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Evaluation of different methodologies for calculating the energy demand and their influence on the design of a low enthalpy geothermal system

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ABSTRACT

The increasing importance of shallow geothermal resources in the decarbonization of heating and cooling systems requires the correct management of all the project stages. One of the fundamental steps in this process is determining the space energy demand, which plays a significant role in the subsequent geothermal design. In the context of Spain, different tools are available for the estimation of the mentioned parameter. For evaluating these procedures, this research applies the principal energy demand calculation tools and uses the outcomes for the later design of the shallow geothermal system. Results show how the Spanish official tools (HULC and CE3X) provide lower energy demand values adjusted to the construction conditions of the building that allow the optimization of the geothermal well field. On the contrary, simpler, and more intuitive applications (regular spreadsheets and GES-CAL) assume higher heating energy demands, which in turn implies an oversizing of the geothermal scheme. Even though all the procedures ensure to cover the energy requirements of the building, the most precise tools manage to reduce the initial investment of the system and its operating costs, in addition to reducing the global CO_2 emissions because of the lower power of the associated geothermal heat pump.

Introduction

The clear evidences of anthropogenic climate change and its detrimental consequences for both humans and global ecology are pushing the energy sector towards a transition to cleaner technologies with lower CO_2 emissions. Despite this fact, the world energy supply is still highly dependent on fossil fuels (~80 % of primary energy), which translates into unacceptable levels of Greenhouse Gases (GHG) emissions and other environmental impacts [1–2].

In the above context, the European Union (EU) is committed to reducing the global GHG emissions by 20 % from the 1990 levels by 2020 and around 80–95 % by 2050 [3]. Increasing the penetration of renewables is mandatory for ensuring the future de-carbonized energy system. In this sense, contributions are required from the different energy consuming sectors, but especially from the building one, which represents in the EU 40 % of the total final energy use, meaning 36 % of the global CO_2 emissions [4]. The principal legislation in the EU for the energy efficient buildings together with the International Energy Agency (IEA) promotes the implementation of heat pumps and renewable energy for the heating and cooling sectors [5–6].

In this context, Geothermal Energy (GE) appears as a renewable ideal solution for reducing the dependence on fossil fuels using the available heat stored in the ground, ground water, or surface water [7]. The implementation of geothermal solutions in Europe is expected to grow in an exponential way over the next decades given the versatile and non-intermittent nature of these resources. The possibilities of using the available geothermal energy include the exploitation of deep geothermal resources, based on hot-water and steam for producing electricity, but also shallow geothermal heat pump systems that constitute a mature technology for space heating and cooling and the production of Domestic Heat Water (DHW). Regarding this last use, which is also the most common way of geothermal exploitation, two main categories or technologies are usually found. The first group, known as Ground Source Heat Pumps (GSHP) systems or closed loop systems, based on the use of boreholes heat exchangers for the thermal exchange between the installation and the surrounding subsurface. GSHPs usually consist of vertical or horizontal boreholes where heat exchangers are connected to the heat pump in a closed circuit. The second typology is commonly known as Ground Water Heat Pump

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Nomenclature

Acronyms

GHG	Greenhouse Gases
EU	European Union
IEA	International Energy Agency
GE	Geothermal Energy
DHW	Domestic Heat Water
GSHP	Ground Source Heat Pump
GWHP	Ground Water Heat Pump
CENER	National Center for Renewable Energies
COP	Coefficient of Performance
NPV	Net Present Value

Parameters

Gains	Heat contribution [W/m^2]
Inertia	Internal thermal mass [kg/m^2.]
Ventilation	Number of renewals per hour.
U_o	Average thermal transmission coefficient including integrated thermal bridge [$W/m^2 \cdot K$]
U_v	Average thermal transmission coefficient considering the average frame and glass [$W/m^2 \cdot K$]
g	Modified solar factor of the glass.
Sup	Linear thermal bridge formed by the intersection between façades and roofs [W/m·K]
Iner	Linear thermal bridge, intersection between façades and intermediate slabs [W/m·K]
Infer	Linear thermal bridge formed by the intersection between façades and floors [W/m·K]

(GWHP) systems or open loops, which can extract groundwater and creating an efficient thermal exchange with the installation [8–9].

Beyond the commented applications of geothermal resources, they are also considered a great contributor in the reduction of the carbon footprint associated to the electricity or the heating/cooling sectors. Regarding the emission of CO_2 and energy efficiency, geothermal heat pumps rank higher than all fossil fuel-based boilers and the air source systems [10–12]. However, and despite advances in this renewable energy have led to the increase in the energy efficiency and its expansion through the global heating/cooling energy sector, geothermal energy is not as widespread as other renewable energies such as solar or wind. This underuse frequently derives from the inappropriate characterization of the geothermal energy source and the incorrect management of all the associated steps [13].

Focusing in this research on shallow geothermal systems, there is a common general lack of knowledge about this energy by users and technicians that lead to certain wrong practices in the different phases of a shallow geothermal project. These actions are commonly the reason of failures during the operation of the installation, compromising its correct operation throughout the initially projected useful life of the systems.

In the above context, one of the fundamental steps when facing the initial stages of this type of projects is the evaluation of the energy consumption of the particular space. There is in fact an increasing interest in decreasing the energy consumption and the associated greenhouse gas emissions in every sector of the economy and especially in the residential one, a substantial energy consumer [14]. The correct determination of a building energy demand requires the management of complex and interrelated variables that usually need adopting comprehensive models and applications.

Different research has addressed the application of software to simulate the energy behavior such as TRNSYS, Energy Plus or ESPr which are useful to provide an estimation of how the building behaves from the energy point of view [15–17].

Analyzing the particular case of Spain (where this work is set), the practical procedure for the estimation of the heating and/or cooling energy demand is usually performed by the use of specific tools that comply the Technical Code for Building [18]. These applications (known as *"LIDER"* and *"CALENER"*) are freely available for technicians and users interested in defining the energy requirements of a particular space [19]. With the transposition of the EU Directive 2012/27/EU to Spanish regulations based on the Royal Decree 235/2013, that ratifies the process for certifying the energy performance of buildings [20], both tools were unified into a single software called the *"Herramienta Unificada LIDER CALENER"* or *LIDER-CALENER Unified Tool*, usually known as *"HULC"* [21,22].

Beyond the standard procedure addressed with the official HULC tool, alternative practices mean the use of simpler methodologies frequently applied for the estimation of the energy demand in single-family buildings. These tools allow saving time and simplifying the calculation process in exchange for less accurate results. Depending on the magnitude and typology of the space, this fact can lead to significant inaccuracies in the subsequent design of the heating and/or cooling system. This is especially influential in the design of shallow geothermal systems and the well field, where the differences in the estimated initial energy demand make the final scheme approach vary to a high degree (depending on the particular installation).

In order to clarify the previously described practices, the present research deals with the calculation of the heating energy demand of a specific building through the use of different tools and applications commonly implemented in this context. From this calculation, the design of a low enthalpy geothermal installation is performed for evaluating the influence of the different energy demand procedures in the final design of the system. This research is expected to represent an important contribution in the field in the sense of establishing the most optimal working procedure with the aim of ensuring the correct operation of the planned geothermal system. The work is structured into several sections. Section 2 describes the case under study and each of the methodologies considered in the pursued evaluation. Section 3 shows the results of applying each procedure on the final geothermal design. Finally, Section 4 and 5 present the discussion and most important conclusions of the work.

Methodology

Characterization of the case under study

Geometric and structural information

With the objective of dealing with the evaluation pursued in this work, a single-family building has been considered. This three-story building is located in the region of Ávila (central Spain) and is constituted by a basement, a ground and a first floor together with an inhabitable rooftop level. The considered space was built in the year 2020. Dimensions and geometric information of each floor are presented in Table 1.

Based on the information presented in the previous Table 1, the total useful living surface of the single-family house is of 161.03 m^2. In addition to the data of this Table 1, another of the initial factors that must be defined about the building refers to the consumption of Domestic Hot Water (DHW). In this case, and taking into account that the building is constituted by 5 bedrooms, the estimated daily use of DHW is, according to the Technical Code for Building, of 140 l/day [15].

On top of the above, for the subsequent calculation of the heating energy demand, the surface and orientation of each façade and the surface of windows placed on them must be also known. This information can be observed in the following Table 2.

Climatological and geological assessment

As mentioned before, the building is located in the Spanish region of

Table 1
Description and geometrical information of the floors that make up the single-family building included in the study.

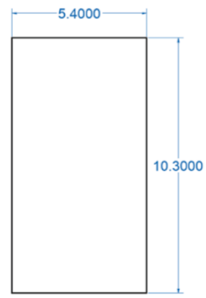
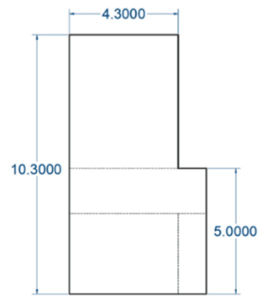
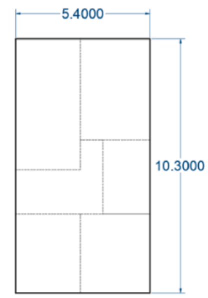
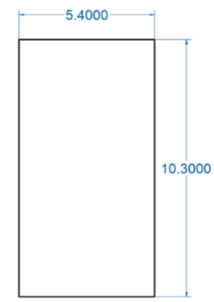
House level	Basement floor	Ground floor	First floor	Rooftop level
Linear dimensions (m) and geometric arrangement				
Surface (m^2)	55.62	49.79	55.62	55.62
Height (m)	2.70	3.00	3.00	0.83

Table 2
Orientation and surfaces of façades and windows.

Façade	Surface (m^2)	Windows (m^2)	Windows (%)
North	42.62	6.02	14.12
South	44.01	9.69	22.02
East	73.71	–	–
West	89.61	–	–

Ávila. The climate of this area is slightly continental, with moderately cold and dry winters and mild summers, usually with cool nights. The average temperatures and rainfall for this area during the period 1991–2020 is shown in Fig. 1.

It is convenient to mention that considering the climatological conditions of the region where the building is set, where the most severe temperatures take place during the cold months, only heating energy needs are considered in this research.

A final aspect to take into account in this section is the geological environment in which the building under study is located. This information, presented in Fig. 2, is required for the subsequent design process of the shallow geothermal system selected as a means of heating solution.

As can be deduced from the previous Fig. 2, the study case is located on an eminently granite site made up of medium-coarse grained adamellites. These geological formations are especially appropriate for the geothermal exchange of the system given the excellent thermal conductivity of this kind of granite materials. For the case of this work, a thermal conductivity value for the ground of 2.85 W/mK is assumed for the later calculation stages [24].

Estimation of the building energy demand

As mentioned in the introductory section, the calculation of the heating energy demand of a given building can be addressed from different perspectives and approaches that can significantly alter the final result of the selected heating/cooling system. The following subsections describe the most frequent procedures used in this sense, and

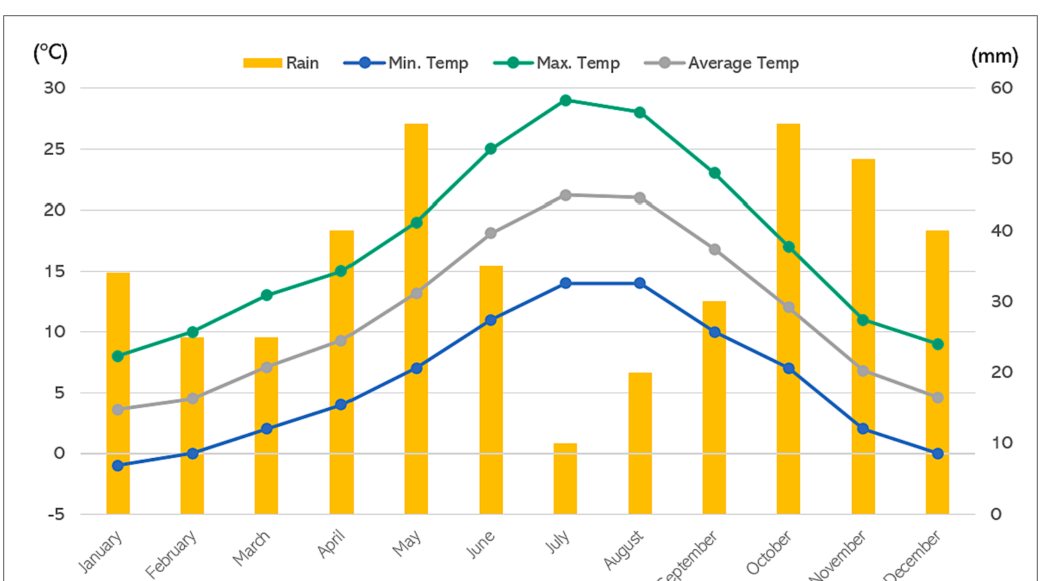


Fig. 1. Average temperatures and rainfall during the historical period 1991–2020 in the area included in the study [23].

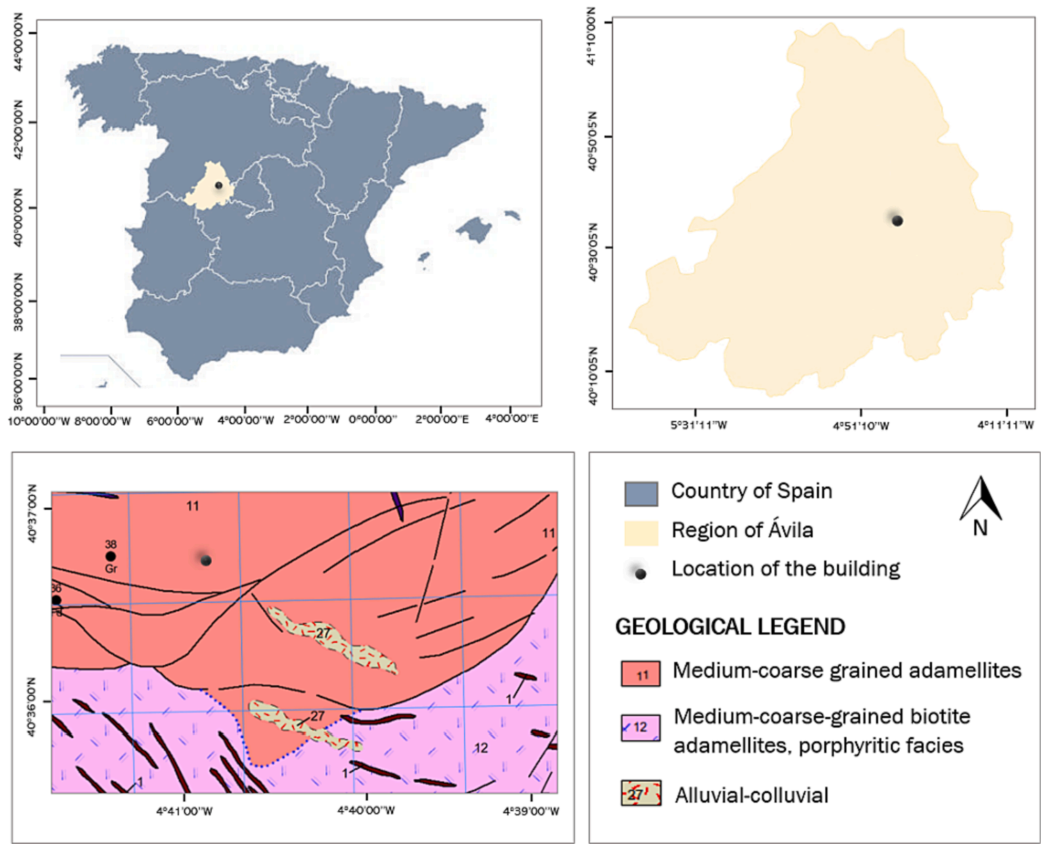


Fig. 2. Location of the building under study and geology of the environment.

that will be considered in this research.

Regulated spreadsheets

One of the simplest and most widely used procedures for estimating the energy demand of a particular space is the use of programmed spreadsheets designed in accordance with the specific regulations in force. The purpose of these tools is to determine in a quick and approximate way the annual and monthly energy demand of a building. This method allows analyzing visually and intuitively the sensitivity of each possible variable on the energy behavior of the building in very early phases of the design, where only geometry is available.

The specific tool used in the present research follows the monthly method prescribed in the standard regulation UNE-EN ISO 52016–1 [25]. During its use, a series of numerical values (surface, height, percentage of openings and surface of each façade) are introduced and the climatic zone where the building is located is selected. Once provided all this set of information, the following variables are evaluated:

- Gains: Contribution of heat in W/m^2 that supposes the use of the building.
- Inertia: Internal thermal mass of the building expressed in kg/m^2.
- Ventilation: Number of renewals per hour.
- U_o: Average thermal transmission coefficient (including integrated thermal bridge) expressed in W/m^2·K.
- U_v: Average thermal transmission coefficient (considering the average frame and glass) expressed in W/m^2·K.
- g: Modified solar factor of the glass.
- Sup: Linear thermal bridge formed by the intersection between façades and roofs expressed in W/m·K.
- Iner: Linear thermal bridge constituted by the intersection between façades and intermediate slabs expressed in W/m·K.
- Infer: Linear thermal bridge formed by the intersection between façades and floors expressed in W/m·K.

CE3X

The second procedure included for the calculation of the heating energy demand of the space here considered is CE3X. This official application is promoted by the Ministry for the Ecological Transition and the Demographic Challenge for the certification of the energy efficiency of buildings. The tool, developed by Efinovatic and the National Center for Renewable Energies (CENER), allows the certification of any type of building in a simplified way to obtain any rating from «A» to «G» but also provides a final value of the heating and/or cooling energy demand [26]. CE3X can be downloaded on the official page of the Ministry for the Ecological Transition and the Demographic Challenge, as well as a complete guide with the main instructions for its use.

The program is based on the comparison of the building object of the certification and a database corresponding to each of the representative climatic zones. The database is conceived to cover the calculation of any case of the Spanish building stock. When the user enters the data of the object building, the program parameterizes these variables and compares them with the characteristics of the cases collected in the mentioned database. In this way, the software searches for the simulations with characteristics most similar to those of the target building and interpolates the heating and cooling demands with respect to them, thus obtaining the heating and cooling demands of the target building. Depending on the level of knowledge about the structural characteristics of the building and thermal installations, the procedure of CE3X establishes different stages of data entry as default, estimated or known (tested/justified) values.

Throughout the use of the program, information (in the mentioned levels) is entered regarding administrative data, general data, thermal envelope, and heating and/or cooling installations.

HULC

When a more precise but also more complex level of calculation is required and when in-depth knowledge of the considered space is available, HULC tool is one of the most frequent options. In the case of Spain, LIDER was the computer application used a few years ago to comply with the general verification of the Energy Demand Limitation requirement established in the Basic Document of Habitability and Energy of the Technical Building Code (CTE-HE1) [27]. As of 2016, it was unified with CALENER (that considers the use of the energy systems) to create HULC (Leader-Calener Unified Tool), whose use is mandatory in the country to perform official energy efficiency certificates.

The tool includes all the updates of the Technical Building Code and is commonly used by professionals when evaluating whether all the legally established energy saving requirements are met on a particular building, offering the possibility of providing both certifications and verifications of the system. The design of HULC is specifically created so that the energy certification of a residential building can be assessed in a clear and visual way. In addition, the energy demand of the space is also provided by the software both for heating and cooling mode, so this module will be applied for the present research.

Throughout the use of this program, the user must enter a series of general information about the building and the energy system, being able to differentiate between the electrical energy generated and the produced self-consumed energy. After entering all these data, it is necessary to define the envelope and the workspace to model the system. At this stage, it is possible to introduce the specific plans of the building (as in the case of this work) or to design it directly on the program. Once the constructive solutions adopted in the building are defined and the corresponding thermal bridges are calculated, the tool allows determining if the building meets the energy demands limited by the Technical Building Code [28]. As a final step, the energy installations of the building can be defined to obtain the global results according to demand, consumption, and CO_2 emissions.

GES-CAL

The last calculation option included in this research is known as GES–CAL. This software has been developed by researchers from the TIDOP Research Group (University of Salamanca) for the modelling and design of shallow geothermal systems [29]. The tool is specially conceived for being used in the region of Ávila (location of the case under study) for which specific thermal measurements of the main underground formations were performed. GES-CAL allows the geothermal calculation in the considered region by clicking in an interactive map of the area which directly applies the thermal conductivity of the geological formations associated to the specific location. This map derives from authors previous field measurements of the thermal conductivity parameter on the predominant materials of the region [24]. The tool also allows the design of the geothermal system in other areas, being necessary for the user to manually enter the thermal conductivity values of the place (obtained from external sources). In addition to the geothermal calculation of the system, the energy demand can be also estimated in the tool by one of its initial modules. For this reason, GES-CAL has been included in this research for both the calculation of the heating energy demand of the building and the corresponding design of the geothermal system.

GES-CAL is principally constituted by five modules, starting by a brief description of the software, and following by the introduction of initial data of the building (in which the energy demand is estimated), the design of the geothermal solution and a final economic and environmental analysis. The initial module conceived for the energy demand allows to introduce the specific value (if known) or to automatically calculate it from easily available information of the space (specification of demand, surface, height, year of construction and orientation), complying the procedures specified at the regulation ISO 52016-1:2017 [25].

Once detailed or calculated the building energy demand, it is possible to define the main characteristics of the closed-loop geothermal system (heat pump parameters, ground thermal properties, and configuration of the geothermal installation) so GES-CAL software finally calculates the design parameters of the geothermal well field, such as the total pipe and drilling length and the schema of the system. After this stage, the software suggests several possible designs so the user can select one of the proposed solutions to ultimately obtain the well field schema besides an economic and environmental analysis of the geothermal system.

It must be clarified that the methodology here included can be extended to other locations out of the region considered in this research, since all the implemented tools are applicable to any scenario and conditions.

As a final remark of this subsection, Table 3 summarizes the main advantages and limitations associated to the use of each of the tools here considered.

Results

Space heating energy demand

Once implemented each of the considered procedures based on the information required in each step, the values of the heating energy demand associated with the conditions of the building considered as case study are included in Table 4. From these values, the geothermal design is addressed with the aim of evaluating the effect of the variations of the heating energy demand on the final shallow geothermal system.

As will be shown in the aforementioned Table 4, results obtained for the energy demand vary in a fairly wide range despite referring to the same building and under the same starting conditions. In the case of the regulated spreadsheet, only the building location and certain geometric parameters of the building related to the surface and general height and the openings are selected. In GES-CAL, the procedure is similar but also the building construction date and its orientation were defined during its use, which provides more information on the structure thermal behavior. Regarding CE3X, the geometric characterization of the building was more precisely established in addition to selecting the

Table 3
Summary of the main limitations and advantages of the tools included in this study.

Application	Advantages	Limitations
Spreadsheet	Simple and intuitive calculation process Weather information for certain predefined locations Distribution of the annual energy demand	Low robustness and low accurate results Oversized results given the lack of definition on the construction building conditions
CE3X	Medium adjusted results according to the construction particularities of the building Use of standard or known building parameters Compliance with provisions of the Technical Building Code	Complex calculation and design of the building if the parameters provided by the default tool are not used Requires experience and knowledge prior to its use
HULC	Maximum adjusted results according to the construction particularities of the building Modeling of the building in terms of geometry and constrction elements Compliance with provisions of the Technical Building Code	Complex constructive and geometrical definition of the building Arduous calculation process with a high degree of complexity Requires experience and knowledge prior to its use
GES-CAL	Simple and intuitive calculation process Additional module for the subsequent geothermal design	Low robustness and low accurate results Oversized results given the lack of definition on the construction building conditions

Table 4
Parameters of the geothermal design performed with GES-CAL software.

Application	Heating demand (kWh/year)	Heat pump power (kW)	Number of boreholes	Total drilling length (m)
Spreadsheet	39199.00	7.84	2	117
CE3X	21658.53	5.41	1	69
HULC	15454.05	4.55	1	50
GES-CAL	34581.51	7.20	2	109

parameters that the tool suggests by default for the starting construction conditions. Finally, in HULC, the building plans were introduced in the tool and each of its construction elements were individually defined, in terms of materials, layout or thermal bridges, which ensures greater adaptation of the results to the real conditions of the building.

It should be noted that, of all these procedures, the regulated spreadsheet (the one that is only conceived for the calculation of the space energy use) also provides a graph of the evolution of this energy demand throughout the entire period of the year, differentiating the contribution of the main factors that are considered in the procedure. This graphic can be observed in the following Fig. 3.

Geothermal design

As already explained, GES-CAL software has also been used for the dimensioning of the geothermal system that will cover the energy needs of the building. As it is a program specifically designed for its use in the province of Ávila, calculations will be precise and based on empirically obtained subsoil thermal properties.

When proceeding to the geothermal design with this tool, the same initial data about the geothermal system are used (Polyethylene double-U vertical heat exchangers of 32 mm, standard geothermal grout (with a thermal conductivity value of 2.4 W/mK), heat pump with Coefficient of Performance (COP) of 4, and granite environment with thermal conductivity of 2.9 W/mK), only varying the value of the heating energy demand obtained by each of the evaluated procedures.

Table 4 includes the main parameters that characterize the geothermal system obtained with GES-CAL for each of the assumptions.

Discussion

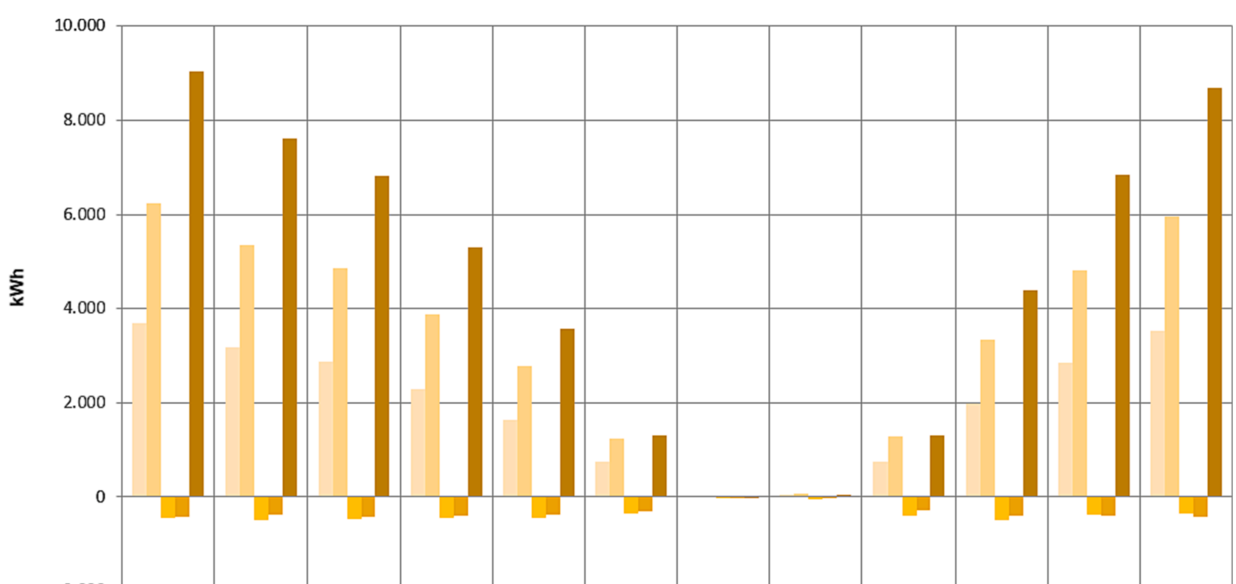
Requirements and reliability of the procedures

Analyzing the results of the energy demand associated with the building under study (Table 4), there are significant variations among each of the procedures used in this research.

HULC and CE3X programs (official tools of the Ministry for the Ecological Transition and the Demographic Challenge) provide the lowest values of heating energy demand required by the building, and this is especially evident in the case of HULC software. This program is undoubtedly the most precise solution and the one that best adjusts to the real construction conditions of the building. In effect, the tool allows defining its envelope and optimizing its energy requirement based on the materials used in its construction. The large amount of information that HULC allows to enter about gaps, construction solutions, thermal bridges, etc. as well as the exact definition of its geometry mean that the final result of its energy demand can be adjusted to the maximum, constituting a reliable value and in accordance with the particular conditions of the building.

Regarding CE3X program, it is considered a version prior to HULC, where the constructive conditions of the building are also taken into account, but without reaching the level of detail that HULC allows. Although both tools comply with the provisions of the Technical Building Code, CE3X cannot adjust the results to the same degree as HULC, which makes the energy demand more conservative and somewhat higher than that obtained with HULC.

Beyond these two official tools, the regulated spreadsheet and GES-CAL program provide the highest values of energy demand. This is due to the lower robustness of these applications, which, even based on specific UNE regulations, are simple solutions that only take into account general geometric parameters of the building and therefore



	January	February	March	April	May	June	July	August	September	October	November	December
Thermal Transm.	3.690	3.162	2.872	2.292	1.635	730	0	42	751	1.971	2.840	3.522
Ventilation	6.237	5.346	4.855	3.875	2.764	1.235	0	71	1.269	3.331	4.801	5.954
Solar Gains	-461	-506	-476	-457	-446	-353	0	-59	-410	-508	-391	-361
Internal Gains	-436	-387	-424	-399	-388	-308	0	-44	-301	-398	-415	-439
Total	9.030	7.614	6.828	5.311	3.565	1.304	0	10	1.309	4.396	6.836	8.676

Fig. 3. Evolution of the heating energy demand for the single-family house obtained with the regulated spreadsheet.

cannot adjust the value of energy demand so as not to compromise the future operation of the selected energy system.

As can be deduced from all of the above, the final energy demand results fundamentally depend on the degree of definition that each tool allows about the constructive characteristics of the building.

Economic evaluation

As a consequence of the differences in the energy demand values obtained from each methodology, the geothermal design is also different in each case. Thus, both the power of the heat pump and the total length of drilling are much lower with the results of CE3X and especially of HULC. In the same way, GES-CAL and the spreadsheet whose energy demand values are higher, require a geothermal well field with a higher drilling length (and number of boreholes) as well as a greater power in the geothermal heat pump. All this means that, although with these last two applications, the building's energy needs would be totally covered, the oversizing that this entails, causes higher initial investment and annual operating cost (Table 5).

Additionally, Fig. 4 shows the evolution of the economic comparison considering the initial investment of each solution and the annual operating costs in terms of Net Present Value (NPV) with a discount rate of 0.18 during an estimated useful life of 30 years.

As derived from the aforementioned Table 5, the differences in initial investment and annual operating costs are significant between the most robust procedure (HULC) and the simplest one (regulated spreadsheet). These deviations are even more evident in terms of the overall useful life of the installation, with a great difference in the operating costs accumulated in year 30 of the system, taking into account the estimated evolution of prices in the established period.

Environmental approach

Beyond the economic analysis previously addressed, this subsection focuses on the comparison of the designs obtained with each tool from the point of view of carbon dioxide gas emissions. These emissions are a direct consequence of the electricity consumption of the geothermal heat pump, so that they will inevitably be higher for the cases of higher heat pump powers associated with the geothermal exchange system. Results of the CO_2 emissions accumulated in the year 30 of the heating system operation are shown in Fig. 4. It is convenient to mention that CO_2 emissions have been determined considering the trend of the electricity system in Spain based on the official data of the International Energy Agency (IEA) [30]. Emissions are thus calculated according to the announced pledges scenario, which estimates in 35 % the reduction of emissions in the next 30 years (2020–2050), and the current conversion factor in the country (0.157 $kgCO_2$/kWh).

As can be clearly deduced from the right graph of Fig. 4, the power of the geothermal heat pump adapted to the specific conditions of the particular scenario means that CO_2 emissions associated with the operation of this equipment are considerably lower. As a consequence, the long-term evaluation of each calculation alternative shows, as in the economic case, that the differences in carbon dioxide emissions can be more than double if the energy demand calculation procedure is not adjusted to the characteristics of the particular context.

Table 5
Economic results for each solution.

Application	Initial investment (€)	Annual cost (€/year) *
Spreadsheet	21958.81	3386.88
CE3X	17954.93	2337.12
HULC	16335.86	1965.60
GES-CAL	20957.78	3110.40

*Considering an electricity prize of 0.18 €/kWh and a heat pump operation of 2400 h/year.

Conclusions

The widespread expansion of shallow geothermal resources starts from the correct management of each of the stages involved in the design and characterization of the system. For this reason, the fundamental objective of this research has been to analyze the influence on the final geothermal scheme of one of the preliminary phases of the process, the calculation of the space energy requirements. With this purpose, different tools and procedures, frequently used in the calculation of the energy requirements of a building in the country of Spain (location of the study case), have been used.

As the results obtained with each methodology demonstrate, those applications in which the degree of detail of the building and its constructive solutions is high, allow maximizing the adjustment of the value of energy demand required by the building. In this way, the geothermal design can also be optimized, reducing the initial investment of the system and the operating costs associated with the operation of the geothermal heat pump (also reducing the emission of CO_2).

All the above becomes more evident in the 30-year global comparison, where it has been possible to observe how the most robust tool (HULC) allows savings of around 40 % and the significant reduction of the emissions of CO_2 compared to the simplest procedure, the spreadsheet used in the study.

In addition to the previously commented, the main findings derived from this research are the following:

- The energy demand preliminarily established on a building plays an essential role in the corresponding geothermal design and in the correct future viability of the proposed system.
- The use of robust tools involves a significant effort that requires the experience and knowledge of the user and exhaustive and detailed data about the construction and the thermal conditions of the specific building.
- Simplified procedures are advisable when opting for quick and simple processes and in those situations where complete knowledge of the geometric and construction conditions of the building is not available.
- The differences in economic and environmental terms of the geothermal system derived from each of the analyzed scenarios are important and must be taken into account when selecting one or another methodology, considering at all times the available information about the building and the size of the installation.

Finally, it should be noted that all the procedures applied in this research provide energy demand values that guarantee that the heating energy system is capable of covering the needs of the buildings, but in the case of the simplest tools, these values are oversized with the economic and environmental consequences that this fact entails. As a final statement, it must be mentioned that future research lines will be aimed at including alternative simulation tools and additional study cases in other conditions and climates that allow evaluating in a more detailed way the suitability of each solution.

CRediT authorship contribution statement

Cristina Sáez Blázquez: Investigation, Methodology, Writing – original draft. **Ignacio Martín Nieto:** Data curation, Methodology. **Natalia Nuño Villanueva:** Data curation, Methodology. **Miguel Ángel Maté-González:** Investigation, Resources, Formal analysis. **Arturo Farfán Martín:** Validation, Supervision. **Diego González-Aguilera:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

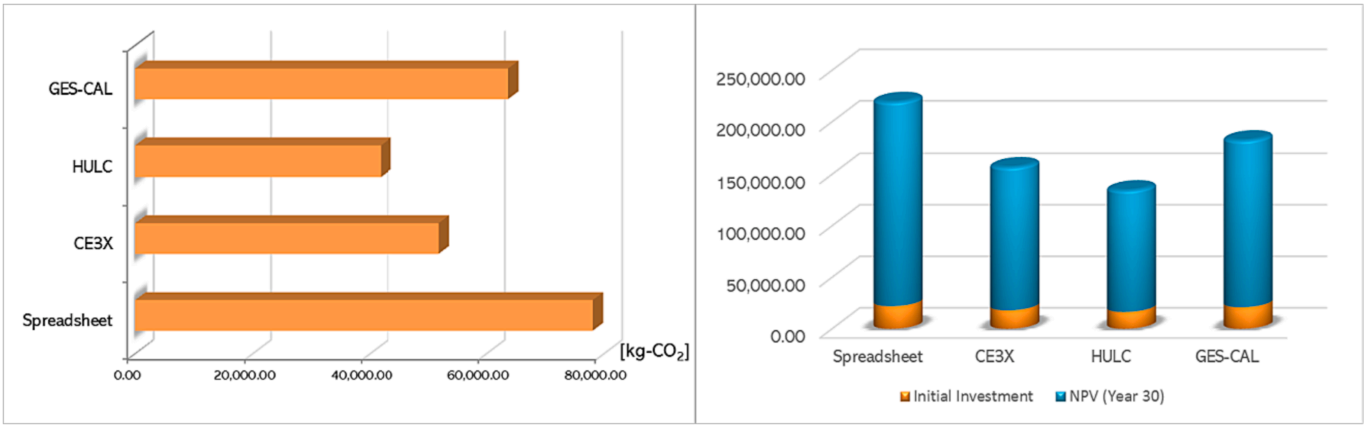


Fig. 4. Economic evaluation based on the initial investment and the annual operation costs in terms of NPV (left) and accumulated CO_2 emissions in the year 30 of the system operation (right).

the work reported in this paper.

Data availability

No data was used for the research described in the article.

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