimal value (which is meaningless), the number of wells is rounded. Then, the length required for every well is equal to the total length calculated, divided by the rounded number of wells obtained.

As a conclusion of this methodology, GeoHPEX has been able to compute the number of wells and length of the exchangers, plus the number of heat pumps, its model, and the characteristics of the heat pumps, which are the requested information for the definition of a whole GSHP geothermal system, achieving the objective proposed for GeoHPEX originally.

As an addition for GeoHPEX, there are different parameters computed by the program that, although are not necessary, can result of interest to the user:

- The thermal energy imbalance for the ground is calculated (subtracting eq. 1.5 from eq. 1.6). This value would inform the user if its soil is heated or cooled along years, which can sometimes be a limitation for the geothermal installation for the environmental impact that it can carry. The computation of the heat extracted and injected to the ground depends on the thermal load and its hours of occurrence, hence the energy supplied to the facility is calculated analogously to the algorithm for the part load factor above, but instead of the hottest or hottest month, for the whole year, and taking into consideration if the heat pump is working supplying heat or cold. Then, (eq. 1.5) and (eq. 1.6) are applied, and subtracting each other to obtain the imbalance of the system.
- As described previously, the equilibrium temperature of the facility is that one in which there is no request of heating or cooling the facility. GeoHPEX evaluates the average temperature of every day of the year for the location: if this temperature is below (equilibrium temperature – 2ºC), then GeoHPEX considers this day as one where heating is required, happening similarly with cooling necessities (equilibrium temperature + 2ºC). The 2ºC range is a range to ensure a real necessity, as the user may not want any conditioning when the thermal load is low. Hence, the program can count the number of days in the year where heating or cooling is required, showed in the tab ‘Results’.
- With the result of the counted days of heat and cool, the program can contrast them with the specified in the database of ICGC loaded by the raster maps. If there is a relative error above 25% the program warns the user in the report, though the results offered by the program are correct. Every use, depending on the characteristics imputed by the user, may or may not fit the data considered by ICGC, therefore offering just a warning in this report.
- In case of imputing the surface of the facility (case of knowing the building typology), the report would show the annual energy consumption of the facility [kWh/m^2 year]

The calculations of GeoHPEX are concluded and can be showed in the tab ‘Results’, in its correspondent edit fields prepared for the purpose, giving a conclusion to this chapter. Those results obtained that do not fit in the ‘Results’ tab or that are of secondary interest for the user, are included in the report generated by GeoHPEX. In the following chapter of the document, the validation of the results generated by the app is studied, together with this report mentioned.

3. Validation of the model. Generated results

The previous chapter explained deeply the mathematical model implemented in GeoHPEX and the construction of the GUI to assist the user in its experience with the program. However, building a model is worthless without any validation, reason why this chapter is dedicated to the validation of the results showed by the application, the corrections and calibration that were required to introduce, and the final results obtained and included in a final report.

Validating an app depends entirely on the nature and purpose for what it serves. In this sense, the purpose of GeoHPEX is the calculation of the number and length of vertical BHEs, together with the estimation of a heat pump system to constitute a global GSHP geothermal installation, which would imply that the program requires checking these results to become a valid model.

The validation of the model can be performed thanks to the ICGC, who counts with different real geothermal installations monitored, together with commercial applications to compute the thermal demand of facilities, that gives enough experience to know the usual distribution of the thermal loads, and usual capacities required for different uses depending on the surface.

As in GeoHPEX there are two mathematical models working together and dependant on one another (thermal load calculation and GSHP sizing), each one requires to be validated. It is begun with the thermal load, as is the first step in the use of the application. According to the finding of ICGC, usual distribution of the thermal load on residential uses follows this particular trend (solar gains are included in internal gains):

	Heating mode	*Cooling mode*
Transmission losses	30%	28%
Fresh air loads (sensible and latent)	65%	27%
Internal gains (sensible and latent)	5%	45%

Table 3.1 Usual distribution of the thermal load on residential uses, according to the experience of ICGC

On average, the results shown by the model on GeoHPEX approximately follows the distribution on Table 3.1, but incur in some mistakes. In fact, it is been noted that the model follows some defined patterns:

- In most of the cases, the design thermal load throwed by GeoHPEX is below the thermal load designed for buildings of similar typology with real installations
- Internal gains are higher than expected and creates a distortion on the results

- Fresh air loads are below the expected, especially for heating mode
- The difference between industrial uses (office, industry, educational buildings, hospitals, etc.) has not been defined.

As a consequence, there has been defined different procedures to mitigate such defects. Although it might not be based strictly on any particular resource, ICGC has validated the results shown after the following corrections:

- Internal gains (both latent and sensible) for the occupants were limited to 55 W (45 W for industrial uses), instead of the original 74.6 from IGSHPA. This effect increases the thermal load for winter design, and does not affect much for cooling designs.
- Fresh air load has been lifted up by multiplying it with a factor of 1.43, which increases both design thermal loads on winter and summer. By this coefficient, fresh air loads meet higher values of design thermal loads for both winter and summer and matches the values of Table 3.1.
- Research on building consumption statistics has been performed [4] [15] [23] [34] [48], to differentiate between each type of industrial uses in the program.

Regarding this research, the objective was to find any evidence on the relationship between the nominal capacities of installations and its use type, in values of per unit surface.

The literature mentioned agree on the tendency of buildings to lower down its consumption year by year, with an actual average energy consumption on residential buildings around 145 kWh/m^2 year [34]. Besides, taking the yearly value of residential uses as base, the relative proportion of the consumption of different industrial uses is kept approximately constant along years [4] [15] [23].

The energy consumption mentioned refers to the global energy consumption of a residence, not just air conditioning. In this sense, the distribution between thermal conditioning and electricity consumption of the values shown in the literature differ between residential uses and industrial ones. Despite this, as the research is intended for industrial uses and the distribution of the energy for the mentioned are proximate [15], then a linear interpolation may become a possibility to adjust the calculations of the app to the different uses.

GeoHPEX uses for its advantage this fact, and has stablished that, depending on the type of use selected by the user in its correspondent tab, the application will multiply the result for the thermal load by the following coefficients, resembling the proportions found in the literature.

Type of use	*Adjustment coefficient*
Residential (without basement)	1
Residential (with basement)	1
Residential (flat)	1
Educational institution	1.05
Office	1.45
Industrial	1.337
Hotel and catering	1.8
Wholesale and retail	1.45
Hospital	1.19
Sports facility	1.146

Table 3.2 Adjustment coefficients set for the use types. Own elaboration

ICGC has accepted this method to differentiate the cases, although it still tends to underestimate the design thermal load for facilities, meaning a need to calibrate the model. To serve as calibration, a real case of GSHP geothermal installation has been confronted to GeoHPEX.

In this case, ICGC took the case of its '*Centre de Suport Territorial Pirineus*' (CSTP), a facility located in the city of Tremp (Lleida). This centre, dependent of the ICGC, counts with a real installation of GSHP system that conditions the facility, with 10 wells of 140 meters deep, carefully monitored.

To check the model, the thermal load for winter and summer were included, together with its energy consumption (they are blurred in the image, as it is protected information). Winter criteria was selected for sizing the system, without curtailing the load. A different pump from the database was selected (in fact, the data of the real model installed was imputed, also blurred), and a U-probe of 40 x 3.7 mm and estimated depth of 140 m was selected.

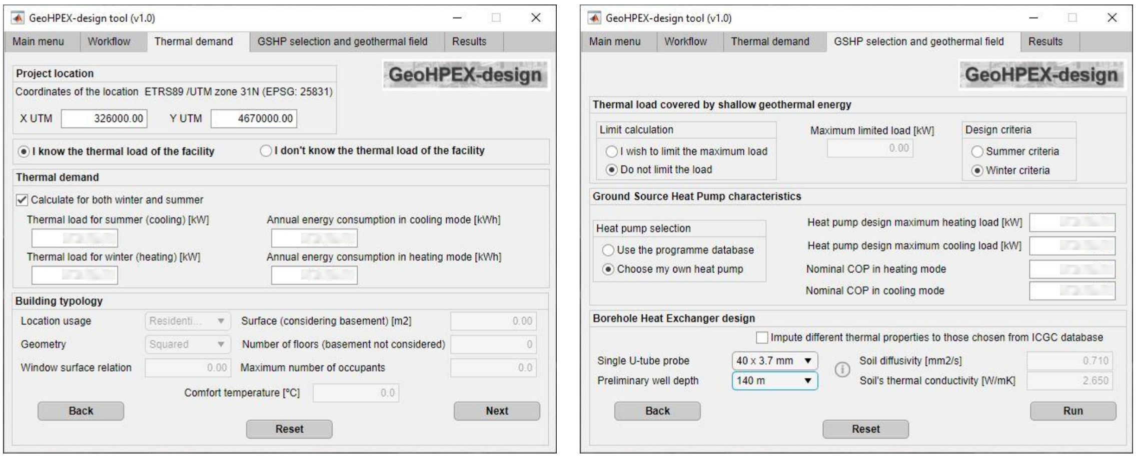


Fig 3.1 Calibration case for CSTP (Tremp, Lleida)

The results obtained in GeoHPEX estimated a total of 9 wells of 140.75 m, which compared with the real installation is one well less than existent. The conductor of this test, Mr. Ignasi Herms, declared that ICGC was aware that the installation was slightly oversized, and concluded that the sized system was correct. As for the thermal imbalance of the ground, the app obtained a result very proximate to the registered on the facility, with an error below 5%, which concludes that no calibration is required on the methodology of thermal demand imputation.

Parallel to this, the same case was tested but defining the building typology instead, same design conditions. In this case, the number of wells required was 5, with lengths estimated of 126 meters, way less than the necessary. Therefore, for industrial uses there has been a systematic increase of the adjustment coefficients of the 160% (e.g. 1.05 is now 2.73, and so on), while the adjustment coefficient for residential uses required an increase of the 70% from the comparison with other geothermal installation checked. With this change, the new results estimate 9 wells with a depth of 143.63 m, much proximate to the real data. Then, the adjustment and calibration are considered finished, therefore validating the mathematical models of the app.

The results showed in the tab 'Results' were explained in section 2.2, though the GUI does not show the complete set of parameters that the program is able to calculate. In this sense, there has been a button programmed to obtain the results of the simulation and generate a .txt report, which will automatically be saved at the file where GeoHPEX is stored. The report contains the following information (see an example of the report in *ANNEX II*.):

- Name of the program and authors
- Date of the simulation
- Thermal load case (thermal definition or building typology)
- Ground properties (ICGC database or user information)
- Location of the facility (automatic recognition of the province in Catalunya)
- Thermal load definition or building description

- Number and lengths of the boreholes. Type of U-probe
- Heat pump model: ID, number of pumps and nominal capacities
- Annual energy consumption per surface
- Annual energy consumption on heating
- Annual energy consumption on cooling
- Annual ground thermal imbalance
- Detection on defects of the results, compared to the database of ICGC

With this report, the user is able to replicate the cases in other occasions, as it possesses the information required to repeat the simulation. After explaining this final report, the description of the functionalities of GeoHPEX is complete, and in further chapters, the analysis of the User eXperience and future improvements is described, finishing with the conclusions extracted from the development of this project.

4. User eXperience and future improvements

The previous chapters were dedicated to the introduction, justification and description of the construction of GeoHPEX from the functional point of view. In this chapter, the evaluation of the User eXperience (UX) will be addressed, to acquire a knowledge on the look-and-feel of GeoHPEX, while this chapter is concluded with an analysis of future improvements that a hypothetical GeoHPEX v2.0 could implement.

Constructing an app is not just simply coding its functions, but also involves numerous concepts that go beyond programming. In this sense, Donald Norman (25th December, 1935), a professor at the university of California on Cognitive Science, published in 1988 the book '*The Design of Everyday* Things' [35] where the term User eXperience was firstly used, defined as the gather of all sensations and feelings that a user encounters with an app. Perhaps the concepts behind this label were already exploited and applied, but it was the first time that someone gave a name to it.

In this publication, the author theorized on the role of design, pointing towards the interaction between user and program, defining specifications and stating tips to obtain the maximum profit in the use of apps, which is a pleasant experience for the user. Moreover, Norman assures that the malfunction of an app is not the user's fault, but because of the lack of assistance from the program.

In this way, Norman defines the UX design as a process that considers "all stages of the product service", to deliver the user a "cohesive, integrated set of experiences". The final objective, as usual, it to "make the app work seamlessly", and therefore it is a methodology for programming that seeks a global conception of apps. The process of UX design consists of three steps, that has been considered in the development of GeoHPEX. The first one, 'Why', consists on the evaluation of the user's motivation for adopting a product, in this case evaluating the reasons to use GeoHPEX. This step was clearly stated in the first moments of the project, defining the intentions of the app and the objective aimed with it.

On the second step, 'What', the UX designer must think on the functionalities that the program will have, as an answer to what possible things could the user do with it. GeoHPEX, in this sense, defined that the user would obtain the results of a GSHP geothermal system, being capable to use different methodologies and selecting numerous possibilities in the design criteria. 'How', the final step, is the process in which the UX designers think on how is it possible to complete the 'What' in an accessible, aesthetical and pleasant way. The design of the GUI, in this case, was the solution considered in GeoHPEX, trying not to overload the user with information requirements and segregating the functionalities in tabs.

The conclusion is a seamless, fluid experience with GeoHPEX, as said by the members of ICGC consulted, following the “Don’t make me think” principle [27]. To conclude this chapter, there has been identified different future improvements that further works could implement, listed below:

- The greatest liability on GeoHPEX v1.0 is the location selector, forcing the user to impute the coordinates of the location instead of offering a visor of the map of Catalunya.

This feature was firstly approached, but discarded for v1.0. The reasons to discard this function relied on the environment for constructing the app. Matlab® is not specialized in maps, and the implementation of a visor would imply loading a large set of maps in the executable file (.exe) of the program, increasing remarkably the size of it. The solution to this feature could come by the implementation of the next future improvement.

- Instead of a standalone application, GeoHPEX v2.0 could be designed in HTML language to be linked at the webpage of ICGC.

The implementation of this improvements would imply notorious advantages compared with GeoHPEX v1.0. In first place, the application would not require the installation of an executable file, which some users may find suspicious and distrustful. Using HTML language, GeoHPEX v2.0 could make use of the map visors of ICGC to select automatically the location of the facility, and as the mathematical model was completed in GeoHPEX v1.0, few modifications would be required.

- A dedicated tool to define the thermal load of buildings could be developed, to amplify the specifications and requirements of facilities.

For this, there exists a tool developed by the Universitat Politècnica de València (UPC) named ‘CLIMA’ [47] that could serve as an example of thermal load estimation. A future GeoHPEX v2.0 could come with another app (GUI included) designed to define the building typology very precisely, that after imputing the information could close and return to the GUI of GeoHPEX, improving the estimation of the thermal load of the first version of the program. This system could enable a possibility to load files of building typologies automatically.

- Amplify the database for commercial lengths, U-probes and heat pumps

The wider this database is, the more adapted to the user GeoHPEX will be. In future works, it would be interesting to amplify the database and allow the user to select from different databases, instead of forcing the user to use the database of ICGC. The implementation of the listed improvements can extend the functionalities and range of application of GeoHPEX v1.0, transforming it in a better tool in terms of amplifying the possibilities and the uses that it can count.

5. Economic analysis of the project.

Having exposed the definition and contents of GeoHPEX, this document is concluded with the display on the costs and resources used for developing the application. This analysis considers the material and human resources that were needed to complete the project, that includes pre-processing and post-processing.

Even though most of the objects were already in the possession of the author for developing the application, this analysis considers that no resources were available at the beginning of the project, and that required to be acquired to develop GeoHPEX.

Moreover, the hourly cost of the members of the team of ICGC and the supervisor are not included, though should be. As seen in the table, the project is considered to have a total cost of 6,844 € (Euro), but including the costs of the above members, the cost of the project could rise approximately to 7,600 €.

From the observations of Table 5.1, it is seen that the majority of the costs come from the engineering work spent on computing and coding, with the 89.77% of the expenses. As for the rest of it, the computer used for programming did not required powerful characteristics, just the enough to run Matlab®:

Microprocessor: Intel® Core™ i7-4510U CPU @ 2.00GHz 2.60GHz

Installed RAM: 8.00 GB

Operating System: Windows 10 home v-1903 (18362.9)

To finish with the economic expenses, the complete list of expenses is displayed below:

Expense	*Fixed costs [€]*	*Hourly costs [€/h]*	*Hours required [h]*	*personnel [-]*	*Total costs [€]*
Toshiba Satellite L50 – B-1HM (2015)	450	0	0	0	450.00
Matlab® licence (education) [31]	250	0	0	0	250.00

Expense	*Fixed costs [€]*	*Hourly costs [€/h]*	*Hours required [h]*	*personnel [-]*	*Total costs [€]*
Engineering work on processing and post processing [46]	0	8	768	1	6,144.00
Engineering work on validation and calibration	0	-	40	3	-
TOTAL COSTS [€]	**-**	**-**	**-**	**-**	**6,844.00**

Table 5.1 Costs required for the development of GeoHPEX

6. Conclusion

To finish the project, this chapter is dedicated to extract the conclusions obtained through the development of GeoHPEX-design tool© v1.0, from the first approach to the methodologies of IGSHPA to the final results and calibration required.

Firstly, the systems of IGSHPA and ASHRAE were analysed and studied, together with the regulatory framework of IDAE. In this sense, as the app is intended to operate at the territory of Catalunya, GeoHPEX should follow the local regulations previous to the implementation of the technical methodology, thus requiring the revision of the regulatory framework and the recommendations offered.

After evaluating the methodologies that could be implemented, the project established the description of the algorithm to calculate the number and length of the vertical BHEs as a combination of the available methodologies, explaining the mechanics to load the information into GeoHPEX, the construction of the GUI and the mathematical models for both thermal load and GSHP system size.

The project deepened into the specifics of these models and the logic behind them, explaining verbally the evaluations carried by GeoHPEX and how Matlab® operates raster files, as it is vital for the project and helps to understand the decisions made during the construction of the application.

Although the methodology was strictly implemented in GeoHPEX, the database of ICGC for real geothermal installations demonstrates that thermal loads calculated in the app were below the required, and consequently the GSHP systems. This feature implied that the models required a validation and calibration, which was carried out using the experience of ICGC. With this change, the tool has been able to fulfil successfully the tests carried out for it, being prepared for the use of citizens and sector's professionals.

Finally, the project evaluated the look-and-feel and experience with the use of GeoHPEX, making sure that the process of designing the app was user-oriented and sought an easy use. With this evaluation, the project has been concluded including possible improvements that could be implemented on the app.

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I would like to thank my family for their support during my stay here, specially my parents and cousins Javi and Sergio. Soon we will see each other in real life, not by phone calls, and enjoy the moments together that we deserve.

Choosing this university has been one of the greatest successes in my life, and has given me the opportunity to grow as a professional and as an individual. Thanks to it, I had the chance to work at Tecnoambiente, S.L.U., where I worked hand in hand with skilled professional from whom I have only learned good things. Their trust in me, beyond the usual for interns, has brough me one of the greatest experiences as an engineer. As for my personal development, the UPC gave me the chance to make great friendships that I will keep. Mikel, Harman, Eric, Luis, Vittorio, Andrea…, you will succeed in whatever challenge you choose, not only for your great professionalism but for the human quality you have.

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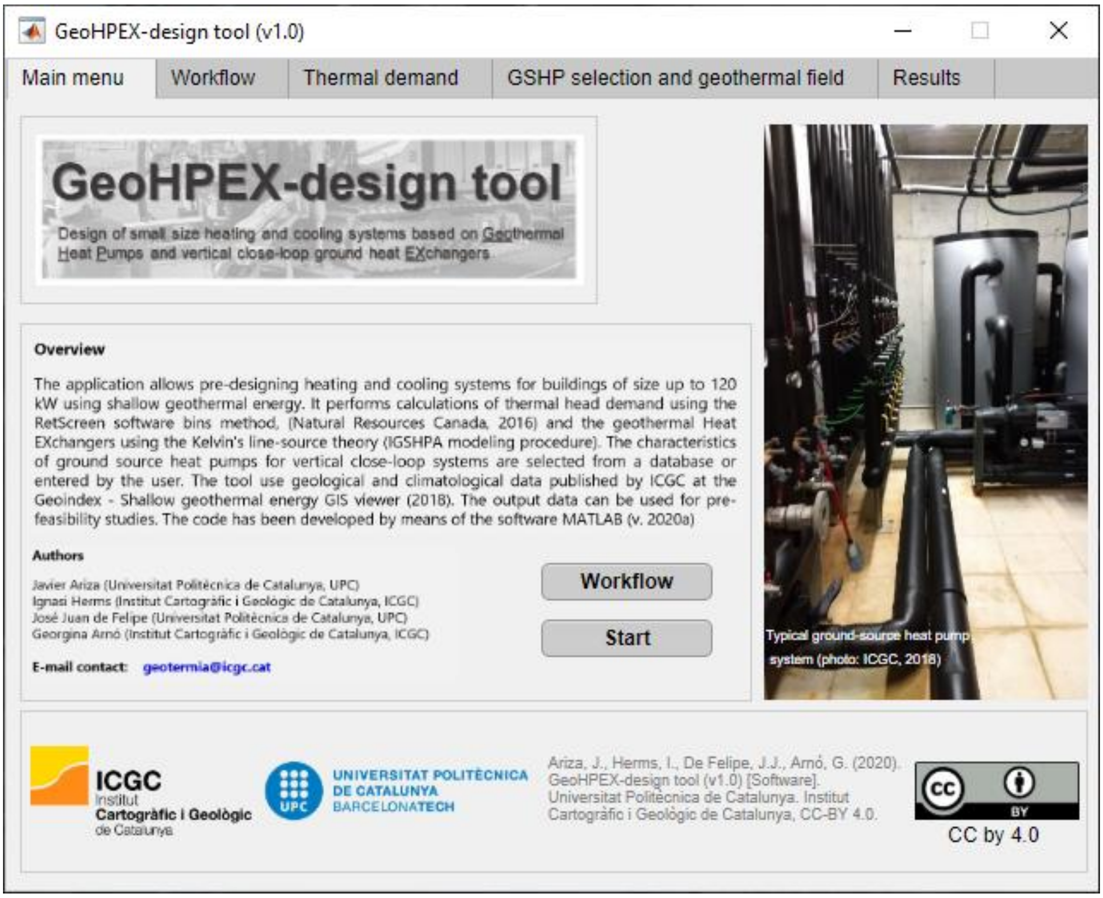
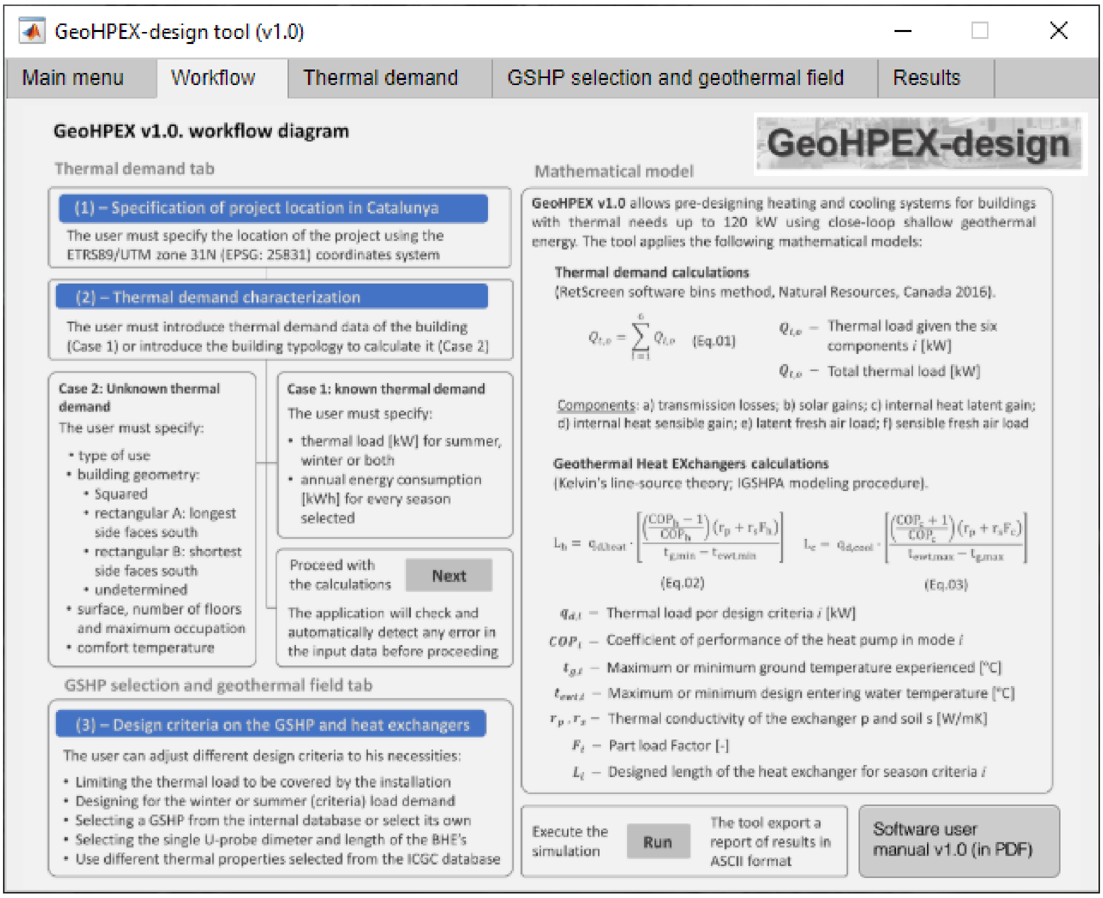
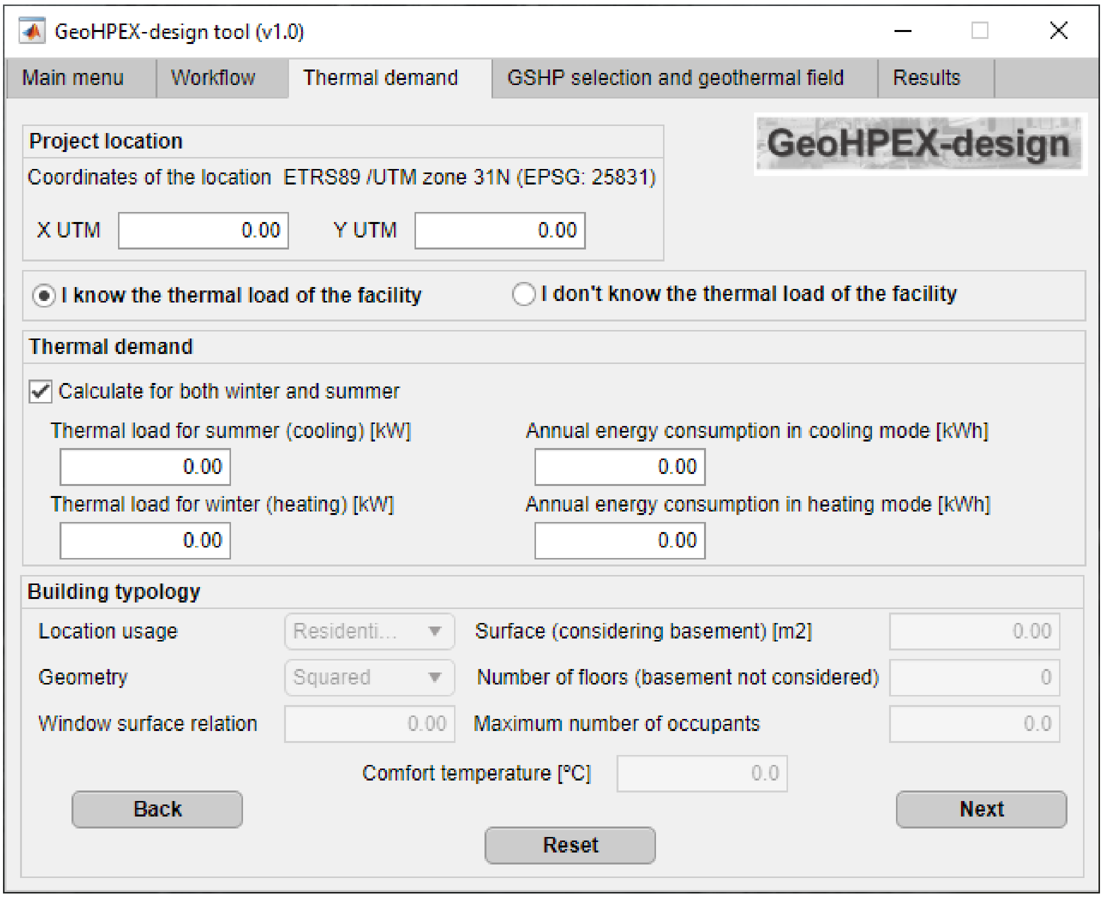
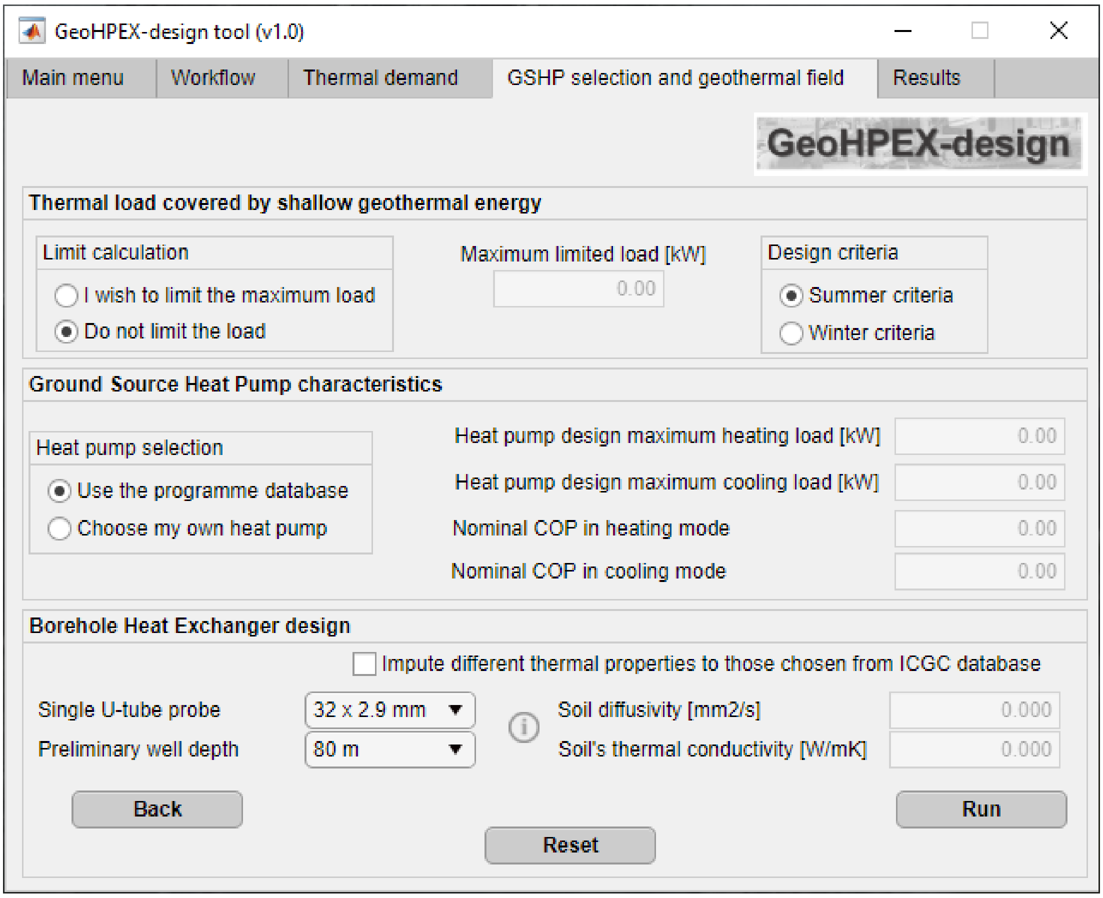
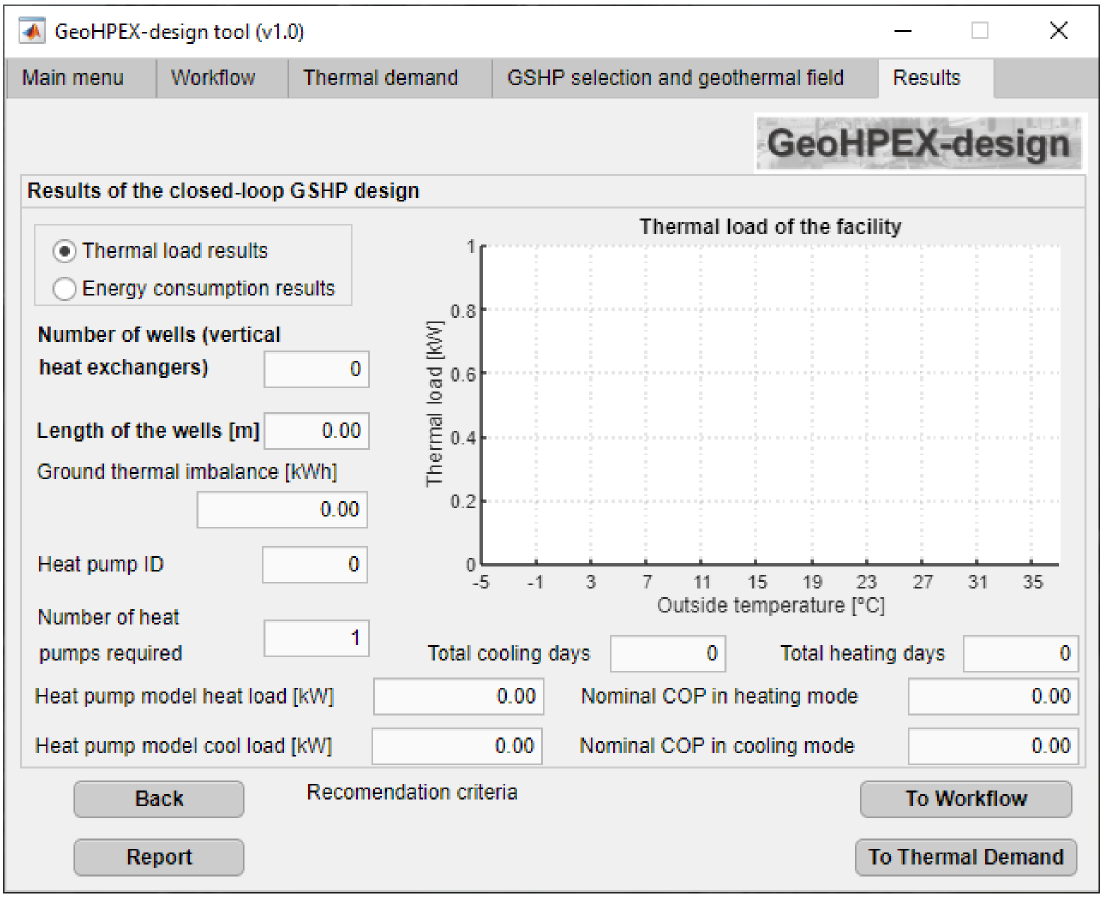
ANNEX I. Graphical User Interface of GeoHPEX-design tool© (v1.0) and error messages programmed

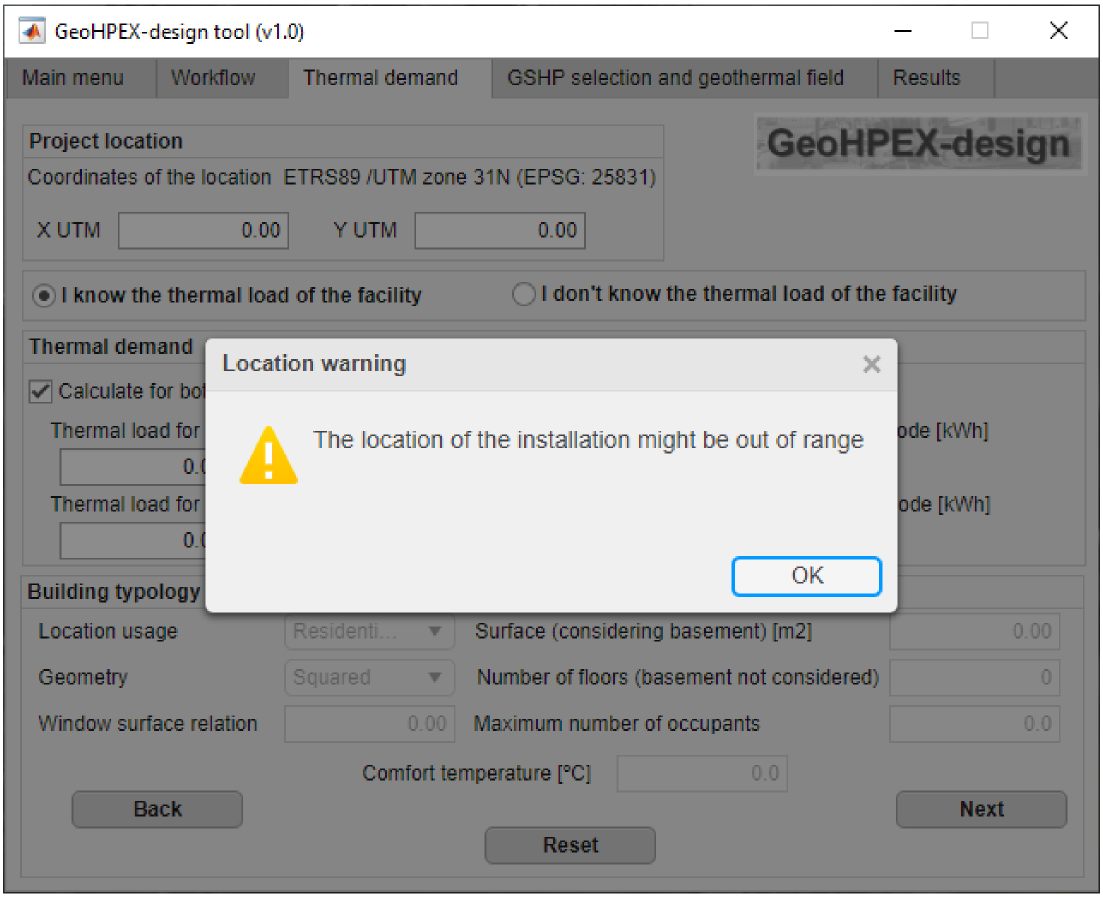


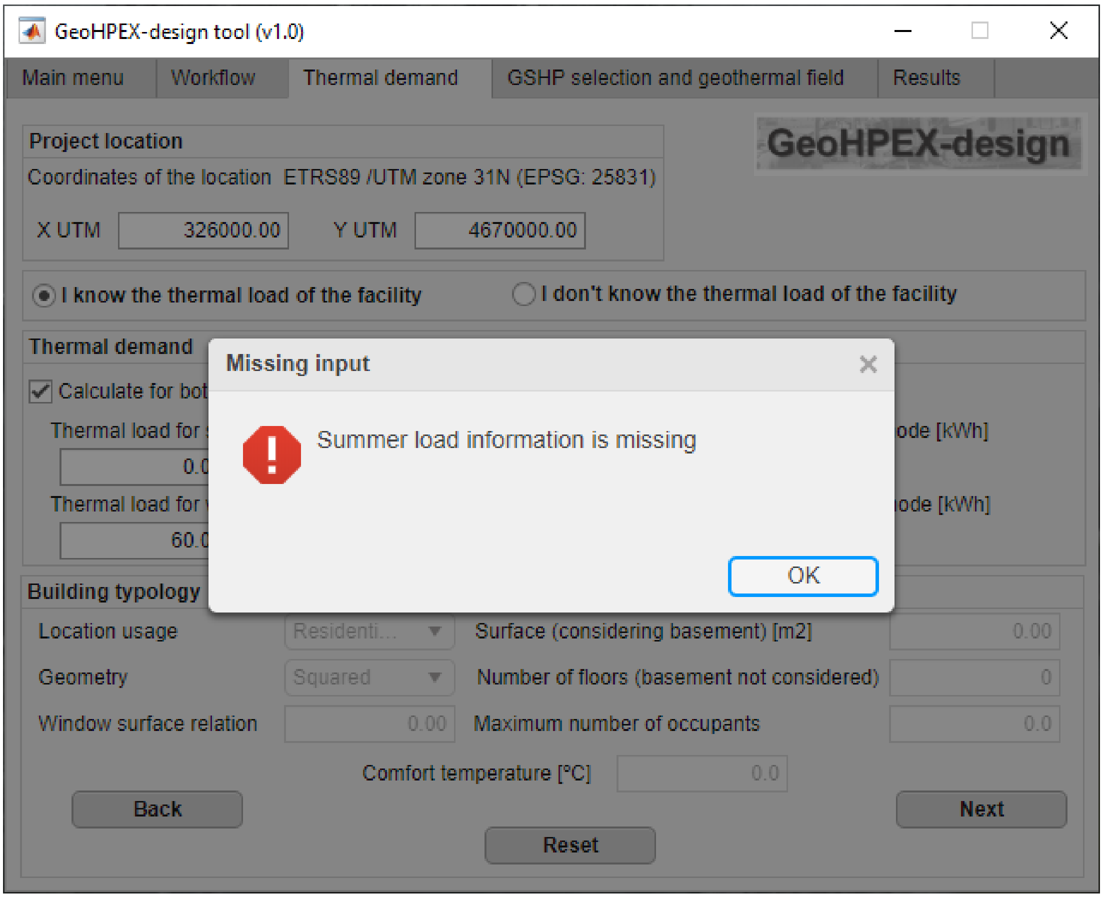

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX v1.0. workflow diagram
GeoHPEX-design
Thermal demand tab
Mathematical model
(1) – Specification of project location in Catalunya
The user must specify the location of the project using the ETRS89/UTM zone 31N (EPSG: 25831) coordinates system
(2) – Thermal demand characterization
The user must introduce thermal demand data of the building (Case 1) or introduce the building typology to calculate it (Case 2)
Case 2: Unknown thermal demand
The user must specify:
• type of use
• building geometry:
• Squared
• rectangular A: longest side faces south
• rectangular B: shortest side faces south
• undetermined
• surface, number of floors and maximum occupation
• comfort temperature
Case 1: known thermal demand
The user must specify:
• thermal load [kW] for summer, winter or both
• annual energy consumption [kWh] for every season selected
Proceed with the calculations
Next
The application will check and automatically detect any error in the input data before proceeding
GSHP selection and geothermal field tab
(3) – Design criteria on the GSHP and heat exchangers
The user can adjust different design criteria to his necessities:
• Limiting the thermal load to be covered by the installation
• Designing for the winter or summer (criteria) load demand
• Selecting a GSHP from the internal database or select its own
• Selecting the single U-probe dimeter and length of the BHE's
• Use different thermal properties selected from the ICGC database
GeoHPEX v1.0 allows pre-designing heating and cooling systems for buildings with thermal needs up to 120 kW using close-loop shallow geothermal energy. The tool applies the following mathematical models:
Thermal demand calculations
(RetScreen software bins method, Natural Resources, Canada 2016).
(Eq.01)
Thermal load given the six components i [kW]
Total thermal load [kW]
Components: a) transmission losses; b) solar gains; c) internal heat latent gain; d) internal heat sensible gain; e) latent fresh air load; f) sensible fresh air load
Geothermal Heat EXchangers calculations
(Kelvin's line-source theory; IGSHPA modeling procedure).
(Eq.02)
(Eq.03)
Thermal load por design criteria i [kW]
Coefficient of performance of the heat pump in mode i
Maximum or minimum ground temperature experienced [°C]
Maximum or minimum design entering water temperature [°C]
Thermal conductivity of the exchanger p and soil s [W/mK]
Part load Factor [-]
Designed length of the heat exchanger for season criteria i
Execute the simulation
Run
The tool export a report of results in ASCII format
Software user manual v1.0 (in PDF)

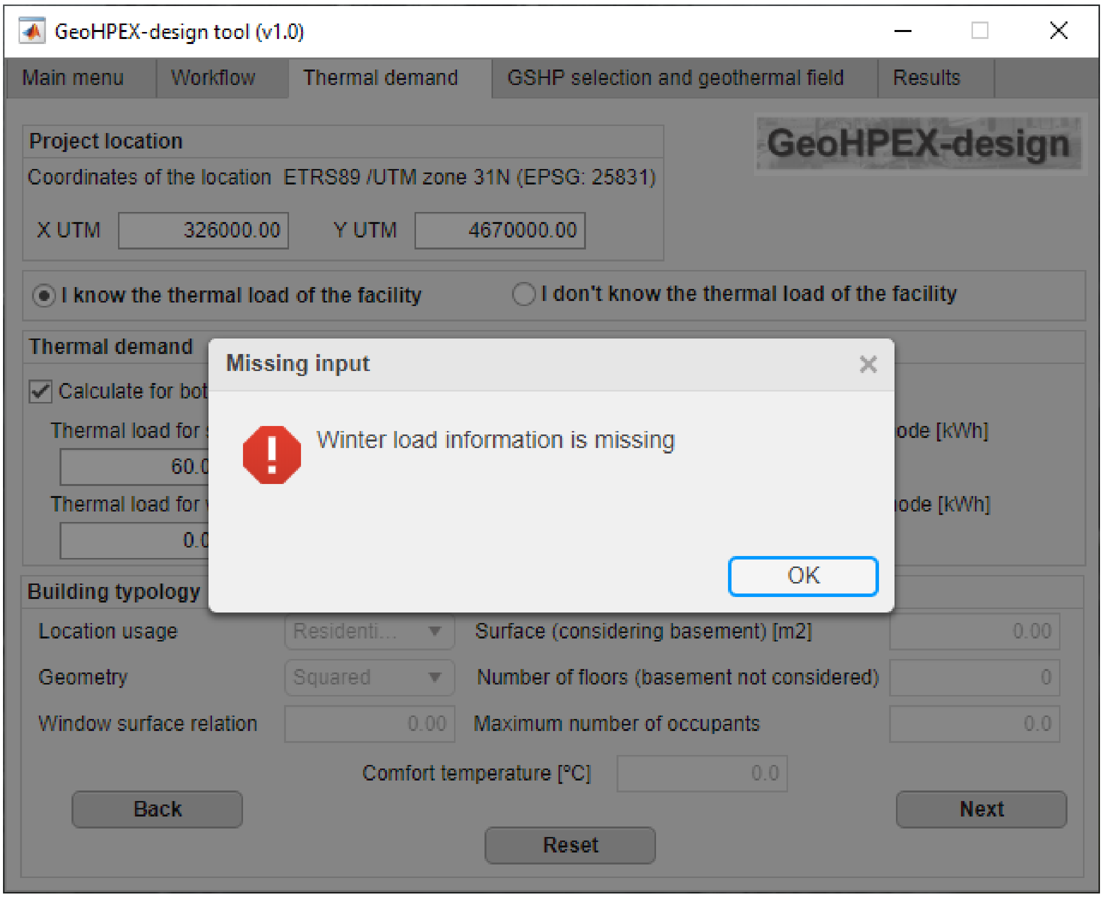

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
GeoHPEX-design
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
0.00
Y UTM
0.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Calculate for both winter and summer
Thermal load for summer (cooling) [kW]
0.00
Annual energy consumption in cooling mode [kWh]
0.00
Thermal load for winter (heating) [kW]
0.00
Annual energy consumption in heating mode [kWh]
0.00
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
0.00
Geometry
Squared
Number of floors (basement not considered)
0
Window surface relation
0.00
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

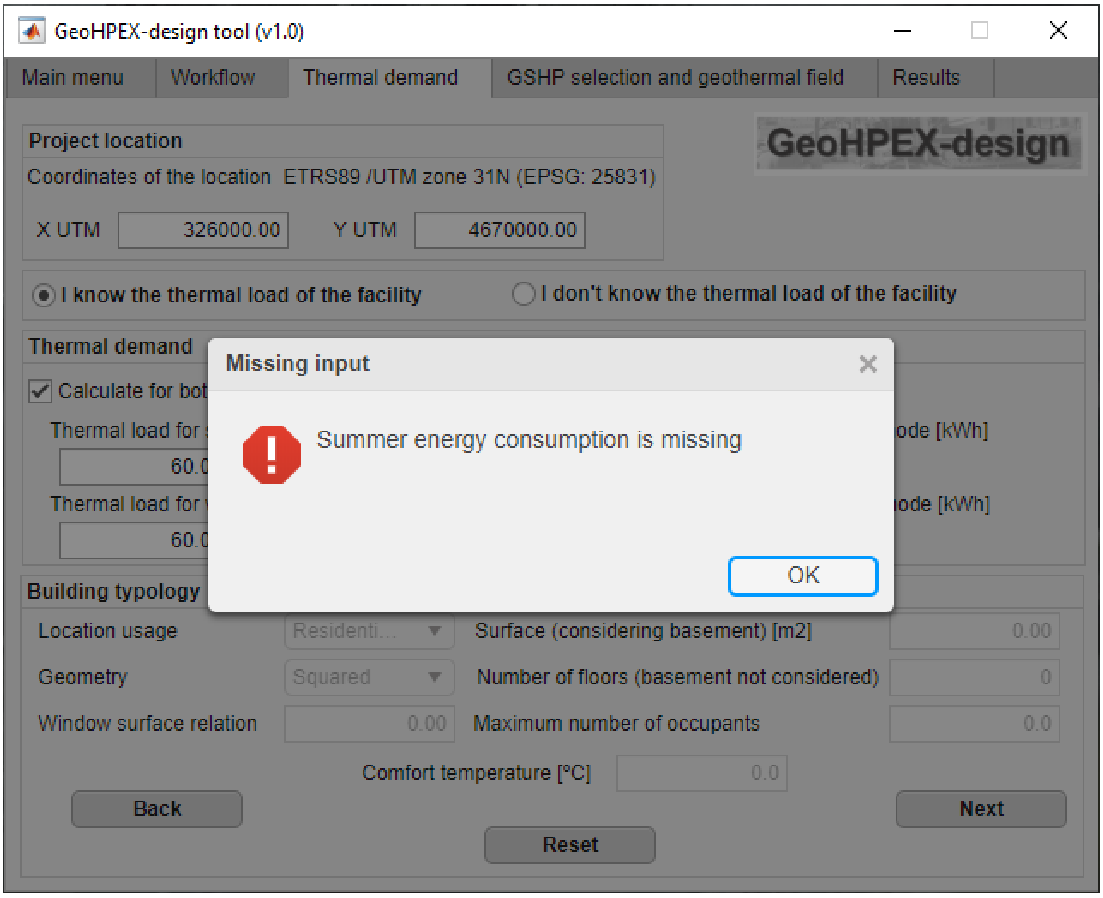

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Ground Source Heat Pump characteristics
Heat pump selection
Use the programme database
Choose my own heat pump
Heat pump design maximum heating load [kW]
Heat pump design maximum cooling load [kW]
Nominal COP in heating mode
Nominal COP in cooling mode
0.00
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
Soil's thermal conductivity [W/mK]
0.000
Back
Run
Reset


GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Results of the closed-loop GSHP design
Thermal load results
Energy consumption results
Number of wells (vertical heat exchangers)
0
Length of the wells [m]
0.00
Ground thermal imbalance [kWh]
0.00
Heat pump ID
0
Number of heat pumps required
1
Thermal load of the facility
Thermal load [kW]
Outside temperature [°C]
Total cooling days
Total heating days
Heat pump model heat load [kW]
Heat pump model cool load [kW]
Nominal COP in heating mode
Nominal COP in cooling mode
Back
Recomendation criteria
To Workflow
Report
To Thermal Demand

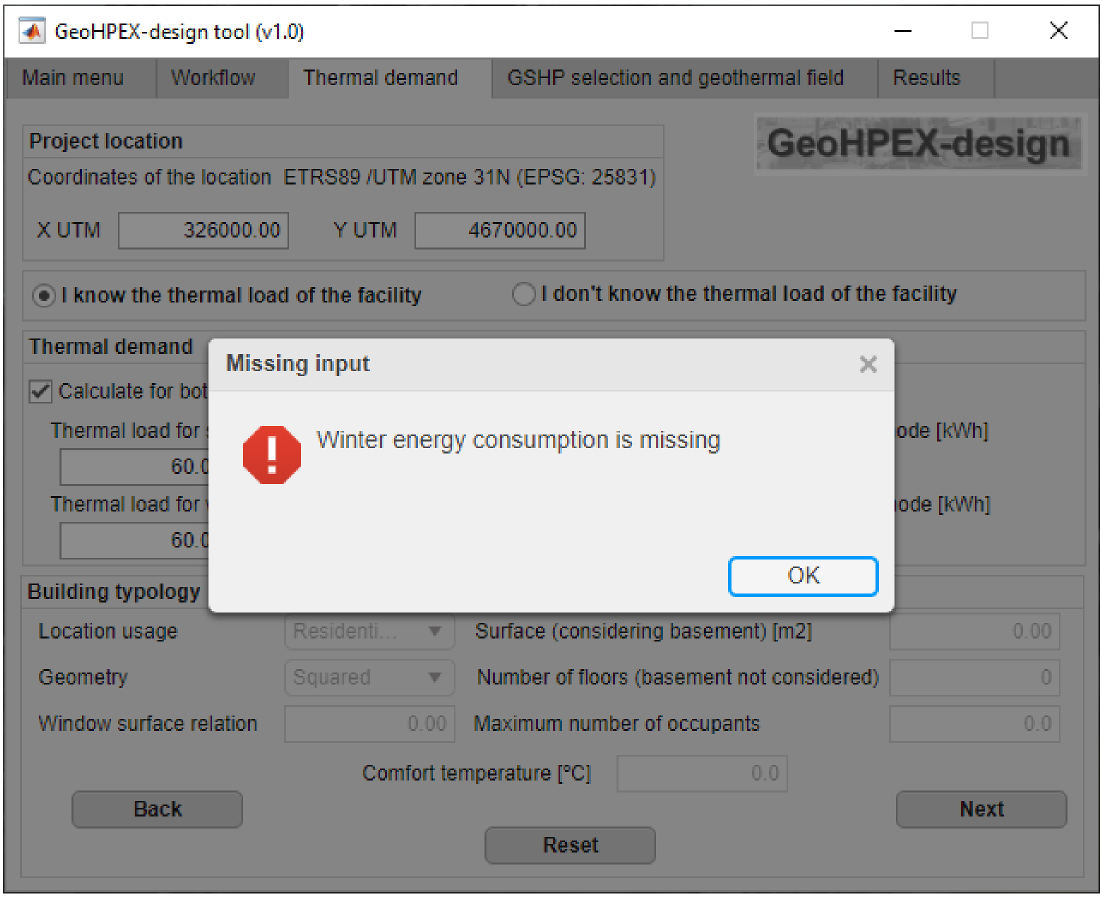

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
GeoHPEX-design
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
0.00
Y UTM
0.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Location warning
The location of the installation might be out of range
OK
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
Geometry
Squared
Number of floors (basement not considered)
Window surface relation
Maximum number of occupants
Comfort temperature [°C]
Back
Next
Reset

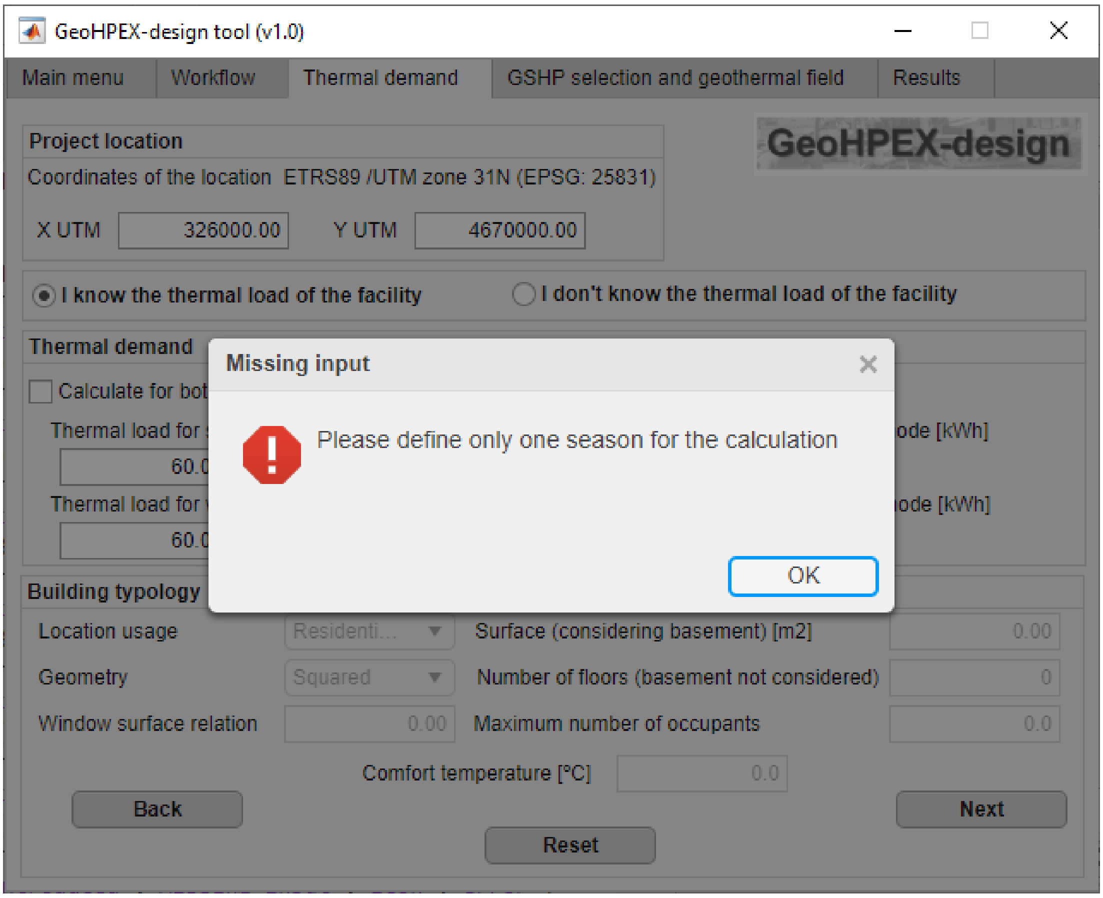

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
GeoHPEX-design
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Missing input
Summer load information is missing
OK
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
Geometry
Squared
Number of floors (basement not considered)
Window surface relation
Maximum number of occupants
Comfort temperature [°C]
Back
Next
Reset

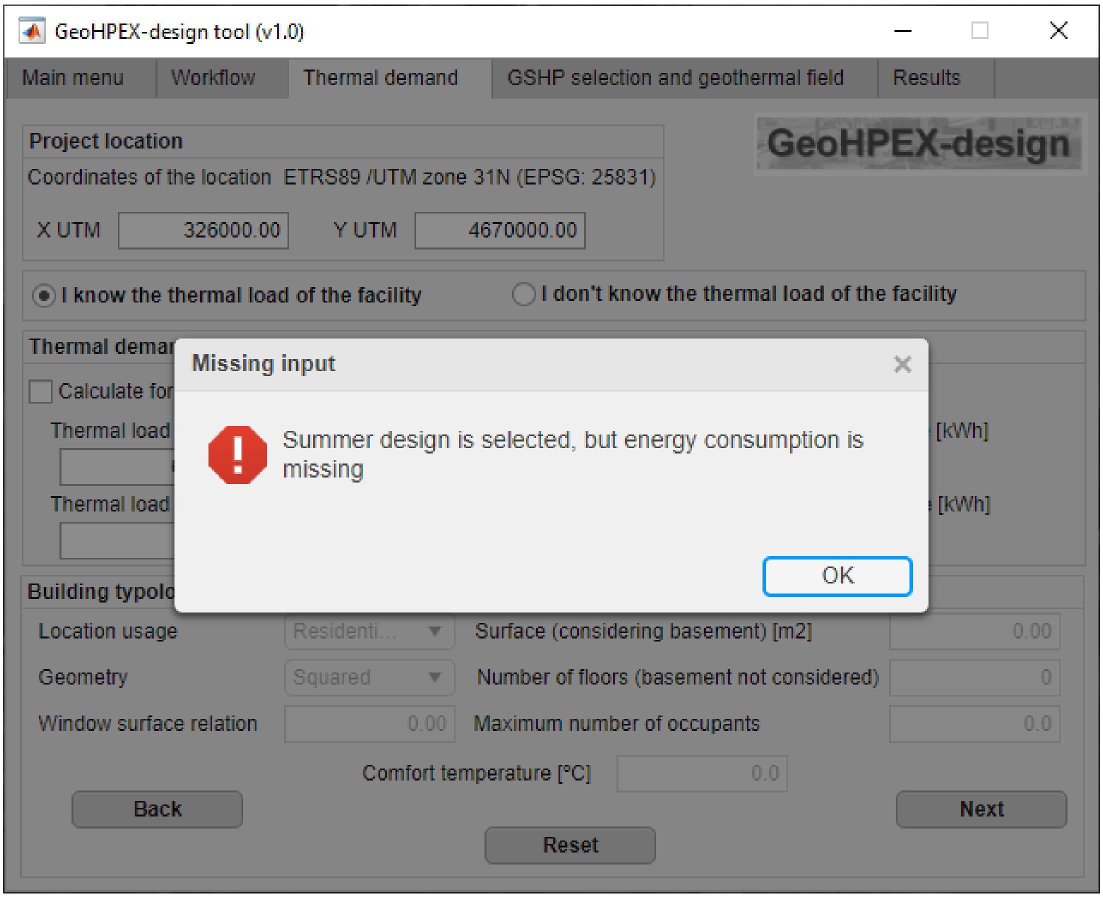

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
GeoHPEX-design
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Calculate for bot
Thermal load for
60.0
Thermal load for
0.0
ode [kWh]
ode [kWh]
Missing input
Winter load information is missing
OK
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
0.00
Geometry
Squared
Number of floors (basement not considered)
0
Window surface relation
0.00
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

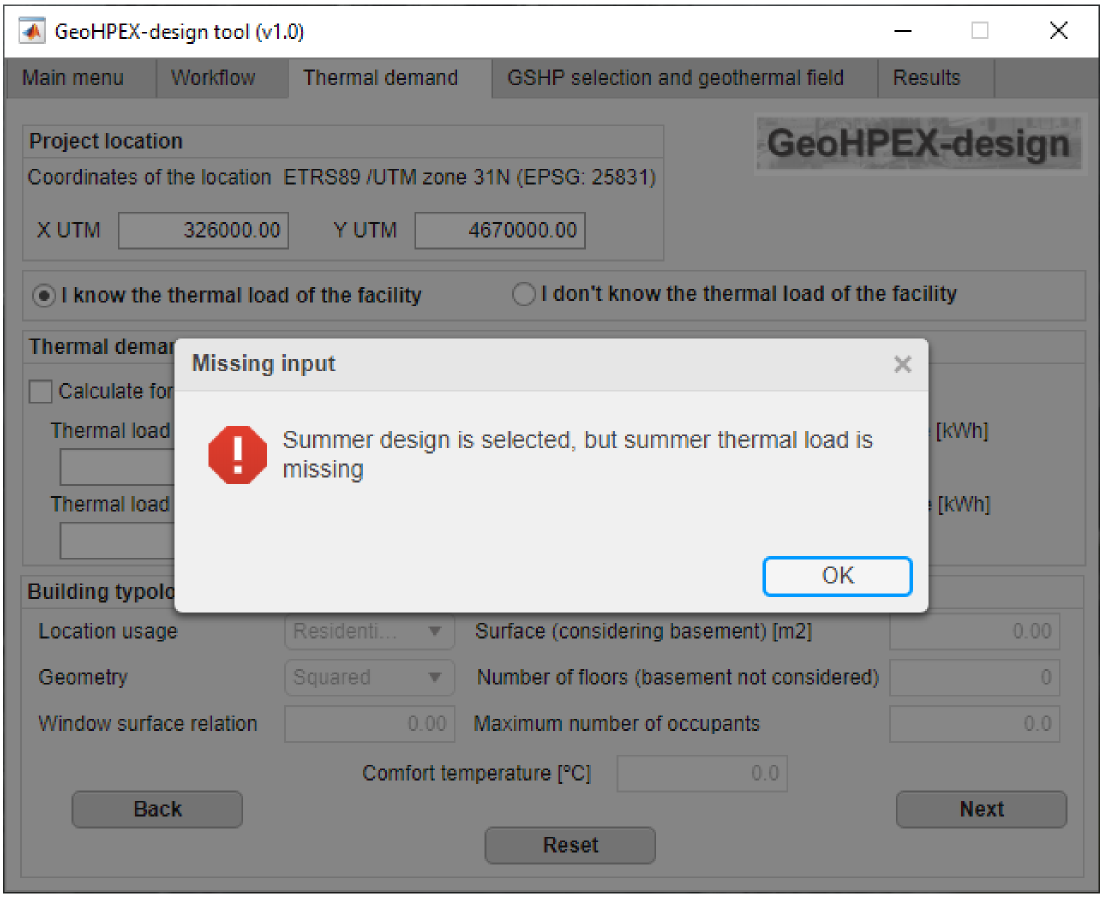

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
GeoHPEX-design
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Calculate for bot
Thermal load for
60.0
Thermal load for
60.0
ode [kWh]
ode [kWh]
Missing input
Summer energy consumption is missing
OK
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
0.00
Geometry
Squared
Number of floors (basement not considered)
0
Window surface relation
0.00
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

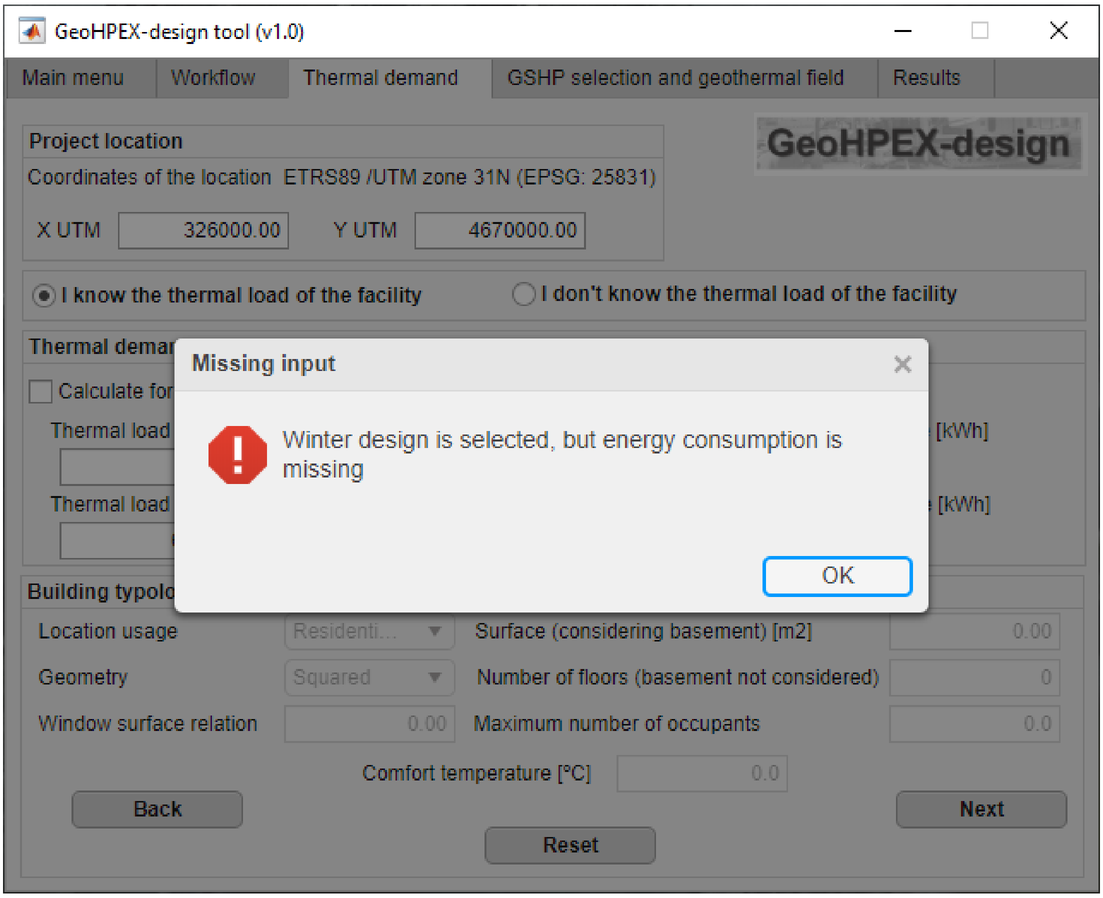
ETSEIB

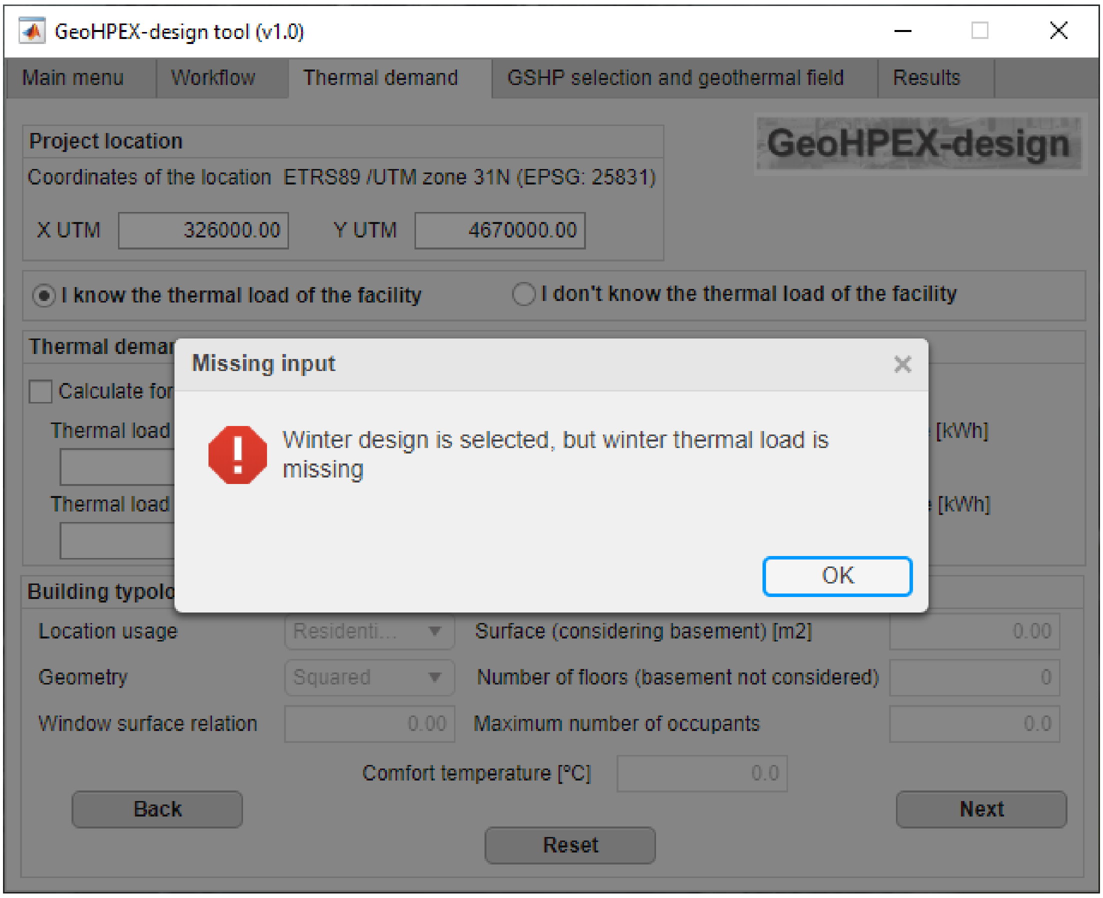

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
GeoHPEX-design
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Missing input
Winter energy consumption is missing
OK
Building typology
Location usage
Surface (considering basement) [m2]
Geometry
Number of floors (basement not considered)
Window surface relation
Maximum number of occupants
Comfort temperature [°C]
Back
Next
Reset

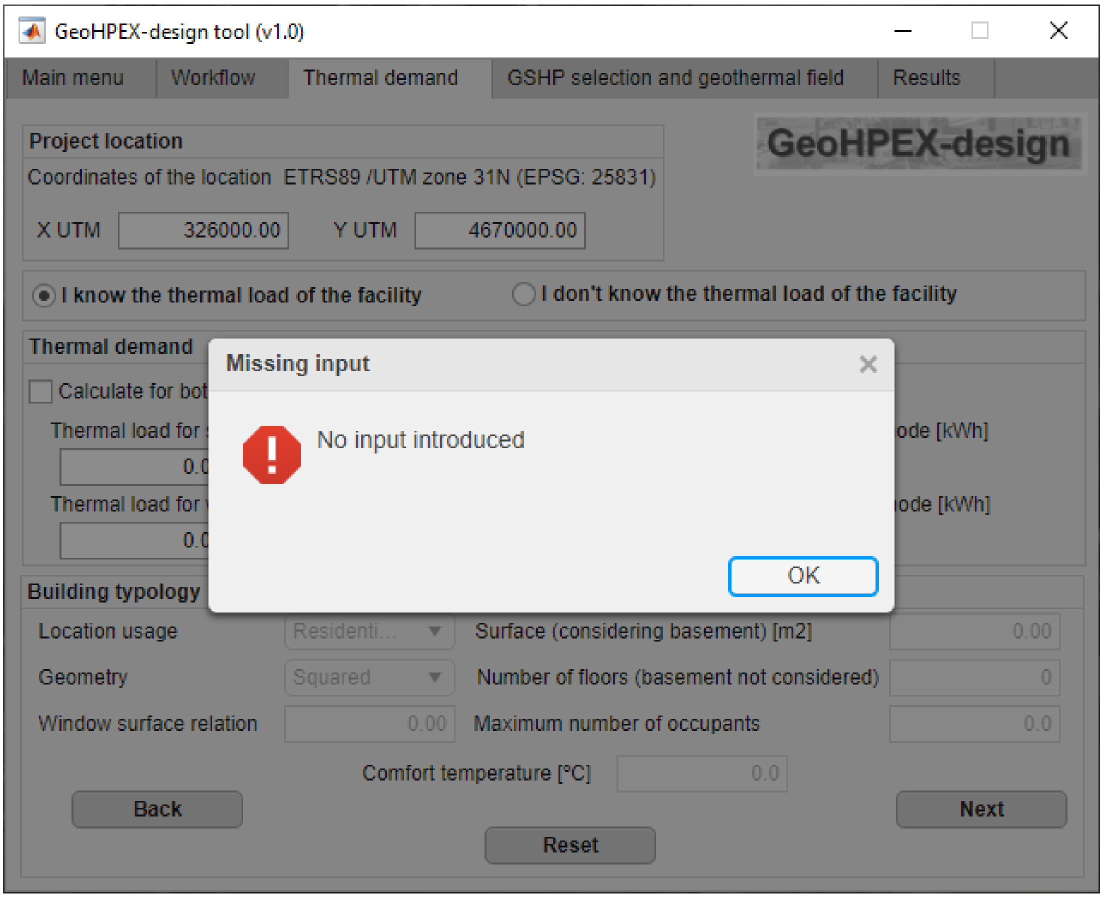

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
GeoHPEX-design
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Missing input
Please define only one season for the calculation
OK
Building typology
Location usage
Surface (considering basement) [m2]
Geometry
Number of floors (basement not considered)
Window surface relation
Maximum number of occupants
Comfort temperature [°C]
Back
Next
Reset

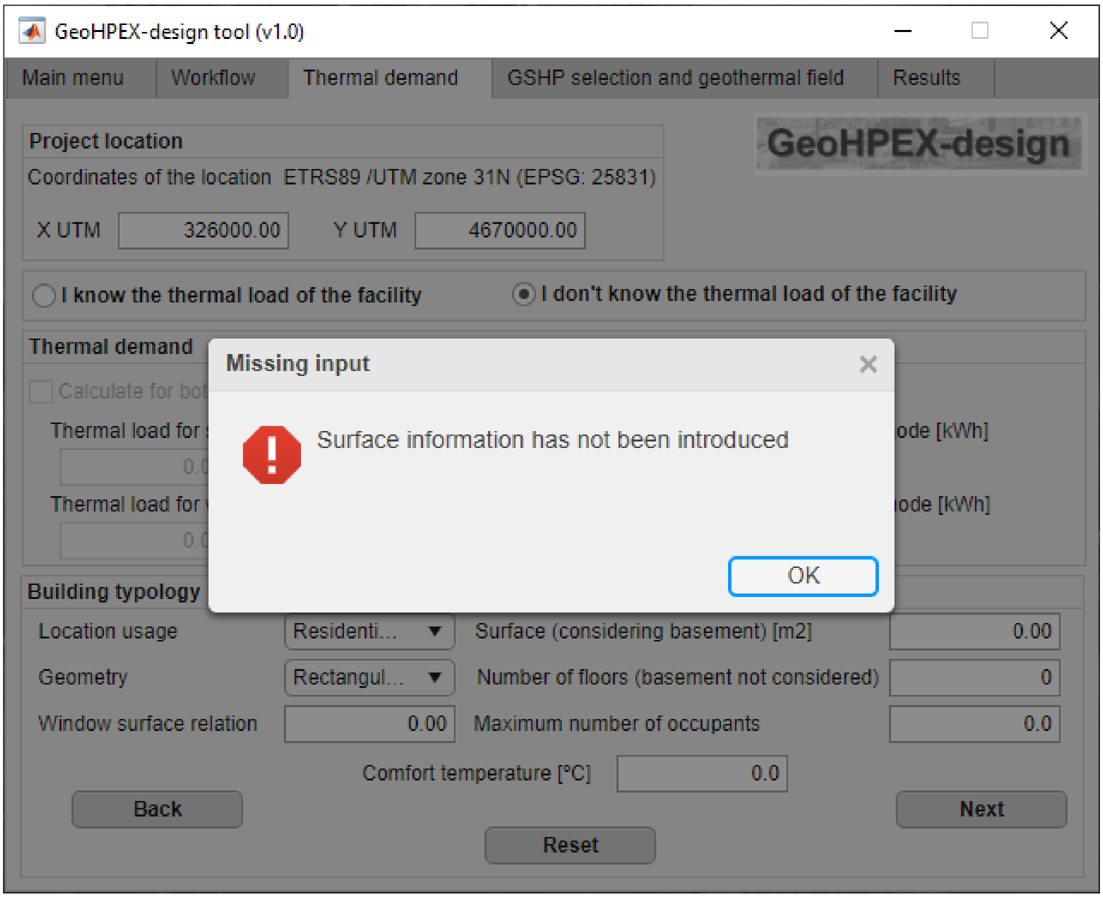

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
GeoHPEX-design
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demar
Calculate for
Thermal load
Thermal load
[kWh]
[kWh]
Missing input
Summer design is selected, but energy consumption is missing
OK
Building typolo
Location usage
Residenti...
Geometry
Squared
Window surface relation
0.00
Surface (considering basement) [m2]
0.00
Number of floors (basement not considered)
0
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

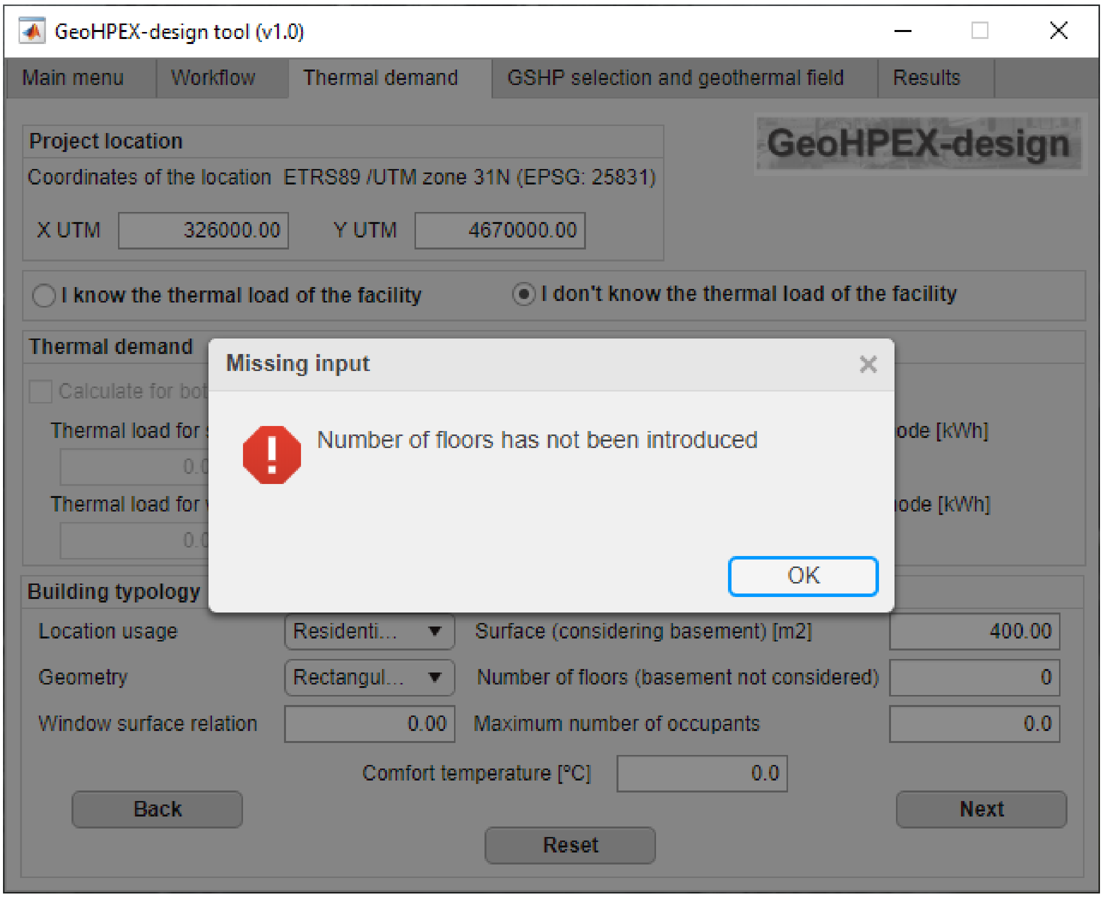

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
GeoHPEX-design
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demar
Calculate for
Thermal load
Thermal load
[kWh]
[kWh]
Missing input
Summer design is selected, but summer thermal load is missing
OK
Building typolo
Location usage
Residenti...
Geometry
Squared
Window surface relation
0.00
Surface (considering basement) [m2]
0.00
Number of floors (basement not considered)
0
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

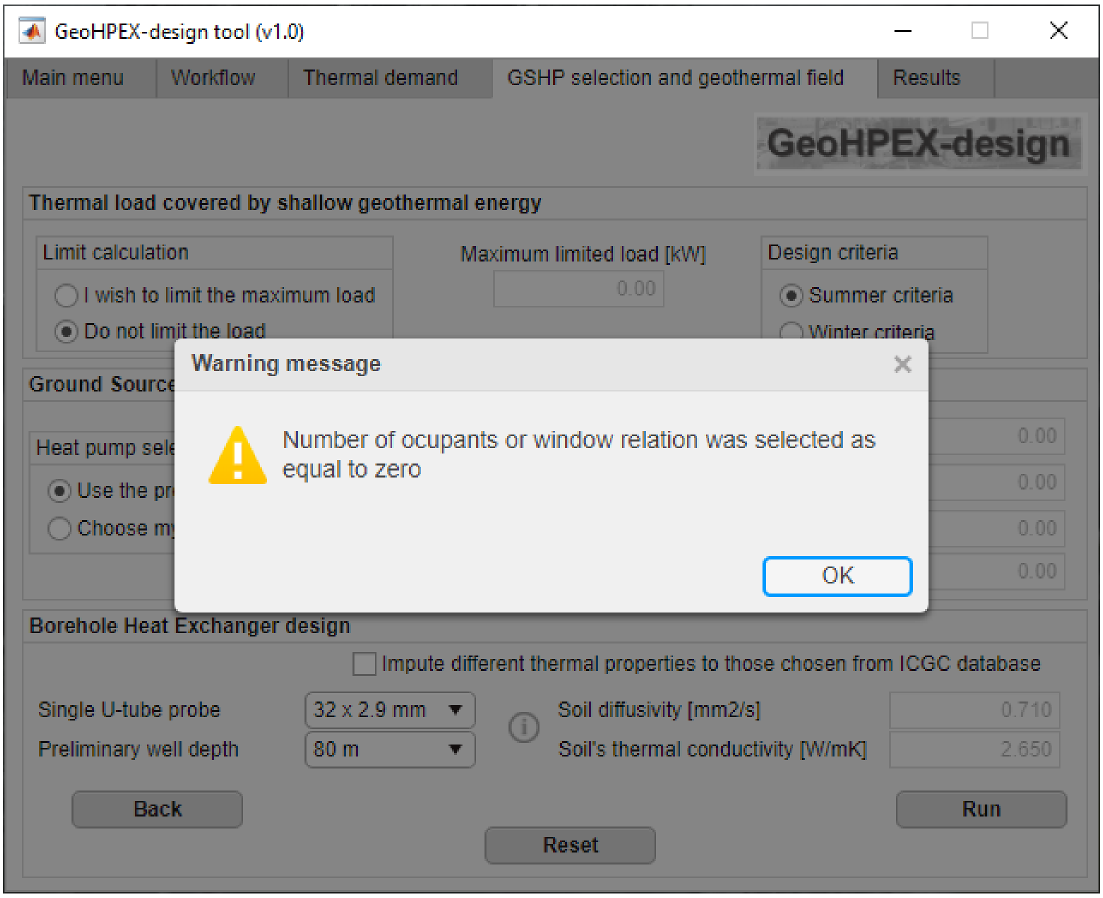

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
GeoHPEX-design
I know the thermal load of the facility
I don't know the thermal load of the facility
Missing input
Winter design is selected, but energy consumption is missing
OK
Location usage
Residenti...
Surface (considering basement) [m2]
Geometry
Squared
Number of floors (basement not considered)
Window surface relation
Maximum number of occupants
Comfort temperature [°C]
Back
Next
Reset

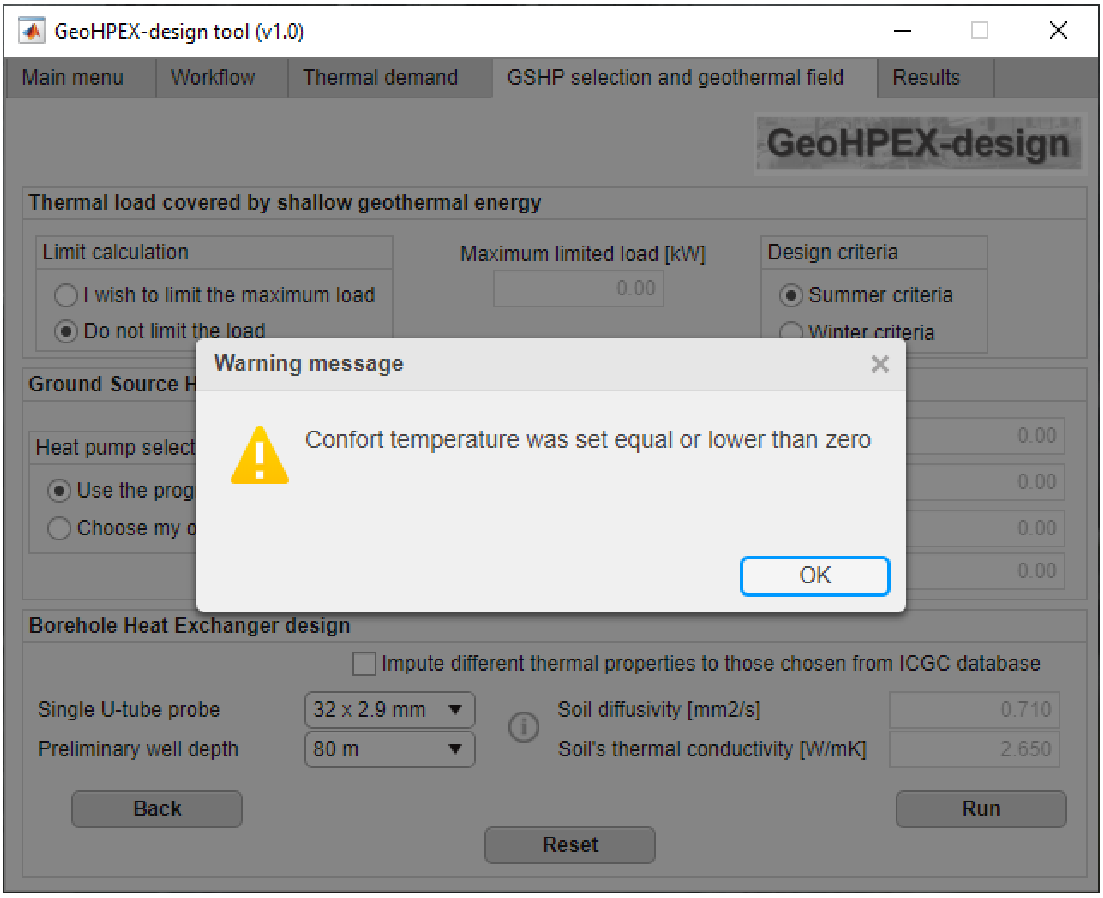

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
GeoHPEX-design
I know the thermal load of the facility
I don't know the thermal load of the facility
Missing input
Winter design is selected, but winter thermal load is missing
OK
Location usage
Residenti...
Surface (considering basement) [m2]
Geometry
Squared
Number of floors (basement not considered)
Window surface relation
Maximum number of occupants
Comfort temperature [°C]
Back
Next
Reset

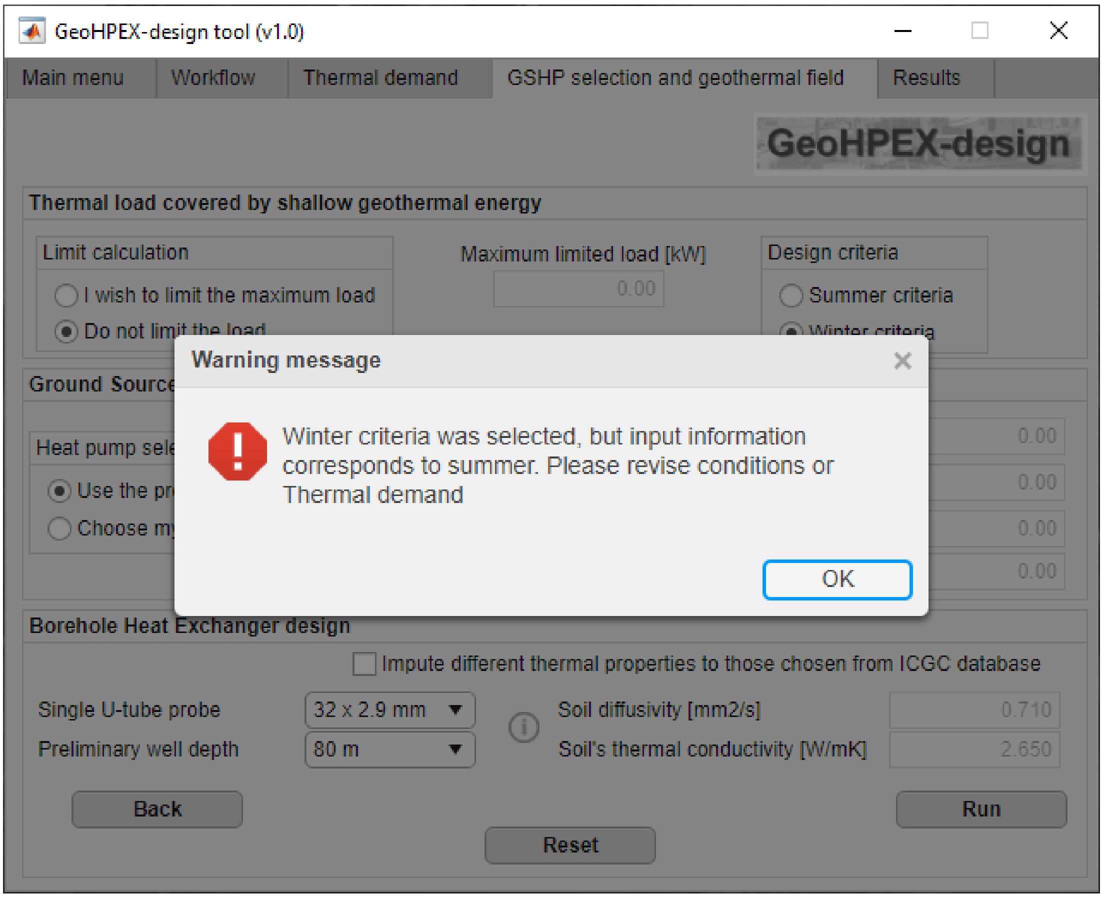

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
GeoHPEX-design
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Missing input
No input introduced
OK
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
0.00
Geometry
Squared
Number of floors (basement not considered)
0
Window surface relation
0.00
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

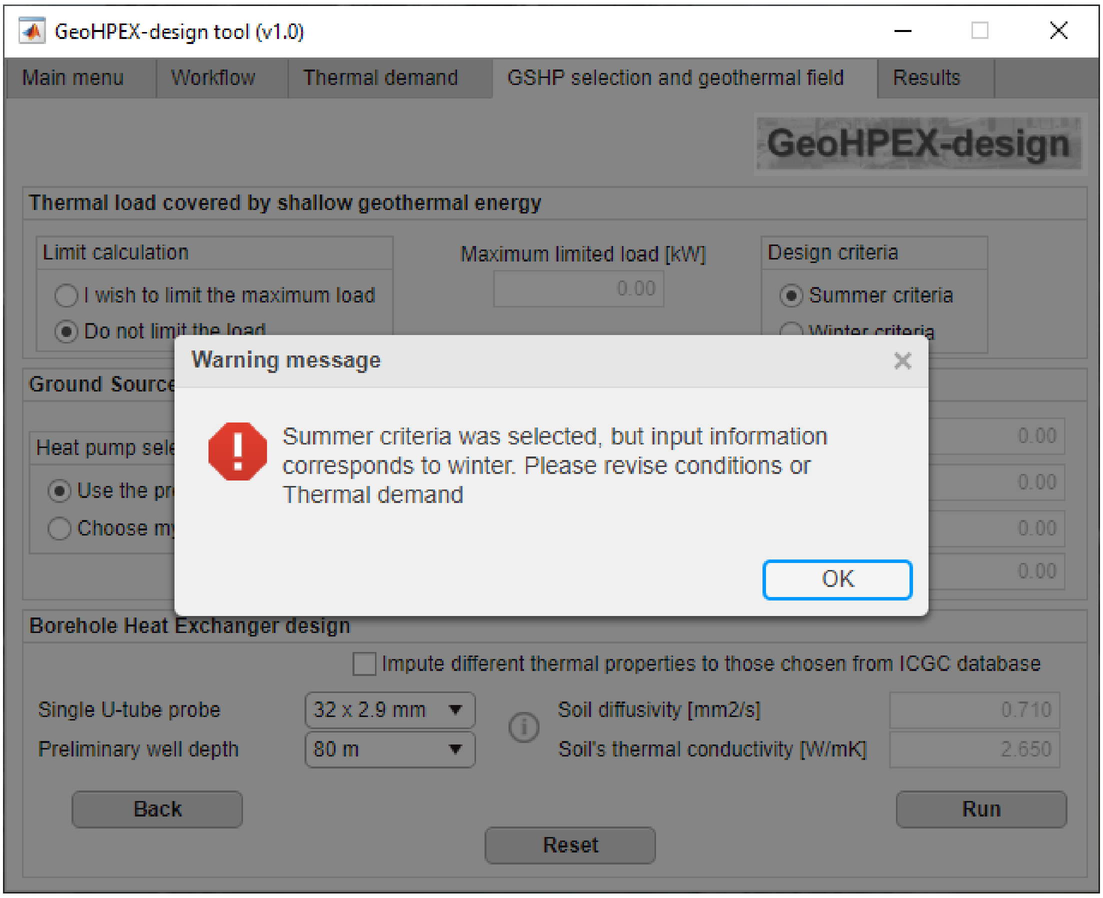

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
Project location
GeoHPEX-design
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Missing input
Surface information has not been introduced
OK
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
0.00
Geometry
Rectangul...
Number of floors (basement not considered)
0
Window surface relation
0.00
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

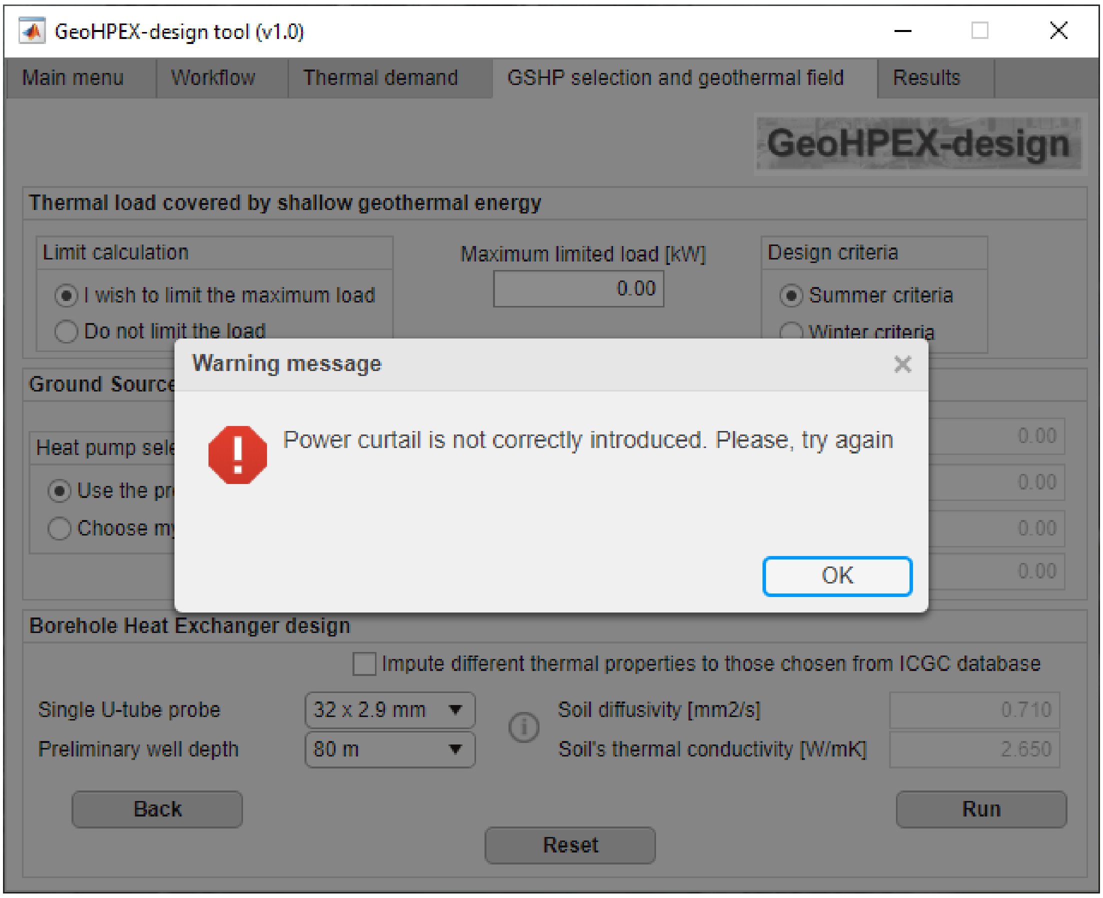

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Missing input
Number of floors has not been introduced
OK
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
400.00
Geometry
Rectangul...
Number of floors (basement not considered)
0
Window surface relation
0.00
Maximum number of occupants
0.0
Comfort temperature [°C]
0.0
Back
Next
Reset

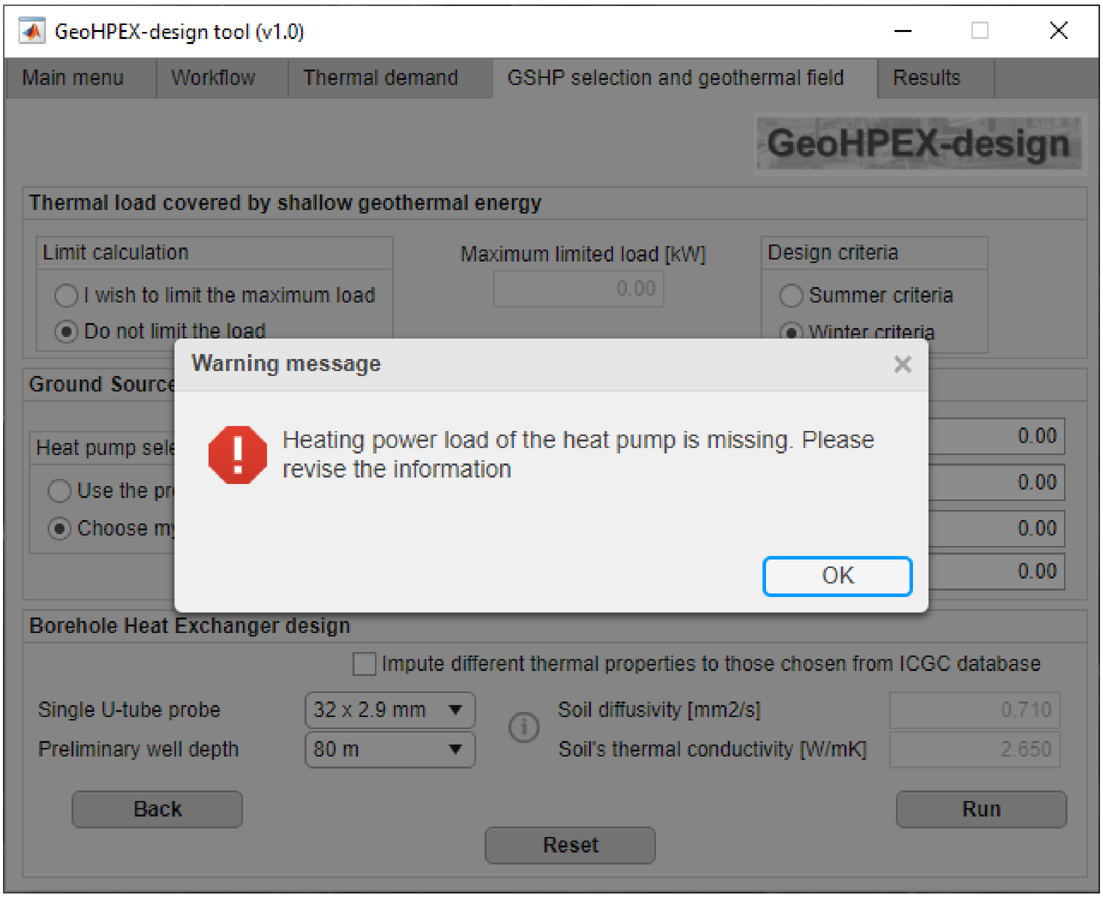

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Number of ocupants or window relation was selected as equal to zero
OK
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Soil diffusivity [mm2/s]
0.710
Preliminary well depth
80 m
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

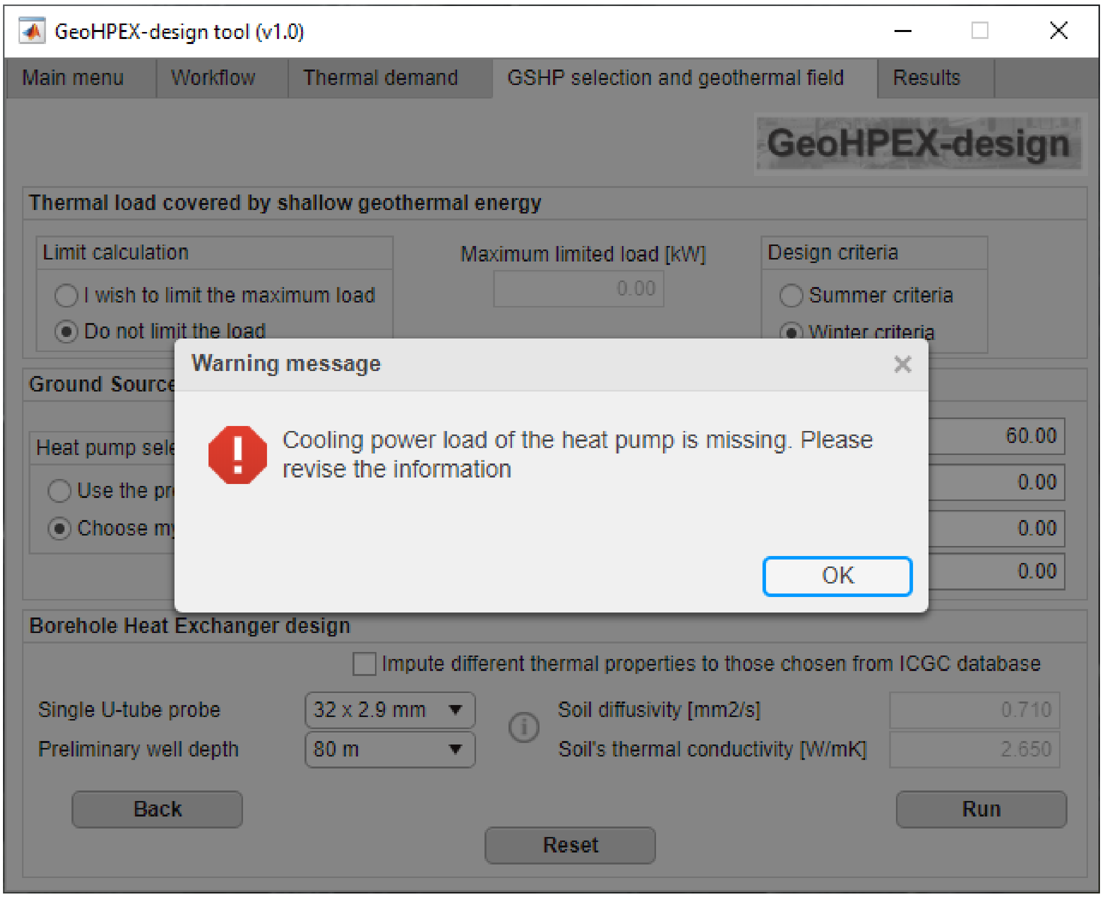

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Confort temperature was set equal or lower than zero
OK
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

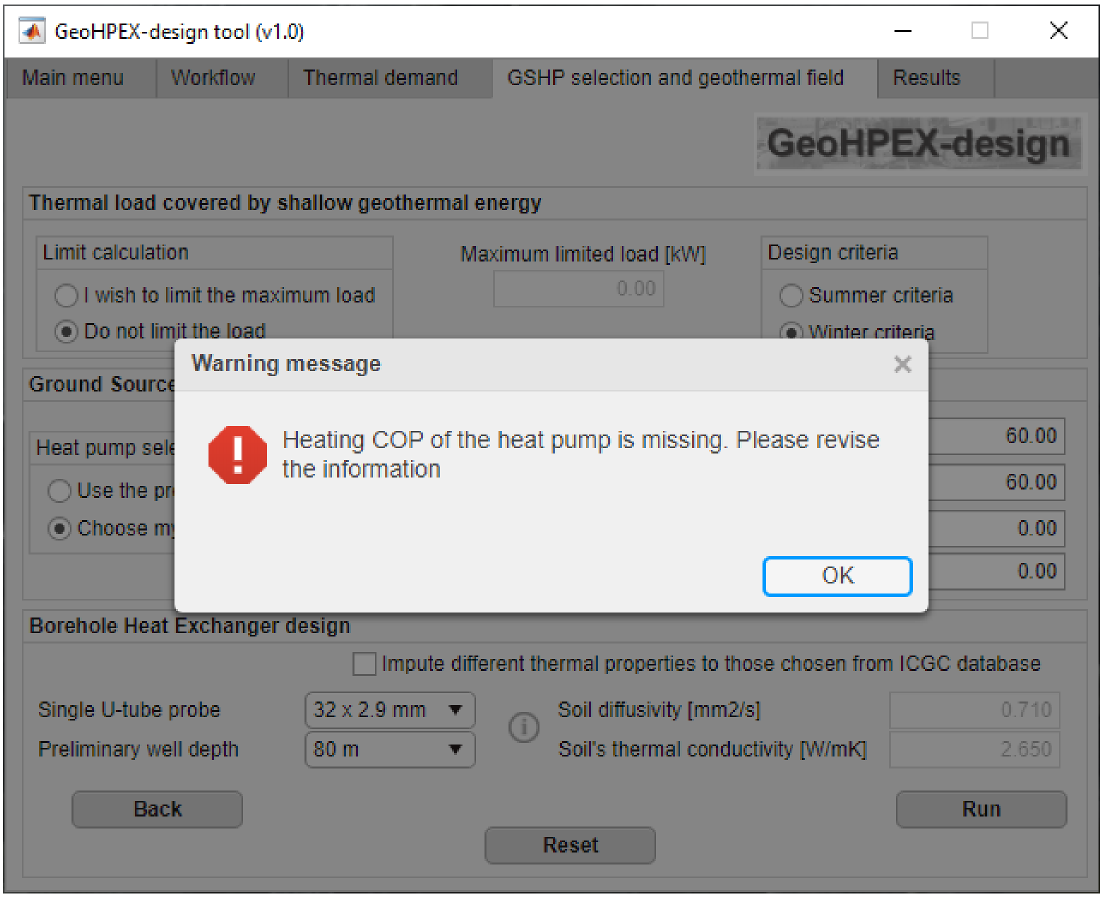

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Winter criteria was selected, but input information corresponds to summer. Please revise conditions or Thermal demand
OK
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

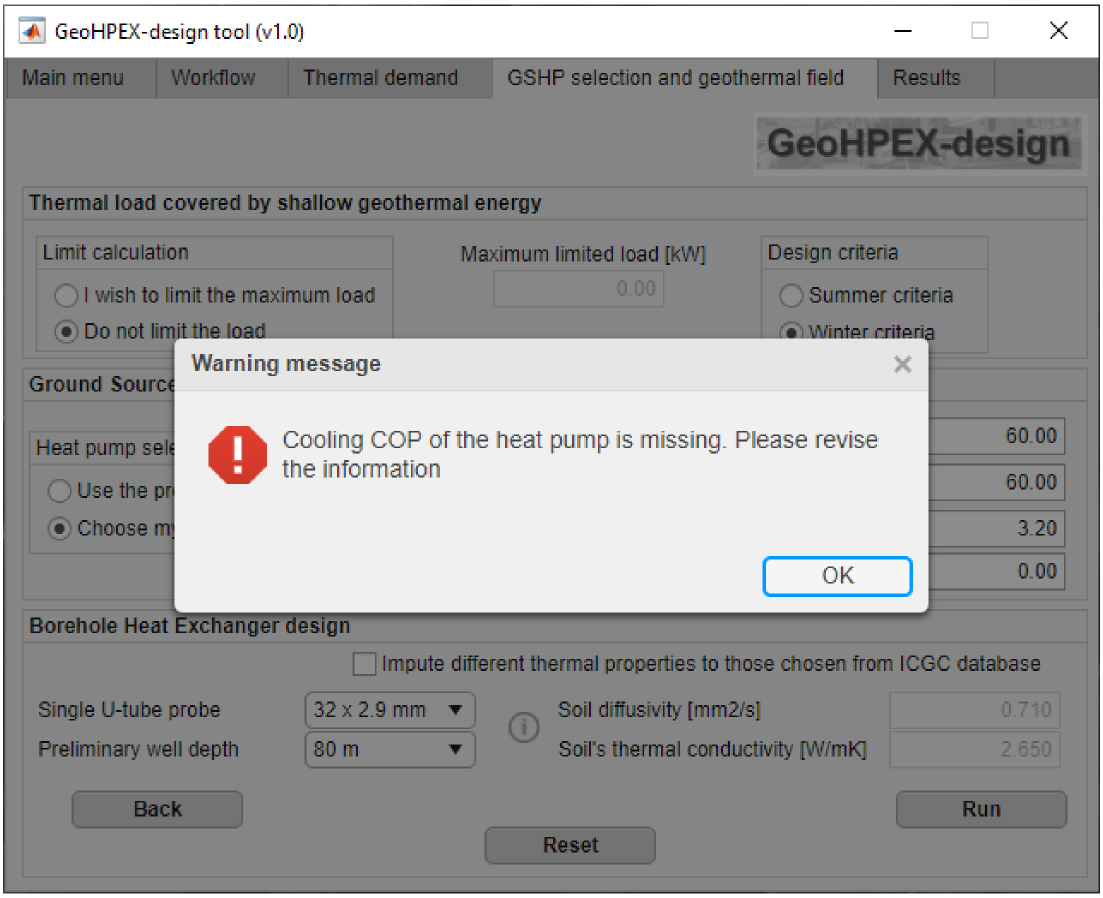

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Summer criteria was selected, but input information corresponds to winter. Please revise conditions or Thermal demand
OK
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

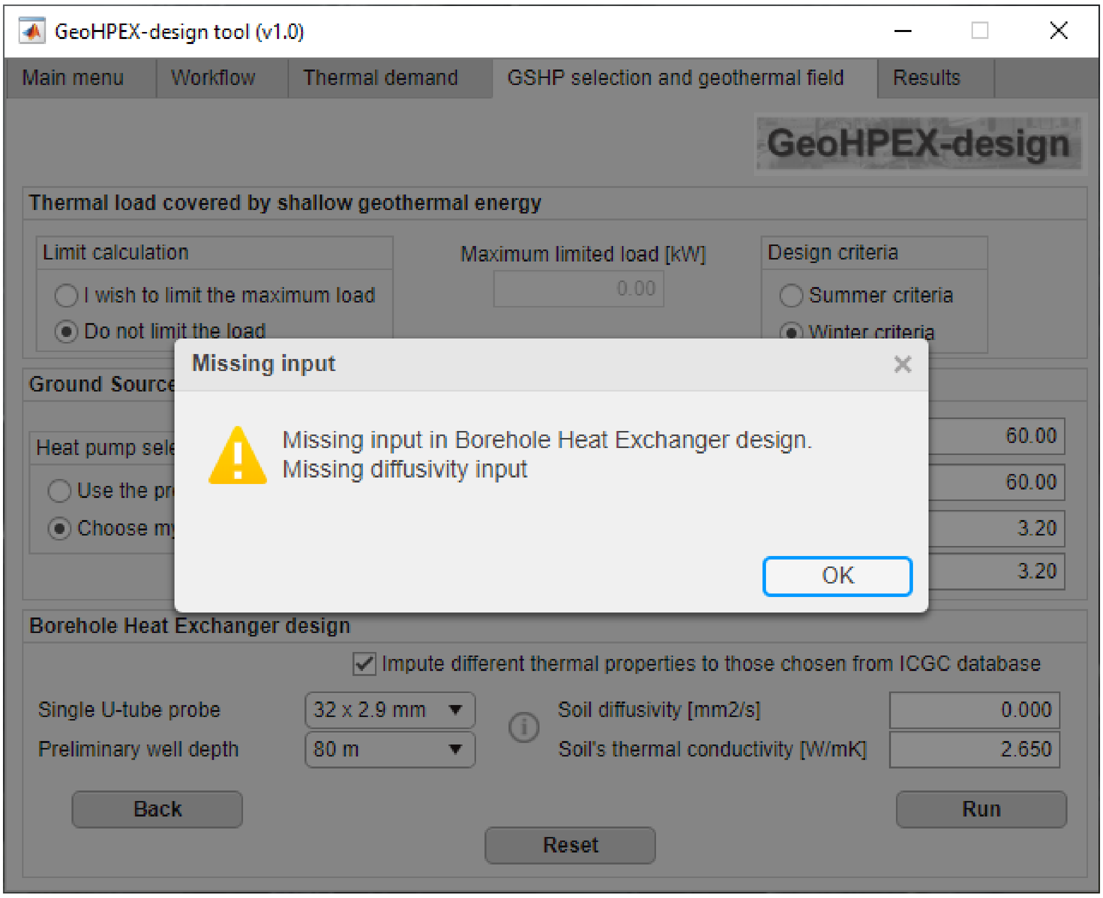

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Power curtail is not correctly introduced. Please, try again
OK
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

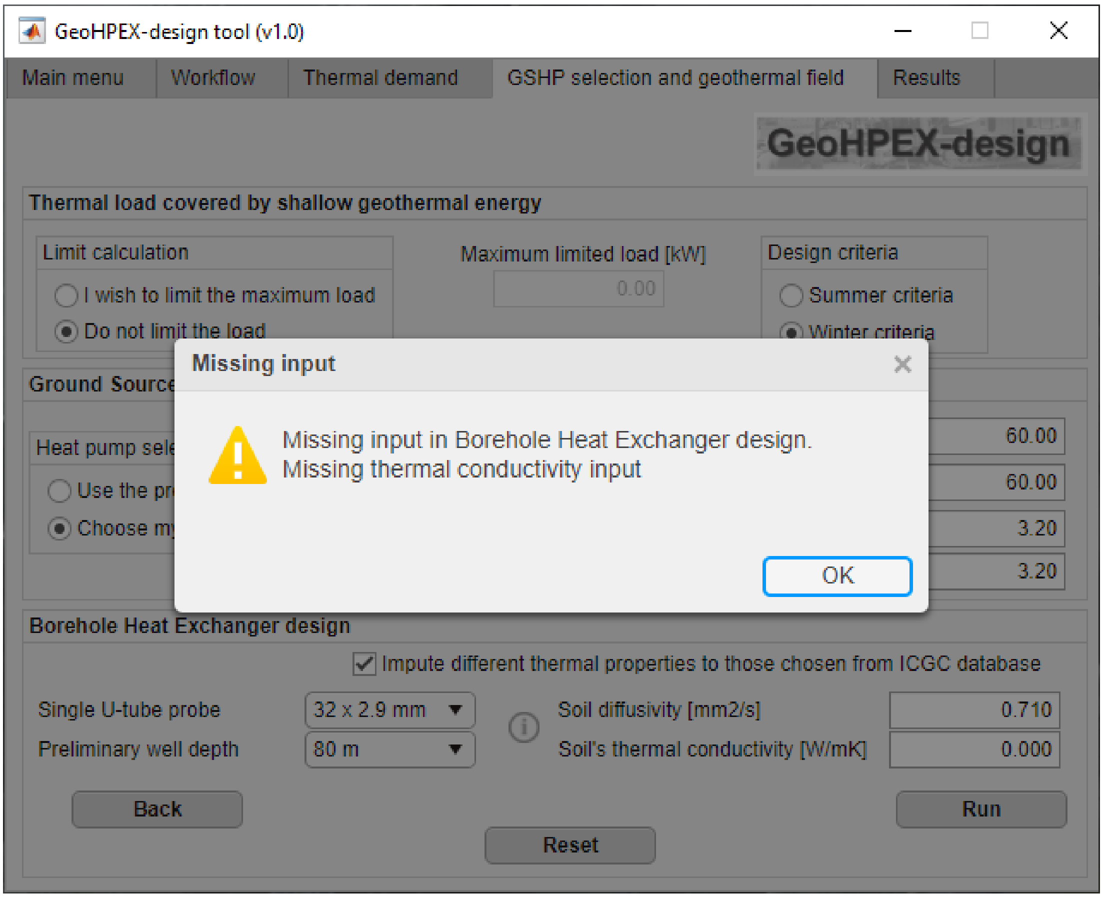

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Heating power load of the heat pump is missing. Please revise the information
OK
0.00
0.00
0.00
0.00
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

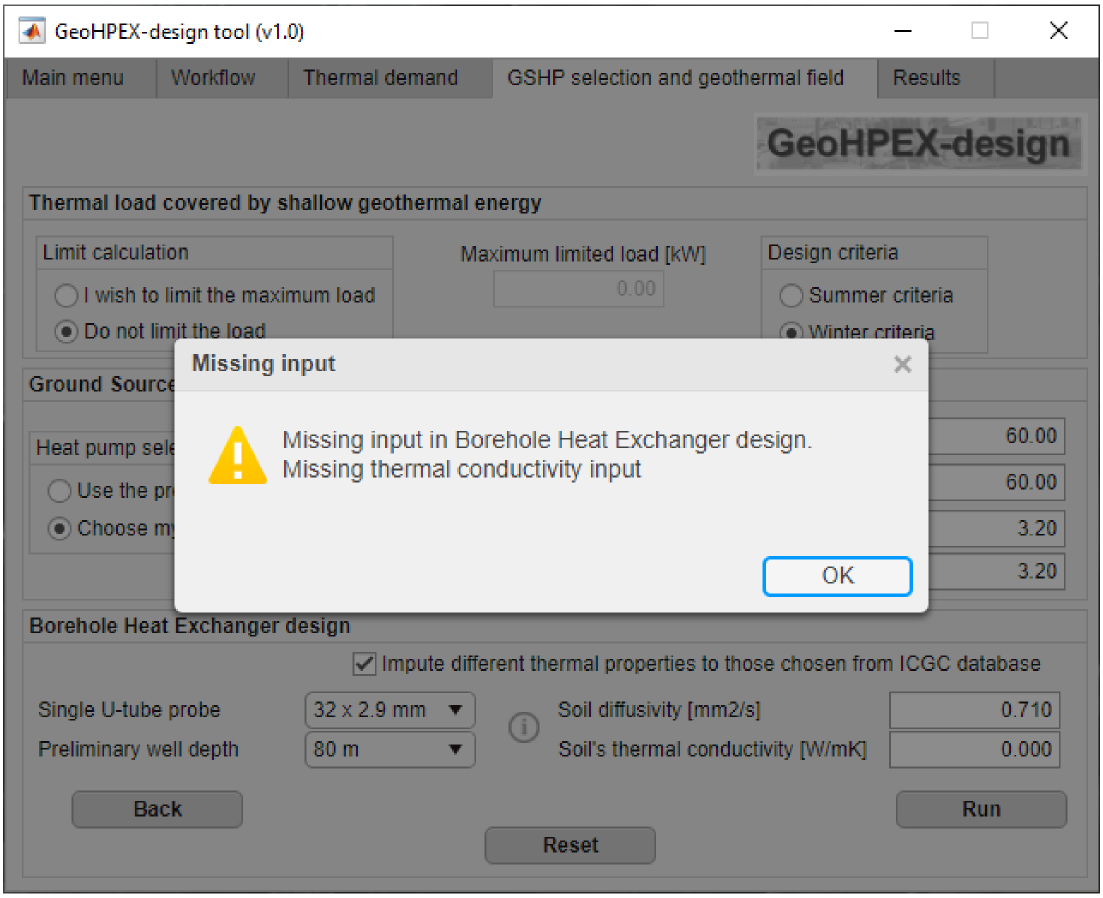

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Cooling power load of the heat pump is missing. Please revise the information
OK
60.00
0.00
0.00
0.00
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

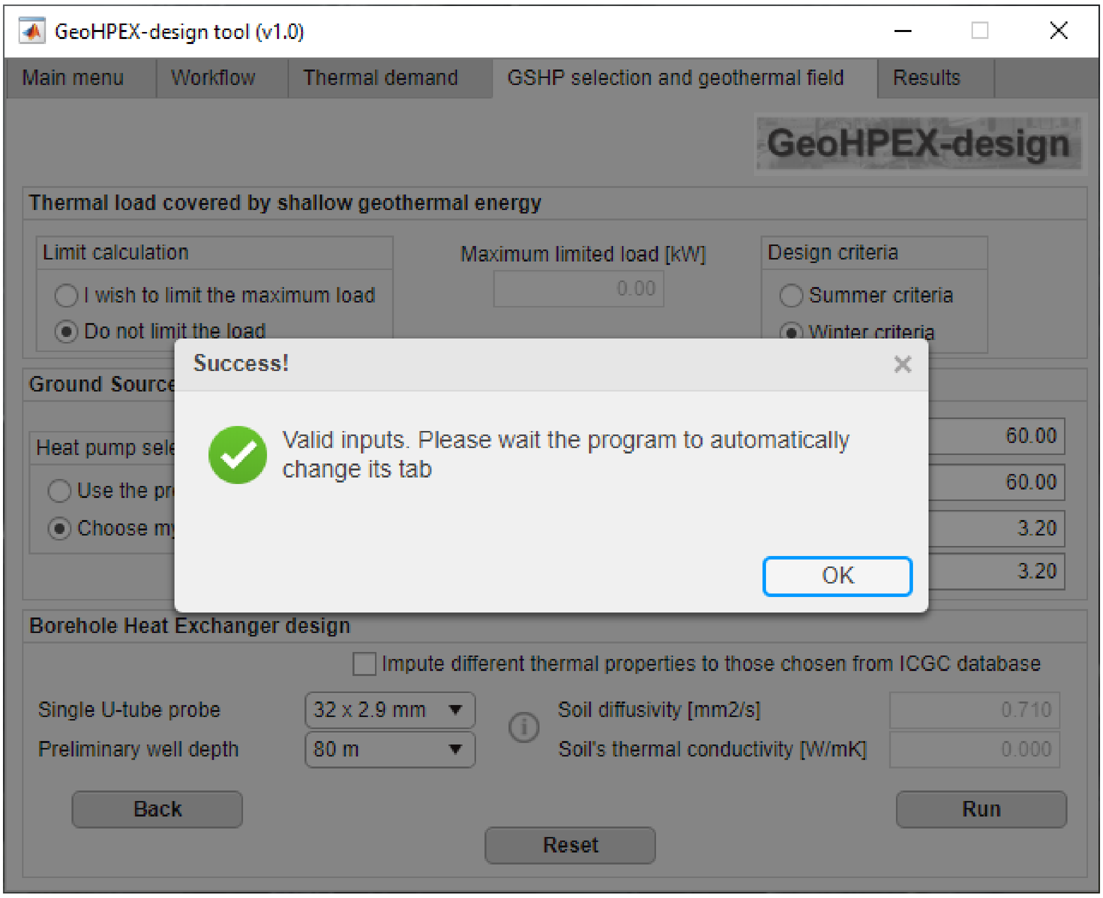

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Heating COP of the heat pump is missing. Please revise the information
OK
60.00
60.00
0.00
0.00
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

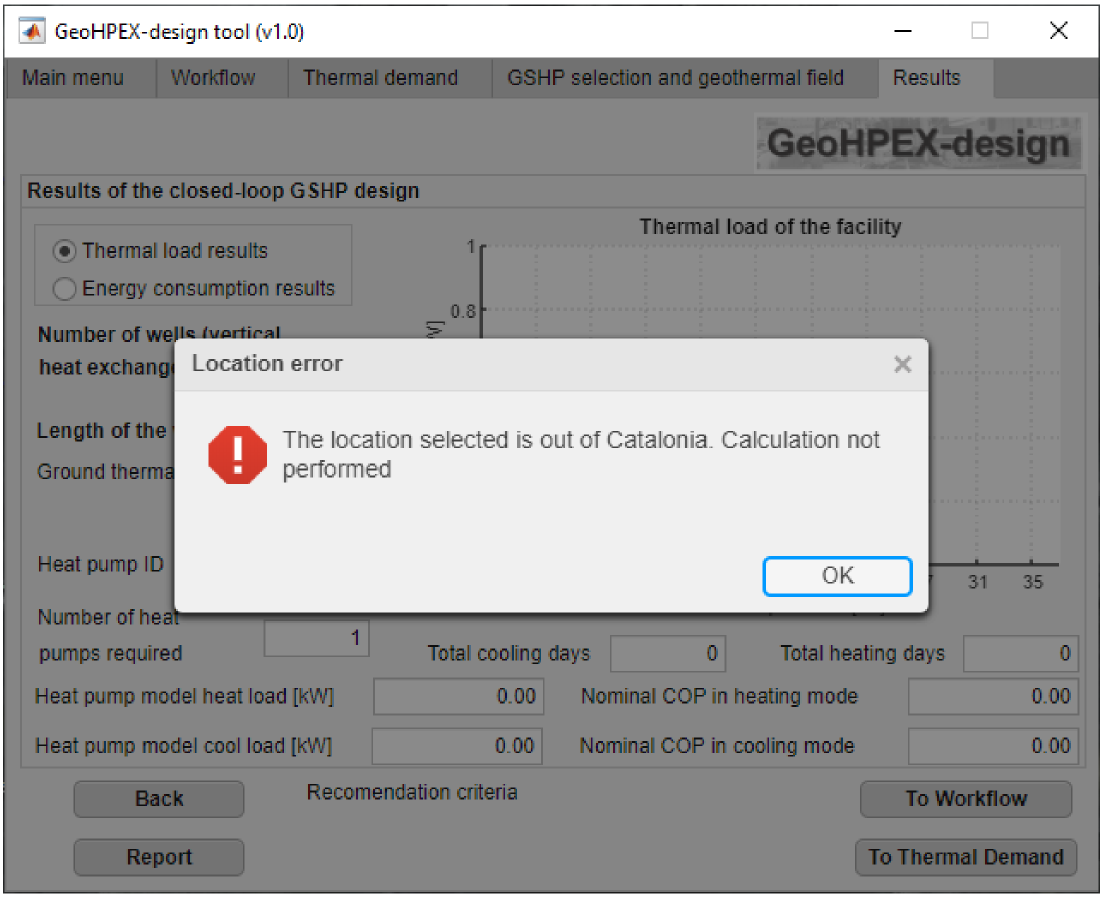

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Warning message
Cooling COP of the heat pump is missing. Please revise the information
OK
60.00
60.00
3.20
0.00
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

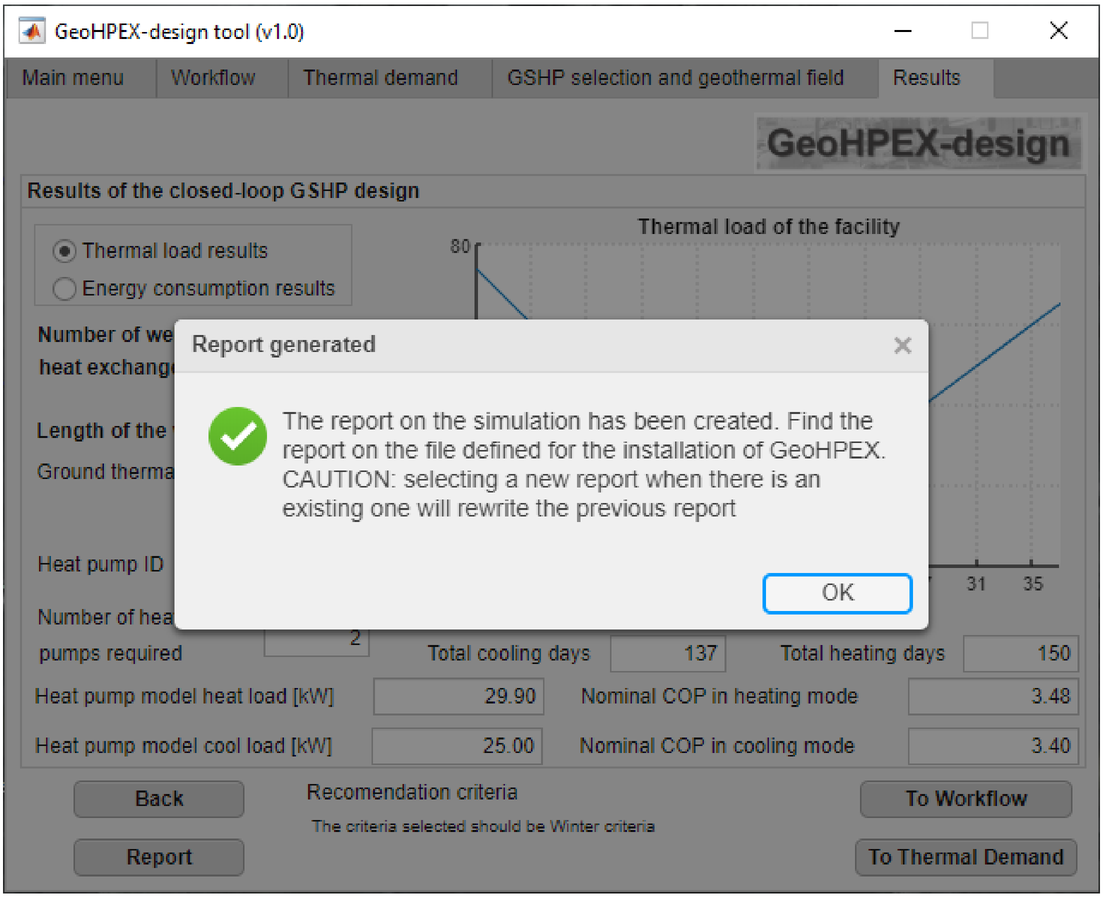

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Missing input
Missing input in Borehole Heat Exchanger design.
Missing diffusivity input
OK
60.00
60.00
3.20
3.20
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.000
Soil's thermal conductivity [W/mK]
2.650
Back
Run
Reset

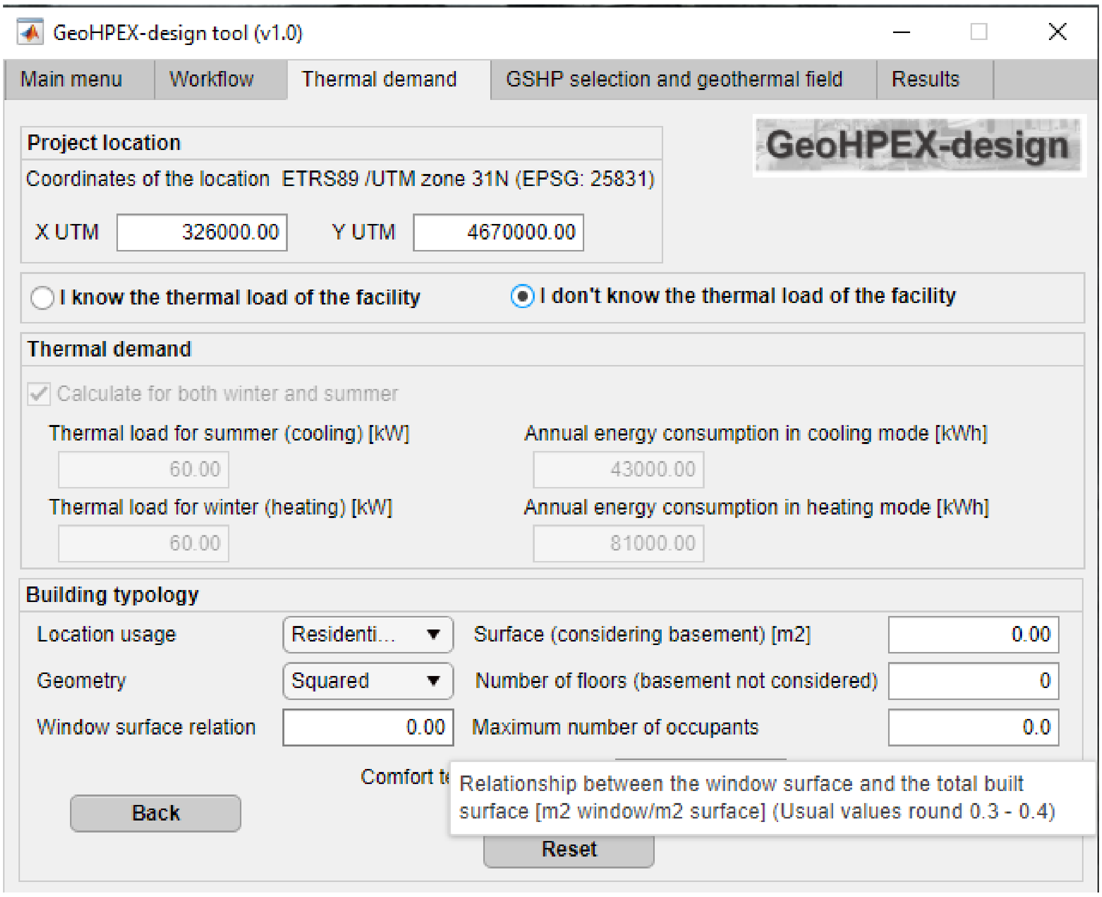

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Missing input
Missing input in Borehole Heat Exchanger design.
Missing thermal conductivity input
OK
60.00
60.00
3.20
3.20
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
0.000
Back
Run
Reset

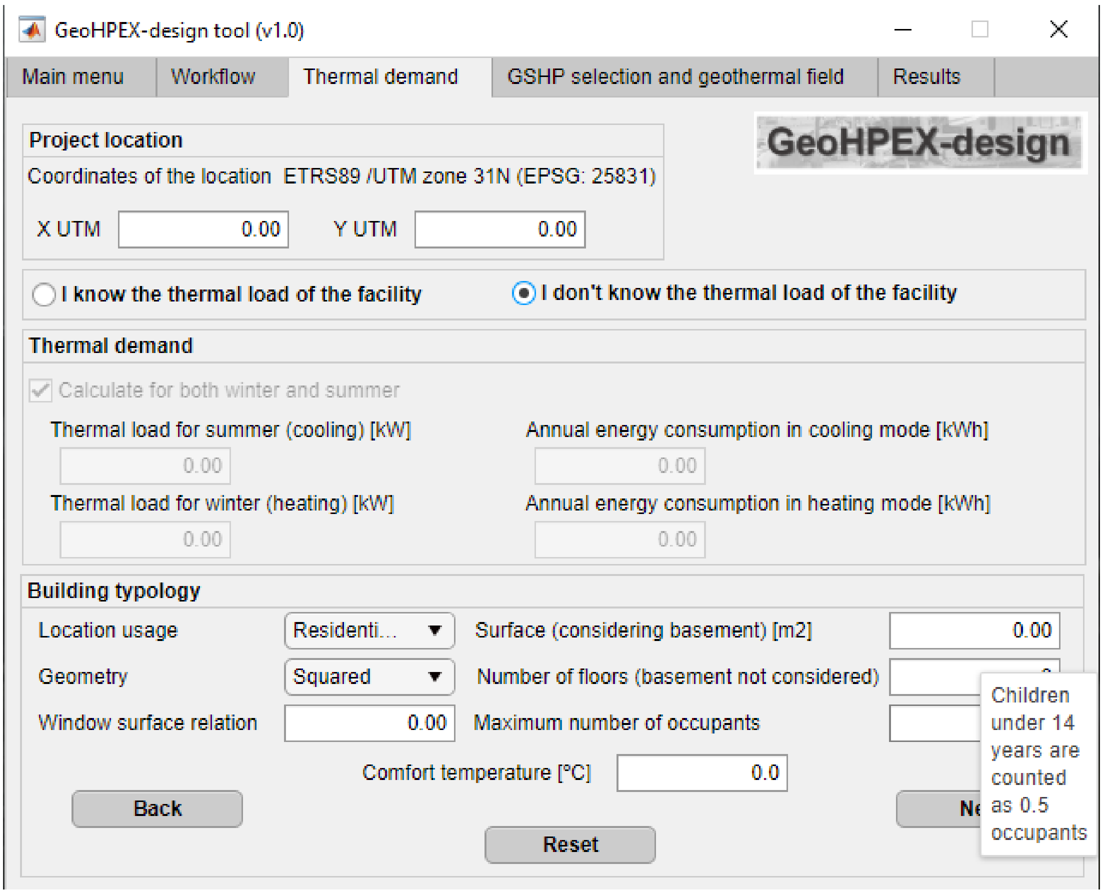

GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Missing input
Missing input in Borehole Heat Exchanger design.
Missing thermal conductivity input
OK
60.00
60.00
3.20
3.20
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
0.000
Back
Run
Reset


GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Thermal load covered by shallow geothermal energy
Limit calculation
I wish to limit the maximum load
Do not limit the load
Maximum limited load [kW]
0.00
Design criteria
Summer criteria
Winter criteria
Success!
Valid inputs. Please wait the program to automatically change its tab
OK
60.00
60.00
3.20
3.20
Borehole Heat Exchanger design
Impute different thermal properties to those chosen from ICGC database
Single U-tube probe
32 x 2.9 mm
Preliminary well depth
80 m
Soil diffusivity [mm2/s]
0.710
Soil's thermal conductivity [W/mK]
0.000
Back
Run
Reset


GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Results of the closed-loop GSHP design
Thermal load results
Energy consumption results
Thermal load of the facility
Location error
The location selected is out of Catalonia. Calculation not performed
OK
Heat pump ID
pumps required
Total cooling days
0
Total heating days
0
Heat pump model heat load [kW]
0.00
Nominal COP in heating mode
0.00
Heat pump model cool load [kW]
0.00
Nominal COP in cooling mode
0.00
Back
Recomendation criteria
To Workflow
Report
To Thermal Demand


GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Results of the closed-loop GSHP design
Thermal load results
Energy consumption results
Thermal load of the facility
Report generated
The report on the simulation has been created. Find the report on the file defined for the installation of GeoHPEX. CAUTION: selecting a new report when there is an existing one will rewrite the previous report
OK
Heat pump ID
pumps required
Total cooling days
137
Total heating days
150
Heat pump model heat load [kW]
29.90
Nominal COP in heating mode
3.48
Heat pump model cool load [kW]
25.00
Nominal COP in cooling mode
3.40
Back
Recomendation criteria
The criteria selected should be Winter criteria
To Workflow
Report
To Thermal Demand


GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
326000.00
Y UTM
4670000.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Calculate for both winter and summer
Thermal load for summer (cooling) [kW]
60.00
Annual energy consumption in cooling mode [kWh]
43000.00
Thermal load for winter (heating) [kW]
60.00
Annual energy consumption in heating mode [kWh]
81000.00
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
0.00
Geometry
Squared
Number of floors (basement not considered)
0
Window surface relation
0.00
Maximum number of occupants
0.0
Relationship between the window surface and the total built surface [m2 window/m2 surface] (Usual values round 0.3 - 0.4)
Back
Reset


GeoHPEX-design tool (v1.0)
Main menu
Workflow
Thermal demand
GSHP selection and geothermal field
Results
GeoHPEX-design
Project location
Coordinates of the location ETRS89 /UTM zone 31N (EPSG: 25831)
X UTM
0.00
Y UTM
0.00
I know the thermal load of the facility
I don't know the thermal load of the facility
Thermal demand
Calculate for both winter and summer
Thermal load for summer (cooling) [kW]
0.00
Annual energy consumption in cooling mode [kWh]
0.00
Thermal load for winter (heating) [kW]
0.00
Annual energy consumption in heating mode [kWh]
0.00
Building typology
Location usage
Residenti...
Surface (considering basement) [m2]
0.00
Geometry
Squared
Number of floors (basement not considered)
Window surface relation
0.00
Maximum number of occupants
Children under 14 years are counted as 0.5 occupants
Comfort temperature [°C]
0.0
Back
Reset

ANNEX II. Report generated by GeoHPEX-design tool© (v1.0)

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GeoHPEX-design tool (v1.0)      Ariza, J., Herms, I., De Felipe, J.J., Arnó, G. (2020)

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|| SIMULATION RESULTS ||
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Date of issue:  June 12th, 2020

SIMULATION CRITERIA

Calculation performed under the methodology of IGSHPA
Thermal load data specified by the user
Borehole heat exchanger field calculation performed under the methodology of IGSHPA
Ground thermal parameters captured from the ICGC spatial database

Ground thermal conductivity: 2.650 W/mK        Ground thermal diffusivity: 0.710 mm2/s

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ETRS89 /UTM zone 31N (EPSG: 25831)     X coordinate:   326000.00       Y coordinate:   4670000.00      Province: Lleida

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|| Final vertical borehole Heat Exchangers (BHE's) field solution ||

Number of BHEs required:          18     Length of BHEs: 82.01 m

U-shaped geothermal probe diameter: 32 x 2.9 mm

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|| Heat pump design ||

Heat pump properties obtained from the database

        Heat pump model ID:        9           Number of heat pumps required:  2

Heating thermal load (design):   29.90 kW      Heating COP:    3.48
Cooling thermal load (design):   25.00 kW      Cooling COP:    3.40

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|| Other considerations ||

Annual thermal energy demanded:         124000.00 kWh/year

Annual thermal energy demanded on cooling:               43000.00 kWh/year

Annual thermal energy demanded on heating:               81000.00 kWh/year

Annual ground thermal imbalance:                -2077.08 kWh    (positive for ground heating)


Note: The number of days requiring heating or cooling differ from the stored
in the database with an error higher than 25%.
Might occur when the user has introduced itself the thermal demand,
when occupation of the building is above average or when use selected
is different from residential
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