Building energy simulation to evaluate the use of geothermal energy for HVAC and on a building of Academia Militar

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Abstract

Building heating and cooling consumes more than 30 % of the energy generated worldwide. Therefore, it is of vital importance to reduce the percentage of building cooling and heating significantly to reduce emissions of pollutants. In this Thesis, the potential of geothermal energy as a Heating, Ventilation and Air Conditioning (HVAC) and Domestic Hot Water (DHW) energy source was evaluated in a dormitory building with 839 m2 area and 78 occupants located in Academia Militar – Amadora Quartering, Portugal. Building Energy Modelling (BEM) tool was used to assess the HVAC results. DHW needs were estimated with information from the bibliography. The building was 3D modeled and characterized. Then, the data was introduced in the software and interpreted. The results obtained indicate 41 MWh for heating (including DHW) and 20 MWh for cooling. About 95 % of the energy needed for heating will be used to produce DHW. The maximum power required in this project is 44.2 kW for heating and 41.3 kW for cooling. In accordance with the results, a Ground Source Heat Pump (GSHP) system, with vertical closed-circuit heat exchangers, was chosen. The new GSHP system was compared, in terms of economy and emissions, with a boiler (COP = 0.68) and a fan-coil system (EER = 2.5). The results reveal considerable savings ascribed to the GSHP system. The geothermal HVAC system represents an annual energy saving of 69.86 % for heating and 46.46 % for cooling (3139 €). Considering both the costs of installation and maintenance of the new system, the GSHP system is going to be more profitable in 10 years and nine months after the installation, increasing the savings over the years. In terms of emissions, the new system produces 79.6 % less CO_2. The emission of around 11 tonnes of CO_2 is avoided. This Thesis call attention to the future of Geothermal Energy under the scope of the Energy Transition and the Paris Agreement ascribed to i) the shift of the worldwide energy sector from fossil-based systems towards renewable energy sources, such as very low-temperature geothermal systems and ii) the need to decrease energy-related CO_2 emissions to mitigate climate change.

Keywords: Renewable Energy, Very Low-Temperature Geothermal Energy; Ground Source Heat Pump Systems; Heating, Ventilation and Air Conditioning; Building Energy Simulation.

1. Introduction

Building heating and cooling consumes more than 30% of the energy generated worldwide (Kashiwase, 2015). The electricity network capacity is estimated to be tripled by 2050. The 80 % of the energy produced in 2050 will come from renewable sources and it is of vital importance to reduce the percentage of building cooling and heating significantly. (DNV-GL, 2018). There has been an increasing demand for Building Energy Simulation (BES) to improve building energy efficiency with the objective of facilitating the design of a built environment that satisfies the living needs, with the least use of resources associated with its construction and operation.

2. Objective

This thesis aims to use a BES tool to evaluate the potential of geothermal energy as a Heating, Ventilation, and Air Conditioning (HVAC) energy source, providing thermal comfort to the building occupants while reducing the use of fossil fuels and its consequent greenhouse gas emissions. The software chosen in this case is Energy Plus (Energy Plus, 2020). The building geometry is defined on Google SketchUp® (Google SketchUp®). The study was developed in a 78-capacity and 839 m^2 building at Academia Militar, in Amadora Quartering, Portugal.

3. Geothermal energy

Underground energy has been used from centuries. The process of Earth´s formation and the energy contained in radioactive elements of the crust make the interior of the Earth generate heat (Unwin, 2019). In the crust, the variation is 3 °C/100 m. In the internal layers (mantle, outer core and inner core), the variation is around 0.1°C/100 m.

4. Background

In Portugal, high temperature geothermal resources are only located in Azores islands. The Ribeira Grande Geothermal Field (RGGF), in S. Miguel Island, has a generation capacity of 27.8 MW. It covers the 42 % of S. Miguel island's demand.

Apart from Azores, there are two projects developed in Coimbra and Aveiro of HVAC systems associated to a geothermal heat pump.

4.1. Local climate

To classify the climate of Amadora, the Köppen classification was used (Beck et al., 2018). Amadora belongs to "Csb". The climate is considered as temperate. It has a dry period in summer with an average temperature of less than 22 °C in the hottest month (August). The mean yearly temperature is 15.6 °C with 796 mm of precipitations (Climate Data, 2020). The maximum mean temperature is in August (21°C) and the minimum mean temperature in January (10.4 °C). The rainiest month is December (124 mm) and the drier is July (4mm).

4.2. Local geology

The building location can be found on sheet nº 34-C (Cascais) of the Portuguese Geological Cartography (Ramalho et al., 2001). The building is located at 134 meters a.s.l. Apart from basalts, there are limestones and sandstones present in the region (Colaço, 2015). Their properties are:

Table 1. Thermal properties of characteristic materials of the ground to be studied. Taken from Colaço (2015).

Rock Type	**T. Conductivity (k)**	**S. heat capacity (C_p)**	**Thermal diffusivity (α)**	
			Minimum	**Maximum**
Basalt	2.2	712 – 879	$0.97 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$
Limestone	2.4	920	$0.64 \cdot 10^{-6}$	$1.54 \cdot 10^{-6}$
Sandstone	2.5	1,005	$0.77 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$

4.3. Building of Academia Militar – Amadora Quartering

The Academia Militar - Amadora Quartering, is the place of Superior Studies where the building to be studied is located. It has an area around 0.85 km^2 and is used as dormitory.

Figure 1. Open 3D view (North orientation). Google Earth. Accessed April, 12, 2020.

The building has 3 floors: ground floor (level 0), first floor (level 1) and second floor (level 2). Every level has a height of 2.7 m and a total useful surface of 839 m^2. The building is divided in different space types: bedrooms, bathrooms, corridors and stairs.

4.4. Heat Pumps

A heat pump is a device based on Carnot's cycle. It performs a job equal to the heat that is transferred by absorbing heat from a cold spot and dropping it to a hotter spot. The efficiency of the heat pumps is determined by the COP (Coefficient of Performance) value. This coefficient gives a ratio between the heat power supplied and the electrical power consumed, mainly by the compressor and usually goes from 4 to 6 (Moran and Shapiro, 2010).

$$COP = \frac{Q_H}{W_{Cycle}}$$

Heat pumps are composed by four components (Figure 2): evaporator (isothermal expansion), Compressor (adiabatic compression), condenser (isothermal compression) and valve (adiabatic expansion). This device is useful for both HVAC and DHW (Domestic Hot Water) production.

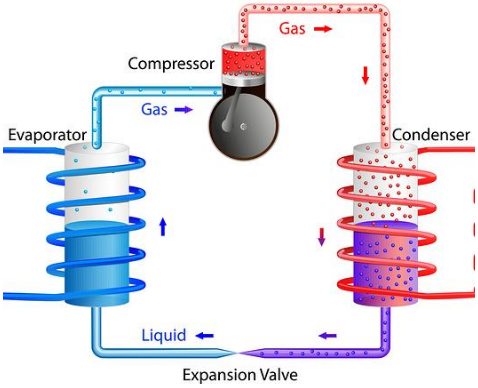

Figure 2. Components of a heat pump. Taken from (AP&T, 2020).

Heat pumps can be classified according to where they get their energy from aerothermal, getting their energy from the air; geothermal, absorbing heat stored in the Earth and hydrothermal systems, using the heat from the water (Natural Resources Canada’s Office of Energy Efficiency, 2004; Martiniez and Gómez, 2005). They can also be classified according to the way they distribute the heat: air, distributing the heat through the airflow and water, compatible with radiators, fan coil units and floor heating. Ground Source heat pumps (GSHP) get the heat from the shallow soil, at temperatures below 30°C. The heat can also be obtained from shallow groundwaters (Martiniez and Gómez, 2005). The biggest advantage of these systems is that they are independent of the outside temperature. For the installation, it is necessary to place the heat exchangers underground. In the case of newly constructed buildings, it is possible to place it under the building itself, as long as there is no water or electrical conduits. Depending on the type of the installation, GHPs can be classified as: i) open circuit: the heat is obtained from the shallow groundwater directly, and ii) close circuit: these installations are based in underground heat exchangers through which circulate a refrigerant that captures the heat stored in the ground. The two types are (Jimeno, 2009):

- Vertical: deeper installation, 80-150 m depth.
- Horizontal: shallow installation, 1-3 m depth (Geoplasma-CE, 2020).

5. Methodology

To perform the building simulation, first, Google SketchUp® was used to make the 3D model of the building in conjunction with the Open Studio, which allowed defining opaque and glazing envelope (window, wall, ceiling, floor, and roof) and shading from surrounding buildings. The uses of Google SketchUp® are:

- Creating 3D models of buildings, furniture, and more,
- Sharing 3D models as animations, creating realistic light and shadows,
- Importing or exporting files with other 3D model programs (Google SketchUp®, 2019).

Then, Open Studio is used to add all the characterization that the constructive elements already created have, such as the materials that compose them. It also enables to work simultaneously with Google SketchUp® and EnergyPlus (Zero Consulting, 2018). Then, Energy Plus was used to consider some parameters such as: weather information (.epw file), schedules, indoor temperature, material properties and internal gains. This software runs the simulation and export a folder with the required results. The type of file used in this project is .idf (Interaction Designer File) (Energy Plus, 2020). DHW demand was calculated by using formulas from the literature, based on their accuracy and simplicity (SEITV, 2019). After entering these inputs, the Energy Plus is executed and the program generates a spreadsheet with the selected outputs. The data extracted from the sheet is the basis for the subsequent calculations.

The main parameters used to characterize the building are:

- Simulation parameters: project building name, position of the building relative to north.
- Simulation control: includes the general settings for calculating simulations.
- Schedule compact: defines the frequency with which a set of phenomena and operations occur. Permits to specify for every zone during any space of time certain activity is performed.
- Materials**:** it encompasses the materials (and its properties) that are used in the construction. There are four different types of materials in the building: Mass materials, non-mass materials, air gaps and windows.

- Constructions: made of one or more layers of materials. It encompasses the different surfaces that are going to be performed in the project considering their function, the boundary conditions and their position in the building.
- Thermal zones: the basic elements for calculating the thermal loads of the model. Each of these zones is considered as an independent element, with its limits and conditions. It was determined to group the areas into four sets (Room, corridor, toilet and stair).
- Internal gains: represents sources of heat to the interior of the thermal zone. Every element that generates calorific energy acts as internal gain.
- HVAC templates: climatization systems that work independently of other elements. Thermostats are temperature regulators.

- Outputs: variables that result from the building energy simulation.

5.1. Building modelling

The 3D model of the building is made with Google SketchUp®. The 2.7 m vertical elevation of the 2D model creates the 3D view of the building. Then, two floors, windows a wall 20 m away was built to represent the effect the shadowing by the buildings nearby are added to have the final model, shown in Figure.

Figure 3. 3D model completed. Google SketchUp®.

After modelling, all the parameters listed are introduced as "inputs" on Energy Plus after having contrasted them in situ. DHW is calculated with the following equation (SEITV, 2019):

$$Q_{DHW} = q_w * p_w * n * V_w * \frac{1}{t_h} * \Delta T \quad (1)$$

Q_{DHW}: DHW power (kcal/h),

q_w: Water Specific Heat (1 kcal/ (Kg °C)),

p_w: Water density. (1000Kg/m^3),

V_w: Volume of water (m^3),

n: number of users,

t_h: HSW warm-up time (h) and

ΔT: Thermal leap (°C).

6. Results

6.1. DHW: energy and power.

The results after applying equation (1) are listed in Table 2.

Table 2. Results of power and energy for DHW.

	Supply water temperature (°C)	**Power (kcal/h)**	**Power (kW)**	**Energy (kWh)**
January	13	27306	32.77	3482
February	13	27306	32.77	3145
March	13.5	26937	32.32	3435
April	14	26568	31.88	3279.
May	15	25830	30.99	3294
June	16	25092	30.11	3097
July	17	24354	29.22	3106
August	17	24354	29.22	3106
September	16.5	24723	29.67	3051
October	16	25092	30.11	3200
November	14	26568	31.88	3279
December	13	27306	32.77	3482

The maximum power requirement is 32.77 kW and the annual energy demand is around 39 MWh.

6.2. Energy

Throughout the year, total energy demands (without DHW) are 1999 kWh for heating and 20278 kWh for cooling. The energy needs are much higher for cooling than for heating. The system is not significantly affected by falling temperatures, requiring only a small amount of energy to warm the building in the winter season. When average daily temperatures remain above 25-27 °C, energy demands begin to rise exponentially. The maximum peak of heating consumption takes place in the end of January, with temperatures lower than 10 °C. About cooling, the maximum peak takes place at the end of August with temperatures higher than 34 °C (Table 3).

The annual energy requirements are around 41 MWh for heating (including DHW) and 20 MWh for cooling. It is noticeable that most of the energy demanded for heating is used to produce DHW (95 %).

Table 3. Energy demands by the model and DHW production. Energy Plus.

	Heating (kWh)	Cooling (kWh)
January	4411.6	0
February	3507.3	0
March	3486	30.3
April	3415	27.6
May	3298	542
June	3097	2309.4
July	3106	6325.5
August	3106	6320.5
September	3051.5	3087
October	3200.3	1590.6
November	3308.4	45
December	3971.6	0

6.3. Power

The maximum power (peak) required is the one needed to cool and heat the building in the colder and hotter days, when performance conditions are maximum.

Table 4. Power required by the model and DHW. Energy Plus.

	Heating (kW)	Cooling (kW)
January	44.2	0
February	40.8	0
March	36.8	3
April	35.2	1.8
May	31.9	16
June	30.1	21.7
July	29.2	39.6
August	29.2	41.3
September	29.7	35.3
October	30	16.3
November	34	1.8
December	41	0

These values represent the minimum power capacity the GSHP chosen has to provide. Table 4 shows the maximum power that is required to the heat pump after adding DHW requirements to the building power needs. The maximum power required in this project is 44.2 kW for heating and 41.3 kW for cooling. The maximum power needed to prepare DHW quadruples the power needed to heat the building.

7. Ground Source Heat Pump

The choice was a DYNACIAT LG 150A, developed by Ciat, an European brand with more than 80 years of experience (CIAT, 2019). Heating power has been set to water at 30-35 °C and cooling power has been set to water at 7-12 °C. The performance characteristics of the chosen geothermal reversible water-water heat pump unit for DHW production, heating and cooling can be seen in Table 5.

Table 5. DYNACIAT 150A basic characteristics taken from CIAT (2019).

DYNACIAT LG 150A	
Power source	Triphasic
Heating power	56 kW
COP	5.45
Cooling power	47 kW
EER	4.67

The cooling fluid, recommended by Ciat, this heat pump uses is R410a. This fluid is a mix of difluoromethane (R-32) and pentafluoroethane (R-140), is widely used in refrigeration.

7.1. Heat exchanger

The chosen tube, fabricated by Muovitech (2020): the PE100, a simple geothermal collector (2 tubes) for vertical installation. After calculations (Ferro Systems, 2020), the heat exchanger requires a minimum length of 635 m to supply the heat pump's demands. These lengths correspond to an exclusive use of heating or cooling. The selected drilling arrangement is boreholes of 80 m depth each. This disposition eases their maintenance and conservation, which is expensive in deeper holes.

7.2. Heat distribution

The water heated or cooled by the heat pump is supplied to the building through 20mm diameter polyethylene pipes that circulate in an approximately 250 meters pipeline installation. Every room to be acclimatized has a ceiling fan coil to distribute the energy produced in the heat pump. The fan coil selected is FWE03CT created by Daikin (2020). This model has an output of 2.44 kW for cooling and 3.13 kW for heating.

8. Economic analysis

In order to ensure the project's long-term benefits and savings compared with the boiler system, first it is necessary to know how much is spent on this building now with the current system. Table 6 shows the cost to produce the energy needed to heat and cool the building. The annual cost of the building's HVAC systems is 4895 €. The low efficiency of the boiler makes the heating price nearly quadruplicate cooling price.

Table 6. Cost of energy for the current system.

	Heating	**Cooling**
Energy	40959.7 kWh	20278 kWh
COP	0.68	-
EER	-	2.5
€/kWh	0.0609	0.1481
Tariff term	25.3 €	-
Cost of energy	3693.60 €	1201.27 €

Besides, the boiler and the air conditioning (A/C) has a maintenance which will have a ten-year cost of around 4500 € and 19803 (507.77 € each device) (CYPE, 2020). The GSHP installation designed in this project has a cost of 63614 €. Besides, there is a decennial price in terms of maintenance, of 18824 €. To this expense it is needed to add the cost of the energy produced for its operation, shown in Table 7.

Table 7. Cost of energy consumption by the GSHP.

	Heating	**Cooling**
Energy	40959.7 kWh	20278 kWh
COP	5.45	-
EER	-	4.67
Energy consumption	7515.54 kWh	4342.18 kWh
Electricity price	0.1481 €/kWh	0.1481 €/kWh
Cost of energy	1113.05 €	643.08 €

The cost of energy is 1113 € for heating and 643 € for cooling. The total annual cost of energy with the heat pump is 1756 €. The efficiency of the system is further intensified in heating, which only doubles the price for cooling in this case. In percentage, the savings are 69.86 % for heating and 46.46 % for cooling. The total annual consumption savings are 3139 € and graphically represented in Figure.

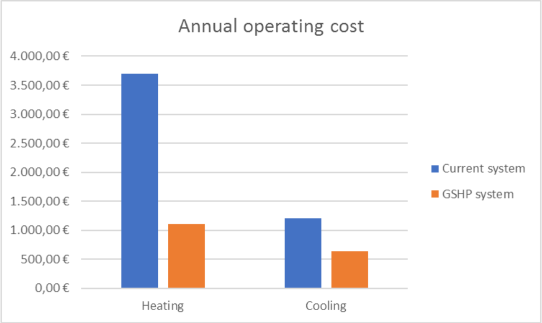

Figure 4. Consumption of both systems.

The feasibility or no-feasibility of the project depends on whether the initial investment saves money in the future and, if it does, how long it takes.

To show it, a graph is made. The graph has two series that show the accumulated expense, (annual consumption and maintenance expenses) calculated above.

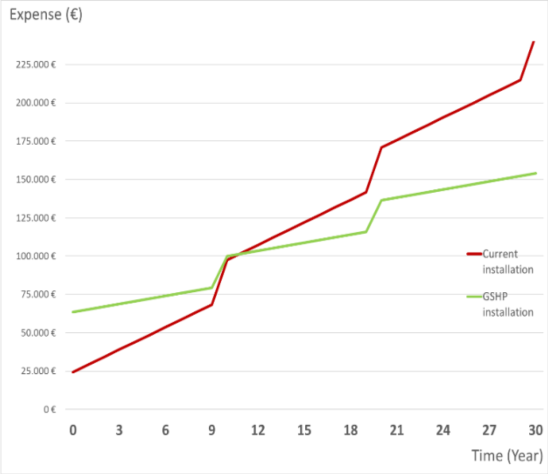

Figure 5. Evolution of total operation and maintenance costs over time.

The graph shows that the high cost of installing the GSHP complete system. “Year 0” starts with the 63614 € invested in the GSHP against the ten-year maintenance costs for the boiler and A/C of 24303 €. The lower annual consumption of the heat pump makes the slope of the green series much lower than for the red. This combined with cheaper maintenance costs (a saving of 5480 € every ten years) makes the GSHP system more profitable than the current one in 10 years and nine months, increasing the savings over the years.

9. Environmental impacts

The reduction of greenhouse gas and particle emissions is key to the viability of this project (this analysis focuses in CO_2 since in this case is the main contributor to the Greenhouse effect). Geothermal project was compared with the actual installation, considering the building uses A/C machines to meet the building’s cooling requirements.

In the existing facility, the sources of emissions are two: the boiler and the electricity used to run the A/C machine (as referred before this equipment does not exist, but it was considered to allow comparisons).

The Air Conditioning emissions due to the production of electricity for its operation are calculated with the last year’s (2019) carbon footprint in EDP Portugal: 250.33 g/kWh (EDP, 2020). The boiler emissions, that uses natural gas and the A/C electricity emissions are estimated in Table 8.

Table 8. CO_2 emissions by the GSHP.

	Heating	**Cooling**
Useful Energy	40959.7 kWh	20278 kWh
COP	0.68	2.5
Final Energy Consumption	60234.85 kWh	8111.2 kWh
CO_2 emissions	12160.09 $kg\ CO_2$	2030.376 $kg\ CO_2$

The boiler and the A/C system are releasing, in additional to other harmful gaseous pollutants, an annually amount of 14190 kg of CO_2. The GSHP does not produce emissions *in-situ* but, obviously, the energy used to run the heat pump also carries a carbon footprint. The GSHP system’s emissions are calculated in Table 9

Table 9. CO_2 emissions by the GSHP.

	Heating	**Cooling**
Useful Energy	40960 kWh	20278 kWh
COP	5.45	4.67
Final Energy Consumption	7516 kWh	4080 kWh
CO_2 emissions	1881 $kg\ CO_2$	1021 $kg\ CO_2$

The HVAC system emits, indirectly by the production of the energy required to function, 2903 kg of CO_2. The high efficiency of the heat pump implies a reduction of 79.6 % of CO_2. The emission of 11 tons of CO_2 is avoided.

10. Conclusions

The use of Energy Building Simulation (Energy Plus) to evaluate the potential of geothermal energy as an HVAC energy source was proven. Supplying thermal comfort to the building occupants and reducing the use of fossil fuels was successfully achieved. The software has been able to easily interpret the generated 3D models. The calculations have approached a great extent of reality. The energy data thrown up has served as a starting point for the calculations. The building requires around 41 MWh for heating and 20 MWh for cooling in order to supply thermal comfort to the building occupants. With the building energy simulation was possible to infer the peak power for both heating and cooling. Additionally, the DHW values for both peak and energy consumption in one year were calculated (outside Energy Plus). To answer the building acclimatization and DHW needs, the heat pump has to be able to provide 44 kW for heating (also considering DHW) and 42 kW for cooling. The GSHP model chosen is a DYNACIAT LG 150A. In terms of economy, the HVAC system is very cost-effective, saving 69.86% for heating and 46.46% for cooling compared to the current system (3139 € saved every year). The substantial initial investment (63614 €) is amortized in 10 years and nine months. As an example, in 20 years, the savings will be 34423 € if this project is applied. Environmentally, the fact that there is no combustion means that there are no greenhouse gas emissions and, besides all that, the CO_2 emitted indirectly by producing the energy it needs drops down 79.6 %. It can be concluded that the project, with a minimum of civil works, makes environmental benefits considerably increase. It is important to highlight that the calculations considered the existence of cooling equipment in the Academia building. This assumption allows the comparison of the two options (as it is and installing a GSHP) and also implies the need of considering cooling for improving thermal comfort in the Academia. A dedicated energy simulation on Energy Plus for the performance of the GSHP was out of the scope of this Thesis. Nevertheless, this analysis would be of extreme relevance and should be considered for future works for a more accurate analysis.

11. Acknowledgements

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