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

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Thesis to obtain the Master of Science Degree in

## Mining and Geological Engineering

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**July 2020**

**Declaration**

I declare that his document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Lisboa University.

**Declaração**

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

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This Thesis would not be possible without the help of Ángel Luís and Susana, my parents, who have always supported me in overcoming all the goals I have proposed.

## Abstract

Building heating and cooling consumes more than 30% of the energy generated worldwide. 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 source of Heating, Ventilation and Air Conditioning (HVAC) and Domestic Hot Water (DHW) energy was evaluated in a dormitory building with 839 $m^2$ area and 78 occupants located in Academia Militar – Amadora Quartering, Portugal. A 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 modelled 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. The 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 tons of $CO_2$ will be 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.



## Key-words

Geothermal energy; Ground Source Heat Pump; Heating Ventilation and Air Conditioning, Renewable Energy; Building Energy Modelling.

## Resumo

O aquecimento e o arrefecimento de edifícios consomem mais de 30% da energia gerada mundialmente. Deste modo, é muito importante diminuir o consumo de energia usada em aquecimento e arrefecimento para reduzir as emissões de poluentes. Nesta dissertação, avalia-se o potencial da energia geotérmica como uma fonte de energia para Aquecimento, Ventilação e Ar Condicionado (AVAC) e Água Quente Sanitaria (AQS) num edifício localizado na Academia Militar – Aquartelamento da Amadora, Portugal, com 839 $m^2$ de área e 78 ocupantes. A ferramenta de Simulação Energética de Edifícios (SEE) foi utilizada para avaliar os resultados de AVAC. As necessidades de AQS foram estimadas com base em informação recolhida na literatura da especialidade. O edifício foi desenhado em 3D e caracterizado. Posteriormente, os dados foram introduzidos no software e os resultados obtidos indicaram 41 MWh para aquecimento (incluindo AQS) e 20 MWh para arrefecimento. Cerca de 95% da energia necessária para aquecimento é usada para produzir AQS. A potência máxima necessária neste projeto é 44,2 kW para aquecimento e 41,3 kW para arrefecimento. De acordo com os resultados obtidos, optou-se por um sistema de Bomba de Calor Geotérmica (BCG) com permutadores de circuito fechado vertical. Em termos de economia e emissões, o novo sistema BCG foi comparado com as instalações atuais do edifício: uma caldeira (COP= 0,68) e fan-coils (EER= 2,5). Os resultados demonstram uma economia considerável com o uso do sistema BCG. O sistema geotérmico para AVAC representa uma economia de energia de 69,86% para o aquecimento e de 46,46% para o arrefecimento (3.139€). Considerando os custos de instalação do novo sistema e a manutenção tanto do antigo sistema como do sistema BCG, o último será mais rentável em 10 anos e nove meses após a sua instalação. Quanto às emissões, o novo sistema produz menos 79,6% de $CO_2$, evitando a emissão de 11 toneladas de $CO_2$. Esta Tese chama a atenção para o futuro da Energia Geotérmica no contexto da Transição Energética e do Acordo de Paris, associado (i) à mudança do sector energético global de sistemas baseados em fósseis para fontes de energia renováveis, tais como sistemas geotérmicos de muito baixa temperatura e (ii) à necessidade em reduzir as emissões de $CO_2$ relacionadas com a energia de modo a mitigar as alterações climáticas.



## Palavras-chave

Energia Geotérmica; Bomb de Calor Geotérmica; Aquecimento, Ventilação e Ar Condicionado; Energias Renováveis; Modelação Energética de Edifícios.

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## List of characters

$T_c$: Cold Temperature (Carnot Cycle),

$T_H$: Hot Temperature (Carnot Cycle),

λ: Thermal conductivity $(W/(m.K))$,

α: Thermal diffusivity,

$k$: Thermal conductivity $(W/(m \cdot K))$,

$C_p$: Specific heat capacity $(J/(kg \cdot K))$,

$p$ : Density ($\frac{kg}{m^3}$),

$\dot{Q}$ : Heat flow (convection, conduction and radiation),

$A$: Surface $(m^2)$,

$\alpha_1$: Nature of body coefficient,

σ: Stefan-Boltzmann's constant,

U: Thermal Transmittance,

$Tout_h$: output temperature mode in °C (heating),

$Tout_c$: output temperature mode in °C (cooling),

$Tin_h$: input temperature mode in °C (heating),

$Tin_c$: input temperature mode in °C (cooling),

$Ph$: heat pump output in kW (heating),

$Pc$: heat pump output in kW (cooling),

$Q$: heat pump flow rate in l/h,

$Rp$: thermal resistence $(K\ m/W)$,

$D_0$: exterior diameter $(m)$,

$D_1$: interior diameter $(m)$,

$Rs$: ground resistance $(W/K\ m)$,

$Fh$: usage factor (heating),

$Fc$: usage factor (cooling),

$Tl$: ground max. temperature (°C) and

$Th$: ground min. temperature (°C).

## List of acronyms

A/C: Air Conditioning,

AP&T: Alaska Power and Telephone Company,

BES: Building Energy Simulation,

CFD: Computational Fluid dynamics,

CIAT: Compagnie Industrielle d'Applications Thermiques,

CINAMIL: Centro de Investigação Desenvolvimento e Inovação da Academia Militar,

COP: Coefficient of Performance,

CVL: Complexo Vulcânico de Lisboa,

DBT: Dry-Bulb Temperature,

DHC: District Heating & Cooling,

DHW: Domestic Hot Water,

DNV-GL: Det Norske Veritas,

EDP: Energias de Portugal,

EP: Energy Plus,

GNR: Republican National Guard,

GROUND-MED: Developed by Advanced ground source heat pump systems for heating and cooling in Mediterranean climate,

HVAC: Heating, Ventilating and Air Conditioning,

IGME: Instituto Geológico Minero,

IST: Instituto Superior Técnico,

NREL: National Renewable Energy Laboratory,

R&D: Research & Development,

RGGF: Ribeira Grande Geothermal Field,

SDR: Standard Dimension Ratio,

W&H: weekend and holiday and

XPS: Extruded polystyrene.

# 1 Introduction

This thesis was developed on a case study at Academia Militar, in Amadora Quartering, Portugal. It's a Superior Study Institution to prepare future Officers to join the Portuguese Army or the Republican National Guard (GNR) (Academia Militar, 2020). It has been active since 1959 and it's located in two different places by Lisbon metropolitan area: Palácio da Bemposta, in Pena (former *parish* that now belongs to Arroios) and Amadora (a city with a population of 175.000 inhabitants, located 10 km to the NW of the centre of Lisbon). Currently, Academia Militar belongs to the Portuguese Universities having a Research Centre (CINAMIL) that coordinates the activities of research and development of the Army (they have more than 25 R&D Projects and around 135 researchers (CINAMIL, 2016)). The installations located in Lisbon (Bemposta Palace) are where Command, Council and Command Support Agencies are located (Academia Militar, 2020).

The students of Academia Militar have some of their classes at Instituto Superior Técnico (IST) and Nova Medical School. Some of the students are Post Graduate students. The other campus, in Amadora, is the one used, among others, as residence of the students. One of the buildings, used by 78 cadets as their dormitory in the Military Academy - Amadora Quartering was the one used as a case study in this thesis.

## 1.1 Motivation

Building heating and cooling consumes more than 30% of the energy generated worldwide. Despite the growth of world population has started to decrease (Figure 1), the level of life of developed countries will be higher, demanding more energy. China and India have a crucial impact due to their economic growth (Kashiwase, 2015).

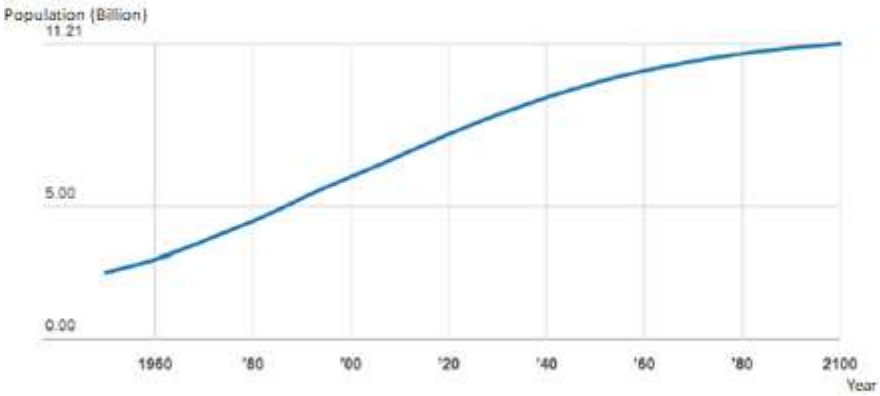


*Figure 1. World population expected by the UN. Taken from Kashiwase (2015).*

The electricity network capacity is estimated to be tripled by 2050. This thesis (Kashiwase, 2015) points also that the energy demand will be doubled. The 80% of the energy produced in 2050, as it is shown in Figure 2, will come from renewable sources. 2090 is going to be the first year with 100% renewable energy with the current expectations (DNV-GL, 2018).

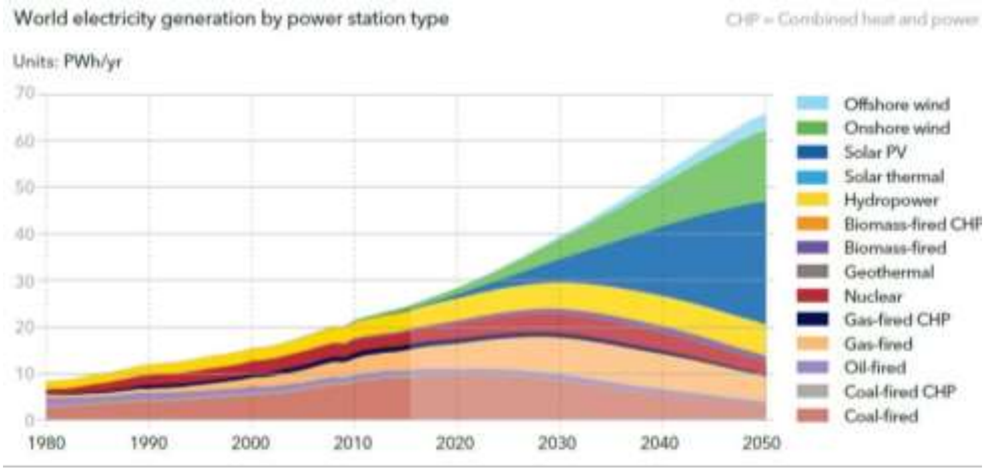


*Figure 2. World electricity generation by power station type. Taken from DNV-GL (2018).*

The above information seems to indicate that the future energy will tend to be 100% renewable. It is of vital importance to reduce the percentage of building cooling and heating significantly to achieve this prediction.

There has been an increasing demand for building energy simulation (BES) to improve building energy efficiency. The ultimate goal of developing and using building simulation techniques and tools is to facilitate the design of a built environment that satisfies the living needs, with the least use of resources associated with its construction and operation (Office of Energy Efficiency and Renewable Energy, 2020). Building simulation tools provide qualitative and quantitative data supporting decision-making and consequently assist the increasing number of building performance codes and standards that support the referred goal (Fumo, 2013; Harish and Kumar, 2016).

These programs have different features and various utilities (Hensen and Lamberts, 2015):

- Architectural Design,
- HVAC Design,
- Building Performance Rating,
- Building Stock Analysis and
- CFD in buildings.

## 1.2 Objective

This thesis aims to use a BES tool to evaluate the potential of geothermal energy as an 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, which engineers use to model both energy consumption: for heating, cooling, ventilation, lighting and plug and process loads (National Renewable Energy Laboratory, 1996; Energy Plus, 2010a). The building geometry is defined on Google SketchUp® (Google SketchUp®), a modelling computer program created by Google for a wide range of drawing (architecture, interior design, civil and mechanical engineering, video games and landscapes design). The analysis focuses on energy savings, implementation and operation costs and benefits. Furthermore, the comparison with analytical calculations is addressed.

## 1.3 Thesis development

The thesis started with the graphic design software Google SketchUp®, with which all primary and secondary geometric elements were built. The organization divided in spaces of the residence was introduced. Next, the Open Studio® (National Renewable Energy Laboratory, 1996) program was used, to convert the geometry as EnergyPlus inputs. Finally, the Energy Plus program was used to simulate the energy needs, considering the building envelope, temperature set points, internal gains and other relevant data when performing building energy simulations. After analysing the simulation results (and calculating the DHW energy needs) a suitable HVAC system was calculated to meet energy requirements. Then, a performance budget and an environmental impact study were performed to evaluate if the new energy proposal is more economical and environmentally friendlier. To conclude the thesis, several conclusions were drawn from the study.

## 2 Geothermal energy

Geothermal energy comes from the Earth's interior and it is obtained from its heat when it is transferred to the sub-surface zones.

Underground energy has been used from centuries. The process of Earth´s formation and the energy contained in radioactive elements of the crust, such as rock and fluids, make the interior of the Earth generate heat (Unwin, 2019). This interior heat causes an increase of temperature called geothermal gradient. In general conditions, the temperature increases 3 $^{o}$C every 100 m downwards (mean geothermal gradient) (IGME, 2000). Figure 3 shows the geothermal gradient changes due to the internal structure of the Earth. In the crust, as it was listed before, the variation is 3 $^{o}$C/100 m. In the internal layers (Mantle, Outer Core and Inner Core), the variation is around 0.1$^{o}$C/100 m.

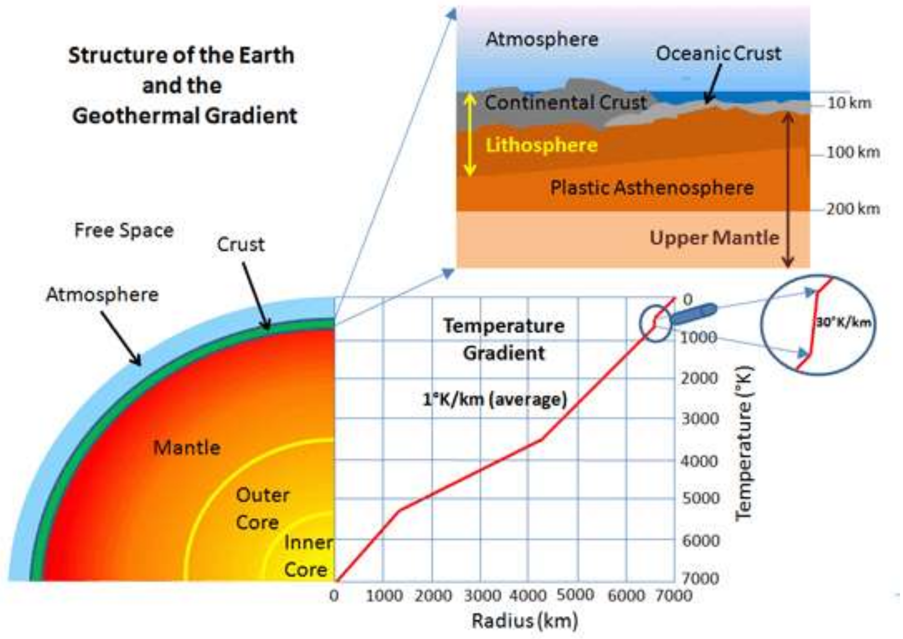


*Figure 3. Structure of the Earth and the geothermal gradient. Taken from Abdulrazzaq (2017).*

Geothermal resources are usually divided in four types (Revenga, 2016):

- High temperature (>150 $^{o}$C),
- Medium temperature (90 – 150 $^{o}$C),
- Low temperature (30 – 90 $^{o}$C) and
- Very low temperature (15 – 30 $^{o}$C).

Uses of geothermal energy are generally electrical energy production and heating and cooling (Revenga, 2016).

Geothermal energy has many advantages, both economic and environmental (OK Diario, 2017):

- Average savings of 50% on the electricity bill,

- As it is renewable energy, can benefit from regional or state subsidies available for such purposes,
- Use of natural energy from the soil and the sun,
- Elimination of the risk of salmonellosis,
- Reduction of $CO_2$ emissions by around 50%,
- The energy source is available 24 hours a day,
- The energy produced by geothermal energy implies a saving of fossil fuels (with all that this implies in the whole life cycle of these) and
- A large number of low-temperature geothermal uses will result in fewer needs for electricity transport infrastructure.

But, as is normal, it also has several drawbacks. The main one is the risk of pollution of the surrounding waters and the atmosphere, due to the gases dissolved in the hydrothermal fluids (Zhua et al., 2017).

## 2.1 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. This process consists of an isothermal expansion, an adiabatic expansion, an isothermal compression and an adiabatic compression. This cycle can be seen in the pressure vs. volume diagram of Figure 4.

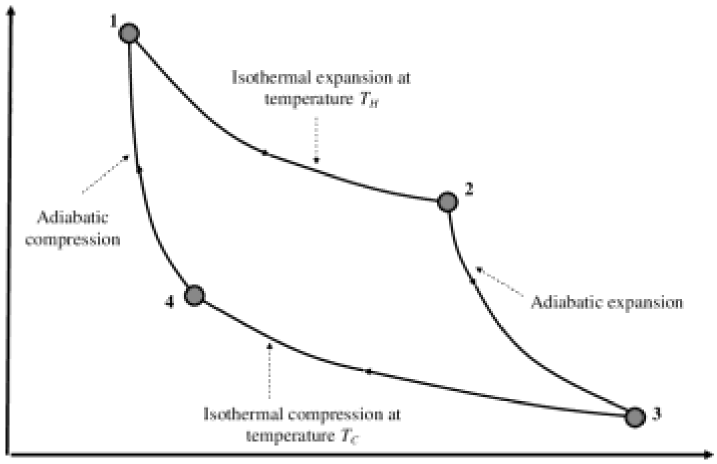


*Figure 4. Carnot cycle (P-V). Taken from Tjiang and Sutanto (2006).*

Heat pumps are reversible; they can be used both to heat and to cool down a room (considering that the application of a certain amount of work is necessary).

In the process, a cooling fluid is used, which is usually mixed water (in a variable percentage with antifreeze). This fluid circulates inside the pipes located in the ground, either buried horizontally or arranged vertically. In winter, when the system heats the house, this fluid is warmed by conduction through the ground and moves to the evaporator. In the evaporator, a heat exchanger takes place with the refrigerating fluid of the circuit, which passes to the vapour state and enters the compressor. In this case, the pressure of the refrigerant rises, increasing therefore its temperature. This gaseous phase refrigerant is circulated through the condenser, where, as it cools and condenses, heats the fluid that will circulate through the system (underfloor heating or fan coil). Finally, the condensed refrigerant is introduced into the expansion valve, where pressure and temperature are reduced so it can be introduced into the evaporator again and the whole process can be started again.

The four components of Figure 5 are:

1-2 Evaporator (isothermal expansion): fluid enters in the engine as liquid and changes almost entirely to vapour, taking an amount of heat of the focus to be cooled. This step is made at constant temperature Tc (Figure 4).

2-3 Valve (adiabatic expansion): fluid remains liquid and lowers its pressure and temperature to get Tc. During the stage, work is given back to the system and there is not heat exchange.

3-4 Compressor (adiabatic compression): fluid increases temperature and pressure to $T_H$ (Figure 4). All the liquid turns into vapour. Work is provided to the system in this stage but there is not heat transfer.

3-4 Condenser (isothermal compression): fluid turns into liquid and gives back heat to the focus to be warmed. Temperature and pressure remain constant.

The Carnot cycle is ideal and reversible. It is impossible to reproduce it in practice due to internal performance of the compressor and the valve. Its utility comes from the fact that it is the most efficient cycle from an energy point of view, as it requires minimum work on the compressor and its efficiency depends only on the temperature difference between the hot and cold points. Therefore, it is used to compare the performance of different cycles (Martiniez and Gómez, 2005).

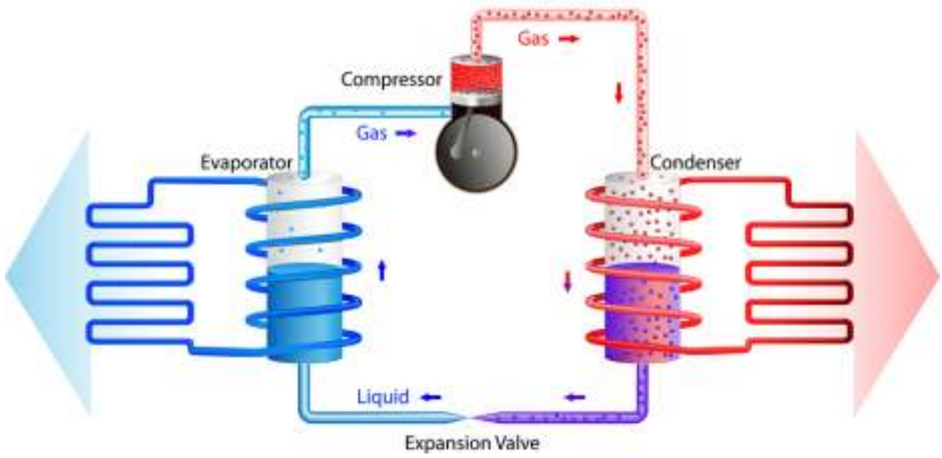


*Figure 5. Components of a heat pump. Taken from (AP&T, 2020)*

Heat pumps can be classified according to where they get their energy from (Natural Resources Canada's Office of Energy Efficiency, 2004; Martiniez and Gómez, 2005):

- Aerothermal, getting their energy from the air,

- Geothermal, absorbing heat stored in the Earth and
- Hydro-thermal, using the heat from the water.

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 (Figure 6). The last of them is the most efficient (but more expensive) method, due to the high temperature of operation (35ºC). When working with radiators, the efficiency of the pump is lowered. Another advantage of floor heating is the uniform distribution of the heat.

*Figure 6. Water distribution with floor heating. Taken from Modular Home (2020).*

The efficiency of the heat pumps is determined by the COP value (Coefficient of Performance). This coefficient gives a ratio between the heat power supplied and the electrical power consumed, mainly by the compressor. Its value is higher than the unit and usually varies between 4 and 6 (a COP of 5 means that 5 power units are obtained for every power unit consumed by the pump). It depends on the type of pump, the operating conditions and the temperature difference between the sources. This high value is related with the fact that these pumps transfer heat by using energy, instead of producing it with energy, as would be the case with electrical resistors (Moran and Shapiro, 2010). Therefore, its equation is:

$$COP = \frac{Q_H}{W_{Cycle}} \quad (1)$$

Where $Q_H$ is the heat provided by the pump and $W_{Cycle}$ is the necessary work for a correct operation of the heat pump and it corresponds also with $Q_C - Q_H$, which is the difference between the heat given by the pump and the heat taken from the cold point.

In this thesis the use of low/very low geothermal energy for air conditioning is analysed. This can be exploited mainly through two methods: horizontal tubes and vertical boreholes. Both techniques require the installation of tubes through which water circulates with antifreeze that performs the heat exchange with the ground and a heat pump. In this case, the surface cannot be impermeable, because rainwater and solar radiation are the factors that most help the energy recharge of the soil. Nor can it be planted, as the roots can damage the tubes through which the heat-bearing fluid passes and lower the efficiency of the cycle. Normally it is not possible to use the ground nearby only for horizontal exploitation, moreover in geothermal installations made after building construction, as in this case.

### 2.1.1 Heat exchangers

Heat exchangers are used to transfer heat between two or more fluids (separated by an insulator or in direct contact) in heating, refrigeration, power plants, etc. In indirect exchangers (the most common), the heat is transferred through a solid wall due to temperature difference of the fluids. The purpose of these devices is to increase or lower the temperature of a given fluid, to vaporize and to condensate gases. The simplest and easiest heat exchanger to learn about is the double tube (Figure 7) heat exchanger (Jaramillo, 2007).

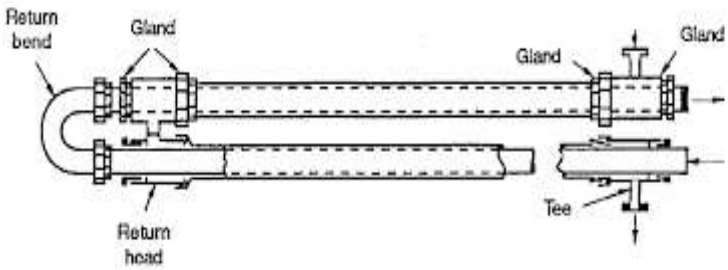


*Figure 7. Double tube heat exchanger. Taken from Reyes (2020).*

Geothermal heat exchangers are used to collect the heat from the ground or to extract it from the facility to climatize.

Open loop systems use pumped groundwater that will be reinjected to the aquifer through a well situated in the water flow direction. Flow rates around 150-200 L/h for each kW are usual in this type of exchangers.

Closed loop systems use water or antifreeze liquid circulating within a closed circuit of tubes. The circuit can be arranged horizontally or vertically (2.1.2).

### 2.1.2 Geothermal heat pumps

This type of heat pumps (Geothermal Heat Pumps – GHP) work in the same way as the aerothermal one, but it gets the heat from the shallow soil, at temperatures below 30°C and is capable to produce energy for heating, cooling and Domestic Hot Water (DHW). 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, as the shallow soil / shallow groundwater temperature remains approximately constant throughout the year, which makes them very efficient. The problem lies in the investment needed.

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:

- Open circuit: the heat is obtained from the shallow groundwater directly, that enters the thermodynamic cycle and return to the ground after passing through it. Constant shallow groundwater temperature of 13 °C the whole year are required.

- Close circuit: these installations are based in underground heat exchangers through which circulate a refrigerant that captures the heat stored in the ground. As explained in the previous points, the two types are (Jimeno, 2009):

- Vertical: deeper installation (80-150 m depth). High thermal stability due to the constant performance even when extreme temperatures are high. Conversely, investment is high.

- Horizontal: shallow installation (1-3 m depth). More sensibility against thermal variations. The investment is lower (the half compared with vertical installations) (Geoplasma-CE, 2020).

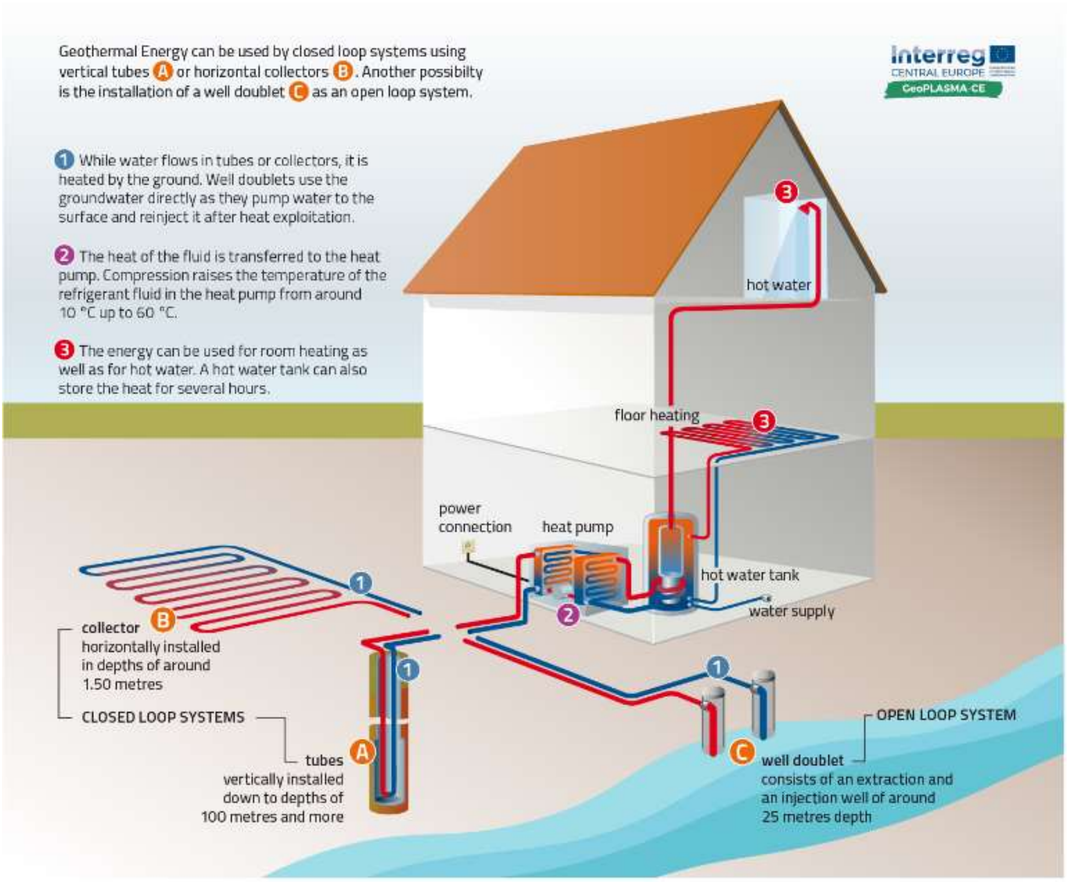


*Figure 8. Geothermal Heat Pumps: open circuit and closed circuit (vertical and horizontal) systems. Taken from Geoplasma-CE (2020).*

Thermal energy in the ground can be transferred by conduction, convection or radiation, which characteristics are explained below:

- Conduction Heat Flow ($\dot{Q}$cd): it is a process of heat transmission based on direct contact between bodies, without an exchange of matter. Heat flows from a higher temperature body to a lower temperature body which is in contact with the first one. Thermal conduction is determined by Fourier's law, which states that the flow of heat transfer by conduction in an isotropic medium is proportional and opposite to the temperature gradient in that direction (Serway, 2014). The equation is:

$$\dot{Q}cd = -kA * \frac{dT}{dx} \tag{2}$$

$\frac{dT}{dx}$: temperature variation trough a determined direction and
$A$: surface where heat transfer occurs.
$K$: thermal conductivity

- Convection Heat Flow ($\dot{Q}$cv): heat transmission occurs through a fluid, liquid or gas due to particle movements (Serway, 2014). Its equation is:

$$\dot{Q}\text{cv} = Cp.v(T - T') \tag{3}$$

$T'$: reference temperature [$^oC$],

$v$: speed fluid vector [$\frac{m}{s}$] and

$C_p$ : specific heat capacity [$\frac{J}{kg \cdot K}$].

- Radiation Heat Flow (P): propagation of energy in the form of electromagnetic waves or subatomic particles through the vacuum or a material. Radiation emission can become dominant against the other two methods when bodies are isolated from the environment or when they are at very high temperatures. A very hot body will generally emit a large number of electromagnetic waves. The amount of radiant energy emitted, or radiated heat is given by Stefan-Boltzmann's Law (Collieu and Powney, 1973). According to this law, this radiated heat is:

$$P = \alpha(\sigma \cdot T^4) \cdot S \tag{4}$$

P: radiated power,

$\alpha_1$: nature of body coefficient. $\alpha = 1$ (for a black body),

σ: Stefan-Boltzmann's constant [$5.67 \times 10 - 8 \frac{W}{m^2 K4}$],

T: absolute temperature [$^oC$] and

S: surface [$m^2$].

There are some ground parameters that are necessary to analyse. Performance of a heat pump varies depending on (Carvalho et al., 2015):

- Thermal conductivity (λ): measured in W/m.K It defines the amount of heat rate that passes through a given area (per unit of temperature gradient) of a given steady state material. In essence, it evaluates a material's ability to conduct heat (Bird et al., 2006).

- Specific heat capacity ($C_p$): it is the amount of heat required to provide a unit of mass of a material to raise its temperature one unit, expressed in J/kg.K. It evaluates the capacity of a material to transfer heat (Lyde, 1996).

- Thermal diffusivity (α): is the relationship between thermal conductivity and thermal capacity (a well diffused material allows a fast temperature variation). The units are [$m^2s^{-1}$]. It measures the rate of heat transferred in a material (Lyde, 1996). Diffusivity tends to increase in the presence of water. The equantion is:

$$\alpha = \frac{k}{\rho C_p} \tag{5}$$

$k$: Thermal conductivity [$\frac{W}{m \cdot K}$],

$C_p$ : Specific heat capacity [$\frac{J}{kg \cdot K}$] and

$\rho$ : Density [$\frac{kg}{m^3}$].

Due to the conditions of the place, the peculiar use of the building and the surroundings (private dormitories) it becomes advisable to use a vertical system.

## 3 Background

### 3.1 Geothermal energy and heat pumps in Portugal

In Portugal, high temperature geothermal resources are only located in Azores islands. The Ribeira Grande Geothermal Field (RGGF), in S. Miguel Island, has been producing electricity from geothermal resources since 1980. This geothermal field, including Pico Vermelho power plant (with a capacity of 13MW), has a generation capacity of 27.8 MW. It is expected an increase of 3.2 MW due to new wells that are going to be drilled during 2020 to reach the theoretical capacity of 30 MW (Carvalho et al., 2015).

It is located in the northern face of Lagoa do Fogo, a volcano with a liquid-dominated high enthalpy system. RGGF reaches more than 245 ºC. The plant consists of four dual turbo-generators installed between 1994 and 1998 and the later creation of Pico Vermelho in 2006. Figure 9 illustrates the definitive scheme.

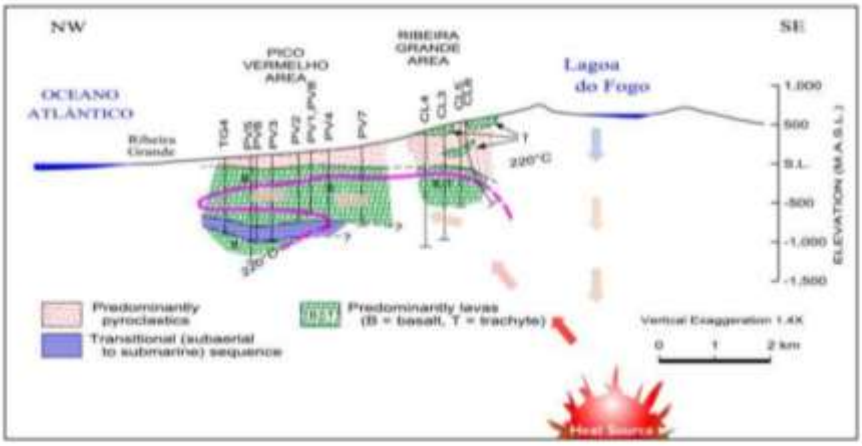


*Figure 9. Generalized cross section of the Ribeira. Taken from Coelho et al. (2019).*

This electricity production has been estimated to contribute to the 42% of the annual average electricity demand of S. Miguel island since 2013 (Coelho et al., 2019). The population of S. Miguel Island is established in 137335 citizens (SREA, 2020). It means that more than 57000 citizens have their electricity needs covered by high temperature geothermal energy.

Low and very-low geothermal energy has two direct applications. The first is a recreational use, bathing and swimming activities in Thermal baths are very common in Portugal as touristic attraction and for curative proposes reclaim. More than 30 thermal baths are operating in the country (Coelho et al., 2019). The other use is district heating and cooling (DHC), which is not as common as in the rest of Europe but its use is starting to be considered by Portuguese government (Euroheat & Power, 2019). Nowadays, in Portugal, the use of low-temperature geothermal is energy has two important projects. in Aveiro and in Coimbra.

Finished in 2013, a ground floor building composed by offices, laboratories and working rooms was developed by University of Aveiro with an HVAC system associated to a geothermal heat pump with a heating power of 272 kW and a cooling power of 245 kW. It has a COP of 4.7 and EER of 4.2. The heat pump is vertically connected 100 m deep with 33 geothermal boreholes. Energy is not only used for heating and cooling, but also for lighting and equipment supply. The mean energy consumption is around 300 kWh/day (Pinto et al., 2017).

*Figure 10. Building used by University of Aveiro to their project. Taken from Pinto et al. (2017).*

The building was modelled in Energy Plus. A comparison between building energy consumption with the traditional system (a boiler with 68% efficiency and a chiller with EER=2.5) and geothermal heat pump was developed. Figure 12 shows a comparison between the two energy systems. Geothermal heat pump HVAC shows a saving of the 34% of the energy compared to the traditional. Although the operation of the pumps consumes more than twice as much energy when it comes to geothermal, the savings in cooling are much greater in comparison (80 MWh saved).

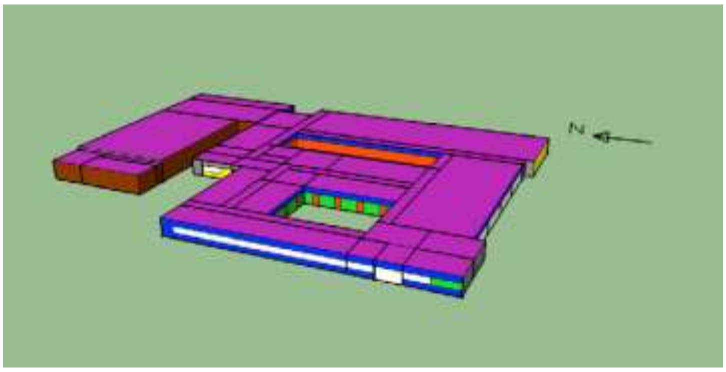


*Figure 11. Building modelled in Energy Plus. Taken from Pinto et al. (2017).*

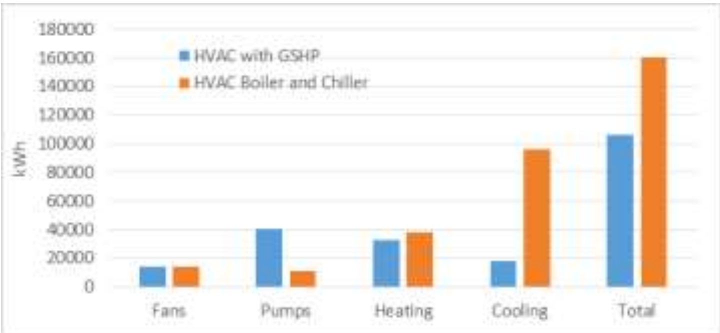


*Figure 12. Geothermal & conventional HVAC energy consumption. Taken from Pinto et al. (2017).*

The project can be used to give an initial overview of the savings that geothermal energy brings, but there are many differences with this thesis and Aveiro's project that may make the results different: size, use of facilities and contribution to electricity.

Coimbra has another relevant project: Developed by Advanced ground source heat pump systems for heating and cooling in Mediterranean climate (GROUND MED, 2020) a thermal simulation of a building’s third floor created to support a correct HVAC dimensioning based on building’s demand and, after achieving it, to select the best boreholes for the heat exchangers. The area to be studied has 970 $m^2$ occupied by 25 persons in office schedule. Whereof 613 $m^2$ are acclimatized. They also used Energy Plus to calculate the thermal needs.

*Figure 13. Building used by GROUND-MED to their project. Taken from Coelho et al. (2011).*

The system needs 48.1 kW for heating and 55.2 kW for cooling. The boreholes distribution was in parallel configuration with 611 m length distributed in 4 in-line boreholes. These results may differ from this project’s due to building characteristics and Coimbra’s climate.

There are also two remarkable but smaller low-geothermal projects in Portugal: in Chaves, with two vertical wells of about 150 m depth used in thermal baths and space heating (an hotel and a swimming pool) and in S. Pedro do Sul, supplying a thermal bath and a small heating system.

## 3.2 Local climate

To classify the climate of Amadora, the Köppen classification was used (Beck et al., 2018). It is the best known and most widely used climate classification by geographers. Its starting point is that natural vegetation is an indicator of climate, and some of its categories are based on the climatic limits of certain forms of plants. Climates are defined by the average annual and monthly values of temperature and precipitation (National Geographic, 2020). As it is shown in Figure 14, Amadora belongs to “Csb” (really close to “Csa”) in Köppen’s classification. It means that the climate is considered as temperate. Also, it has a dry period in summer with an average temperature of less than 22 $^oC$ in the hottest month (August). The climate data has been taken from a raster file with a World map divided into the different Köppen regions compatible with Google Earth taken from Institute fo Veterinary Public Health (2020).

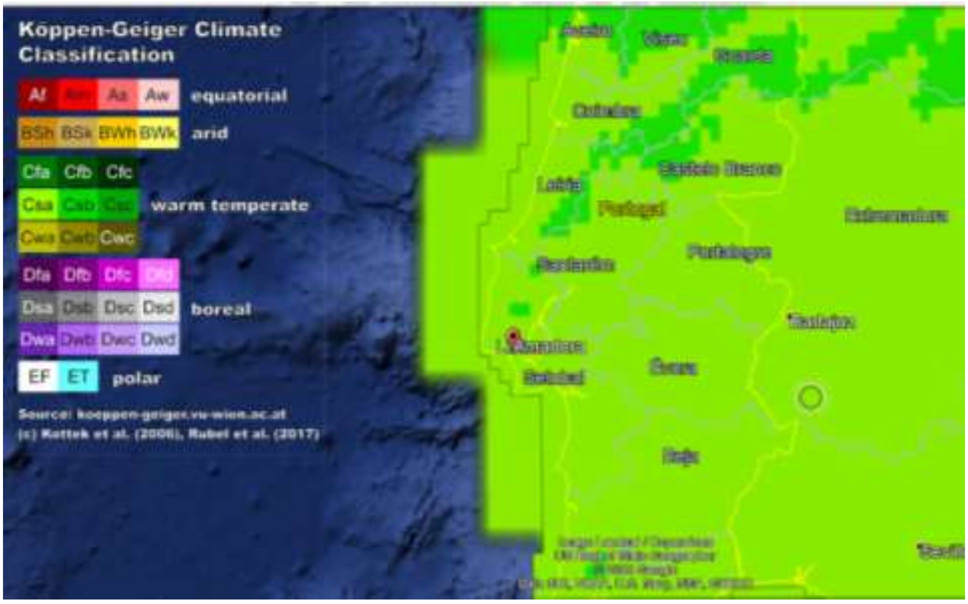


*Figure 14. Amadora's Köppen climate classification. Software used: Google Earth. Accessed March, 24, 2020.*

Climate in Amadora is dry and hot, with the great amount of precipitations happening in winter. The mean yearly temperature is 15.6 ºC with 796 mm of precipitations (Climate Data, 2020). Table 1 shows a summary of the mean values of maximum, minimum and mean temperature and precipitations per month from 1982 to 2012.

*Table 1. Historic data of Amadora's climate. Taken from Climate Data (2020).*

| | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean temperature (°C) | 10.4 | 11.1 | 12.6 | 14.3 | 16.2 | 18.8 | 20.8 | 21 | 20.2 | 17.3 | 13.5 | 10.9 |
| Min temperature. (°C) | 7.4 | 8 | 9 | 10.5 | 12 | 14.5 | 16.1 | 16.2 | 15.8 | 13.6 | 10.4 | 8.1 |
| Max temperature. (°C) | 13.5 | 14.3 | 16.2 | 18.2 | 20.4 | 23.1 | 25.6 | 25.9 | 24.6 | 21.1 | 16.7 | 13.7 |
| Precipitation (mm) | 114 | 101 | 102 | 56 | 48 | 22 | 4 | 7 | 24 | 74 | 120 | 124 |

The maximum mean temperature is in August (21 ºC) and the minimum mean temperature in January (10.4 ºC). The rainiest month is December (124 mm) and the drier is July (4mm).

## 3.3 Local geology

The building location can be found on sheet nº 34-C (Cascais) of the Portuguese geological cartography (Ramalho et al., 2001) at a scale of 1:50.000. Academia Militar is located in a flat area with heights from 121 m to 136 m a.s.l. The building is located at 134 meters a.s.l. measured in Google Earth. As it can be seen detailed in Figure 15, the geology is dominated by Late Cretaceous geological formations, from the Mesozoic Era. This formation receives the name of Lisbon volcanic complex ($\beta^1$) "Complexo Vulcânico de Lisboa (CVL)".

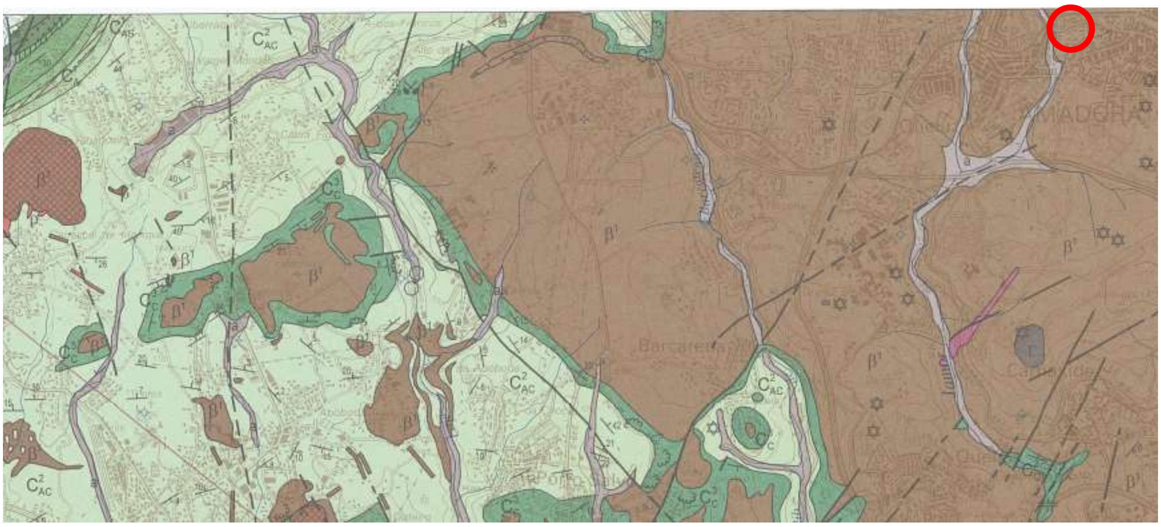

*Figure 15. Geology of Amadora region (Building location in red circle). Taken from Ramalho et al. (2001).*

The Lisbon volcanic complex is formation is extended around 200 km between Lisbon, Sintra, Mafra, and Runa. It consists of a succession of lava flows, mainly composed by basalts, separated by levels of pyroclastic materials and sedimentary layers (Terrinha et al., 2008). Apart from basalts, there are limestones and sandstones present in the formation (Colaço, 2015). Their properties are:

*Table 2. Thermal properties of characteristical materials of the ground to be studied. Taken from Colaço (2015).*

| **Rock Type** | **T. Conductivity (k)** | **S. heat capacity ($C_p$)** | **Rock density ($p$)** | **Thermal diffusivity (α)** | |
|---|---|---|---|---|---|
| | | | | **Minimum** | **Maximum** |
| Basalt | 2.2 | 712 – 879 | 2880 | $0.97 \cdot 10^{-6}$ | $1.17 \cdot 10^{-6}$ |
| Limestone | 2.4 | 920 | 2400 | $0.64 \cdot 10^{-6}$ | $1.54 \cdot 10^{-6}$ |
| Sandstone | 2.5 | 1005 | 2560 | $0.77 \cdot 10^{-6}$ | $1.17 \cdot 10^{-6}$ |

## 3.4 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 $km^2$. Figure 16 shows (in red) the area occupied by the campus as well as the location of the building (arrow in black).


*Figure 16. Academia Militar in Amadora (Bird-eye View). Software used: Google Earth. Accessed April 12, 2020.*

The building chosen is used, like the other buildings around it, as student dormitory. Figure 17, Figure 18, Figure 19 and Figure 20 show pictures taken by the thesis' author and from Google Earth.

*Figure 17. Lateral view of the building. Photo taken in March 4, 2020.*

*Figure 18. Frontal view of the building. Photo taken in March 4, 2020.*


*Figure 19. Open 3D view (North orientation). Google Earth. Accessed April 12, 2020.*

*Figure 20. Open 3D view (West orientation). Google Earth. Accessed April 12, 2020.*

As it can be seen in the last picture, the adjoining buildings interferes in the study in the way that solar exposition is reduced, in the east and north face of the building, due to shadowing. The distance between them is 20 m and the building architecture is similar.


*Figure 21. Measured distance between buildings. Google Earth. Accessed April 12, 2020.*

### 3.4.1 Building Characteristics

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 useful surface of 839 $m^2$ (surface to be heated). It has rooms for 78 students. The building is divided in different space types: bedrooms, bathrooms, corridors and stairs. Figure 22 shows the plain view of the three levels (all three are similar). The use of each space is shown in Table 3.

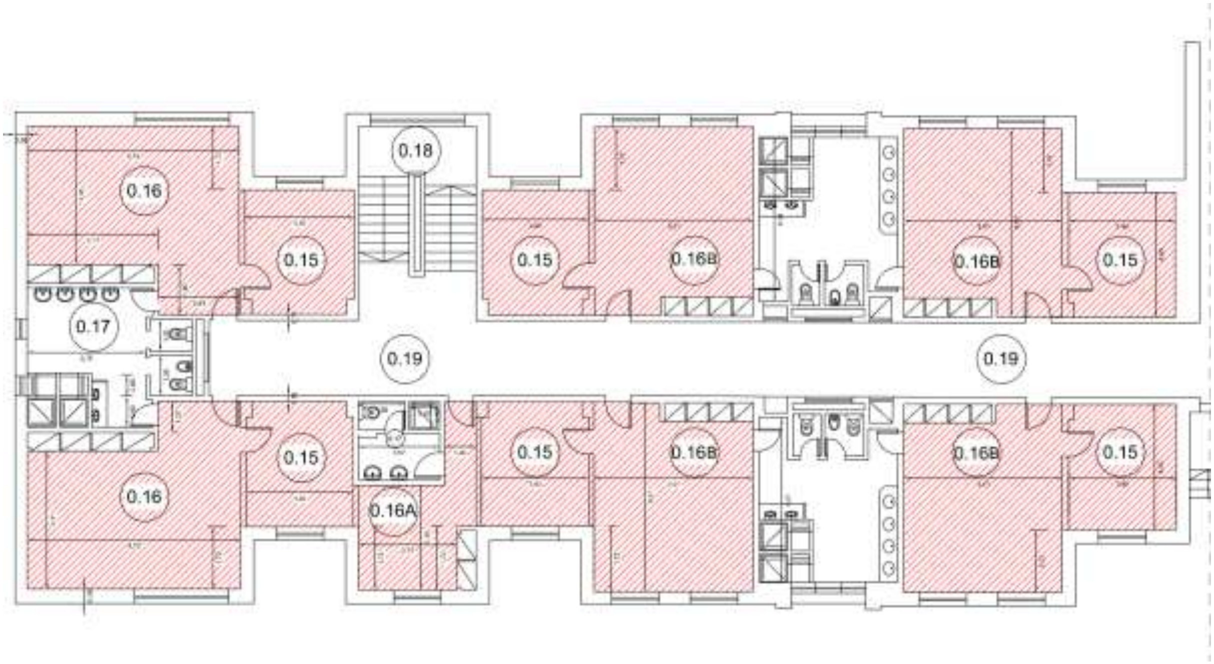


*Figure 22. Plain view of the interior of the building. Taken from Gonçalves (2017).*

The rooms coloured in red are the ones that must be heated and cooled. Bathrooms, corridors and stairs remain out of the study.

*Table 3. Description of the use of the spaces of the building and surfaces of the rooms.*

| Space | Use | Area |
|---|---|---|
| **0.15** | Study room | 13.6 $m^2$ |
| **0.16** | Big-size room: 4 students | 33.7 $m^2$ |
| **0.16B** | Room: 4 students | 30.1 $m^2$ |
| **0.16A** | Small room: 2 students | 10.3 $m^2$ |
| **0.17** | Bathrooms | |
| **0.18** | Stairs | |
| **0.19** | Corridors | |

As it can be seen in Figure 22, there are 6 study rooms, 2 big-size rooms, 4 rooms and 1 small room per level. The total area to be heated is 279.8 $m^2$ per level, 839.4 $m^2$ in the all building.

### 3.4.2 Building materials used

It is crucial to analyse the building envelope (from the walls and floor that separate it from the outside, to the interior walls and floors). Depending of the materials used to build it, the level of thermal insulation of the building will change, altering the amount of energy needed to climatize the building. A well-isolated building will lower the temperature drop in winter and keep it cool in the hottest days with less energy.

An in-situ analysis of the building was performed in March 4 of 2020 by the team. The thermal characteristic of the materials and construction was retrieved from LNEC ITE 50 (Pina and Matias, 2006) and used to simulate the real composition of the building. This book is used to support studies on the thermal performance of buildings. All the constructions are analysed in 3.4.2.1 and 3.4.2.2 and its materials are detailed in 4.3.2.

#### 3.4.2.1 Exterior envelope

Corresponds to all the constructions that separate the interior of the building with the outside: the exterior floor (level 0), the exterior walls and the exterior roof (level 2).

The exterior floor and the exterior roof have 279.8 m$^2$ (3.4.1). The exterior wall has 180.7 m$^2$ area per level, calculated after measuring the perimeter of the outside walls and subtracting the area of the exterior windows. The composition of each element is shown in Table 4 (from the outside layer to the interior).

*Table 4. Composition and width of the different materials of the exterior surroundings' constructions.*

| | **Exterior floor** | | **Exterior roof** | | **Exterior wall** | |
|---|---|---|---|---|---|---|
| **Composition** | | | | | Ceramic coating | 20 mm |
| | | | Exterior coating | 20 mm | Plaster | 20 mm |
| | | | Bentonite | 100 mm | Perforated bricks | 150 mm |
| | | | XPS | 40 mm | | |
| | Concrete | 250 mm | Waterproof net | 6 mm | Air-box | 20 mm |
| | XPS | 40 mm | Bentonite | 100 mm | XPS | 40 mm |
| | Bentonite | 100 mm | Concrete | 200 mm | Perf. Bricks | 110 mm |
| | Ceramic coating | 20 mm | Plaster gypsum | 20 mm | Plaster gypsum | 20 mm |
| Width | | **400 mm** | | **490 mm** | | **380 mm** |

Exterior windows have a double layer of 3 cm glass with a hollow space of 13 mm between them. There are also curtains inside the rooms that contribute shading the interior of the building.

#### 3.4.2.2 Interior envelope

Corresponds to all the constructions that make frontier between the climatized and non-climatized rooms and the other separations that take place inside: the interior floor (Level 1 and 2), interior walls and interior ceiling (level 0 and 1). The interior walls occupy an area of 275.3 m$^2$ each level, 826 m$^2$ in total. The ceiling and interior floor have 279.8 m$^2$ (3.4.1) subtracting the area occupied by the stairs (22.05 m$^2$). There are 277.75 m$^2$ of interior ceiling and interior floor per level, 555.5 m$^2$ in total. The composition of each element is shown in Table 4 and Table 5 (from the outside layer to the interior).

*Table 5. Composition and width of the different materials in the interior.*

| **Interior floor** | | **Interior ceiling** | | **Interior wall** | |
|---|---|---|---|---|---|
| Plaster<br>Concrete blocks<br>Wooden floor | 20 mm<br>200 mm<br>10 mm | Wooden floor<br>Concrete blocks<br>Plaster | 10 mm<br>200 mm<br>20 mm | Plaster<br>Masonry concrete block<br>Plaster | 20 mm<br>150 mm<br>20 mm |
| | **230 mm** | | **230 mm** | | **190 mm** |

Doors are not considered in this Thesis as the model remains simpler and there is not great variability in the simulation.

# 4 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, roof) and also shading from surrounding buildings.

Then, Energy Plus was used to consider 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). Figure *23* shows the relationship between the three programmes graphically.

The Domestic Hot Water demand was calculated by using equations from the literature, based on their accuracy and simplicity (SEITV, 2019).

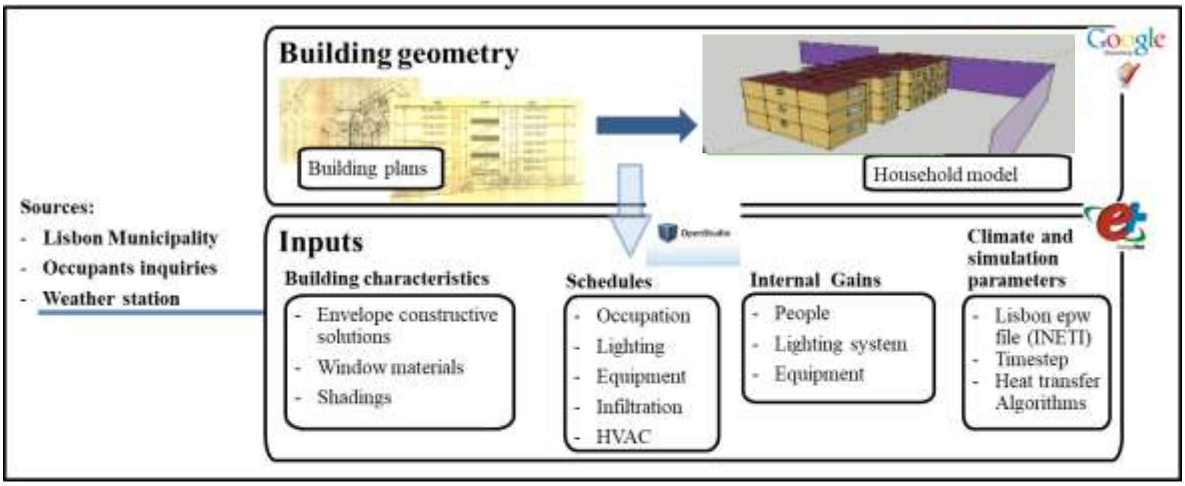


*Figure 23. Explicative scheme of the input processes. Taken from Gomes (2019).*

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.

## 4.1 Software used

### 4.1.1 Google SketchUp

Google SketchUp ® is a free program (there is also a paid version: Google SketchUp ® Pro) used for 3D modelling in a wide range of drawing applications. It was developed by Last Software. The first version was released in August 2000, with the purpose of offering a 3D building creating tool. On March 14, 2006, Google acquired Last Software and the development rights of the software. Google SketchUp ® allows to conceptualize and model 3D images of objects (Google SketchUp®, 2019). The building is shaped, projecting the different rooms or areas, building all the surfaces and sub-surfaces that are necessary. The construction elements must be registered as variables within the Open Studio program. Summarizing, 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).

### 4.1.2 OpenStudio

It is an open-source group of applications for building energy analysis released in April 2008 by National Renewable Energy Laboratory (NREL), a part of the U.S. Department of Energy. Its aim is to help building designers to perform more efficient projects.

This application is used to add all the characterization that the constructive elements already created have, such as the materials that compose them. It supports an iterative workflow of design, simulation and analysis to measure the energy impact of the project (National Laboratory of the U.S. Department of Energy, 2020).

The centrepiece of OpenStudio is a plug-in for Google SketchUp®. This plug-in takes advantage of the ability to generate Sketchup's 3D geometry to define the thermal model of the building. The OpenStudio plug-in enables to (Zero Consulting, 2018):

- Use Google SketchUp ® tools to create and edit zones in EnergyPlus,
- Work simultaneously with Google SketchUp ® and EnergyPlus,
- Equalize different desired conditions to the limits of each surface,
- Add the internal gains detailed in EnergyPlus to any zone and
- Develop a model of the building through a graphic interface, something that EnergyPlus lacks.

In this project, every room, corridor or stair has its own thermal zone. This allows the chance to add a special feature that just affects to a determined space of the building. For example, not every space has the same use, equipment or heating installations. Figure 24 shows one thermal zone (a bedroom)

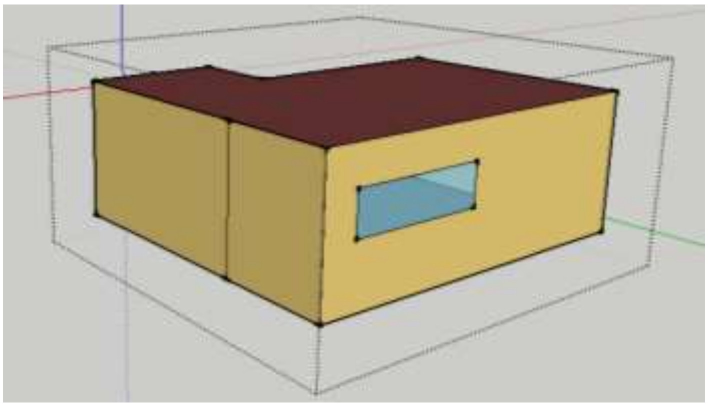

*Figure 24. An EnergyPlus zone. Google SketchUp®.*

### 4.1.3 Energy Plus

Is a free Building Energy Modeller (BEM) developed in 1997 by the U.S. Department of Energy. Energy Plus was released to replace the DOE-2, also a freeware created by the U.S. government in 1979 (Lee, 2018). As it was mentioned in 4.1.2, it works together with Open Studio.

It is used by architects and engineers to define the energy requirements of a building, optimize the performance of geometric installations and, to adapt an already defined building to the requested thermal conditions in an efficient way (Energy Plus, 2020a).

The finished Open Studio file is used for heat flow and consumption calculations. From it, it is possible to add new variables and obtain results.

The possibilities this software enables (National Renewable Energy Laboratory, 1996; Crawley et al., 2001) are:

- Comprehensive solutions for each thermal zone where both zone conditions and HVAC systems converge;
- air conditioning and air flow movement simultaneously in zones;
- time intervals that can be defined by the user;
- calculation of thermal balances on surfaces combining radiation and convection;
- possibility of introducing files on climatological data of the environment in which they are located;
- daylighting control, simulation and control of luminaires;
- a variety of possibilities to introduce internal gains and material properties to a better characterization of the model and
- different options of energy balance outputs.

Within the different applications that Energy Plus offers to perform simulation projects, EP Launch and EP Editor are the most popular. EP Launch has the model calculation engine and has input and output of .idf data. The IDF editor is the program used to create, add and edit elements, zones and conditions to the building model. It consists on a list of all the parameters of the building, subdivided in calculation sheets where variables and conditions are introduced as it can be seen in Figure 25.

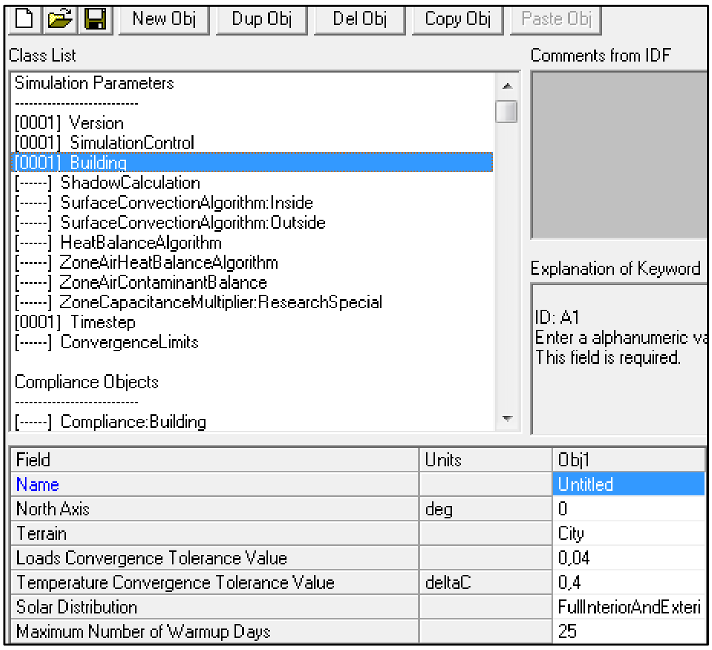


*Figure 25. IDF Editor window. Energy Plus v6.0.*

### 4.1.3.1 IDF Editor parameters

In this section, the elements that define the architecture, energy equipment and routine operations in the building that can be added and edited in the software are listed.

- Simulation parameters: project building name, position of the building relative to north.

- Simulation control: includes the general settings for calculating simulations. It is possible to activate or deactivate the "Sizing Calculations", making the thermal calculations in each zone and for each HVAC system.

- Schedule Compact: used to define the frequency with which a set of phenomena and operations occur. Permits to specify for every zone during any space of time (day, week, weekend …) certain activity is performed. Illumination, temperature or the presence of people doing certain activities are some examples.

- Materials**:** it encompasses the materials (and its properties) that are used in the construction. It consists of a spread sheet prepared to detail different properties, as shown in Figure 26.

| Field | Units | Obj1 | Obj2 | Obj3 |
|---|---|---|---|---|
| Name | | F08 Metal surface | I01 25mm insulation | I02 50mm insulation |
| Roughness | | Smooth | MediumRough | MediumRough |
| Thickness | m | 0,0008 | 0,0254 | 0,0508 |
| Conductivity | W/m-K | 45,28 | 0,03 | 0,03 |
| Density | kg/m3 | 7824 | 43 | 43 |
| Specific Heat | J/kg-K | 500 | 1210 | 1210 |
| Thermal Absorptance | | 0,1 | 0,1 | 0,1 |
| Solar Absorptance | | | | |
| Visible Absorptance | | | | |

*Figure 26. Example of three materials and its properties. Energy Plus v6.0.*

There are four different materials in Energy Plus depending on their characteristics or their functions in the building:

- Mass materials: their thickness and surface are considered, e.g., concrete, wood, etc,
- Non-mass materials: their thickness is not considered but its properties,
- Air gaps: Situated between various layers in walls or in windows and
- Windows: excluded from mass materials because of its particular characteristics (solar transmittance, reflectance and emissivity). It includes glass-materials, curtains and blinds).

- 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. Walls can have different materials depending if they are constructed to separate the building from the exterior or to separate two interior zones. It is important to ensure that the interior surfaces have the same construction on each of the two faces that make it up. Energy Plus references the roofs as standard order constructions, while the floors are reverse order constructions. Constructions are always referenced in the software from the outside, as it is shown in Figure 27.

| Field | Units | Obj1 | Obj2 | Obj3 |
|---|---|---|---|---|
| Name | | Exterior Floor | Interior Floor | Exterior Wall |
| Outside Layer | | Betao - 25cm | F16 Acoustic tile | Ceramica vidrada - |
| Layer 2 | | XPS_4 | F05 Ceiling air spac | Reboco - 2cm |
| Layer 3 | | Betonilha - 10cm | Alv Bloco Betao - 1 | Tijolo Furado_15 |
| Layer 4 | | Ceramica vidrada - | | Ar Vertical Up - 15 |
| Layer 5 | | | | XPS_4 |
| Layer 6 | | | | Tijolo Furado_11 |
| Layer 7 | | | | Gesso cartonado - |

*Figure 27. Example of three constructions. Energy Plus v6.0.*

- 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. All internal loads are calculated for each zone. To facilitate the calculations and interpretations with great amount of zones they may be grouped into sets of areas that share the same characteristics in terms of use of air conditioning, equipment, the presence of internal loads, boundary conditions or type of construction such as rooms, toilets, storage rooms, garages, corridors, terraces, stairs, kitchens, etc. As there are 54 zones in this project, 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: acclimatization systems that work independently of other elements. Thermostats are temperature regulators (given maximum and minimum permissible values of temperature). It is also possible to make the temperature dependent on a "Schedule compact".

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

## 4.2 Building modelling

The 3D model of the building is made with Google SketchUp ®. The software is set up in meters and linked with Open Studio to export the model. Figure 22 is used as template to draw the sectorial division of the building in the software. Vectors are drawn dividing the rooms and the facade of the building (always regarding real measurement) as it can be seen in Figure 28:

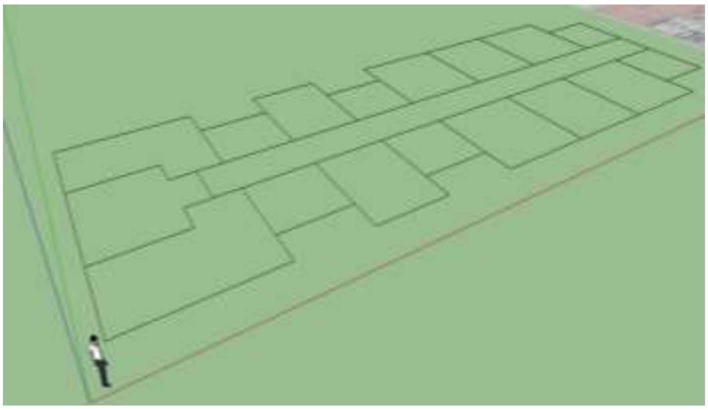

*Figure 28. Vectorial division of the building (2D). (Google SketchUp, 2019).*

The 2.7 m vertical elevation of the 2D model creates the first 3D view of the building:

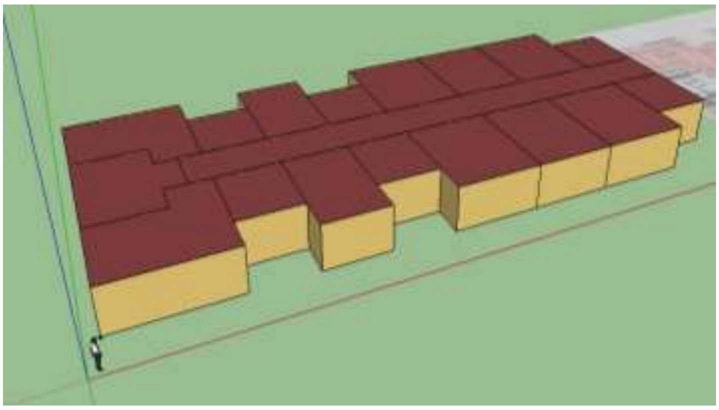

*Figure 29. Ground level of the building 3D. (Google SketchUp, 2019).*

After building the three levels by copying the model built in Figure 30, the windows were drawn. Their position is 0.75 m below the roof and, generally, in the middle of the wall (except for the big-size rooms).

Every space (room, corridor, bathroom or stair) of the 3D model is an Energy Plus Zone. It is important because it gives the chance to work just with one zone while leaving all other areas undisturbed. Every construction is classified according to its outside boundary (3.4.2.1 and 3.4.2.2): Interior floor, exterior floor, exterior roof, exterior wall, interior wall, interior ceiling and windows. To finish the model geometry, a wall 20 m away was built to represent the effect the shadowing by the buildings nearby. The building model was positioned according to its orientation as presented in Figure 30 (green axis represents the north).

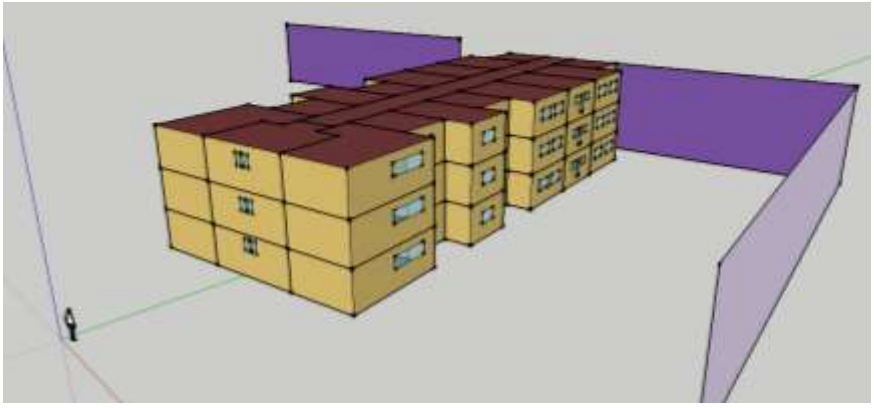

*Figure 30. 3D model completed. Google SketchUp®.*

## 4.3 Building Characterization

After creating the model, the .idf file is exported to Energy Plus where parameters detailed in (4.1.3.1) are introduced.

### 4.3.1 Schedules

The information about students' habits was considered to detail occupation schedules for different spaces and their level of human activity after an interview with the building manager.

"Room occupation by people" and "Bathroom use" (Table 6 and Table 7) detail the presence of people in the rooms and bathrooms by time interval. One of the members of the management team of Academia Militar explained the schedule of the students. They wake up at 7:00 and go to sleep at 24:00. During the weekend most of the cadets go home and the rest stay in the building freed to any military activity. They take three shower baths during weekdays and one or two during weekend and holiday (W and H). They have free time to stay in the building (usually for studying in the room) from 12:30 to 13:00 and from 18:00 to 20:00. The presence of people is represented with fractions: "1" means full capacity and "0" means empty. Their activity level is based on information detailed in *Annex 1. Activity level measurement*.

*Table 6. Building schedules: Room occupation by people and its activity level. Taken from Energy Plus (2010b).*

| | **Room occupation by people** | | **Activity level (W)** |
|---|---|---|---|
| | Type of variable: Fraction | | Type of variable: Any number |
| **Time** (until) | **Weekdays** | **W and H** | **Everyday** |
| **07:00** | 1 | 0.3 | 72 |
| **08:00** | 0.5 | 0.15 | 150 |
| **12:30** | 0 | 0 | 72 |
| **13:00** | 0.8 | 0.25 | 150 |
| **18:00** | 0 | 0 | 72 |
| **20:00** | 0.8 | 0.25 | 120 |
| **21:00** | 0 | 0 | 72 |
| **24:00** | 1 | 0.3 | 100 |

*Table 7. Building schedules: Bathroom use and its activity level. Taken from Energy Plus (2010b).*

| | **Bathroom Use** | | **Activity level (W)** |
|---|---|---|---|
| | Type of variable: Fraction | | Type of variable: Any number |
| **Time** (until) | **Weekdays** | **W&H** | **Everyday** |
| **07:00** | 0 | 0 | 72 |
| **08:00** | 1 | 0.3 | 190 |
| **12:30** | 0 | 0 | 72 |
| **13:00** | 1 | 0 | 72 |
| **18:00** | 0 | 0 | 72 |
| **19:00** | 1 | 0.3 | 190 |
| **24:00** | 0 | 0 | 72 |

Table 8 shows an approximate use (as it is impossible to calculate accurately) of stairs and corridors. This approximation is also based on the movements the trainees do to make the activities detailed at the beginning of this paragraph.

*Table 8. Building schedules: Stairs and corridors' use.*

| | Stair use | | Corridors use | |
|---|---|---|---|---|
| | Type of variable: Fraction | | Type of variable: Fraction | |
| **Time** (until) | **Weekdays** | **W and H** | **Weekdays** | **W&H** |
| **07:00** | 0.25 | 0.08 | 0.25 | 0.08 |
| **08:00** | 0.175 | 0.04 | 0.175 | 0.04 |
| **12:30** | 0 | 0 | 0 | 0 |
| **13:00** | 0.2 | 0.05 | 0.2 | 0.05 |
| **18:00** | 0 | 0 | 0 | 0 |
| **20:00** | 0.2 | 0.05 | 0.2 | 0.05 |
| **21:00** | 0 | 0 | 0 | 0 |
| **24:00** | 0.25 | 0.08 | 0.25 | 0.08 |

The desired temperature to be kept indoors with heating or cooling is variable during the day. It depends on the activities of the recruits or their presence or not in the building. Table 9 shows the maximum or minimum temperature from which the HVAC system will start to work to keep it (temperature set points).

*Table 9. Building's indoor temperature schedule.*

| | Indoor Temperature | |
|---|---|---|
| | Type of variable: Temperature (ºC) | |
| **Time** (until) | **Heating** | **Cooling** |
| **05:00** | 17 | 26 |
| **19:00** | 18.5 | 28 |
| **24:00** | 19 | 26 |

### 4.3.2 Material properties

All the values presented in Table 10 were taken from the material catalogue and LNEC ITE 50 (Pina and Matias, 2006). The software uses these values to calculate the thermal conductivity values of the envelope.

*Table 10. Width, specific heat and thermal conductivity of the materials used. Taken from Pina and Matias (2006).*

| **Material** | **Width (mm)** | **λ: Thermal conductivity** $[W/(m.K)]$ | $C_p$**: Specific heat capacity** $[J/(kg \cdot K)]$ |
|---|---|---|---|
| Plaster | 20 | 1.8 | 1050 |
| Concrete | 200/250 | 2.2 | 900 |
| Bentonite | 10 | 1.65 | 900 |
| Waterproof net | 2 | 0.14 | 1040 |
| XPS | 40 | 0.037 | 1550 |
| Plaster gypsum | 20 | 0.25 | 1090 |
| Perforated brick | 110/150 | 0.39 | 920 |
| Concrete blocks | 150/200 | 0.75 | 840 |
| Wooden floor | 10 | 0.14 | 1200 |
| Ceramic coating | 20 | 1.3 | 950 |
| Exterior coating | 20 | 1.1 | 900 |
| Glass | 20 | 0.9 | - |
| Curtain | 2 | 0.042 | 1700 |

### 4.3.3 Constructions

The information introduced is the same as reflected in Table 4 and Table 5: Exterior floor, Exterior roof, Exterior wall, Interior floor, Interior ceiling and Interior wall.

Heat transfer between any zone to be heated or cooled and the area around is mostly characterised by the Thermal Transmittance Coefficient (U-value) of the elements that separate them. The values of U have been calculated by the Energy Plus, considering air surface resistance and are reflected in Table 11.

*Table 11. Thermal transmission coefficients (U). Energy Plus Outputs.*

| Construction | U factor with film |
|---|---|
| Exterior wall | 0.465 |
| Exterior floor | 0.702 |
| Exterior roof | 0.636 |

### 4.3.4 Zones

As it was explained, one zone is created for each space. There are 54 zones in total. As the distribution of the zones is homogeneous and specific in the case of student buildings, it is possible to classify these zones into 4 large groups:

- Rooms: 12 per floor, 36 in total (study room, big-size room, room and small room),
- Toilets: 4 per floor, 12 in total,
- Corridors: 1 per floor, 3 in total and
- Stairs: 1 per floor, 3 in total.

### 4.3.5 Internal gains

Divided in three types depending on the origin of the source (people, lights and electric equipment):

- People: occupants, as they generate calorific energy, they contribute in the calculations. For each room was introduce as "Number of people" the maximum number of people that can live there (4 or 2, depending on the type of room) and 2 per bathroom. Their activity level is measured following the data shown in Table 6, regarding to rooms and in Table 7, regarding to toilets. As a radiant fraction, it is regarded 0.6 (Energy Plus, 2010a);

- Lights: this information was not available but considering the areas and from talks with the building manager during the audit visit it was considered 150 W for each zone (room) and;

- Electric equipment: there is a laptop per student (40-65 W) and one smartphone is assumed for every student (10-20 W). Another 25 W are associated to each student (small appliances). This yields an approximate result of 90 W consumed per student, 7.02 kW overall. It is assumed a maximum simultaneous use of 40%: 2.8 kW.

### 4.3.6 Thermostat

It provides the system with information on temperature limits, outside which the HVAC system works to bring the interior of the building back into the "comfort" temperature range. There is a minimum temperature, below which there will be heating. There is also maximum temperature, above which there will be cooling. Temperatures are listed in Table 9.

### 4.3.7 Outputs

The most relevant outputs for analysing the thermal performance of the building are Heating and Cooling needs. In this study the outputs retrieved from the simulation were:

- Ideal Loads Air Heating Energy: it indicates the amount of heating energy consumption each hour of the day during the year to maintain the indoor temperature above the thermostat limit (J).

- Ideal Loads Air Cooling Energy: it indicates the amount of cooling energy consumption each hour of the day during the year to maintain the indoor temperature above the thermostat limit (J).

- Outdoor Dry Bulb: presents the outdoor Dry-Bulb Temperature (DBT). Temperature data was extracted from a database of .epw files (Energy Plus). Energy Plus takes the information from local weather data records and "standard" years in terms of temperature. As there was no information for Amadora, the Lisbon archive (PRT_Lisboa.085360_INETI) was chosen for reasons of proximity (Energy Plus, 2020b).

### 4.4 Domestic Hot Water (DHW)

In this building, despite toilets are not climatized (3.4.1), they have strong influence in the HVAC geothermal evaluation because there is always hot water for human consumption which requires an amount of heating energy for its preparation. The water is stored in the existing tanks.

Despite the EP the software is prepared to calculate it, Domestic Hot Water (DHW) needs were calculated from the equations provided by (SEITV, 2019) due to its simplicity:

$$\boldsymbol{Q_{DHW} = q_w * p_w * n * V_w * \frac{1}{t_h} * \Delta T} \quad (6)$$

$Q_{DHW}$: 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

$\Delta T$: Thermal leap (°C).

A person uses 123 litres per day (9594 (SEITV, 2019). As there are just 6 showers per floor, $n$ is equal to 18 users, the largest number of users for a simultaneous use.

The heating time of the total water volume has influence on the power sizing. It depends on the level of demand for DHW. Following recommendations and similar projects (E-Ficiencia, 2019) , $t_h$ is 1h. The thermal leap (ΔT) varies each month, considering 50 °C (Danfoss, 2020) as the heating temperature and 15 °C as the average supply water temperature which varies each month (Moel et al., 2010; Carvalho et al., 2015), maximum two degrees down in the coldest months and two degrees up in the hottest months. To calculate the energy consumption (kWh), it is therefore sufficient to multiply the result of each month by its number of days.

# 5 Results and Discussion

After properly set all the parameters listed in 4.3, the simulation using Energy Plus was performed. The results (Outputs) are provided in the format of a spread sheet (.xls). This folder lists all heating and cooling energy values for each hour and each room and, due to its great amount of data, results are shown with the total amount for each month.

As referred before the DHW were calculated outside Energy Plus and are presented next.

## 5.1 Domestic Hot Water (DHW), power and energy

Table 12 shows the results after applying equation (6) for each month. The result is expressed in (kcal/h) but transformed into units of the international system.

*Table 12. Results of power and energy for DHW.*

| | Supply water temperature (°C) | Power (peak) (kcal/h) | Power (peak) (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.

The energy and power demand obviously do not vary significantly and remains pretty constant during the year (with a daily consumption around 100 kWh), as it does not depend on the outside temperature and underground water temperature has minimal year-round variations.

## 5.2 Energy

Table 13 shows the total energy for heating and cooling (in kWh) the building needs every month (without DHW) to keep the building at the required temperature in 4.3.1.

It is also worthwhile, in terms of efficiency, to calculate it by square metre. As detailed in 3.4.1, the area to be heated is 279.8 $m^2$ per floor. The total area raises 839.4 $m^2$. Table 14 shows the energy consumption by square meter.

*Table 13. Energy consumption by the model without DHW). Energy Plus Outputs.*

| | Heating (kWh) | Cooling (kWh) |
|---|---|---|
| **January** | 929 | 0 |
| **February** | 361 | 0 |
| **March** | 50 | 30 |
| **April** | 136 | 27 |
| **May** | 4 | 542 |
| **June** | 0 | 2309 |
| **July** | 0 | 6325 |
| **August** | 0 | 6320 |
| **September** | 0 | 3087 |
| **October** | 0 | 1591 |
| **November** | 29 | 45 |
| **December** | 489 | 0 |

*Table 14. Energy consumption by the model per $m^2$ (without DHW). Energy Plus Outputs.*

| | Heating (kWh/m²) | Cooling (kWh/m²) |
|---|---|---|
| **January** | 1.1 | 0 |
| **February** | 0.4 | 0 |
| **March** | 0.1 | 0.04 |
| **April** | 0.2 | 0.03 |
| **May** | 0 | 0.65 |
| **June** | 0 | 2.8 |
| **July** | 0 | 7.5 |
| **August** | 0 | 7 |
| **September** | 0 | 4 |
| **October** | 0 | 2 |
| **November** | 0.04 | 0.05 |
| **December** | 0.6 | 0 |

Throughout the year, total energy demands are 1999 kWh for heating and 20278 kWh for cooling.

The building needs 2.4 kWh/$m^2$ to heat and 24.2 kWh/$m^2$ to cool the building. Figure 31. Energy needs (kWh) for heating and cooling and average annual temperature. and Figure 32 are bar diagrams created to ease the results´ analysis and to establish a possible relationship between energy and outdoor air temperature. On the x-axis, time (the whole year) is represented. On the y-axis, two different units are represented: kWh and ºC (energy and air temperature). Three parameters are represented: energy consumption for cooling (blue), energy consumption for heating (red) and outdoor air temperature (green).

The energy needs are much higher for cooling than for heating. It can be explained due to the tempered winters and hot summer of this zone (3.2). All months except January, February and December need energy for cooling. The small amounts of energy for cooling demanded from March to May and November can be rare, but it has an explanation: the internal gains combined with the west-east orientation (many hours of sun exposure, both in the morning and in the evening) of some rooms generate cooling needs, even though lower temperatures outside than those programmed in the thermostat. This explains also why heating is not needed from June to November and more than 70% the total heating energy is required in December and January.

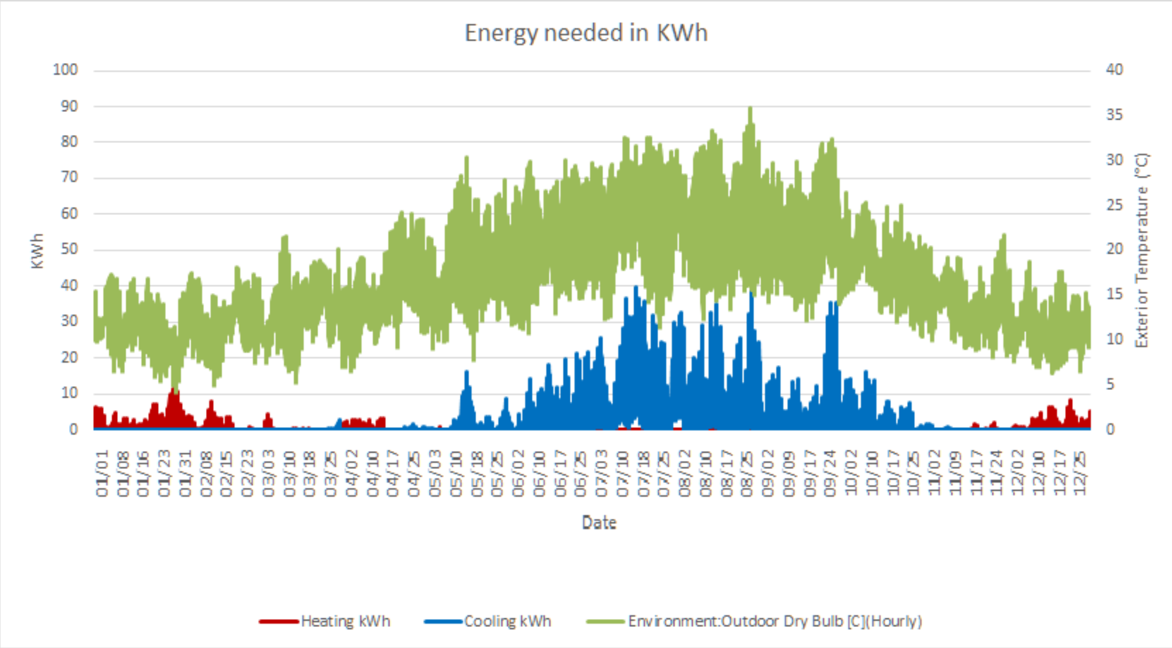


*Figure 31. Energy needs (kWh) for heating and cooling and average annual temperature.*

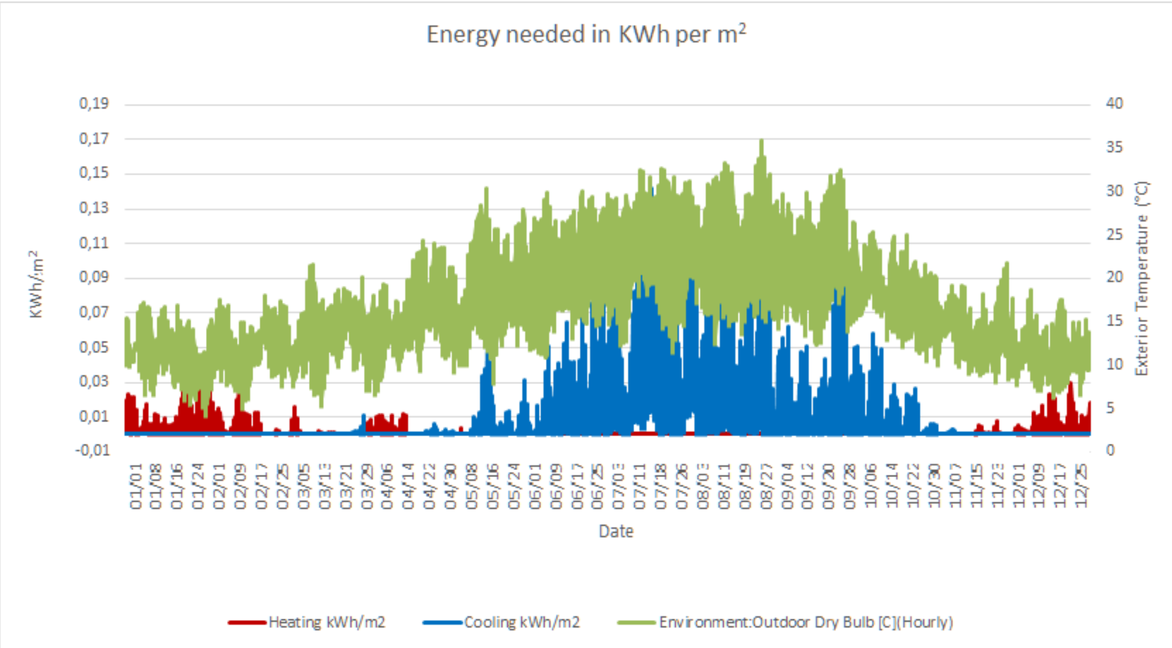


*Figure 32. Energy needs (kWh/m$^2$) for heating and cooling and average annual temperature.*

The diagrams show how 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 12-14 $^oC$, energy demands begin to disappear. On the other hand, the system suffers considerably from rising temperatures, requiring a large amount of energy to cool the building in the high temperature season. When average daily temperatures remain above 25-27 $^oC$, energy demands begin to rise exponentially. The maximum peak of heating consumption takes place in the end of January, with temperatures lower than 10 $^oC$. About cooling, the maximum peak takes place at the end of August with temperatures higher than 34 ºC. Again, this is related with the internal gains (mainly due to occupation) and also to solar gains.

Table 15 shows the total energy (kWh) that is required to the heat pump after adding DHW requirements to the building energy needs.

*Table 15. Energy demands by the model and DHW production.*

| | **Heating (kWh)** | **Cooling (kWh)** |
|---|---|---|
| **January** | 4412 | 0 |
| **February** | 3507 | 0 |
| **March** | 3486 | 30 |
| **April** | 3415 | 28 |
| **May** | 3298 | 542 |
| **June** | 3097 | 2309 |
| **July** | 3106 | 6325 |
| **August** | 3106 | 6321 |
| **September** | 3052 | 3087 |
| **October** | 3200 | 1591 |
| **November** | 3308 | 45 |
| **December** | 3972 | 0 |

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

## 5.3 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. These values represent the minimum power capacity the GSHP chosen (6.1) has to provide.

Table 16 shows the maximum power required for cooling and heating (in kW) every month (without DHW).

*Table 16. Power required by the model (without HSW).*

| | Heating (kW) | Cooling (kW) |
|---|---|---|
| **January** | 11.4 | 0 |
| **February** | 8.1 | 0 |
| **March** | 4.5 | 3 |
| **April** | 3.4 | 1.8 |
| **May** | 0.9 | 16 |
| **June** | 0 | 21.7 |
| **July** | 0 | 39.7 |
| **August** | 0 | 41.3 |
| **September** | 0 | 35.3 |
| **October** | 0 | 16.3 |
| **November** | 2.1 | 1.8 |
| **December** | 8.2 | 0 |

The maximum power required for heating the building is 11.4 kW (in January). The maximum power required for cooling the building is 41.3 kW (in August).

Naturally, the trend remains unchanged and the cooling needs for power are much higher than heating needs. The exponential growth of energy demands in summer causes threefold increase of power compared with winter. The influence of weather is actually proven as the bigger power requirements match with hotter and colder months (3.2).

Table 17 shows the maximum power that is required to the heat pump after adding DHW requirements to the building power needs.

*Table 17. Power required by the model and DHW.*

| | 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 |

It can be concluded that the maximum power needed to prepare DHW quadruples the power needed to heat the building. The maximum power required in this project is 44.2 kW for heating (with DHW) and 41.3 kW for cooling.

# 6 Ground Source Heat Pump

## 6.1 Ground Source Heat Pump selection

After obtaining the power requirements in the project (5.3) the next step was to choose a heat pump that can meet the demands of the building, (attached in Table 18, as a summary).

*Table 18. Heat pump design: power requirements.*

| Heating (kW) | Cooling (kW) |
|---|---|
| 44.2 | 41.3 |

The choice was a DYNACIAT LG 150A, developed by Compagnie Industrielle d'Applications Thermiques (CIAT), an European brand with more than 80 years of experience (CIAT, 2019). Table 19 includes a list with the different models of the company and their powers. A detailed breakdown of the features is shown in *Annex 2. Heat Pump (DYNACIAT LG 150A) characteristics*.

*Table 19. DYNACIAT models: power capacity. Taken from CIAT (2019).*

| Model | Heating power (kW) | Cooling power (kW) |
|---|---|---|
| **100A** | 38 | 32 |
| **120A** | 44 | 37 |
| **130A** | 51 | 42 |
| **150A** | 56 | 47 |
| **180A** | 70 | 58 |
| **200A** | 77 | 63 |
| **240A** | 89 | 74 |
| **260A** | 101 | 84 |
| **300A** | 114 | 94 |

Heating power has been set to water at 30-35 $^{o}$C and cooling power has been set to water at 7-12 $^{o}$C. The previous model (130A) could work for this project but, due to its proximity to the peak value, the following one is chosen. The performance characteristics of the chosen geothermal reversible water-water heat pump unit for DHW production, heating and cooling can be seen in Table 20.

*Table 20. 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. It does not contribute to the destruction of the ozone layer. The properties of R410a are detailed in *Annex 3. R410a characteristics*.

## 6.2 Heat exchanger

The geothermal heat exchanger choice comfortably exceeds heat pump requirements. The chosen tube is fabricated by Muovitech: the PE100, a simple geothermal collector (2 tubes) for vertical installation. Its characteristics are detailed in *Annex 4. PE100 CHARACTERISTICS*.

The criteria used to calculate the lenght is taken from Ferro Systems (Ferro Systems, 2020):

$$Tout_h = Tin_h - \frac{1000 \cdot Ph \cdot \frac{COP-1}{COP}}{Cp \cdot (^{Q}/_{3600})} \quad (7)$$

$$Tout_c = Tin_c + \frac{1000 \cdot Pc \cdot \frac{EER+1}{EER}}{Cp \cdot (^{Q}/_{3600})} \quad (8)$$

$Tout_h$: output temperature mode in ºC (heating),

$Tout_c$: output temperature mode in ºC (cooling),

$Tin_h$: input temperature mode in ºC (heating),

$Tin_c$: input temperature mode in ºC (cooling),

$Ph$: heat pump output in kW (heating),

$Pc$: heat pump output in kW (cooling),

$Cp$: specific heat of fluid in J/Kg and

$Q$: heat pump flow rate in l/h.

This heat pump has an interval of values for inlet temperatures: 7-12 °C and 30-35 °C (CIAT, 2020). The following values were considered for the estimation of exchanger length.

- $Tin_h$ is set to be 32°C and $Tin_c$ is 8 °C.
- Power values (44.16 & 41.29 kW),
- COP (5.45) and
- EER (4.67) previously calculated are introduced.
- $Cp$ for R410a is 1,840 J/Kg and
- $Q$ is 16200 l/h.
- Output temperatures are 3.64 °C and 38.05 °C.
- Maximum ($T_{max}$) and minimum ($T_{min}$) temperature is the mean between input and output temperatures: 35.03 and 5.82 °C.

The resistance of the exchanger tubes to the flow of heat is calculated from this equation:

$$Rp = \frac{1}{2 \cdot \pi \cdot Kp} \cdot Ln(\frac{D_0}{D_1}) \tag{9}$$

$Rp$: thermal resistance ($K\ m/W$),

$Kp$: thermal conductivity ($W/m\ K$),

$D_0$: exterior diameter ($m$) and

$D_1$: interior diameter ($m$).

$Kp$ is 0.43 (Ferro Systems, 2020). $D_0$ and $D_1$ are 0.032 and 0.0291 m, as referred in PE100 characteristics. Tube resistance is 0.035161 $K\ m/W$.

Finally, the length of the exchangers is calculated accordingly to:

$$Lh = \frac{Qh \cdot \frac{COP - 1}{COP} \cdot (Rp + Rs \cdot Fh)}{Tl - T_{min}} \tag{10}$$

$$Lc = \frac{Qc \cdot \frac{EER + 1}{EER} \cdot (Rp + Rs \cdot Fc)}{T_{max} - Th} \tag{11}$$

$Rs$: ground resistance ($W/K\ m$),

$Fh$: usage factor (heating),

$Fc$: usage factor (cooling),

$Tl$: ground max. temperature (°C) and

$Th$: ground min. temperature (°C).

The ground resistance is the inverse of the ground conductivity (3.3), therefore $Rs$= 0.4 $W/K\ m$. Usage factor was considered, in both cases as 0.25. In Europe, most soils present roughly constant temperatures (over 50 m the values are around 10 °C and 15 °C) (Moel et al., 2010; Carvalho et al., 2015). $Tl$ and $Th$ are estimated as 15 °C and 13.5 °C respectively.

Table 21 shows the final results:

*Table 21. Heat exchangers' length.*

| **Length for heating** | **Length for cooling** |
|---|---|
| 635 m | 234 m |

The system 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. It was verified that Table 21 results are greater than for a period of maximum demand of cooling, adding the power of the DHW and therefore correctly supplying periods of mixed peak demand.

The selected drilling arrangement is 8 boreholes of 80 m depth each. This disposition eases their maintenance and conservation, which is expensive in deeper holes (Coelho, 2007).

### 6.3 Heat distribution

The water heated or cooled by the heat pump is supplied to the building through 20 mm diameter polyethylene pipes that circulate in an approximately 250 metre pipeline installation. Every room to be climatized has a ceiling fan coil to distribute the energy produced in the heat pump. The fan coil selected is FWE03CT created by Daikin (Daikin, 2020). This model has an output of 2.44 kW for cooling and 3.13 kW for heating, power which is far superior to the maximum power requirement by room (1.98 kW for cooling in August).

# 7 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.

## 7.1 Current system operating costs

The building has an old boiler that uses natural gas as fuel. The efficiency of this boiler is around 68% (Gonçalves, 2017). The building does not have a cooling system but, to make real comparisons, an air conditioning system (A/C) is considered (one device per room). After consultation with various brands and manufacturers, the reference value chosen is EER=2.5. Table 22. Cost of energy for the current system per year shows the cost to produce the energy needed to heat and cool the building, 5.2. Energias de Portugal (EDP) current prices for electricity (cooling) and gas (heating) were chosen to do the balance (Selectra, 2020). Electricity tariff term is not considered as it is going to be paid whether or not there is cooling installation.

*Table 22. Cost of energy for the current system per year*

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

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. Besides, the boiler and the A/C has a maintenance which will have a ten-year cost of around 4500€ and 19803€ (507.77€ each device) (CYPE, 2020).

Next step is to encompass the cost of the GSHP installation and the annual costs. Lastly, both options are compared and the return on investment time is calculated.

### 7.1.1 GSHP installation investment

Table 23 shows the cost of each element in the installation. Drilling costs are estimated, including labor, as 40€ per drilled meter (Coelho, 2007). Heat exchanger and heat pump unitary price is checked in the current price lists (CIAT, 2019; Muovitech, 2020). The rest of the material prices and their maintenance cost are consulted (estimated in the case of heat pump) in the price generator provided by CYPE (CYPE, 2020).

*Table 23. Project realization budget.*

| Element | Amount | Unit | U. price (€/unit) | Ten-year maintenance per unit (€) | Total price (€) |
|---|---|---|---|---|---|
| **DYNACIAT LG 150A** | 1 | - | 19014 | 7500 | 19014 |
| **Muovitech PE100 (80m)** | 8 | - | 816.07 | 142.82 | 6528 |
| **Injection Tube** | 656 | m | 1.24 | - | 813.44 |
| **Drilling operations** | 656 | m | 40 | - | 26240 |
| **Fancoil FWE03CT** | 39 | - | 184.32 | 261.05 | 7188 |
| **Distribution pipe (20mm)** | 275 | m | 13.93 | | 3830.75 |
| **Total installation budget** | | | | | 63614.19 |

This project development has a budget of 63614.19€. Besides, there is a decennial price in terms of maintenance, of 18823.51€.

### 7.1.2 Heat Pump annual operating cost

Table 24 shows the annual expenditure to cover the energy needs of the building. As explained in 2.1, the heat pump energy consumption can be calculated matching its COP and EER with the energy produced.

*Table 24. Cost of energy consumption by the GSHP.*

| | Heating | Cooling |
|---|---|---|
| **Energy produced** | 40959.7 k$Wh$ | 20278 k$Wh$ |
| **COP** | 5.45 | - |
| **EER** | - | 4.67 |
| **Energy consumption** | 7515.54 k$Wh$ | 4342.18 k$Wh$ |
| **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, apart from being clear, 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 savings are graphically represented in Figura 33.

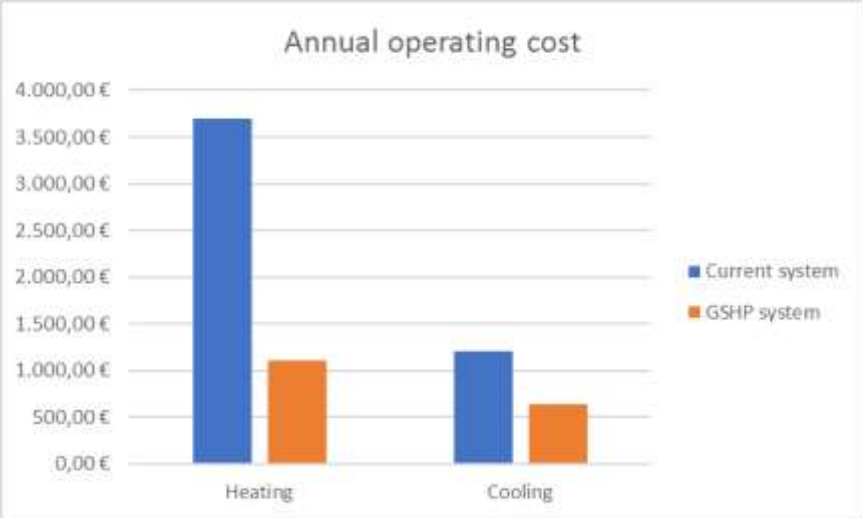


*Figure 33. Evolution of total operation and maintenance costs over time.*

### 7.1.3 Feasibility analysis

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 30-year graphic analysis is made (Figure 34). The graph has two series that show the accumulated expenses, including the annual consumption and maintenance expenses shown in 7.1.1 and 7.1.2: red series shows the cost with the current installation and the green series the one with the GSHP installed. Boiler and A/C maintenance decennial expenses are considered to start the first year of study.

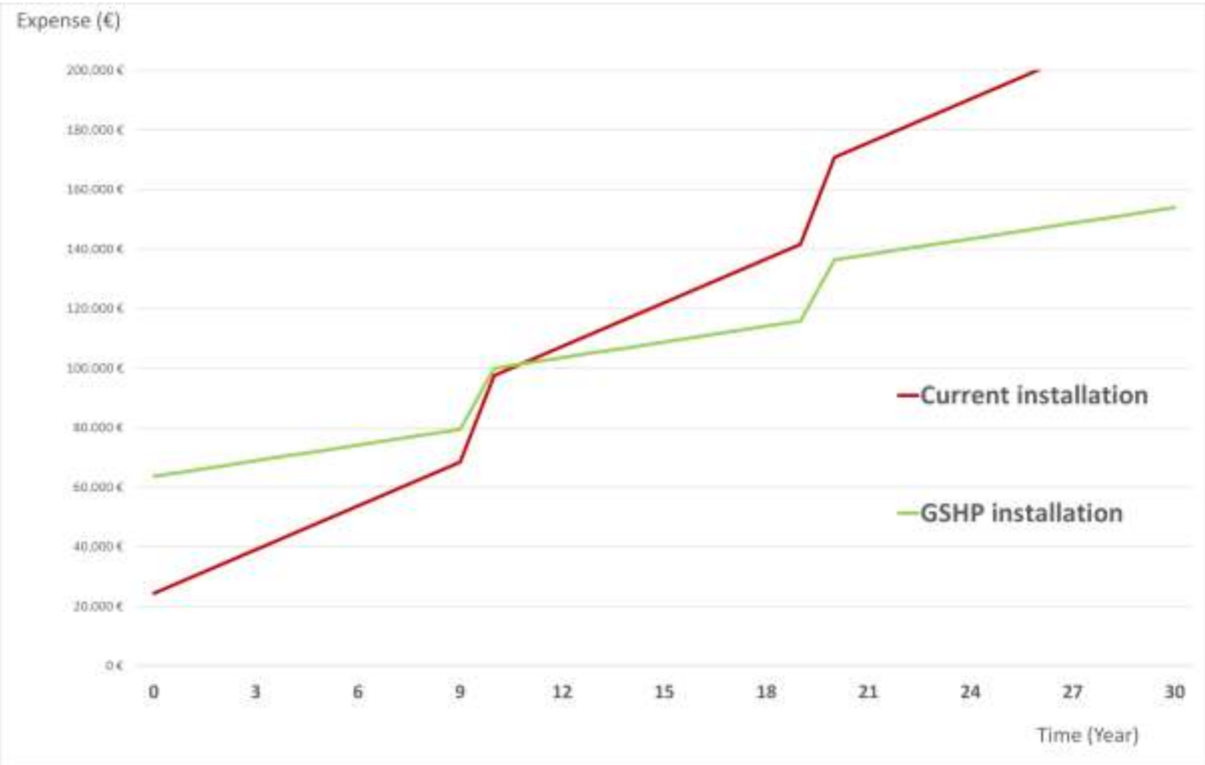


*Figure 34. Evolution of total operation and maintenance costs over time.*

The graph shows that the high cost of installing the GSHP complete system. “Year 0” starts with the 63614.19€ 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 heat pump system more profitable than the current one in 10 years and 9 months, increasing the savings over the years.

# 8 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 is 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 boiler emissions, that uses natural gas and the A/C electricity emissions are estimated in Table 25.

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).

Figure 35 shows the origin of the energy produced in 2019.

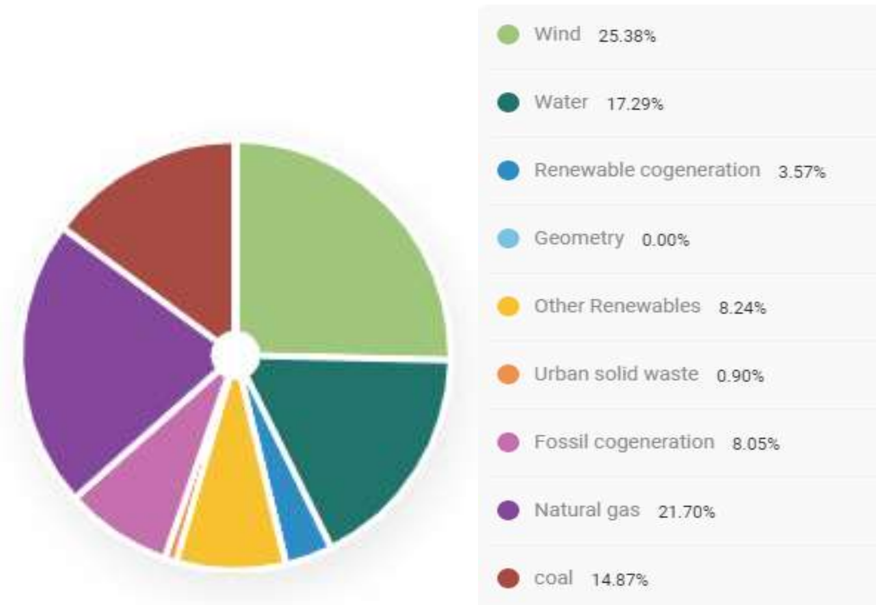


*Figure 35. Source of energy in Portugal in 2019. Taken from EDP (2020).*

Urban solid waste comes from 50% renewable sources and the 100% of natural gas comes from non-renewable sources. The 58.5% of the total energy produced comes from renewable sources.

*Table 25. $CO_2$ emissions by the boiler. Taken from Oficina Catalana del Cambi Climatic (2011).*

| | **Heating** | **Cooling** |
|---|---|---|
| **Useful Energy** | 40960 $kWh$ | 20278 $kWh$ |
| **COP** | 0.68 | 2.5 |
| **Final Energy Consumption** | 60235 $kWh$ | 8111 $kWh$ |
| **$CO_2$ emissions** | 12160 $kg\ CO_2$ | 2030 $kg\ CO_2$ |

The boiler and the A/C system are releasing, in additional to other harmful gaseous pollutants (NOx, $CH_4$, etc.), 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 26.

*Table 26. $CO_2$ 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 11288 kg of $CO_2$ is avoided.

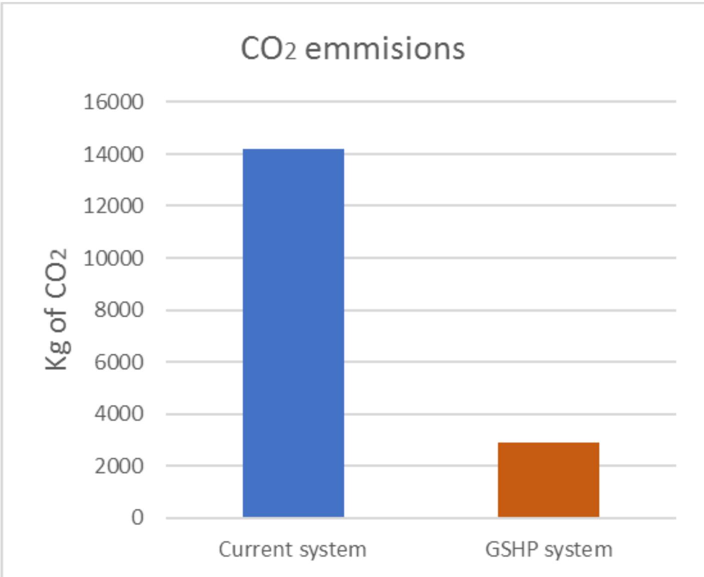


*Figure 36. $CO_2$ emissions by both systems.*

# 9 Concluding Remarks

The relevance 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.

All the data introduced corresponds to the real data of the building and to the case study (or have been estimated with verified bibliography). The geological and climatological data used corresponds to Amadora region. Building materials and distribution were confirmed in the field and with the building's official plans. This guarantees that 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 (3138.74€ saved every year). The substantial initial investment (63614.19€) is amortized in 10 years and nine months. As an example, in 20 years, the savings will be 34422.68€ 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.

Also, as a proposal for deepening the study, it is proposed to investigate how modeling varies in other locations with different climates and geologies. It would also be interesting to see how the model behaves when varying thermostat temperatures or building usage times, as a consideration of different occupant's expectations.

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## Annex 1. Activity level measurement

The following text is extracted from “The Encyclopedic Reference to EnergyPlus Input and Output” (Energy Plus, 2010b):

This field is the name of the schedule that determines the amount of heat gain per person in the zone under design conditions. This value is modified somewhat based on a correlation to account for variations in space temperature. The schedule values may be any positive number and the units for this parameter is Watts per person. This schedule represents the total heat gain per person including convective, radiant, and latent. An internal algorithm is used to determine what fraction of the total is sensible and what fraction is latent. Then, the sensible portion is divided into radiant and convective portions using the value specified for Fraction Radiant (above). See the Engineering Reference document for more details.

Values for activity level can range anywhere from approximately 100-150 Watts per person for most office activities up to over 900 Watts per person for strenuous physical activities such as competitive wrestling. The following table (Table 10) is based on Table 4 from the 2005 ASHRAE Handbook of Fundamentals, page 8.6. In addition to the information from the ASHRAE HOF, there is an added column of values in W/Person such as necessary for the activity level schedule values. This column uses the standard adult body surface area of 1.8 $m^2$ to multiply the activity levels in $W/m^2$ that are used in the table.

*Table 27. Metabolic Rates for Various Activities. Taken from Energy Plus (2010b).*

| Activity | Activity Level W/Person EnergyPlus Schedule Value | Activity Level $W/m^2$ | met* |
|---|---|---|---|
| *Resting* | | | |
| Sleeping | 72 | 40 | 0.7 |
| Reclining | 81 | 45 | 0.8 |
| Seated, quiet | 108 | 60 | 1 |
| Standing, relaxed | 126 | 70 | 1.2 |
| *Walking (on level surface)* | | | |
| 3.2 km/h (0.9 m/s) | 207 | 115 | 2 |
| 4.3 km/h (1.2 m/s) | 270 | 150 | 2.6 |
| 6.4 km/h (1.8 m/s) | 396 | 220 | 3.8 |
| *Office Activities* | | | |
| Reading, seated | 99 | 55 | 1 |
| Writing | 108 | 60 | 1 |
| Typing | 117 | 65 | 1.1 |
| Filing, seated | 126 | 70 | 1.2 |
| Filing, standing | 144 | 80 | 1.4 |
| Walking about | 180 | 100 | 1.7 |
| Lifting/packing | 216 | 120 | 2.1 |
| *Miscellaneous Occupational Activities* | | | |
| Cooking | 171 to 207 | 95 to 115 | 1.6 to 2.0 |
| Housecleaning | 207 to 360 | 115 to 200 | 2.0 to 3.4 |
| Seated, heavy limb movement | 234 | 130 | 2.2 |
| Machine work | | | |
| sawing (table saw) | 189 | 105 | 1.8 |
| light (electrical industry) | 207 to 252 | 115 to 140 | 2.0 to 2.4 |
| heavy | 423 | 235 | 4 |
| Handling 50 kg bags | 423 | 235 | 4 |
| Pick and shovel work | 423 to 504 | 235 to 280 | 4.0 to 4.8 |
| *Miscellaneous Leisure Activities* | | | |
| Dancing, social | 252 to 459 | 140 to 255 | 2.4 to 4.4 |
| Calisthenics/exercise | 315 to 423 | 175 to 235 | 3.0 to 4.0 |
| Tennis, singles | 378 to 486 | 210 to 270 | 3.6 to 4.0 |
| Basketball | 522 to 792 | 290 to 440 | 5.0 to 7.6 |
| Wrestling, competitive | 738 to 909 | 410 to 505 | 7.0 to 8.7 |

*Note that one met = 58.1 $W/m^2$

## Annex 2. Heat Pump (DYNACIAT LG 150A) characteristics

*Table 28. DYNACIAT LG 150A characteristics. Taken from CIAT (2020).*

| | |
|---|---|
| **PERFORMANCE** | |
| **Power source** | Triphasic |
| **Heating power** | 56 $kW$ |
| **COP** | 5,45 |
| **Cooling power** | 47 $kW$ |
| **EER** | 4,67 |
| **SOUND LEVELS** | |
| **Sound power** | 70 $dB$ |
| **Sound pressure at 10 m** | 39 $dB$ |
| **DIMENSIONS** | |
| **Length** | 600 $mm$ |
| **Width** | 1044 $mm$ |
| **Height** | 901 $mm$ |
| **OPERATING WEIGHT** | |
| **Standard Unit** | 220 $kg$ |
| **Unit with evaporator** | 271 $kg$ |
| **Unit with condenser** | 271 $kg$ |
| **TOTAL** | 334 $kg$ |
| **FLUID VALUES** | |
| **Refrigerant (R-410A)** | 4,6 $kg$ |
| **Oil charge** | 3,6 $kg$ |
| **MINIMUM FLOW RATES** | |
| **Evaporator** | 4,5-4,8 $l/s$ |
| **Condenser** | 4-4,2 $l/s$ |

## Annex 3. R410a characteristics

*Table 29. R410a characteristics. Taken from GASSERVEI (2019).*

| **Physical properties R-410a** | |
|---|---|
| **Molecular weight** | 72,6 $g/mol$ |
| **Boiling temperature (1atm)** | -51,58 $°C$ |
| **Boiling temperature desiccation** | 0,1 $K$ |
| **Critical temperature** | 72,13 $°C$ |
| **Critical pressure** | 47,964 $atm$ |
| **Steam pressure** | 3,3 $bar$ |
| **Liquid specific heat (25 ºC)** | 1,84 $kJ/kg * K$ |
| **Steam specific heat (25 ºC)** | 0,83 $kJ/kg * K$ |

## Annex 4. PE100 CHARACTERISTICS

*Table 30. PE100 characteristics.*

| **Feature** | **Value** |
|---|---|
| **Diameter of probe** | 90 $mm$ |
| **Diameter of tube** | 40 $mm$ |
| **Nominal pressure** | 16 $atm$ |
| **Thickness** | 3,7 $mm$ |
| **SDR** | 17 |
| **Welded ballast** | 15 $kg$ |
| **Operating temperature** | −20-30 $°C$ |

## Annex 5. Conversion factors for $CO_2$ emissions

*Table 31. $CO_2$ conversion factors. Taken from Oficina Catalana del Cambi Climatic (2011).*

| | |
|---|---|
| **Conversion factor (boiler)** | 10,65 $kWh/Nm^3$ |
| **Emission factor (boiler)** | 2,15 $kg\ CO_2/\ Nm^3$ |
| **Emission factor (cooling)** | 0.25033 $kg\ CO_2/\ kWh$ |