

Feasibility study for application of a ground source heat pump

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Masters Dissertation

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Master's in mechanical engineering

September 2021

Resumo

O presente trabalho retrata a possibilidade de substituição de uma caldeira a gás por uma bomba de calor geotérmica. O edifício em questão é uma igreja construída em 1930 e situa-se em Cork, Irlanda. O sistema de distribuição de água quente (sistema hidrónico) dispõe de antigos radiadores de ferro fundido que transmitem o calor para o interior da igreja. Como a cidade de Cork apresenta um clima temperado oceânico, o arrefecimento não será tema do trabalho, focando-se simplesmente na substituição da fonte de calor existente mantendo o sistema de distribuição (radiadores com bombas circulantes). Para um melhor aproveitamento das energias renováveis, será estudado a hipótese de instalação de painéis fotovoltaicos no telhado da igreja, de modo que se consiga diminuir a necessidade de consumo elétrico de rede contribuindo para uma menor pegada ecológica do sistema global e redução de custos.

O trabalho começou com a fase de enquadramento geral na tecnologia da geotermia. Havendo muitas hipóteses disponíveis para o usufruto desta fonte de energia renovável, foi necessário estudar todas as oportunidades que surgiram. Olhando para o país em questão, e através de casos de estudo semelhantes a este, estudou-se uma possível reabilitação do sistema de aquecimento da igreja, usando os recursos geotérmicos de baixa entalpia. Sabendo da boa localização da igreja, que se situa ao lado do rio Lee, quis-se aproveitar a elevada capacidade térmica da terra molhada. Por causa da chuva constante e da presença de aquíferos no subsolo da igreja, a terra adquire uma boa condutibilidade e difusidade térmica, facilitando assim, a transferência de calor para as sondas geotérmicas. Foi decidido devido à falta de espaço que as sondas deviam ser inseridas na vertical com uma profundidade de 75 m, pois a igreja encontra-se no meio da cidade.

O software *TRNSYS* dispõe de muitas funcionalidades que foram usadas para a realização das simulações dinâmicas. Depois de se ter analisado o edifício em questão e o seu clima, assim como o seu perfil típico de serviço, inseriram-se os dados no *TRNBuild*, um subprograma que caracteriza a envolvente da igreja e calcula os coeficientes de transferência de calor. Numa primeira fase modelou-se a caldeira de gás com uma potência máxima de 103 kW e mais tarde decidiu-se analisar o comportamento térmico de uma bomba de calor usando primeiramente radiadores e depois piso radiante. É necessário realçar que os valores de consumo são tão elevados, pelo facto de a igreja ser utilizada todos os dias e de em Cork ser necessário algum aquecimento no verão (dependendo da temperatura de conforto).

Uma vez determinadas as necessidades de aquecimento do edifício ao longo do ano, escolheu-se o mês de janeiro, considerando ser este o mês mais frio, para dimensionar a bomba de calor. Escolheu-se a WW 125 SR da WAMAK de 89 kW que permite o alcance da temperatura perto dos 75 °C, ideal para o uso em radiadores. Os módulos fotovoltaicos escolhidos para a simulação são da SolarWorld com um pico de 280 Wp e um rendimento de aproximadamente 16%. Maximizou-se o espaço disponível no telhado da igreja com duas linhas de 30 módulos em série, que nos permitiu uma geração anual de 10 645 kWh de corrente alternada, através de um inversor, que pode ser injetada diretamente no sistema. Conclui-se que o pavimento radiante se torna muito atrativo para este caso de estudo, tendo em conta que as temperaturas de saída exigidas são muito menos elevadas (40-60°C), melhorando o COP na ordem dos 3.5, e reduzindo o tempo de retorno de investimento.

Abstract

The present work portrays a possibility of replacing a gas boiler with a geothermal heat pump. The building in question is a church built around 1930 and is in Cork, Ireland. The hot water distribution system (hydronic system) has old cast iron radiators that transmit heat to the interior of the church. As the city of Cork has a temperate oceanic climate, cooling will not be discussed in this work, which focus on replacing the existing heat source while maintaining the same distribution system (radiators with circulating pumps). For a better use of renewable energies, the hypothesis of installing photovoltaic panels on the roof of the church will be studied, to reduce the need for electrical consumption of the grid, contributing to a lower ecological footprint of the global system and the associated costs.

The work started with the general framing phase in geothermal technology. With many possibilities available for the use of this renewable energy source, it was necessary to study all the opportunities that arose. Looking at the country in question, and through similar case studies, it was decided that it would be interesting to rehabilitate the church's heating system, using low-enthalpy geothermal resources. Knowing the good location of the church, which is located next to the River Lee, we wanted to take advantage of the high thermal capacity of the wet soil. Due to constant rainfall throughout the year and the presence of aquifers in the subsoil of the church, the earth acquires good thermal conductivity and diffusivity, thus facilitating the transfer of heat to the geothermal probes. It was decided due to the lack of space that the probes should be inserted vertically with a depth of 75 m, as the church lies in the middle of the city.

TRNSYS has many features that were used to perform dynamic simulations. After analyzing the building in question and its climate, as well as its typical service profile, the data was inserted in *TRNBuild*, a subprogram that characterizes the church's envelope and calculates the heat transfer coefficients. In the first phase, the gas boiler was modeled with a maximum output of 103 kW. It is necessary to emphasize that the consumption values are so high since the church is used in a daily basis and that in Cork some heating is necessary in the summer (dependent on the comfort temperature).

Once the building's heating needs were determined throughout the year, the month of January was chosen, considering this to be the coldest month for dimensioning the heat pump. The WW 125 SR of WAMAK (89 kW heating capacity) was chosen, which allows the outlet temperature to reach around 75 °C, ideal for use in radiators. The photovoltaic modules chosen for the simulation are from SolarWorld with a peak of 280 Wp and an efficiency of approximately 16%. The space available on the church roof was maximized with two lines of 30 modules in series, which generates 10 645 kWh of alternating current (using an inverter) per year, which can then be injected directly into the system. One can conclude that the radiant floor is a very attractive solution for this case study, considering that the required outlet temperatures are much lower (40-60°C), improving the COP in the order of 3.5, and reducing the return-on investment

Agradecimentos

Em primeiro lugar quero agradecer à minha orientadora na FEUP, Professora Ana Palmero, pela oportunidade de realizar este estudo. Apesar da mobilidade até Cork não ter sido possível, por causa do contexto pandémico que se vive, a professora manteve-se disponível para me ajudar nos cálculos, orientando me para que conseguisse concluir este trabalho, facilitando também o acesso ao programa *TRNSYS*.

Um grande agradecimento ao Fr. John Fitzgerald e à Mrs. Carla da paróquia do Sagrado Coração de Jesus de Cork, que com a toda amabilidade e disponibilidade me enviaram fotografias da igreja e do equipamento de aquecimento, que me permitiu prosseguir com os cálculos necessários.

Agradeço ao Professor Sreto Boljevic da universidade de Munster pela ajuda e apoio que me deu ao longo deste semestre, estando disponível para responder e clarificar as dúvidas que foram surgindo.

Quero também agradecer ao Engenheiro João Sousa, que me enviou os dados necessários para a escolha acertada da bomba de calor e sugestões que ajudaram a desenvolver este projeto.

Por fim, mas não menos importante, agradeço a toda a minha família e amigos que estiveram sempre presentes ao longo deste percurso e que me apoiaram e incentivaram quando mais precisei.

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List of acronyms

BHE – Borehole Exchanger

CAP - Climate Action Plan

EC – European Community

CFC - Chlorofluorocarbons

COP - Coefficient of Performance

DECC - Department of Energy and Climate Change

GSHP - Ground source heat pump

HCFC - Hydrochlorofluorocarbons

HDPE - High density Polyethylene

HFC - Hydrofluorocarbons

MTU - Munster Technology University

NMP - National Mitigation Plan

TRNSYS - Transient Simulation System

PV - Photovoltaic

SEAI - Sustainable Energy Authority of Ireland

UK – United Kingdom

VAT - Value Added Tax

Nomenclature

ach – air change per hour

A_{drilling} – required area to drill (boreholes) [m^2]

A – area [m^2]

h – coefficient of convection [$\frac{W}{m^2K}$]

l – length of the pipes [m]

l_{length} - length of boreholes [m]

l_{distance} - distance between boreholes [m]

n – number of boreholes

η - gas boiler efficiency

Φ - diameter of pipes [mm]

P_{Earth} - power extracted from the soil [kW]

P_{El} - electrical power input [kW]

ρ – air density [$\frac{kg}{m^3}$]

Q - heating power [kW]

Q_{pipes} - heat loss of pipes

T_{int} - inside temperature [$^{\circ}C$]

T_{ext} - outside temperature [$^{\circ}C$]

V_{air} - infiltration flow rate [$\frac{m^3}{s}$]

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1. Introduction

1.1 Project framework

The present work is the result of an Erasmus+ Internship in Ireland, however due to the context of the covid-19 pandemic, it was not possible to be carried out. The MTU would be available to host, however it was decided to do the work remotely, and the necessary data for the realization of this study was sent via email.

This case study is part of a project called “GeoAtlantic”, which aims to explore the use of geothermal energy in communities through the joint development of tools and methodologies to create necessary conditions to favour the energy transition in the Atlantic Area.

The Sacred Heart Church that serves as a case study for the realization of this dissertation, is in Cork, Ireland. This building is a catholic temple dedicated to the worship of the Sacred Heart of Jesus. The church was built in 1930 and has a maximum capacity of 300 people, although nowadays, people don't go as often as they used to. Currently, the church has a hydronic system of radiators supplied by a gas boiler for space heating and is therefore a good example for retrofitting an old building with a ground source heat pump (GSHP).

The geothermal heat pump makes use of the heat stored underground or in groundwater for air conditioning and domestic hot water production. This technology produces fewer polluting agents and uses a low consumption of conventional electricity due to having a higher performance. Changing the heat source of the church will contribute to suppress the building thermal needs from fossil fuels and photovoltaic cells will be installed to reduce grid consumption of the pump.

1.2 Motivation

Energy is becoming a conditioning factor in future socio-economic development. One of the main challenges facing society is to meet the energy demand at the time and place. The current development paradigm is unsustainable in the medium and long term due to crisis and disruptions resulting from an increasing shortage of fossil fuels and the resulting environmental degradation. Without abundant and economic accessible sources of energy that are harmless for the environment, it is not possible to ensure the maintenance of the current paradigm. There is a strong global trend for countries to decrease their dependence on fossil fuels, motivated by the need to control carbon dioxide emissions to the atmosphere. This transition is possible but requires a new order of investment priorities supported by a national and global level including a change in behaviour and mentality [1].

Achieving a high energy efficiency means lower consumption, which leads to lower energy bills, environmental protection, and countries reliance on external suppliers of oil and gas. To emphasize the importance of these goals, the EU has been setting targets to reduce greenhouse gas emissions, improve energy efficiency and enlarge the renewables share on energy [2]. Countries like Ireland, France, and the UK, are still far from achieving on what has been agreed [3], as one can see in Figure 1. However, they take part on the project “GeoAtlantic” and can

use this opportunity to explore and promote geothermal energy. Figure 2 illustrates the low impact on carbon dioxide of geothermal energy comparatively to fossil fuels [4].

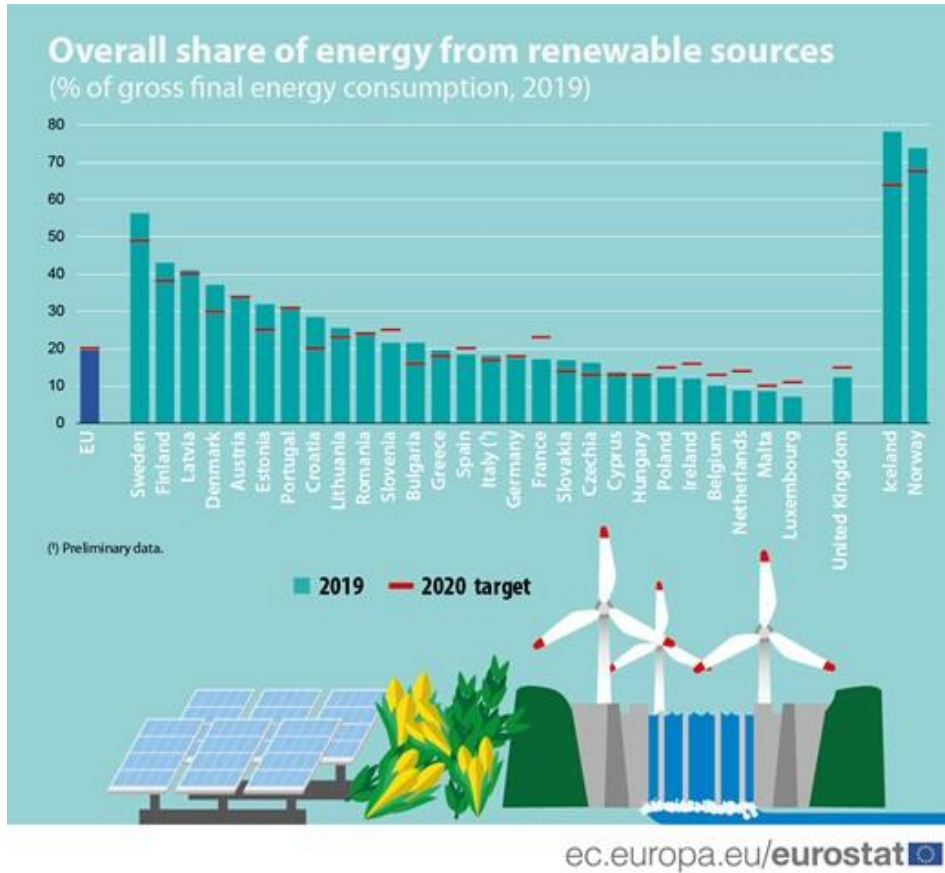


Figure 1- Share of energy from renewable sources [2]

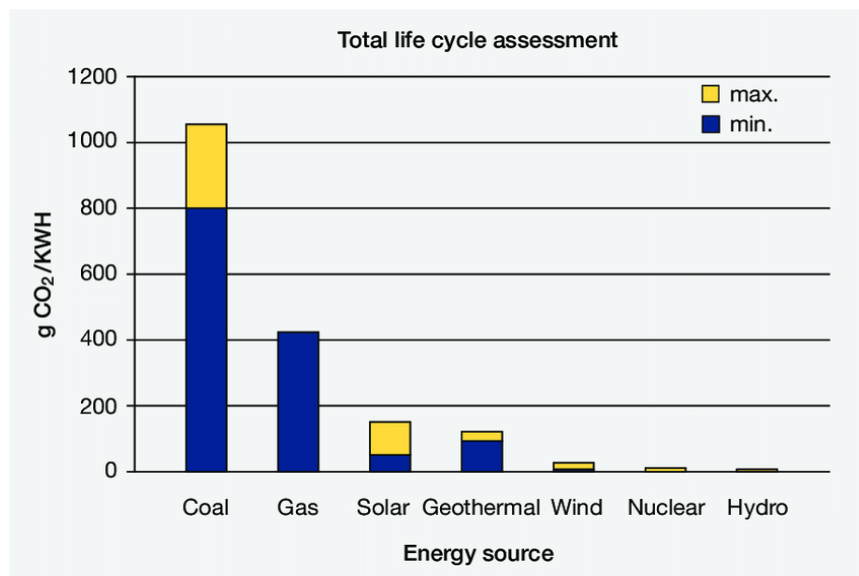


Figure 2 – Energy sources impact on carbon dioxide [4]

According to the European directive n° 2010/31/CE, 40% of the total energy consumed in the EU is due to commercial buildings and households. Since the sector is in continuous growth, an increase in this consumption is expected over the years. Consequently, the use of energy from renewable sources is an important measure to reduce the EU’s energy dependency and greenhouse gas emissions [5].

Figure 3 shows that Ireland has always had very high energy dependence values, and in recent years it has managed to decrease. The increase of 220% in renewable energies between 2005 and 2017 and the exploration of the Corrib gas field have been one of the main reasons for this improvement [6].

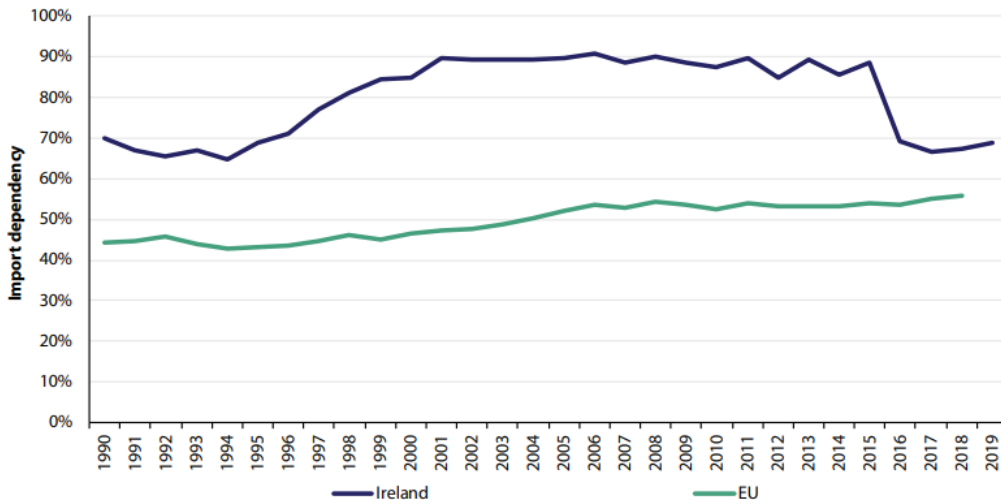


Figure 3 – Ireland’s Import Dependency [6]

This import dependency of Ireland can be fought using more renewables sources for instance in the energy used for heat, since the value stagnated at 6.3% in 2019. Geoatlantic’s project proposes innovations and new technologies that can facilitate the optimal exploitation of resources of the regions where the change to a new energy model has already started, like the case from Ireland [6,7].

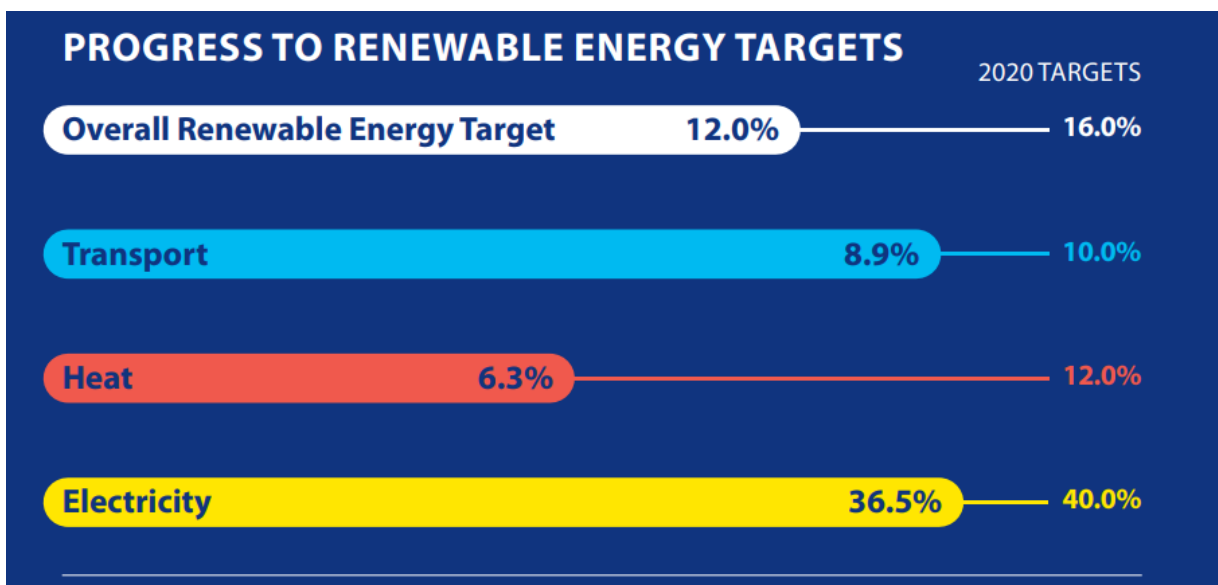


Figure 4- Ireland’s renewable energy targets [6]

1.3 Objectives

As already mentioned on the cover, the title is called “Feasibility study for application of a ground source heat pump”. This means that this work will study the use of a geothermal heat pump and the repercussions that will derive from it. For the development of this work, the hydronic system already installed will be considered, leaving it only to change the heat source to a renewable one, in this case, geothermal energy. The software *Transient System Simulation Tool or TRNSYS* will be used to predict and calculate the data of a hypothetical implementation of a heat pump combined with a PV-system. This simulation will allow to obtain the respective heating loads, bringing this behaviour as close as possible to the real model.

It is essential to understand the potential of low enthalpy geothermal resource existing in the site to make the most out of this source and with it maximize the energy efficiency of the heat pump. Studies will be made to ensure that the new energy source will achieve the same results as the gas boiler, so that the occupants won't feel any difference.

After evaluating the data, it is important to compare them in economic and ecologic terms, as well as the weight of each one in reducing the overall consumption of the existing system. Different approaches of heating systems for the church will be reviewed and finally the difference of the performance will be calculated for all analysed solutions using the geothermal heat pump.

The feasibility study should compare the results as it analyses the most efficient one including a simulation of time for return on investment.

2. State of the art

In this section, the knowledge about geothermal energy and all its surroundings is deepened, to explain the results obtained and the proposed solution. It is therefore an important chapter since it serves as basis of all the work done.

2.1 Geothermal energy

This energy lies dormant beneath the surface of the earth and most of it is produced when radioactive elements decay in the earth's crust or mantle. It heats the rock and the water-bearing layers, so it can be easily accessed if we bore into the earth. The available potential exceeds the energy required by mankind many times over. Energy for electricity, heating, or cooling can be generated emission-free from geothermal energy. Continuous flow of energy is available regardless of the weather, time of day or season what makes geothermal an attractive energy supply.

Like biomass and hydropower, it is not only capable of peak loads but also of base loads. Another positive aspect is their particularly small space requirement in relation to performance. It can therefore play an important role in the energy mix of the future. Iceland, for instance, already covers most of its heating and electricity needs with geothermal energy [8]. It is important to note that the presence of this energy on the surface is dependent on various geological phenomena, not being of a uniform character, favouring areas where the earth's crust is less thick or close to places where geological accidents occur, as is the case of failures. Figure 5 illustrates that the countries with the greatest geothermal power generation capacity are precisely those where there are volcanic activities [9].

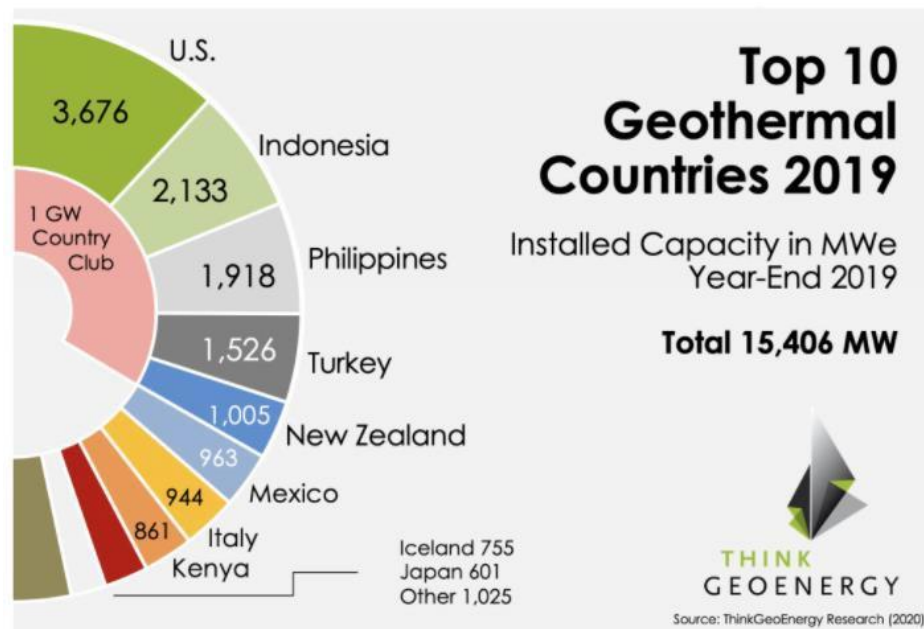


Figure 5- Top 10 Geothermal countries 2019 [9]

This renewable energy is harnessed through the presence of a fluid, usually water, that transports heat from the earth's interior to the surface. Conventional geothermal is characterized by storage in a geothermal reservoir (composed of a fluid), which can be used to produce electricity or heat. Geothermal reservoirs are classified according to the temperature at which the heat-carrying fluid is found.

- High enthalpy reservoirs ($T > 150\text{ }^{\circ}\text{C}$)
- Medium enthalpy reservoirs ($150\text{ }^{\circ}\text{C} > T > 100\text{ }^{\circ}\text{C}$)
- Low enthalpy reservoirs ($100\text{ }^{\circ}\text{C} > T > 30\text{ }^{\circ}\text{C}$)
- Very low enthalpy reservoirs ($T < 30\text{ }^{\circ}\text{C}$)

Most of the countries in Europe will have great difficulties in being able to look at geothermal as a great resource to produce energy, because of its geology. However, this does not mean that it is not a very important resource, in terms of the use of heat, either for industrial purposes or space-heating. It is possible to find in some regions aquifers near the surface with temperatures between 40 and $75\text{ }^{\circ}\text{C}$, which can be used for thermal supply purposes. For this renewable energy to get its full potential, it is necessary to invest more in the geological knowledge of the territories [10].

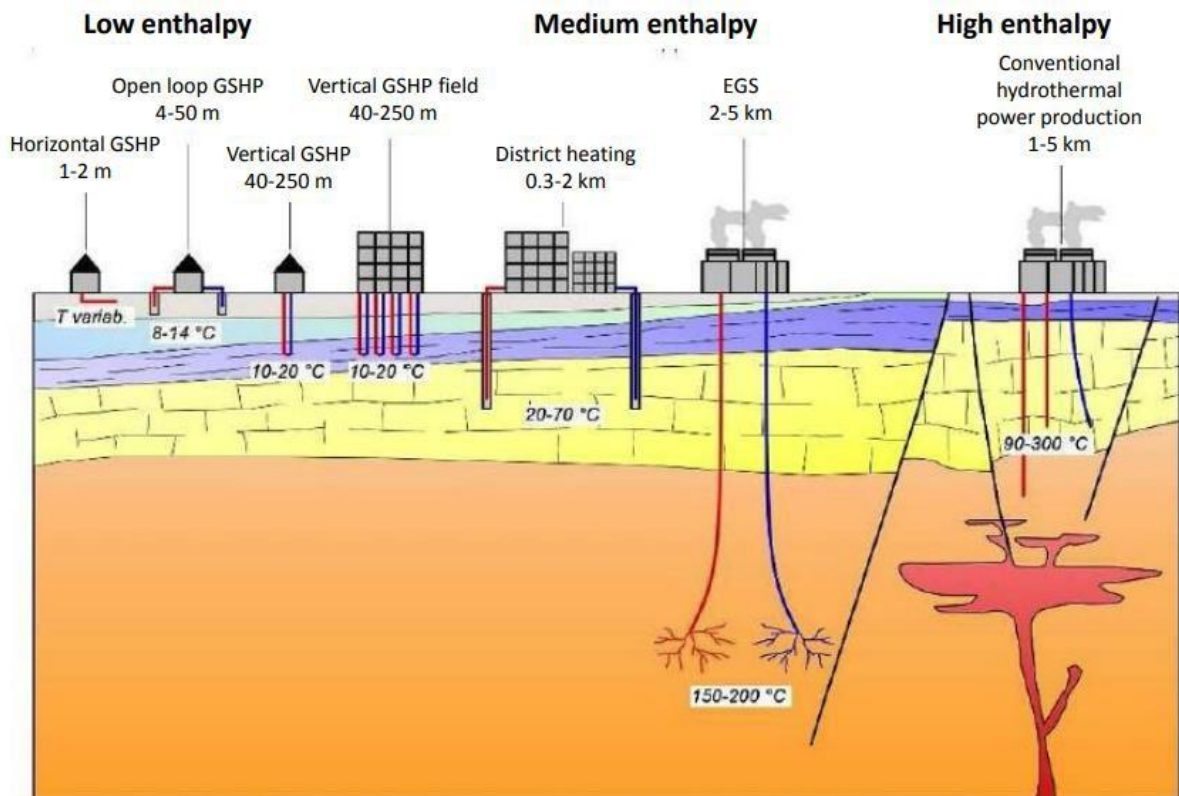


Figure 6- Geothermal reservoirs [11]

2.2 Geothermal energy in Europe

Europe is the world leader in geothermal direct use and there is a huge potential regarding aquifers. It is used in 32 European countries, accounting for over 40% of world's direct utilisation. Figure 6 shows us that in addition to low enthalpy locations, several sites also contain high temperatures areas which are often directly linked to the active volcanic systems. These underground conditions are favourable for power generation [11].

Figure 7 shows the most suitable European areas to drill until a depth of 50 m. However, there are regions which apparently have low index value that can still be advantageous for drilling. Areas close to the coast or alluvial plains coursed by a river are some examples [12].

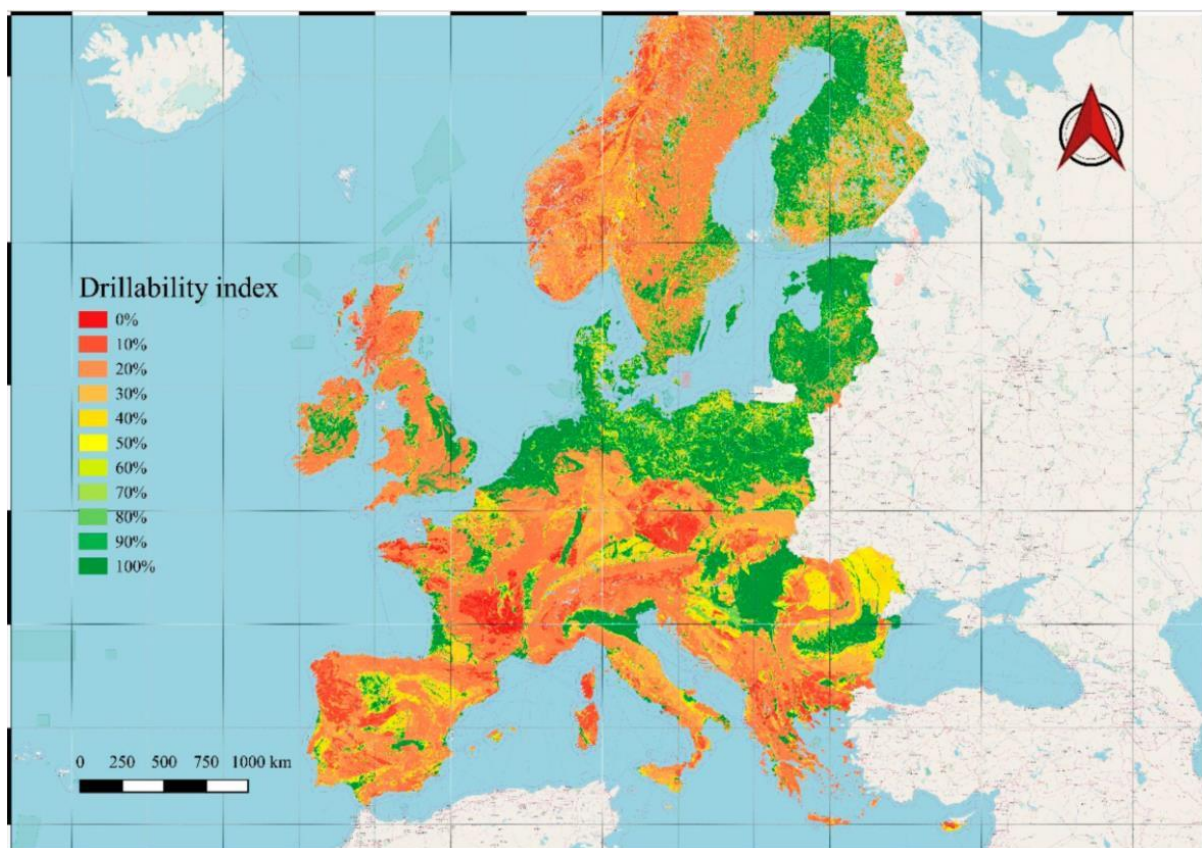


Figure 7- Drillability index (50m depth) [12]

Different regions make use of different technologies and so countries like Iceland, Italy and Turkey which have high-temperature resources, can generate power. France, Germany, Poland, Hungary, and Romania use hydrothermal resources in sedimentary basins for direct use and since geothermal energy is available everywhere and it can be seized by ground source heat pumps both for heating and cooling. Figure 8 illustrates the installed capacity of European countries to produce electricity and one can notice the relationship between tectonic/volcanic activity and availability of geothermal energy [13,14].

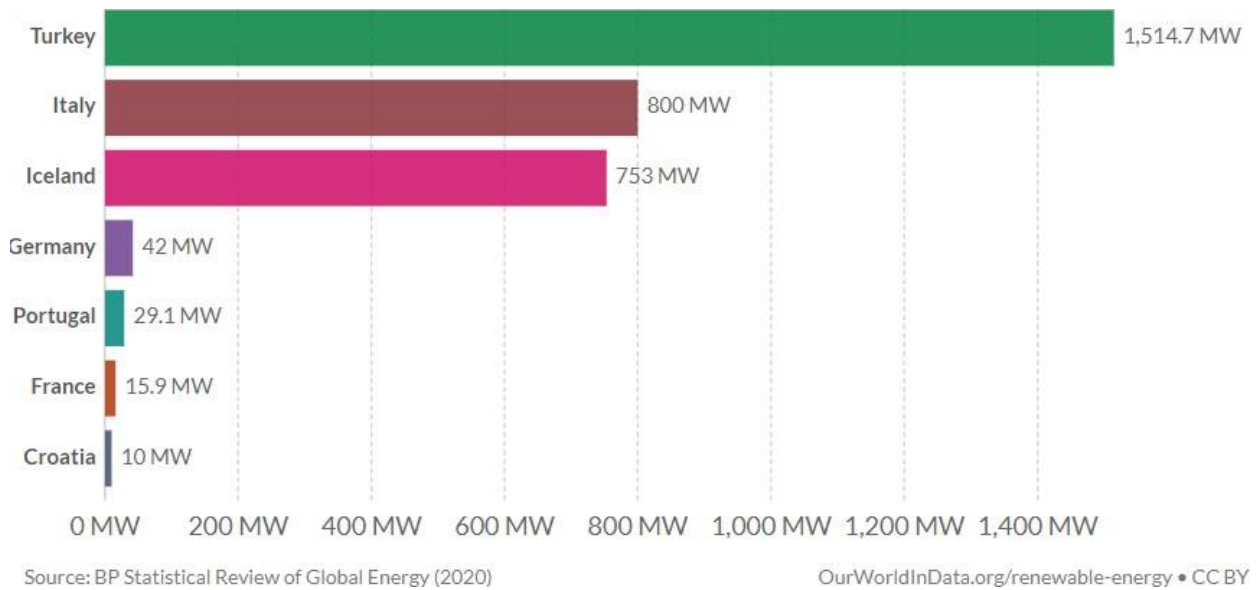


Figure 8- Installed geothermal energy capacity 2019 [14]

2.2.1 Geothermal in Ireland

Ireland’s geothermal map indicates a high potential for the use of ground source heat pumps. Although volcanic activity is not present in its subsoil, Ireland has good conditions for using the previous mentioned aquifers. Shallow geothermal energy resources are favoured by the Irish climate that is warm and has mild maritime conditions. Constant rainfall keeps moisture in the ground which works as an excellent conductor, allowing heat to move towards a thermal collector system. Closed and open loop technologies are therefore the most common applications used in the Irish soil [15].

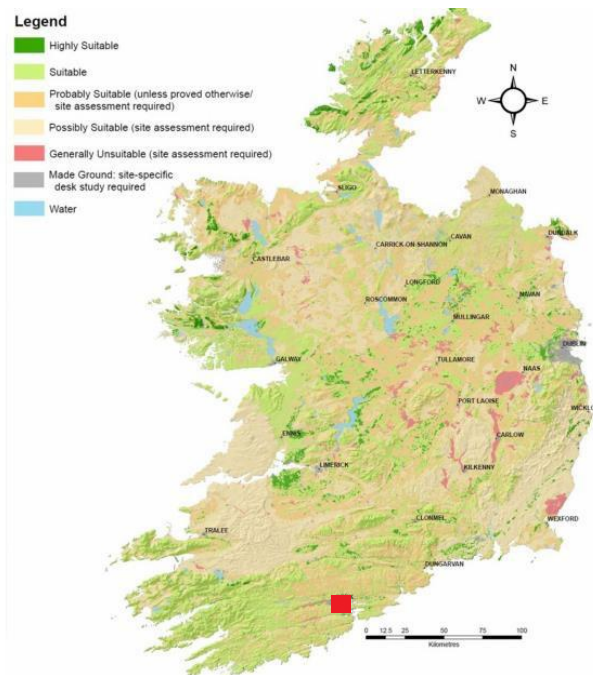


Figure 9- Vertical Closed Loop Collector Suitability Map (GSI,2016)

Ambient energy (ground-source and air-source) has grown more than ten times between 2005 and 2019 and is responsible for 17% of renewable heat energy in 2019. For this reason, fossil fuels used for heat has reduced by 16%, which contributed towards the 12% for renewables target set by the Republic of Ireland [6].

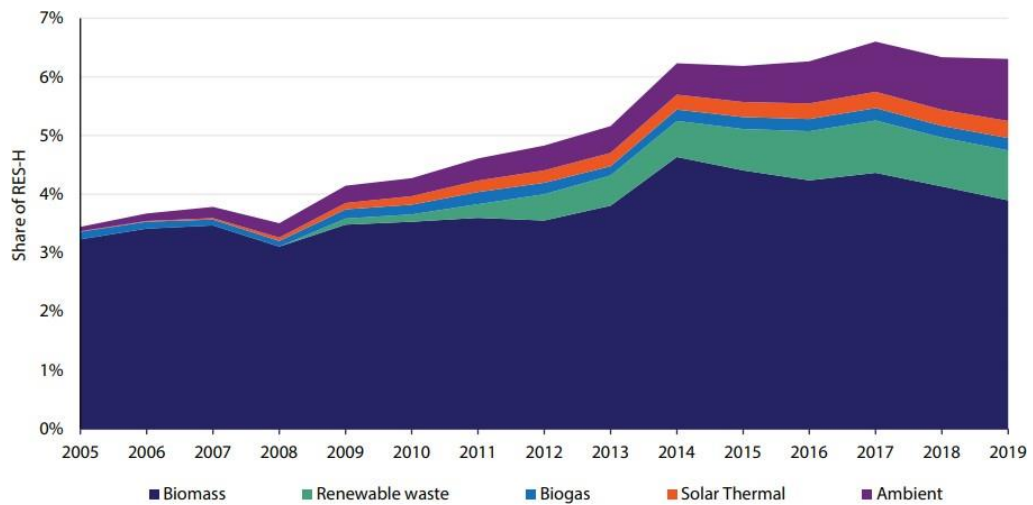


Figure 10- Renewable energy contribution to thermal energy (SEAI,2020)

2.2.1.1 Legal framework of geothermal harnessing

According to the Statutory Instrument No.147 of 2011, Ireland has no specific legislation or regulatory framework covering geothermal energy beyond a definition of “geothermal energy” as “energy stored in the form of heat beneath the surface of solid earth”. Although the lack of geothermal legislation does not prevent exploration for, or development of, geothermal energy, it can be riskier and more uncertain to investors (including authorities/municipal users).

The Climate Action Plan (CAP), the National Mitigation Plan (NMP) and the National Renewable Energy Action Plan (2010) support the case for the development of a policy and legislative framework to enable the realisation of Ireland’s geothermal energy potential. It is very important to speed up the process of legislation for this energy source, so that the country and the main investors can organize and govern themselves by the standards accepted by the European community. The Department of the Environment, Climate and Communications (DECC) developed a guide plan with different stages to establish a policy and regulatory framework for geothermal energy in Ireland, summarized in Table 1 [16,17].

Table 1- Action Plan from the DECC [16]

Stage	Milestone	Timeframe
Activation Stage	Publication of the technical and non-technical roadmaps	Immediate – complete
Development Stage	Prepare draft policy statement	Q3 2021
	Undertake public consultation on draft policy statement	Q4 2021
Finalisation Stage	Publish final policy statement Prepare supporting legislation	<ul style="list-style-type: none"> • To Minister/Government by • Seek to secure Oireachats approval by
Implementation and Review Stage	Implementation and review	2022 onwards

2.3 Heat Pumps

To transfer heat from a cold to a warm source there are some equipment that use physical processes like for example, heat pumps. The most well-known and widespread machines are essentially consisting of a closed circuit, where a fluid (refrigerant) is continuously compressed and expanded. In every compression/expansion cycle, the fluid removes a little heat from the cold fluid and transfers it to the hot one. Air would be the logical choice for the fluid, since its abundant, ecological and does not cost money. However, it is not used because it involves work cycles with very low thermal yield. In other words, there is not enough heat that one can extract from.

The heat pump efficiency, or “coefficient of performance” (COP), is usually indicated as the system performance coefficient and whose values are typically between 2.5 and 6, depending largely on the temperatures of the source and the desirable temperature. This means that removing heat from a given power supply requires only 1 kW of electricity to generate between 2.5 and 6 kW of thermal power. In this case the heat pump system is consequently about 2.5 to 6 times more efficient than other conventional systems using fossil fuels. COP for heating is defined as the heat supplied to the hot reservoir (Q_H) divided by the work (W) done, explained in equation 1.

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

2.3.1 Operating principles

A heat pump extracts energy from the relatively low temperature of the environment and increases its temperature for heating purposes. Its basic operating principle is based on the use of a heat source (water, earth, or air), from which it draws thermal energy to supply it to the desirable source. Two heat exchangers are required, one to absorb (evaporator) and another to release heat (condenser). Having suitable thermodynamics properties, the refrigerant

temperature can be manipulated by its pressure, and therefore to increase and reduce this property, a compressor and an expansion valve are needed. [18]

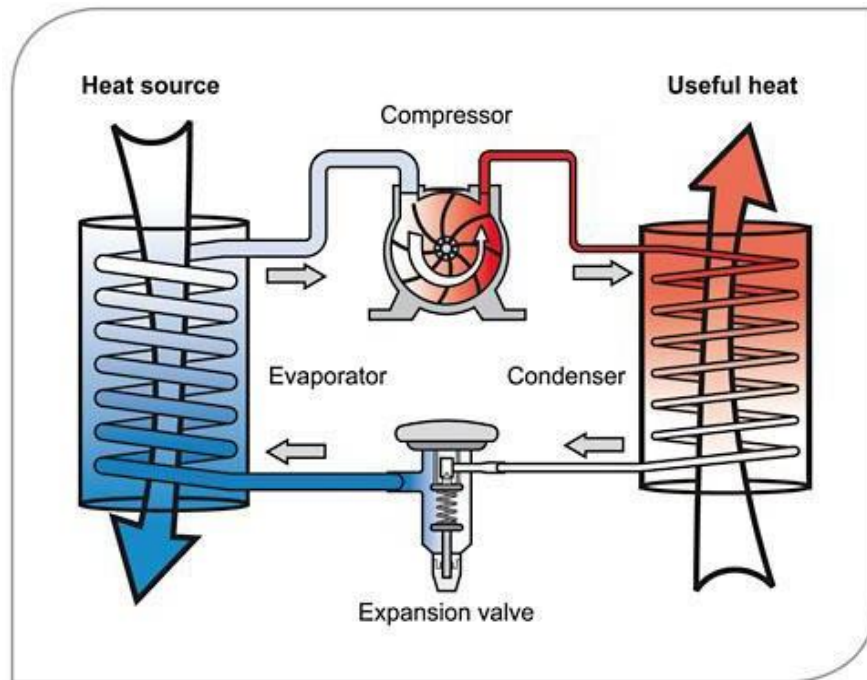


Figure 11- Heat pump principle [19]

According to the second law of thermodynamics, heat is only transferred from a hot source to a cold source. That is why it is necessary to provide work. That is, heat pumps require an external source of electricity. For GSHP the soil represents a "source" (when working in heating) or a "well" (in cooling mode) of heat.

To achieve optimal heat transfer, several types of fluids are used so that they evaporate when heat is absorbed and condense when heat is released. These state passages increase considerably the amount of heat that each work cycle is capable to absorb and yield. In the first case are called heat pumps, in the second refrigerators. Heat pumps are always more efficient at heating than pure electric heaters, based on Joule effect on electrical resistance, even when thermal energy is extracted from the cold air of winter [18].

2.3.2 GSHP

The ground source heat pump (GSHP) takes advantage of the constant temperature and stable soil conditions to increase efficiency and thereby reduce operating costs. These can be combined with heating solar modules, improving further efficiency levels.

Heating/cooling systems using geothermal heat pumps capture a combination of the heat stored in the soil, produced by the sun, along with the heat derived from the magmatic activity inside the earth. Like refrigeration or air conditioning equipment, these systems use the principle of heat pumps to force the transfer of thermal energy. The heat is transferred from a cold place to a warm place against the natural flow direction. They can also optimize the transfer of heat from a warm space to a cold one as explained before.

Unlike aerothermal heat pumps, that move heat to/from outdoor atmospheric air, GSHP exchange heat with the subsoil. Because subsoil temperatures are much more stable and moderate (especially after a certain depth), the systems are more energy efficient throughout the year when compared to air/air systems. During winter, the GSHP extracts heat from the soil to allow space-heating, transferring it back to the ground during summer to space-cooling. Some of these systems are prepared to work only in one of two modes (heating or cooling), depending on weather conditions. The heat exchange with the subsoil can occur in three ways [18].

- Direct exchange, where the evaporator / condenser circuit of the heat pump is in direct contact with the ground.
- Closed circuit systems, where the heat pump performs the heat exchange with the soil indirectly, through a hydraulic circuit in which a refrigerant fluid circulates.
- Open circuit systems, in which groundwater is collected and where heat exchange occurs.

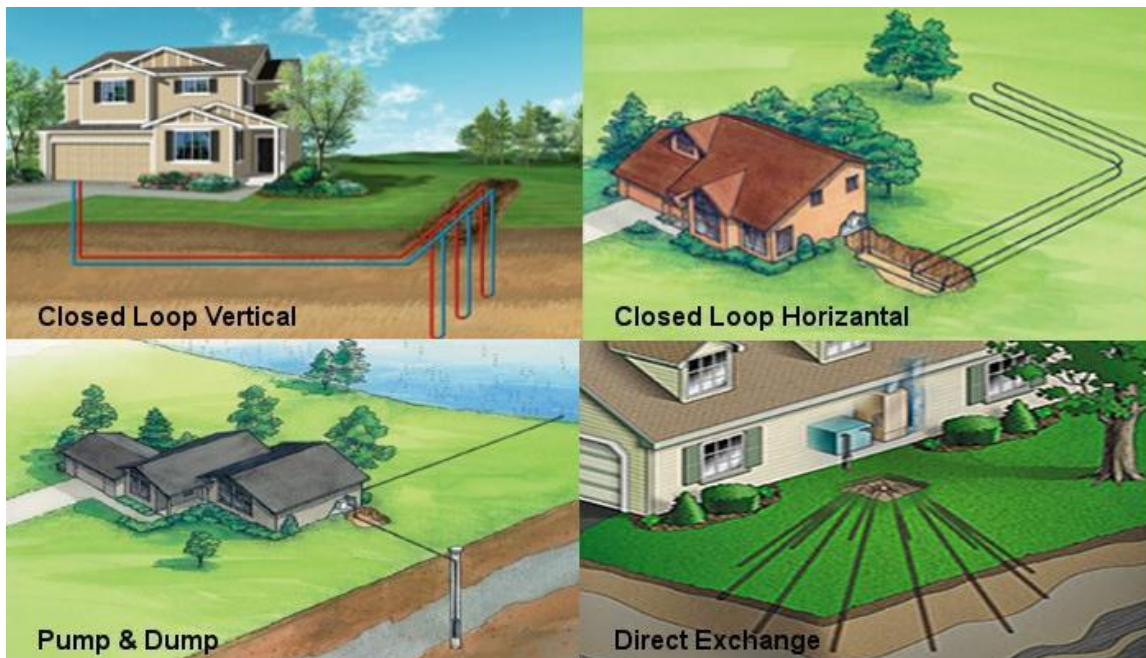


Figure 12- Installation types GSHP [18]

Table 2- Pros and Cons of geothermal systems [20]

	Direct exchange	Closed circuit		Open circuit
		Vertical Loop	Horizontal Loop	
Advantages	Simple and cost-effective Less components Theoretically more efficient, since copper is a highly conductive material	Ideal for limited areas. Constant temperatures	Lower installation costs Easier maintenance	Lowest installed cost Low maintenance Low operating costs
Disadvantages	Pipe corrosion since copper piping corrodes far more easily than plastic. Refrigerant leaking can lead to an environmental hazard	Higher installation costs Problems in some geological formations	Require more space to install. Performance dependent on season	Possible damage to piping in public bodies of water. Temperature variations Local water and environmental regulations may restrict use

2.3.3 Vertical loop system

A vertical system can be divided into 3 different closed circuits. In the heating mode, the borehole exchangers (BHE), which can be bored 100 meters deep into the earth, serve as heat exchangers for the first circuit. A mixture of water and an antifreeze serve as a transport fluid and absorb the constant temperature of the earth. This heat will be then used to evaporate the refrigerant that flows in the second circuit (heat pump) and returns colder to the ground. The best advantage of the vertical towards the horizontal system is that the ground temperature below 10 m doesn't vary as illustrated in Figure 13. Another great advantage that makes vertical systems very attractive is the fact that as you dig deeper, the probability of finding aquifers increases. It is known that wet soil conducts heat better than dry land, because of the presence of water [21].

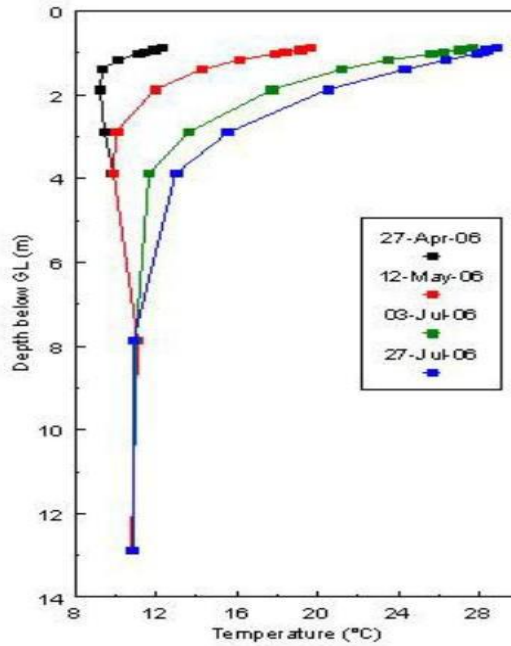


Figure 13- Ground temperature vs Depth in the UK [22]

The refrigerant fluids are characterized by evaporating at low pressures (low temperatures) and condensing at high pressures (high temperatures). When heat is exchanged in the evaporator from the brine (first circuit) to the refrigerant, it turns into gas, being now possible to get compressed and achieve a high temperature level. Low-heat was turned into high-heat, and this will be transferred to the existing heating system of the house through the condenser. If the distribution system is hydronic, the water distributes the heat through house pipping completing the third circuit.

The refrigerant loses a lot of heat and the temperature drops changing from gaseous to a liquid state. With the help of an expansion valve, the liquids pressure and temperature drop considerably. Figure 14 explains briefly the three existing cycles in a vertical GSHP system, where red indicates high temperatures, and the blue colour indicates low temperatures [21].

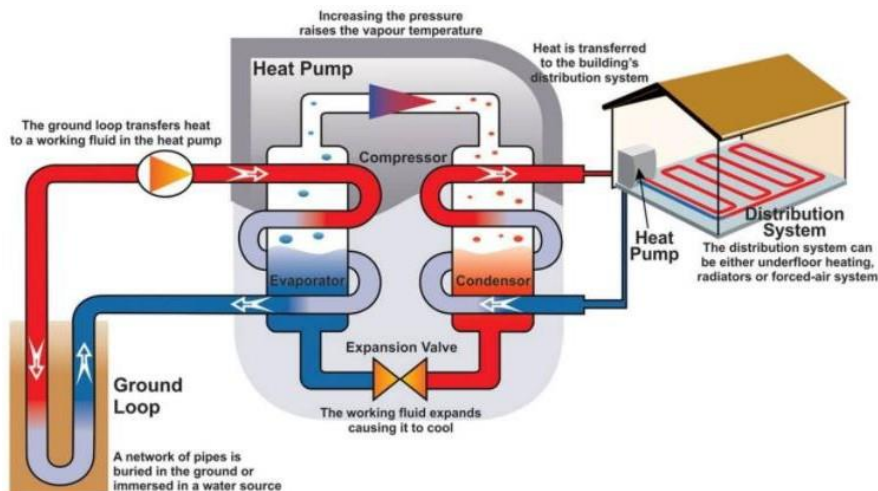


Figure 14-Simplified system [21]

2.3.4 Refrigerants

The role of the refrigerant fluid in the heat pump is very important, since it is responsible for transporting heat between the interior and the exterior. Heat pumps with one compression cycle work in a closed system, which means that the refrigerant will suffer in each cycle, two phase changes.

Nowadays there is a lot of variety in refrigerants that supply the market for heat pumps and refrigerators. Each of them has its advantages and disadvantages and will always depend on the purpose of the application. There are two categories, namely synthetic and natural. The synthetic refrigerants can be subdivided in three groups [24].

- CFCs: Chlorofluorocarbons, like R-12 and R-502. Currently prohibited by its high ozone depletion potential (ODP), in addition to also causing greenhouse effect
- HCFCs: Hydrochlorofluorocarbons, like R-22. They were substitutes for CFC's because they had less destructive power for the environment, although ending up being banned.
- HFCs: Hydrofluorocarbons, such as R-134a, R-407c, R-507a, R-422d. These are free of chlorine and do not destroy the ozone layer but still cause greenhouse effects.

Natural refrigerants include ammonia (R-717), hydrocarbons such as propane and butane (R-290 and R-600a) and water itself (R-718). There are several relevant characteristics when selecting a coolant agent for an application with a certain temperature jump.

- Good thermodynamic properties
 1. Evaporation pressure
 2. Far critical point (Refrigerants working near the critical point experience less heat transfer)
 3. Low freezing point: It's vital that solidification does not occur.
 4. Compression ratio: Lower pressure differences between evaporator and condenser lead to less compression work.
 5. Efficiency in heat transfer: It is desirable to have a good convection coefficient that improve heat transfer in exchangers.
 6. Low pressure losses in its circulation through the circuit
 7. High volumetric cooling capacity: High amount of heat absorbed in the evaporator per unit volume of vapor drawn in by the compressor.
- Adequate security features
 1. Toxicity: this is a disadvantage, for example of ammonia-based refrigerants
 2. Flammability, as occurs for example with hydrocarbons. Not very high working pressures

- Other technical criteria
 1. Action on metals: for example, halogen compounds are incompatible with zinc and magnesium while ammonia is with copper.
 2. Compatibility with plastics, elastomers, and oils
 3. Thermal stability

- Environmental criteria: Refrigerants containing chlorine are prohibited. It is recommended to lower the global warming potential.
- Economic criteria: The more economical, the more viable the installation will be, especially for high power equipment with greater amount of refrigerant fluid [24].

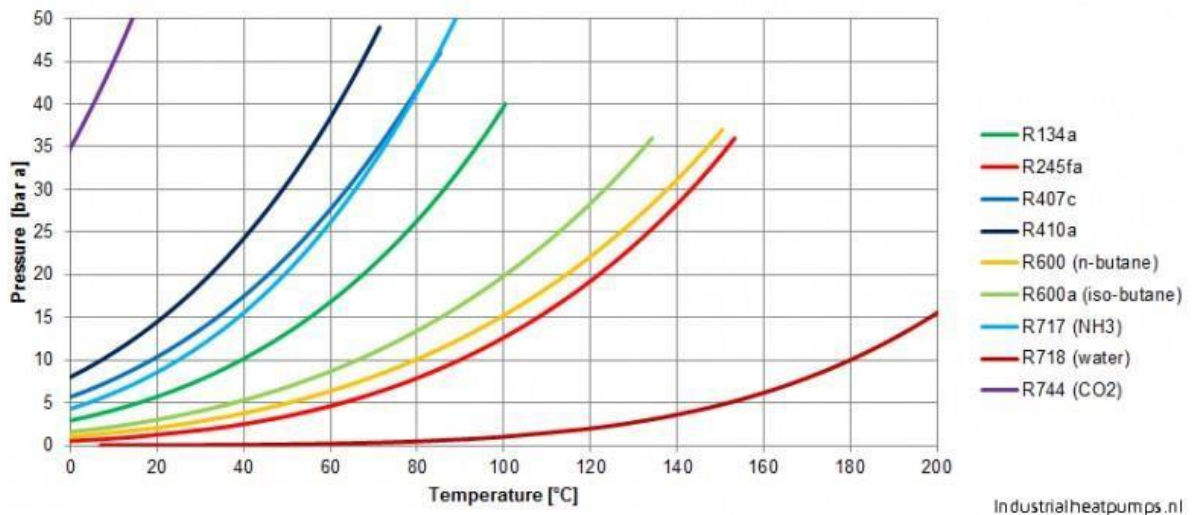


Figure 15- Evaporation temperature vs pressure [23]

For industrial heat pumps, Ammonia is the most suitable refrigerant since it presents high efficiency and can easily be applied below temperatures of 80 °C. It is a natural coolant agent (doesn't contribute to greenhouse effect) and although being toxic, leakages can be easily detected due to its strong odour [23].

3. Case Study

3.1 First considerations and site location

The building intended for the study of this work, illustrated in Figure 16, is a catholic church located near the river Lee, in Cork, Ireland. It was built between 1925-1931 and serves nowadays as a temple for the devotion to the Sacred Heart of Jesus. Appendix A depicts the 3D model, in a simplistic way (used later for the simulation). It is important to approximate the volume, area, and the respective materials of the building in question as well as its climate, to achieve a closer study of reality.

The people in charge of the church explained that there is no need for air conditioning, since the building maintains a balanced temperature for the hottest days, due precisely to the massive structure and the temperate climate. For that reason, only the heating system will be analysed.



Figure 16- Sacred-Heart church 3D [25]

As illustrated in Figure 9, Cork lies in a suitable location for vertical geothermal systems. However, in urban places its necessary to check on a case-by-case basis, as one must see the available space and external influences outside the site. The great advantage of the specific location of this church is due to the presence of the river Lee, that flows less than 50 meters away. This means that the ground beneath the earth is rich in water channels, making the soil wet and thus more conducive to conducting heat so that the system is more efficient [26]. Table 3 explains the difference between the thermal properties of wet and dry soil. It is of great importance since water makes the soil 3-4 times more conductive, enhancing the heat flux of the exchangers (buried in the ground).

Table 3- Thermal properties of different ground types [26]

Soil/Surface Type	Thermal Conductivity $W\ m^{-1}\ K^{-1}$	Thermal Conductivity Reference	Diffusivity m^2/s
Dry Soil	0.138	16	1.1×10^{-7}
Wet Soil	0.657	17	1.9×10^{-7}
Dry Sand	0.326	17	2.74×10^{-8}
Wet Sand	1.128	17	4.92×10^{-8}
Concrete	1.279	17	4.92×10^{-8}

*Estimated from $\alpha = k/(\rho C_p)$ for soil organic matter.

Another important aspect to analyse and consider is the region's climate. The efficiency of technologies that use renewable energy will always depend on the climatic conditions of the site to be applied. Hence, the climatic data from Cork, which will later be used in *TRNSYS* program to simulate the building heating needs, are shown in Figure 17. Cork has an oceanic climate/maritime climate, being the Atlantic Ocean the greatest weather influence that prevents any extremes in Ireland's temperatures [44]. The constant rainfall throughout the year wets the soil, contributing to a continuous regeneration of geothermal energy and reinforcing the optimal performance for this case study.

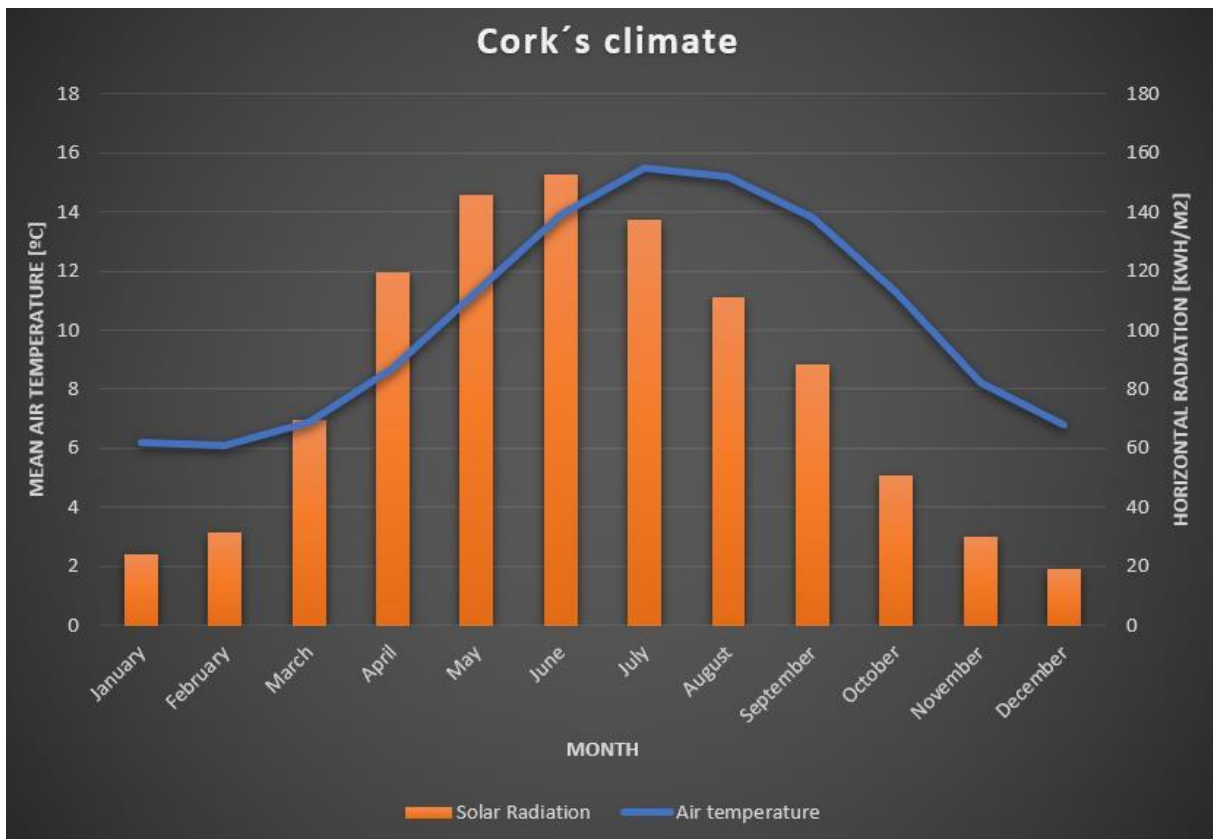


Figure 17- Cork's climate

3.2 Building framework

The church under study is an old building and its construction materials are reduced to stone, wood and plasterboard that surrounds the exterior and interior surfaces. The great challenge for heating a church is to combat the building's heat losses, considering that they are usually old structures and without adequate thermal insulation. Historic buildings like this church are listed as "Ecclesiastical Exemption" (Church of England, Roman Catholic, Baptist Union, Methodist and URC), meaning that these denominations deal with Listed Building issues to the interior of the building themselves [28].

Considering the governing law on historic buildings, it will not be possible to make improvements in the conservation of heat inside the church, since it is protected. However, general measures for the energy improvement of a building, such as insulation on roof, floor, walls, the use of double glazing, will be applied theoretically in this case. According to IRED (2020) a badly insulated house will lose heat in the following proportions:

Table 4 – Proportionate heat loss from old buildings [29]

Roof	25%
Outside walls	35%
Doors and windows	25%
Ground floors	15%

Heat loss equation (2) determines the energy that is transferred between the interior and exterior and can be used for every part of the building presented in Table 4. Each section has its coefficient of convection, which is dependent on the thermal characteristics of the materials used and the meteorological conditions (windspeed for instance).

$$Q = h * A * (Text - Tint) \quad (2)$$

Where:

Q , is the transferred heat, W

h , is the coefficient of convection, $\frac{W}{m^2 K}$

A , represents the area, m^2

$Tint$, is the room temperature, K or °C

$Text$, is the outside temperature, K or °C

Equation 2 indicates that the greater the temperature difference between the interior and exterior of the building, the greater will be the heat loss. As this paper will only be about heating, it is always assumed that the interior will be hotter than the outside, and thus the heat output will have a negative sign, representing a loss in the global system.

TRNSYS will also account for solar radiation, wind, humidity, outside temperature as well as losses due to conduction and radiation. By assuming these losses and gains, the air temperature inside the church will change overtime.

3.3 Building description

Due to the lack of information available on the construction materials used in this church, which is usually the case in very old buildings, this study will take into consideration of a church that closely resembles the present case study [30]. Photographs of the exterior and interior of the sacred-heart church were requested to be able to interpret and verify that this approach is correct. Another point to note besides the stone floor is the presence of many single glazed windows. Bearing in mind that there is one main aisle arched high roof and two side aisle low roof, a ceiling height of 7 m was considered as shown in Table 9.



Figure 18- Interior of the building

Through Figures 16 and 18, it is possible to reach a simplified model that was created with the following characteristics, summarized in the next tables, and introduced in *TRNSYS building project* for further analysis.

3.3.1 Total dimensions and building orientation

Table 5 – Important parameters [27]

Site	Latitude	Longitude	Elevation m	Heating degree-days 18°C	Annual external mean air temperature °C	Annual global irradiation on horizontal plane $\frac{kWh}{m^2 \text{ year}}$
Cork	51.903°	-8.468°	60	2135	9.9	972



Figure 19 - 2D view of the site [25]

3.4 Present heating system

When the current heating system of the church was implemented (it is suspected that it was around the 70s, replacement of the boiler in 1989), the most common practice was used in this type of buildings, namely the hydronic system or “wet” system. As the name suggests these are water distribution systems, where heat is then transmitted, in this case, by cast iron radiators. These radiators can be connected in parallel or in series. The one-pipe method (series) has a big disadvantage because the water passes through all radiators without being reheated. This implies that the water reaches the last elements relatively cold, taking a long time for them to get hot.

Widely used in the 1970s, the two-pipe method (parallel) has the great advantage that all radiators heat up at the same time, since the water after passing through one radiator returns for the boiler to be reheated. Considering small heating systems there will be no major differences between the two methods [31]. In this church there are 10 radiators installed in a parallel configuration.

Water is heated through a fired-gas boiler with a rated 103 kW heat output and then transported through pipes ($\Phi = 1 \frac{1}{2}$ in or $\Phi=38.1$ mm) using a circulation pump. The velocity of the heating water through pipes should not exceed $3 \frac{m}{s}$ and it is important to keep in mind that the radiator itself has its own pipe configuration [32]. An identical scheme is shown in the Figure 20.

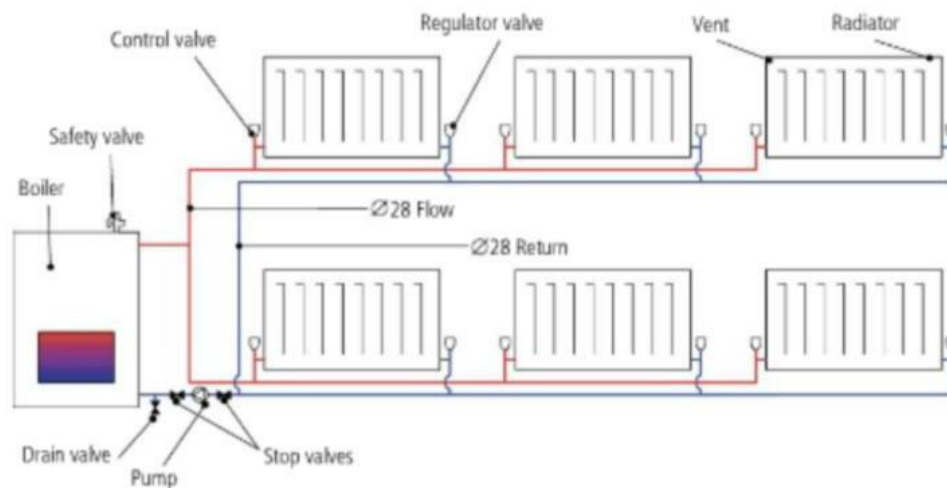


Figure 20 – Radiator two-pipe scheme [33]

Appendix B and C have all the available data provided by gas boiler manufacturer *Buderus Logano 305G*. It was started to be commercialized in 1989 and is still produced today and the burner for this application is the *Riello 40 GS10* which was approved by the EN 676 [34,35]. As the efficiency of this combination approaches 92 % and considering that it can meet great thermal needs quickly, especially on the coldest days, there have been no complaints from regulars of this church over the years.



Figure 21- Gas boiler and burner specifications

Regarding the heat exchange between water and air, the church disposes of 14 old cast iron radiators, previously mentioned. Figure 22 demonstrates that the radiators have 4 columns and 24 elements, being 1.2 m long and 0.9 m high. To be able to estimate the heat output, it was necessary to use information from radiator producers of this type. For that purpose, a copy of the company *MaxHeat* catalogue was analysed and a specimen with the desired dimensions was found with only 4 sections less [36]. This catalogue is available in the Appendix D and provided a value of around 3360 W for this study case, counting 140 W for each section. It is important to have in mind that the heat output of a radiator is highly dependent on the mean temperature between the inlet/outlet and the surrounding temperature, in other words, the heat output is proportional to the temperature of the water inside it.



Figure 22 - Cast iron radiator

Manufacturers and buyers often refer to "thermal amplitude" when trying to estimate the heat delivered by a radiator. This thermal jump value, according to EN 442 is 50 K or °C, assuming normally a room temperature of 20 °C [37,38]. To be able to calculate the heat dissipated by a radiator, it is necessary to consider some characteristic parameters.

$$Q = cp * m \dot{i} * (Tg - Th) \quad (3)$$

$$Q = h * A * (T_{pj} - T_n) \quad (4)$$

$$\varphi * Q = T_n - T_{bz} \quad (5)$$

$$T_{pj} = 0.5 * (Tg + Th) \quad (6)$$

Where: c_p is specific heat capacity of water, $J / (kg K)$, m is water flow rate through every radiator, kg/s ; T_g and T_h are supply and return water temperatures, $^{\circ}C$; T_{pj} is average surface temperature of radiator, $^{\circ}C$; h is heat transfer coefficient of radiator, $W/m^2 * C$; T_n is room air temperature, $^{\circ}C$; T_{bz} is base temperature of non-heating room, $^{\circ}C$; Q is heat supply to room from radiator, J ; φ is room thermal response factor to heat supply from radiator [49].

A typical church's minimum temperature was set at $10-12^{\circ}C$, to preserve artifacts and its own interior [39]. The author also reveals the need to reach $18^{\circ}C$ as a comfort temperature, admitting in some cases that $20-23^{\circ}C$ would be more suitable, like in this case study due to the advanced age of most of the churchgoers and low attendance. For this setting conditions to be reached throughout the winter, the boiler itself allows to regulate the desired water temperature that supply the radiators.

Figure 23 shows the adjustment at $75^{\circ}C$, being a typical temperature for radiator heating, allowing it to have a high heat dissipation. Equation 3 can this way prove the average “thermal amplitude” of $50-60^{\circ}C$. (Assuming the typical range between $10-20^{\circ}C$ (outlet boiler/return) in heating systems) [38]. The outlet temperature of the radiators is dependent on the mass flow of the water. By increasing the flow rate and in turn, its speed, the water will have less time to cool, thus increasing its return temperature and the mean temperature in the radiator.



Figure 23 - Hot water temperature

3.4.1 Equations for consumption, savings, and ROI

Equations 7 to 13 will be used for the analysis of results so that it is possible to compare the proposed solutions with the current system and choose the best solution considering the proposed objective. Not all solutions include a photovoltaic system, insulation, or underfloor heating. Therefore, the investment will vary depending on the analysis solution.

$$\text{Gas consumption [kWh]} * \text{Price per kWh} = \text{Total costs in €} \quad (7)$$

$$\text{Gas consumption [kWh]} * \text{CO}_2 \text{ kg per kWh} = \text{Emissions in kg} \quad (8)$$

$$(\text{Electricity consumption [kWh]} - \text{PV gains [kWh]}) * \text{Price per kWh} = \text{Total costs in € (PV)} \quad (9)$$

$$(\text{Electricity consumption [kWh]} - \text{PV gains [kWh]}) * \text{CO}_2 \text{ kg per kWh} = \text{Emission in kg (PV)} \quad (10)$$

$$\text{Breakeven in years} = \frac{\text{Investment in €}}{\text{Savings in €/year}} \quad (11)$$

$$\text{Savings in €} = \text{Total costs in € (gas boiler + radiators)} - \text{Alternative solution costs in €} \quad (12)$$

$$\text{Investment in €} = \text{PV system} + \text{GSHP system} + \text{Insulation} + \text{Radiant floor} \quad (13)$$

4. Model in TRNSYS

TRNSYS or *Transient System Simulation*, is very versatile helping to understand the thermal loads and functioning of transient systems. It allows the user to choose the climatic data of the site under study and has many different components (“*Types*”) that were developed to correspond to the needs of each case. It has also sub-programs incorporated that complement *TRNSYS*, providing a vast library with all physical and thermodynamic properties, central to the calculation of heat transfer. Although it was created more than 45 years ago, it continues to be extremely current, since with each passing year new features of new technologies and repairs are added. Despite not having the commercial license to use the program, what limits the full use of *TRNSYS* when running the simulations, it was possible to take advantage of the *Demo18* that manages to solve the problem in question.

To model the case study with the present heating system, *Type 56* was used. This component calculates the thermal behaviour of a building having multiple thermal zones. Once the building is described, the model is generated through the pre-processor program called *TRNBuild* [40].

4.1 Zone properties and orientation

Although *Type 56* has the possibility to create multiple zones, only one will be used to recreate the church environment. As has already been said, churches are massive structures built based on masonry with no isolation. It is expected to have high heat losses and due to its heavy construction (high thermal capacitance) and interior components such as benches, stones, pictures, and other objects, to be very difficult to heat up.

The first step is to introduce the dimensions of the building and its orientation, corresponding to Figure 19. The orientation of the building is extremely important, especially in buildings with large outdoor areas and respective windows, as *TRNSYS* will consider all meteorological factors such as solar incidence, wind speed, humidity, and temperature. It takes just one mismatched wall, to provide distorted results from reality.

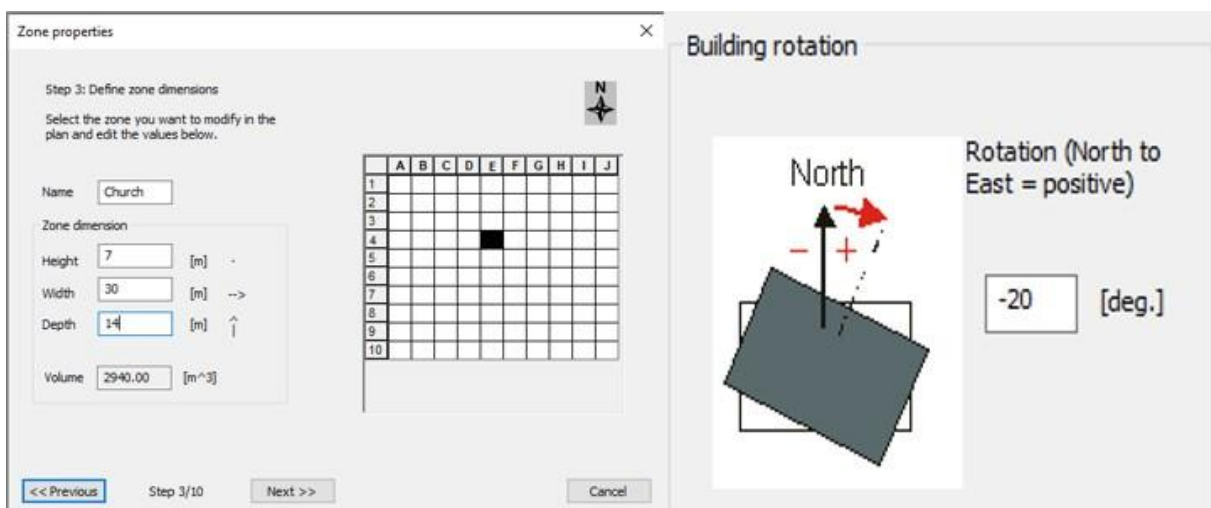


Figure 24 - Zone properties and orientation

When looking closely at the available images of the church, nearly half of the glazing is north oriented, while the other half is facing south. Glazed doors and windows are retracted in the

same way for convenience. Figure 24 illustrates the layout of the program and to achieve equality in orientation, a deviation of -20° was proposed.

4.2 Ventilation and Heating

There is no denying that today's building materials have better finishes and insulating properties but even modern buildings can't escape from deteriorating over time. Mainly churches that are already of a certain age, suffer from a typical problem of historic buildings, namely infiltration or natural (unwanted) ventilation. Due to contracting and expanding, the building envelope will gain certain flaws (small openings) that allow outside air to enter.

To be able to approximate the results of the real case, constant air change value of 0.5 ach (due to infiltrations) and an addition of 0.2 ach when the church is in operation were established. These values were thus chosen, due to the large volume inside the building, and the fact that there are relatively few openings to the outside. Figure 25 illustrates these values, and a schedule has been made according to typical mass times of the parish.

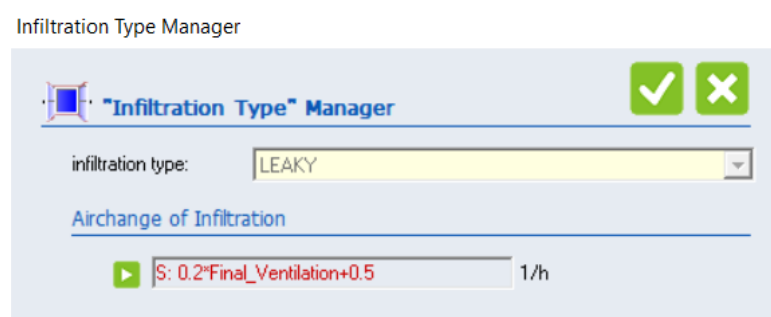


Figure 25 – Air change per hour

According to information about the church's mass times, a schedule presented in Table 6 was prepared to match the reality. Always during mass hours, the doors will be considered open, as there are many people arriving later and with the movement, the addition of ventilation must be considered. Regarding the heating schedule, caretakers of the church start the boiler 1h30 in advance before mass so that a comfortable interior temperature is reached when people arrive. Between the end of the mass and people leaving the church, another half hour of boiler operation was counted, since it is typical for people to socialize after.

Table 6 - Ventilation and heating schedules

SCHEDULE	VENTILATION	HEATING
WEEKDAYS	8-11h	6h30-11h30
SATURDAYS	12-13h and 18h30-19h30	10h30-20h
SUNDAYS	8h30-13h	7-13h30

4.3 Air node church

The building model in *TYPE 56* is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and capacities which are closely connected with the air node (furniture, for example). Thus, the node capacity is a separate input in addition to the zone volume [40].

TRNBuild, as shown in Figure 27, allows to characterize our zone according to what is intended. As already said, the walls, the ceiling, the floor, and windows were so chosen to resemble the case study of similar churches. Table 7 summarizes all the important aspects introduced in the sub-program to characterize the building accordingly. It is noteworthy the construction in masonry and the non-use of insulation as well as great thicknesses of material. The wall represented in Figure 28 demonstrates the use of masonry (brick) under the plaster that was replicated in *TRNBuild*. This program allows to calculate the respective *U-coefficients*, which are dependent on the materials used as well as their thicknesses.

As it does not have thermal insulation, the values of these coefficients tend to be higher than in a more recent building. The only factor that helps is its heavy structure, then the thicker the walls, the harder it is, heat to be transferred.

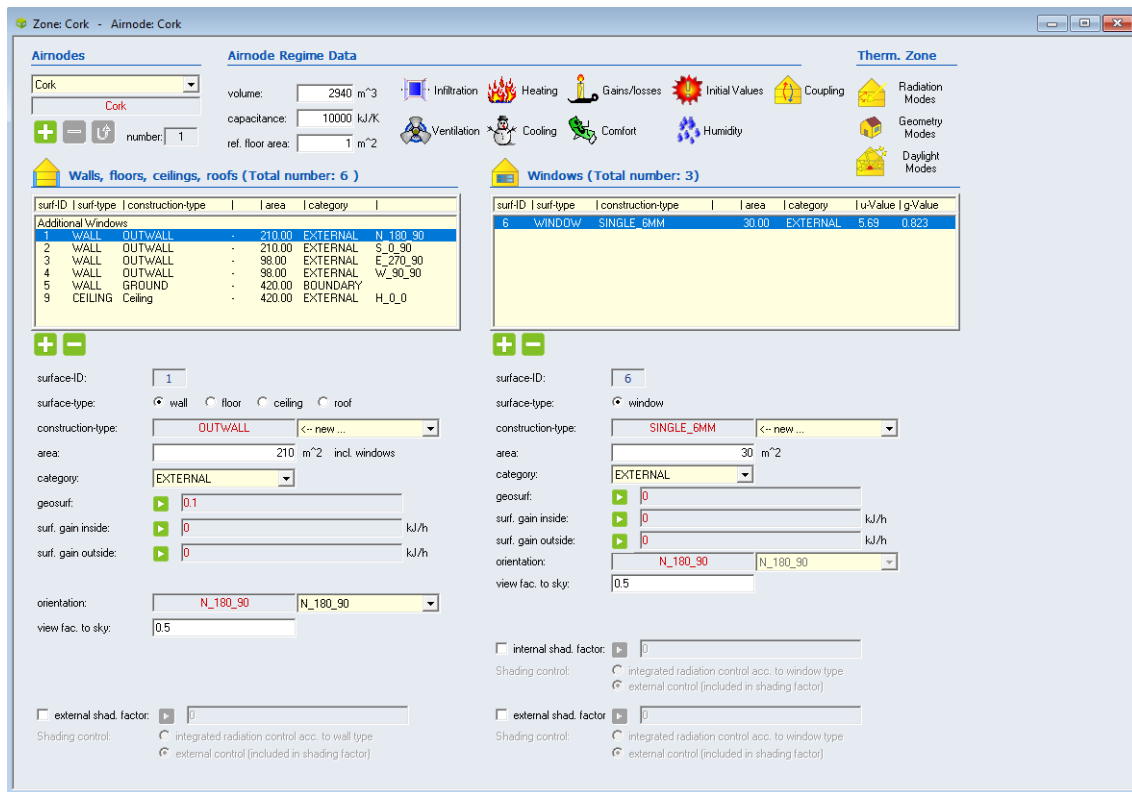


Figure 26- Airmode-Church

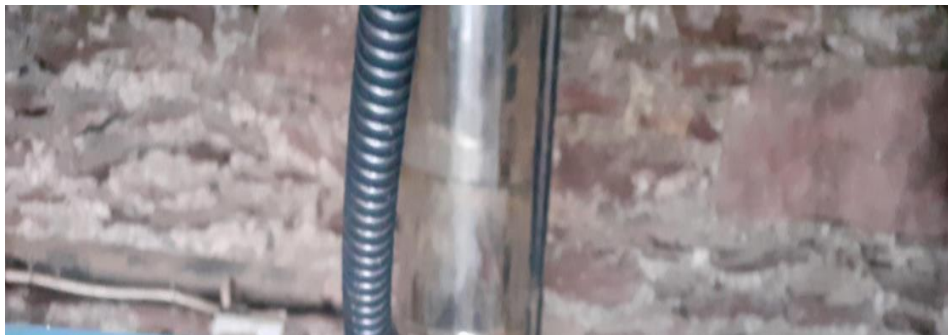


Figure 27 - Masonry wall of the church without plasterboard

Table 7, present the dimensions and thermal characteristics of the materials used and found in *TRNSYS* extensive library. These values were approximated to other churches from the same year of construction, to obtain more accurate results. As one can see, the walls are very thick and without any type of thermal insulation.

Table 7 - List of the parameters used in *TRNSYS* and *TRNBuild*.

Construction	Length m	30	
	Height m	7	
	Width m	14	
	Heated Volume m^3	2940	
Material [39]	External wall (616 m^2)	Brick 700 mm and Plaster 50 mm	U value: 0.971 $\frac{W}{K * m^2}$
	Windows (65 m^2) 46 % North, 46 % South, 8% East orientated	Single glazed 6 [mm]	U value: 5.69 $\frac{W}{K * m^2}$
	Floor (420 m^2)	Uninsulated stone 150 [mm]	U value: 2.376 $\frac{W}{K * m^2}$
	Roof (420 m^2)	Brick 350 mm and Plaster 25mm	U value: $2.052 \frac{W}{K * m^2}$
Weather File	Cork Airport		
System	Central Heating with radiators (natural gas boiler)		
Internal gains	People	Occupancy: 35 per mass (100 W per person [40])	
Air Exchanges	Infiltration: 0.5 ach (constant) + 0.2 ach (operative)		

Although being called “radiators”, most of their energy is transferred into the air through convection, in which case, the radiative effect has been assumed as 20% of the total as referred in Figure 28 [32]. Equation 14 explicit the average heating power of the present system adjustable through the boiler’s outlet temperature. For the next calculations uninsulated copper pipes and a $\Delta T=60\text{ }^{\circ}\text{C}$ were assumed.

$$Q_{heating} = \frac{(Q_{max}+Q_{min}) \cdot \eta}{2} - Q_{pipes} * l = \frac{(103\text{ kW}+75.8\text{ kW}) \cdot 0.92}{2} - 0.115 \frac{\text{kW}}{\text{m}} * 70\text{m} = 74.2\text{ kW} = 267\,120 \frac{\text{kJ}}{\text{h}} \quad (14)$$

Where,

Q_{max} , is the maximum heat output of the boiler

Q_{min} , is the minimum heat output of the boiler

Q_{pipes} represents the heat loss of the pipes

l stands for the length of the pipes towards the radiators (35 m each path)

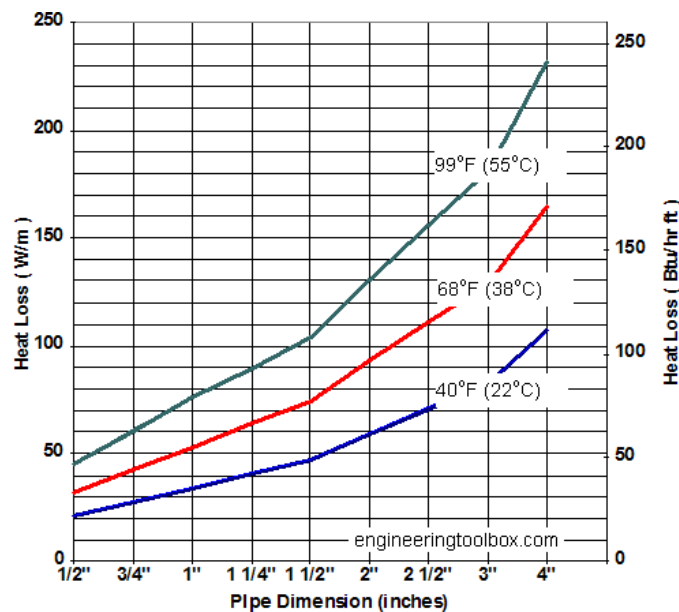


Figure 28- Heat loss vs Pipe dimension [32]

As is known, the church has registered a low attendance, with an estimated average of 30 people per mass on weekdays and 45 on weekends. As the church’s occupancy rate is around 10% of maximum capacity, these are numbers that have reduced influence on thermal effects of the node but were also accounted for. It has been studied that an adult emits an average of 100 W of sensible heat, when seated without much activity [41]. The gains calculated in Equation 6 will be accounted accordingly to the same ventilation schedule established in the Table 6.

Thermal energy generated by the electrical equipment (lighting) is neglected because they are installed in the upper parts of the building. Knowing that the hot air rises in relation to the cold, this heat becomes useless for warming people. This is even more evident when the average height of the building is 7m.

$$\text{Average attendance per mass} = \frac{\text{attendance per week}}{\text{number of masses}} = \frac{525}{15} = 35$$

$$Q_{\text{people}} = 100 \text{ W} * 35 * 3.6 = 12\,600 \frac{\text{kJ}}{\text{h}}$$

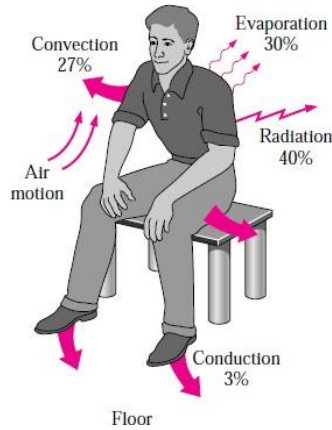


Figure 29- Heat loss human body [42]

TRNBuild allows us to divide the heat transferred into two parcels, namely radiation and convection. In the case of radiators, it was explained that 20% of the total heat (equation 4) is transferred by radiation, while the rest is transferred by convection. Regarding the heat transferred by people, 60% accounts for convection and the rest by radiation since the heat through conduction will be neglected [42]. Table 8 shows the *TRNBuild* thermal gains menu, thus representing the different heat transfer components for each case.

Table 8 - Heating properties introduced in *TRNBuild*

Heating/gains	Total output $\frac{\text{kJ}}{\text{h}}$	Radiative fraction	Convection fraction
Radiators	267 120	20 %	80 %
People	12 600	40 %	60 %

4.3.1 Convective heat balance

For a better understanding of the thermal balance calculation in the node performed by *TRNSYS*, Figures 31 and 32 were developed to represent both convective and radiative gains/losses.

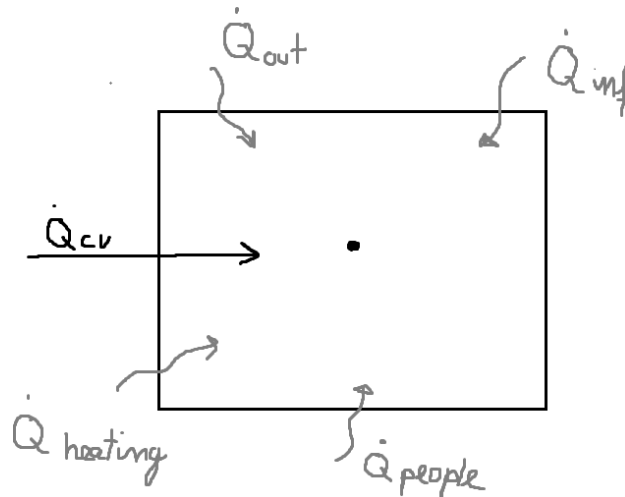


Figure 31- Convective heat gains/losses air node

$$Q_{cv} = Q_{heating} + Q_{out} + Q_{inf} + Q_{people} \quad (15)$$

Where,

Q_{cv} , stands for convective heat.

$Q_{heating}$, is heat provided by the system (radiators).

Q_{out} , is the heat represented in equation 2

Q_{inf} , is the heat transferred through infiltrations.

$$Q_{inf} = V_{air} * \rho * cp * (T_{out} - T_{in}) \quad (16)$$

considering air as the fluid

Q_{people} , is the heat produced by the people

4.3.2 Radiative heat balance

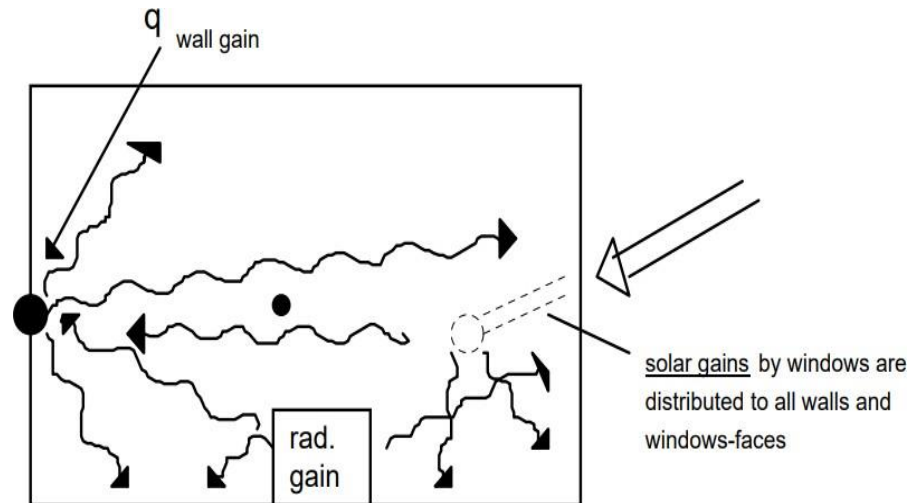


Figure 32- Radiative Heat flows (only) to the walls and windows [40]

$$Q_{rad} = Q_{wall} + Q_{sol} + Q_{long} + Q_{radiator} \quad (17)$$

Where,

Q_{rad} , is the total radiative gains for the wall surface temperature node

Q_{wall} , is the radiative zone internal gains received by wall

Q_{sol} , is the solar gains through zone windows received by walls

Q_{long} , is the longwave radiation exchange between this wall and all other walls, windows ($\epsilon=1$)

$Q_{radiator}$, is the radiative fraction of the cast iron radiators

4.4 Geothermal heat pump

To simulate the ground source heat pump (GSHP) it was necessary to consider some data on the thermal conditions of the soil as well as the properties of the chosen pump. For this case study a so called “closed-loop” system will be used and applied to borehole heat exchanger (BHE) composed of high-density Polyethylene (HDPE). These vertical pipes are buried to a certain depth where brine circulates and absorbs the heat stored in the ground. The fluid after reaching a certain temperature (dependent on the application) goes to the heat pump, which uses that “low” heat to vaporize the used refrigerant. It is then possible through the compressor to reach high temperatures that will then heat the central heating water.

There is a lot of variety in heat pumps and their sizing will always depend on each case, considering that the most important is to meet the customer’s needs. For this church, since it is a retrofit of an old building, the major concern was that the performance of the new system should correspond to the old one. For this purpose, the result of the current heating equation (4) was used, and this power of 75 kW was chosen as a reference. Another key aspect for choosing the heat pump is the capacity of the pump to reach temperatures of at least 75 °C. As previously mentioned, this temperature is extremely important to achieve, since it is from there that radiators can transmit high loads of energy.

However, this heat output is normally referred to conditions that are not those of the case study. Each manufacturer will have to set the COP and its heat power according to the inlet and outlet temperature. This information is then introduced in *TRNSYS* as an external file (*Type 927*). Datasheet of the manufacturer *WAMAK* is presented in the annex x. In Table 9 is presented a resume of the main parameters of the heat pump chosen for the simulation. The value of 89.1 kW corresponds to a source temperature of 30 °C and an outlet temperature of 70 °C, which will not be the case for this study.

Table 9 - Main parameter of the heat pump unit

Model	Heating capacity (W30°C/W70°C)	COP (heating)	Input	Maximal flow temperature	Refrigerant
WW 125 SHR HD Modul	89.1 kW	4.2	21.21 kW	82 °C	R134a

For a good use of the energy of the soil, it was decided to bore vertical probes with a depth of 75 m. Here the temperature will be constant and around values between 12°C-14°C which offers great potential at a comparatively low price [45]. Choosing the source temperature of 12°C and the outlet temperature for the radiators of 75 °C the follow parameters of the heat pump are obtained through interpolation and resumed in Table 10. As one can see, the COP drops considerably, so it is much less efficient as the temperature difference between source/outlet increases.

Table 10 - Parameters of the heat pump for this case study [46]

Data conditions	Heating capacity kW	Power input kW	COP
W12°C/W75°C	53.83	22.52	2.39

To calculate the dimensions of the earth boreholes, it is first necessary to determine the required heat performance that must be extracted from the soil. This calculation can be performed using equation x [47].

$$P_{Earth} = (COP - 1) * P_{el} = (2.39 - 1) * 22.52 \text{ kW} = 31.3 \text{ kW} \quad (18)$$

Using the paper where a feasibility study in Cork has been made, the same values have been chosen for this case. Both sites are in the presence of a river or a lake, which positively affects the thermal extraction of the soil. These properties are summarized in Table 11 and introduced in *Type 557* (heat exchanger).

Table 11 - Heat exchanger design properties [48]

Temperature of the ground	Thermal conductivity of the ground	Heat capacity of the ground	Distance between Boreholes	Type	Pipe diameter	Energy yield
12 °C	0.657 W/mK	$2400 \frac{\text{kJ}}{\text{m}^3\text{K}}$	5 m	Single-U	DN32 mm	55 W/m

The length of drillings and number of holes can be calculated with the equation (19) and (20).

$$l_{length} = \frac{P_{Earth}}{p_{drilling}} = \frac{31.3 \text{ kW}}{\frac{55 \text{ W}}{\text{m}}} = 570 \text{ m} \quad (19)$$

$$n = \frac{l_{length}}{depth} = \frac{570 \text{ m}}{75 \text{ m}} = 7.6 \approx 8 \quad (20)$$

The boreholes are spaced 5 m from each other so that there is no interference [47]. Therefore, having 8 boreholes and considering a rectangular section, the drilled area will be 200 m^2 as shown in equation 21. Behind the church there is plenty of unused area that can be used for this purpose.

$$A_{drilling} = n * l_{distance}^2 = 8 * 5 \text{ m}^2 = 200 \text{ m}^2 \quad (21)$$

4.5 PV-System

It is known that when introducing a heat pump, it will consume a lot of electrical energy. The implementation of a photovoltaic system allows to alleviate the associated costs of the heat pump, since it avoids the consumption of grid electricity. This energy (depending on the country) is mostly generated through fossil fuels, which increases the ecological footprint of electrical equipment.

The church disposes of a south-facing roof with an area of 90 m^2 . Each module possesses 60 mono crystalline cells and occupies an area of 1.25 m^2 . With the available roof space from the church and using only the south facing side, it is possible to install two lines with 30 modules in series each, totalling 60 modules. Through the equipment available from *TRNSYS*, namely the *Type 190* (Photovoltaic panel), the energy that can be generated and converted into AC using an inverter for the use of the pump will be simulated. The equipment chosen to be placed on the roof of the church is from the company *SolarWorld* and each module has a maximum power of 280 Wp. Figure 16 shows the sloping roof (38°) of the church what means that there will be no problem of overlapping (shadows) between the modules.

The regime chosen for the simulation (self-consumption) means that all the electric energy produced is injected into the consumption facility. The surplus can be supplied to the distribution network. This implementation of the photovoltaic system requires a high initial investment, but it is ecologically clean, has a high durability and practically does not need maintenance. All meteorological parameters are given by the weather file from *METEONORM*.

5. Results

5.1 Inside temperature variation

A dynamic simulation was carried out to understand the church's heating needs throughout the year. To be able to understand if the current system corresponds to the desired thermal needs, the interior temperature of the church without heating was simulated. This temperature varies according to the climatic conditions and building's envelope properties, making it possible to perceive the need for heating the building. The thermal needs are dependent on the desired temperature profile, and it is based on these values that the heating designers choose a suitable heating system.

Through the simulation analysis on Figure 33 it is possible to notice that the interior temperature of the church reaches minimum temperatures around 5 °C which can be very harmful for the interior of the church. During winter, the maximum temperature recorded does not reach 15 °C, being necessary to have a heating system. In summer, one can see that the comfort temperature (21-23 °C) mentioned above is not reached most of the time, being therefore an argument for the need for heating at that time of the year. Cooling is not justified, as the church does not reach high temperatures due to its large size and heavy structure as well as the temperate climate in Cork.

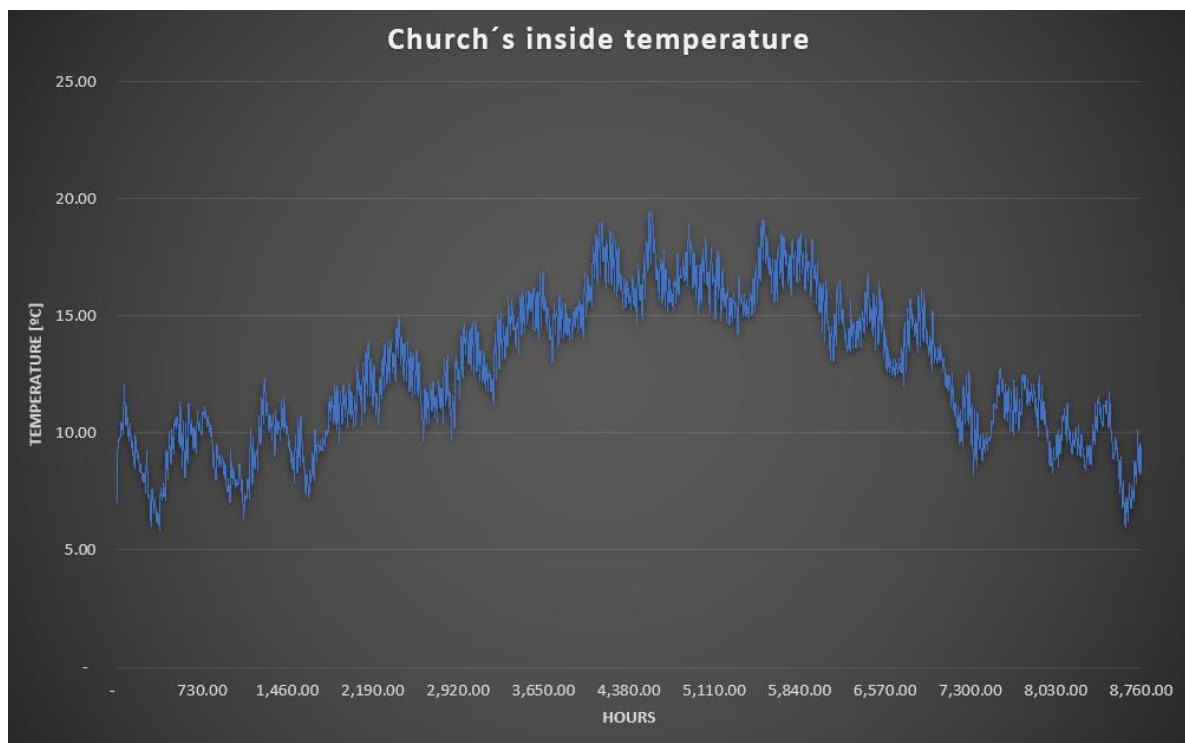


Figure 30- Inside temperature variation without heating

5.2 Present heating system simulation

As in all heating/cooling cases, energy consumption/demand will always depend on the desired profile. Although there are no thermostats to measure and control the interior temperature of the building, it is estimated through the comfort temperature of 21-23 °C, that this is the profile when operating. There is no minimum temperature limit, which makes it possible for the interior of the church to undergo changes due to low temperatures at night. The minimum temperature in the churches, previously mentioned, should be greater than or equal to 10 °C, depending on each building’s interior [39]. This serves as guide for the people in charge of historic buildings, and it is up to them to decide whether it is necessary to be strict about the care of artifacts. Obviously, if the church has old paintings, musical instruments (for example an organ) or other objects that require special care, this minimum temperature can be adjusted accordingly.

To get results close to reality, *Type 1231* (radiator), *Type 700* (boiler), *Type 4a* (storage tank) and *type 114* (circulation pump) were used as well as *type 516* and *type 1233* to control the elements of the heating system. Figure 31 illustrates the schematic of the heating system that is used nowadays in this church. Annex Y presents a table summarizing the properties and the assumed characteristics of the components used.

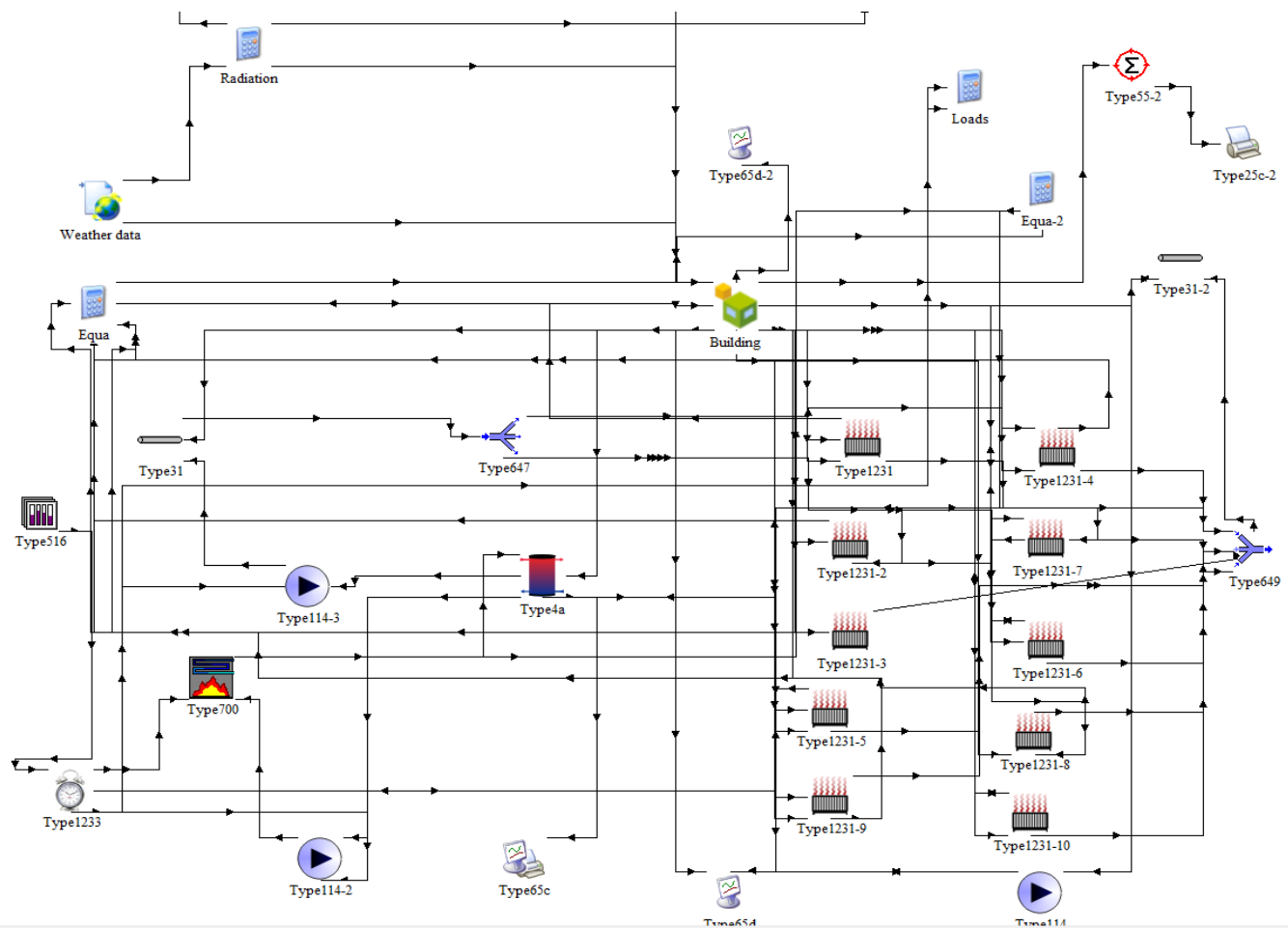


Figure 31- Heating schematic on TRNSYS

Figure 32 illustrates that heating is demanded in every season of the year. The large amount of rain throughout the year means that the solar radiation received does not reach very high values, thus justifying the use of heating to maintain the conditions of 21-23 °C implemented in this profile, especially in summer. This church has relatively high energy demand because it is used every day, unlike many others, where it is only celebrated a mass once or twice a week. The month of January requires a great thermal response from the heating and for that reason the thermal peak loads of that month were simulated to see if the current heating system can match these needs. As one can see, even in summer there is a heat demand of 33 kW to ensure that the desired temperature is reached in time. The results of the simulation are shown in Figure 32.

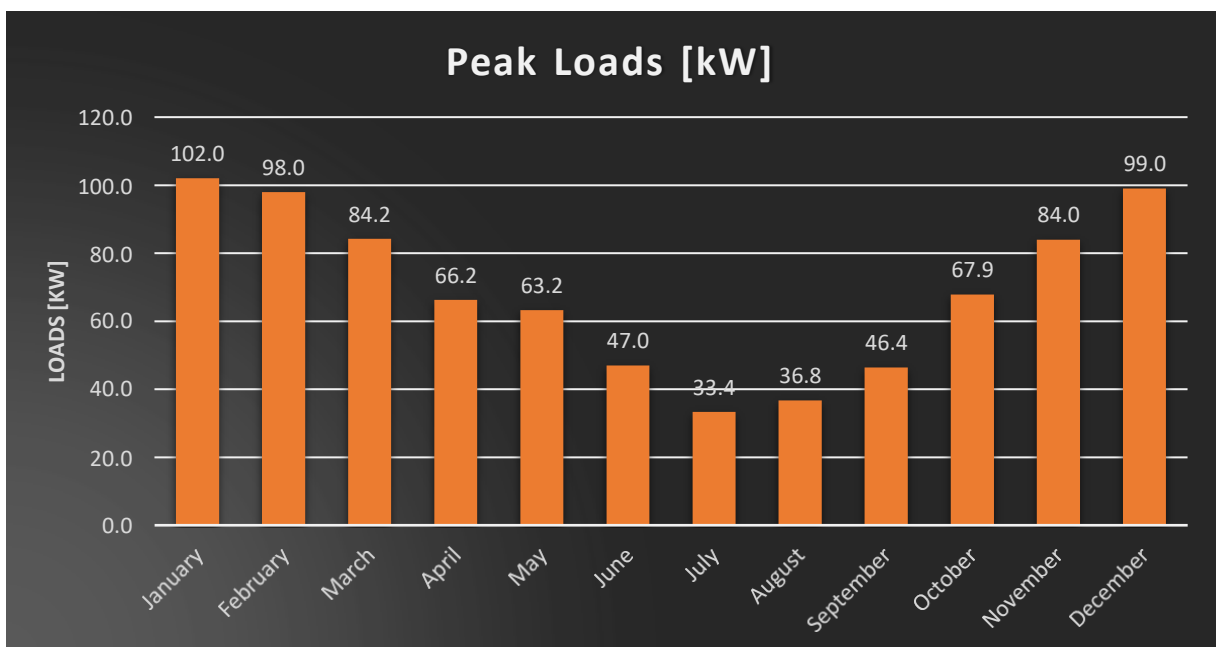


Figure 32- Heating peak loads

With the outside temperatures reaching negative values, and adding the fact that between Fridays and Saturdays, there are 23h where the heating is off, a peak of 102 kW was recorded. It is established that the present heating system is well sized since it can achieve this heating demand.

To better understand the behaviour of heating and the variation in the temperature inside the church, 3 days in January were chosen. One can see through Figure 33, that the desired temperature is reached and already at 7:30 am, it has already reached 17 degrees. This ensures that people can enjoy a comfortable temperature in the first mass of the day. It is also clear that once that the temperature rises, the boiler demand decreases. Since the church has no type of insulation, the heating losses are very high, which is noticeable in the speed with which the temperature drops as soon as the gas boiler turns off. The gas boiler is programmed for the inlet temperature to the radiators to be 75 degrees and the interior temperature not to exceed 23 degrees. In this way, the boiler adjusts the heat power automatically depending on the feedback from these two conditions.

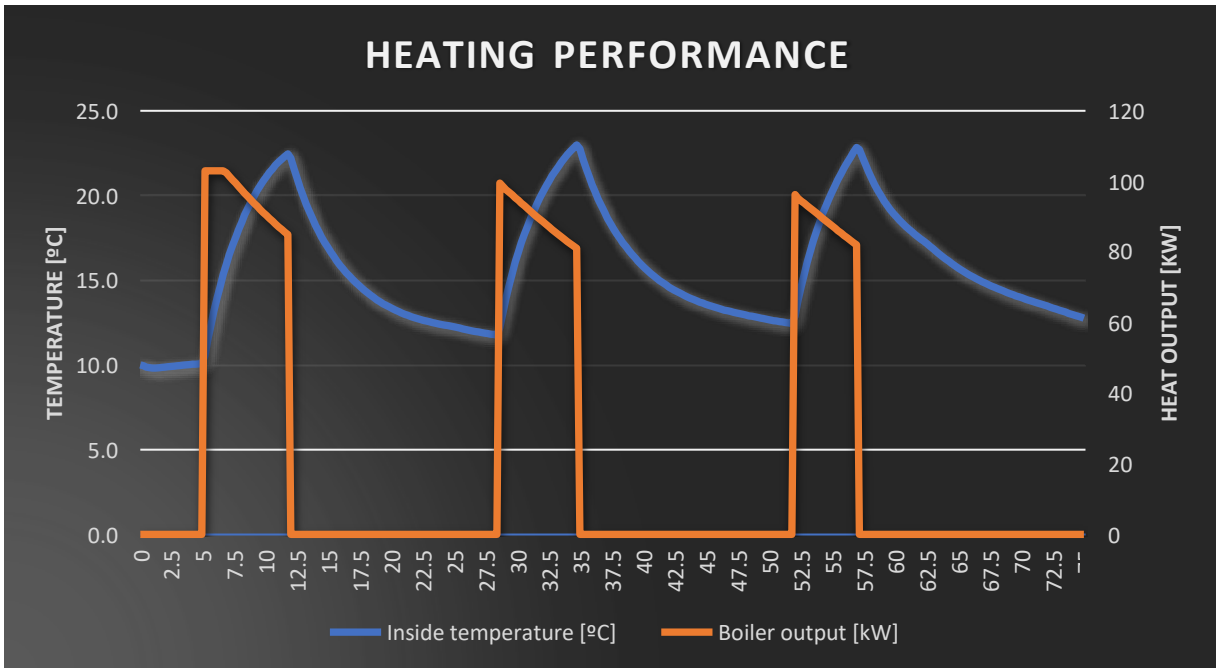


Figure 33- Heating performance and temperature variation

As previously mentioned, radiators are the elements that will emit the heat produced by the boiler. Knowing that its calorific power is situated at 3.36 kW under standard conditions, this is variable depending on the temperature difference between the surrounding air and the water temperature. Figure 34 shows that right at the beginning of the heating, its output reaches the value of approximately 6.5 kW since the temperature of the church in the morning is very low. Obviously, it goes down as the temperature of the church warms up. The surface temperature shows a constant value of around 70 degrees, which is the result between the difference of the entering water and the surrounding air temperature.

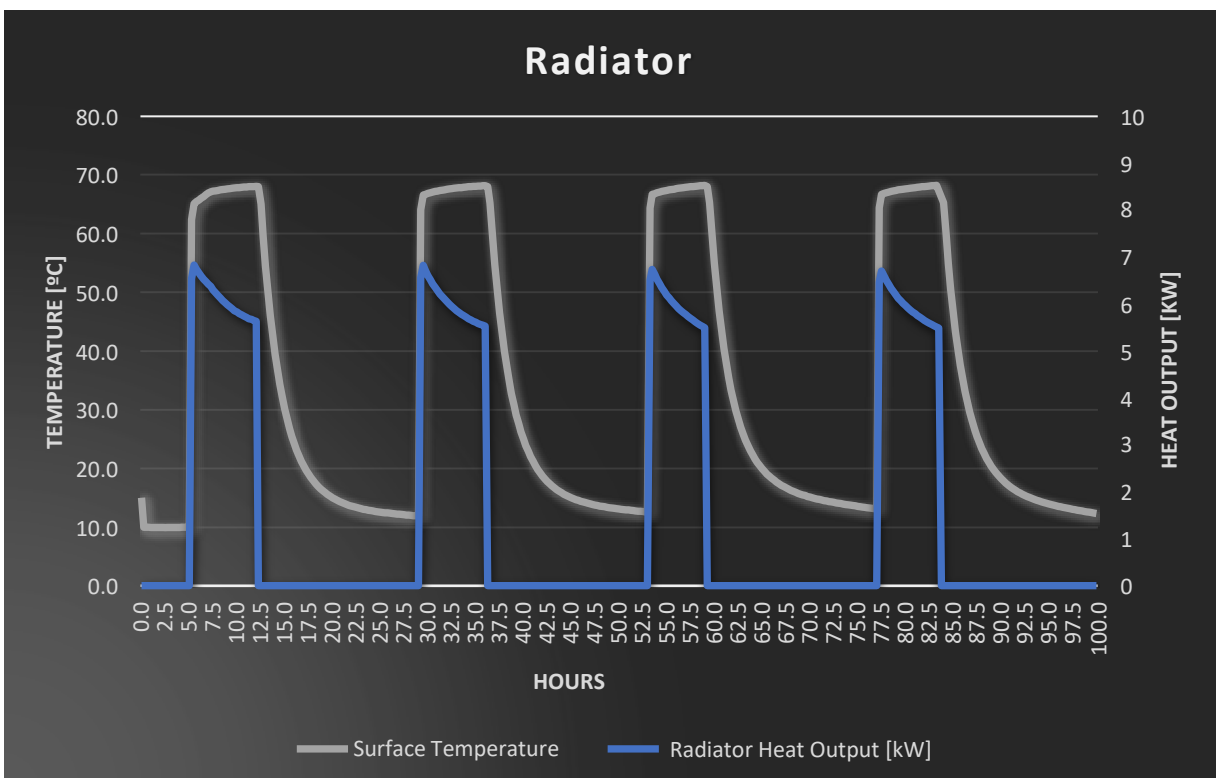


Figure 34 - Cast-iron radiator performance

A storage tank is used in this simulation so one can avoid higher peak loads that occur in each morning, when the boiler is turned on. It is important to emphasize that the temperature difference between inlet and outlet (cold side/hot side) is usually between 20 degrees. The hot side water (top) is transported through circulation pumps to the ten radiators in the church and the cold side water (bottom) returns to the gas boiler.

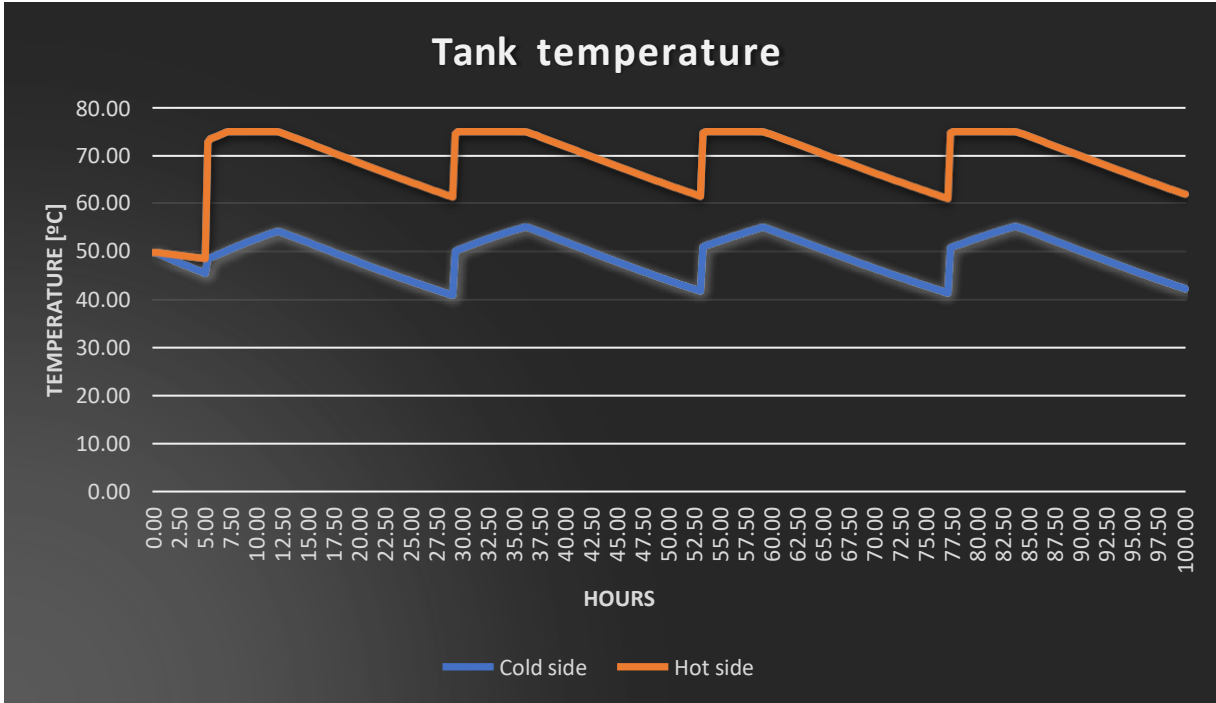


Figure 35- Storage tank temperature

The gas consumption of the church is very high, not only in winter but also in summer, due to the climate conditions in Cork and the usage profile that was chosen for this simulation. The boiler is used daily for at least 6 hours a day. Taking these conditions into account, we arrive at a total annual value of 167 255 kWh that was transformed into heating energy. Figure 37 allows us to identify the gas consumption of each month.

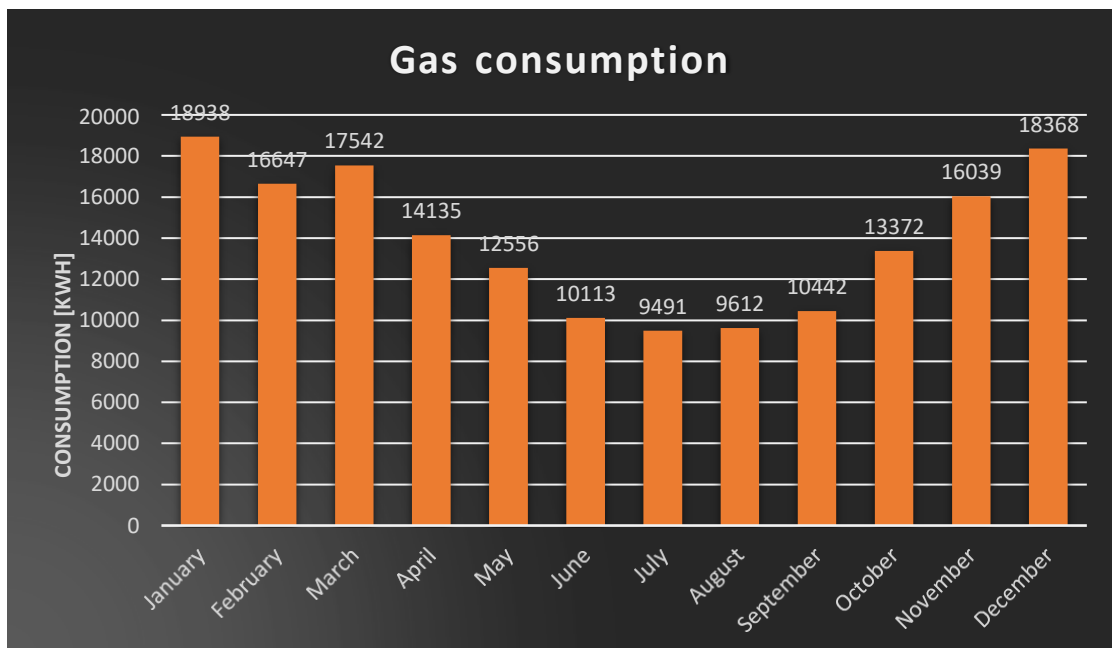


Figure 36- Annual gas consumption profile

Using the previous simulated data, and the price of kWh for natural gas 2020 in Ireland [6], one can calculate its annual costs and the ecological impact, being one of the main reasons for the analysis of this study. The electrical equipment (except heat sources) was not addressed for this case study, because the focus is the replacement of the central heating. Table 14 explains that one needs to consider that the boiler has a performance of 92% which means that the actual annual gas consumption reaches 181 800 kWh/year.

Table 12 - Fuel and consumption values for the first simulation

Fuel	Consumption [kWh/year] ($\eta=0.92$)	Price [€/kWh] [6]	CO2 emissions [kg/kWh] [43]
Natural gas	181 800	0.0707	0.184

Table 13 - Annual Costs and emissions for the first simulation

ANNUAL COSTS	ANNUAL CO2 EMISSIONS
$181\,800\text{ kWh} * 0.0707 \frac{\text{€}}{\text{kWh}} = 12\,853\text{ €}$	$181\,800\text{ kWh} * 0.184 \frac{\text{kg}}{\text{kWh}} = 33\,451\text{ kg}$

5.2.1 Thermal insulation influence

The present study, as mentioned above, intends to evaluate the behaviour and thermal efficiency of the system and other renewable alternatives, in this case the geothermal heat pump. However, there is a very important component in the analysis of different buildings, namely the thermal insulation.

As the church in this study is an old, protected building, it has the worst rating possible of thermal efficiency. Thus, a simulation was done with the same heating system, simply theoretically adding insulation to the roof, floor, walls, and using double windows. Although it is not possible to make any changes to the building, these simulations are carried out to reinforce the importance of the advantages of having a well-insulated building. Through *TRNBUILD*, it was possible to apply a generic insulation and Figure 38 shows the percentage of each element of the building in heat loss in the church. Alone the roof can save up to 21 000 kWh in one year which represents almost 40% of the total savings.

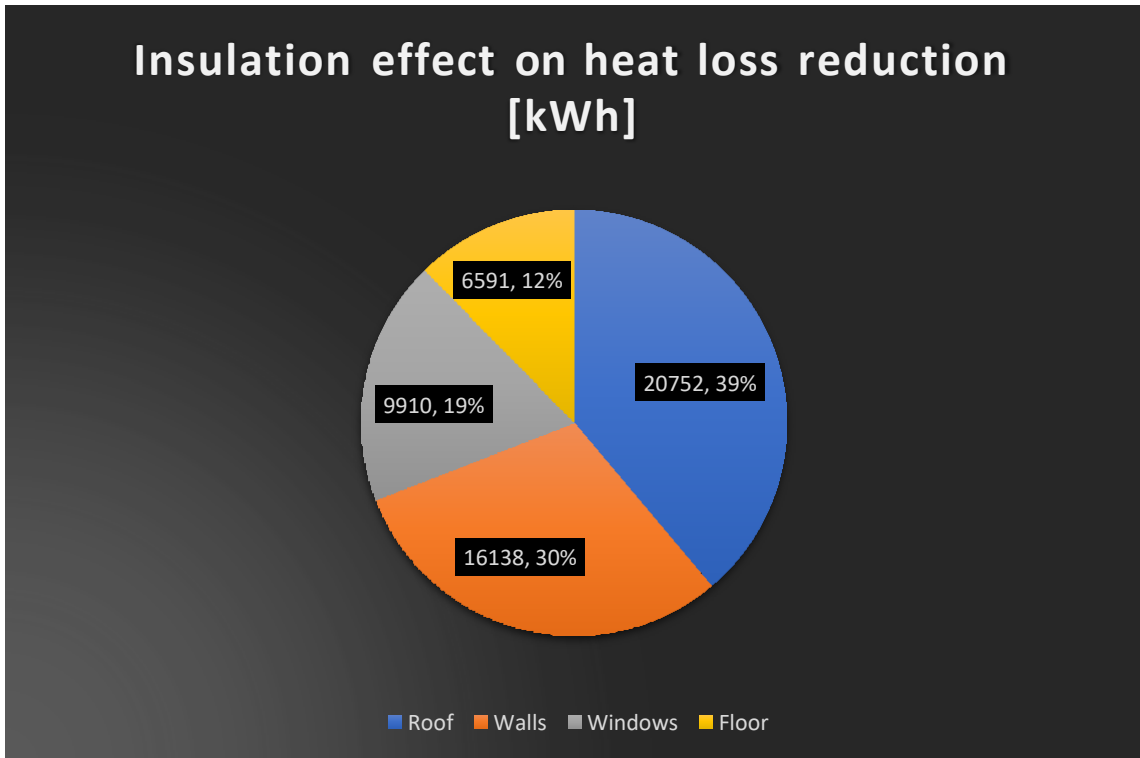


Figure 37 - Insulation effect

The graph represents energy losses, and these values do not represent the savings in natural gas consumption. These simulations were carried out to understand how much energy is lost without insulation. This is indirectly linked to gas consumption, as without insulation, the boiler needs to work harder to reach the same temperature. So, figure 39 shows the difference in energy peaks compared to the church without insulation. In winter, there is almost a 20 kW peak load difference, which reinforces that with insulation one could buy a less powerful boiler, being more economically and environmentally friendly.

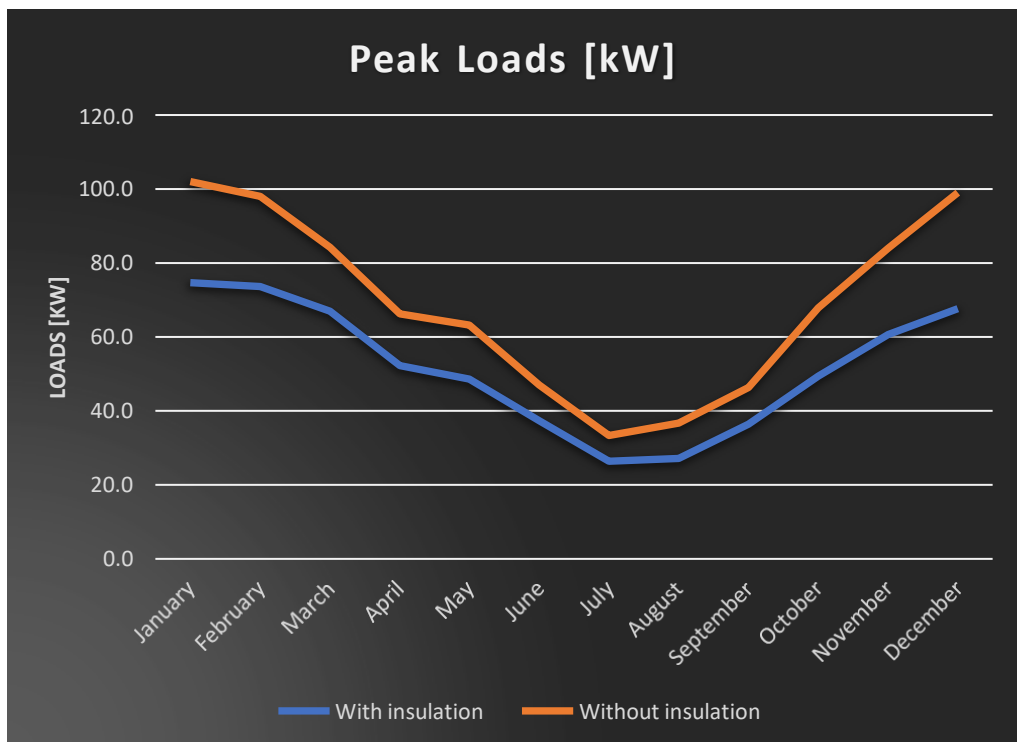


Figure 38 - Peak Loads (insulation)

Figure 40 shows us the difference between the dynamic response of the insulated the church versus the non-insulated church. It is clearly shown that the desired temperature is reached faster and that it takes the longer the heat to get lost. These are expected results from the influence of an insulating building since the objective is to preserve the heat as long as possible.

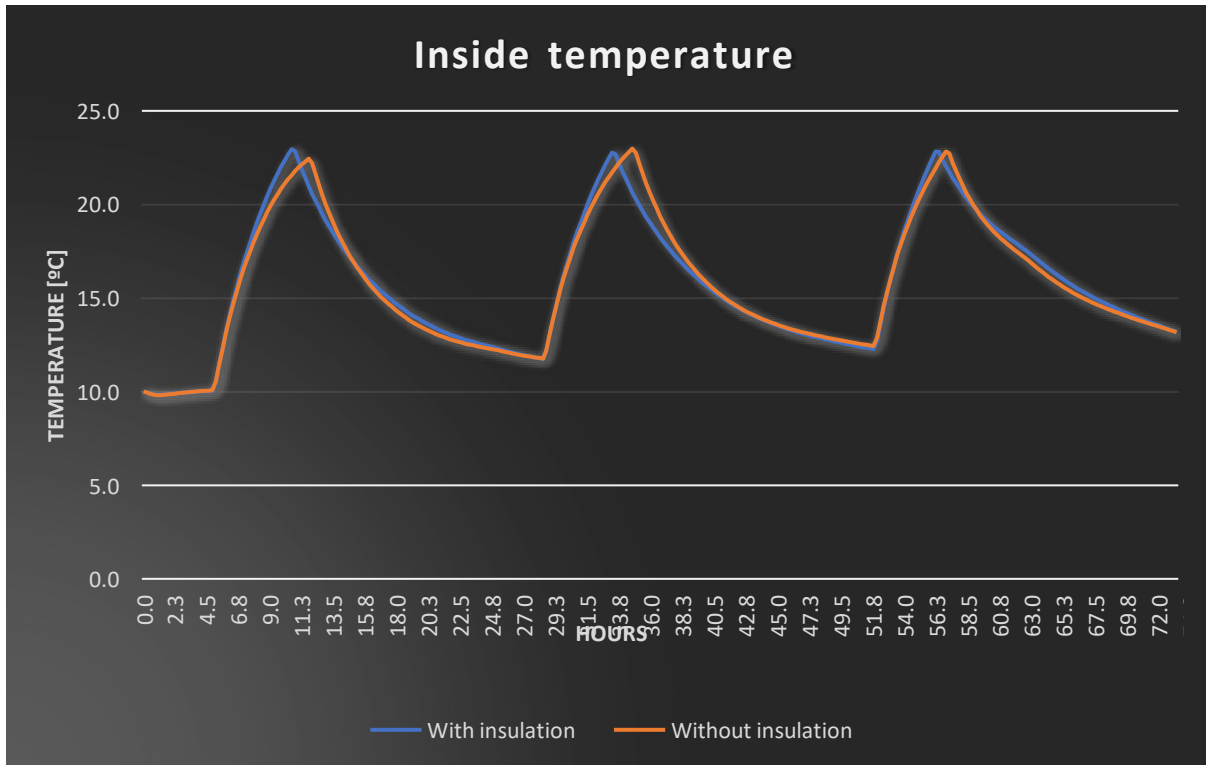


Figure 39 - Thermal response

After the new simulations with isolation are carried out, Table 14 and 15 show the new accounts for gas consumption and the consequent ecological footprint. This insulated church could save up to around 1 145€ and 3000 kg of CO₂ per year with the same boiler. For the reader to understand better, a household heated by gas on average, consumes this amount of CO₂ annually. In other words, the simple fact that this church uses insulation, it would be possible to save what is consumed in a house per year.

Table 14- Fuel and consumption values for the second simulation

Fuel	Consumption [kWh/year] ($\eta=0.92$)	Price [€/kWh] [6]	CO ₂ emissions [kg/kWh] [43]
Natural gas	165 614	0.0707	0.184

Table 15- Annual Costs and emissions for the second simulation

ANNUAL COSTS	ANNUAL CO ₂ EMISSIONS
$165\,614\text{ kWh} * 0.0707 \frac{\text{€}}{\text{kWh}} = 11\,708\text{ [€]}$	$165\,614\text{ kWh} * 0.184 \frac{\text{kg}}{\text{kWh}} = 30\,472\text{ kg}$

5.3 Solution with GSHP, radiators and PV-System

The next simulations were carried out according to the main objective of the present case study. The gas boiler was therefore replaced by a vertical geothermal heat pump. For the following simulations, simply account the power used in the circulating pumps between the heat exchanger and the heat pump, as the other two circulating pumps already existed in the original system.

The entire hydronic system was used, simply with the addition of new components such as *type 927* and *type 557b*, which respectively represent the heat pump and the borehole heat exchanger. The objective is to know if simply with this replacement of the heat source, it will be feasible to use this emerging technology. Not only will the economic and ecological aspect be analysed, but also the thermal response capacity that the heat pump will have compared to a gas boiler. Figure 41 shows us the new components introduced in *TRNSYS*.

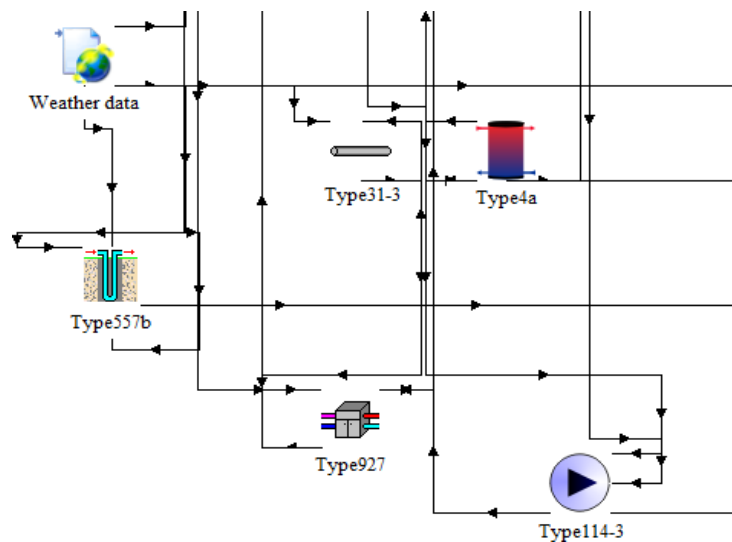


Figure 40- GSHP and BHE

Once the parameters of the used heat pump (attached) were inserted, the thermal response of the two heating modes was compared. The temperature of the church when heated by the heat pump rises much more slowly than the simulated gas boiler. This is a very important aspect to consider since the consumer must think about the importance of having a comfortable temperature as quickly as possible. In this case study, one of the main concerns is to know if a heat pump can achieve the same performance as a gas boiler. Through Figure 42, it is possible to notice a delay in heating and in the maximum temperature reached.

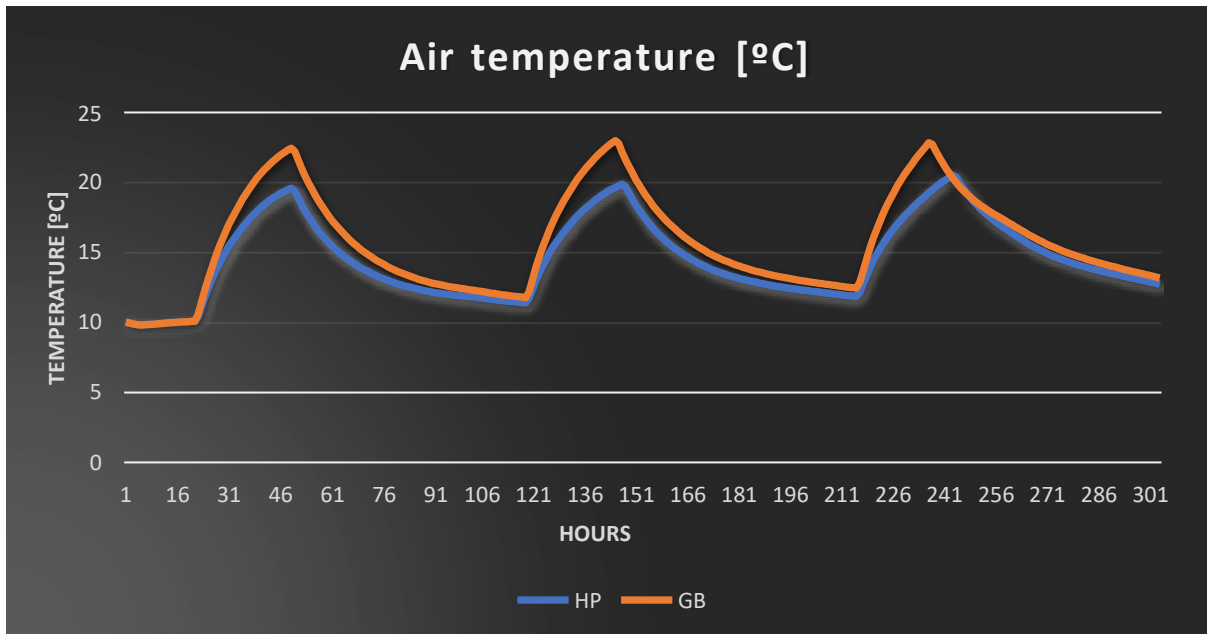


Figure 41 - Thermal response HP vs GB

The reason why this happens can be explained with Figure 43. The temperature leaving the heat pump hardly reaches 70 degrees. This temperature difference makes the heat dissipated by the radiators much smaller. Furthermore, the entire hydronic system was designed to respond to a gas boiler and was not adapted for the chosen heat pump. Thus, existing radiators would have to be oversized or replaced with underfloor heating, which will be explored later. A heat pump is attractive for use at temperatures between 35-50 degrees, as seen in appendix E, due to higher COP. While a gas boiler responds very well to large heat needs (sprinter), a heat pump works best in continuous register (marathon). Something that in this case study would not be possible, as we need punctual thermal responses.

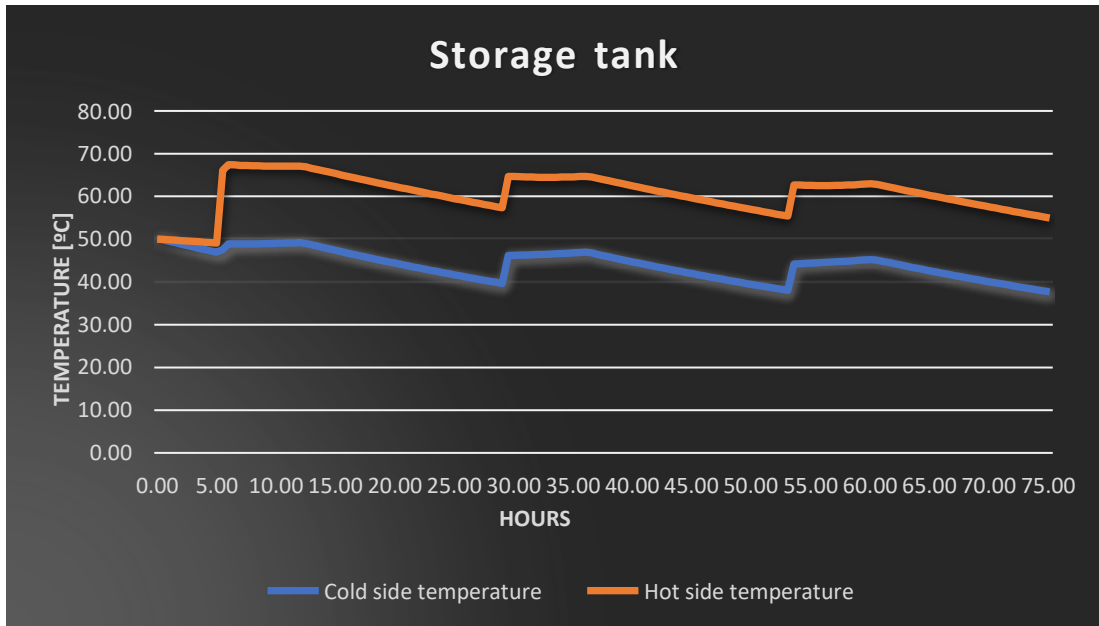


Figure 42- HP storage tank

One of the most important data to obtain when running simulations with heat pumps is the COP. Equation 1 literally explains the problem of using this heat pump in conjunction with the current hydronic system (aiming 75 degrees). The higher the heat pump outlet temperature, the lower its performance. However, the higher the inlet temperature (source), the greater its efficiency. This explains why the COP increases slightly in the warmer months. Whilst the soil temperature is constant throughout the year, the transport pipes between the borehole exchanger and the heat pump are subject to heat gains/losses depending on the ambient temperature. If one would use an air source heat pump this difference would be much bigger, since the air changes its temperature with great speed. The values of the COP rounds 2.35 what does not match its potential. Thus, for each kWh of electrical energy, the heat pump produces about 2.35 kWh of thermal energy. It was expected, as previously mentioned, that the heat pump, considering this application, would not have very promising values, since a high outlet temperature is being required.

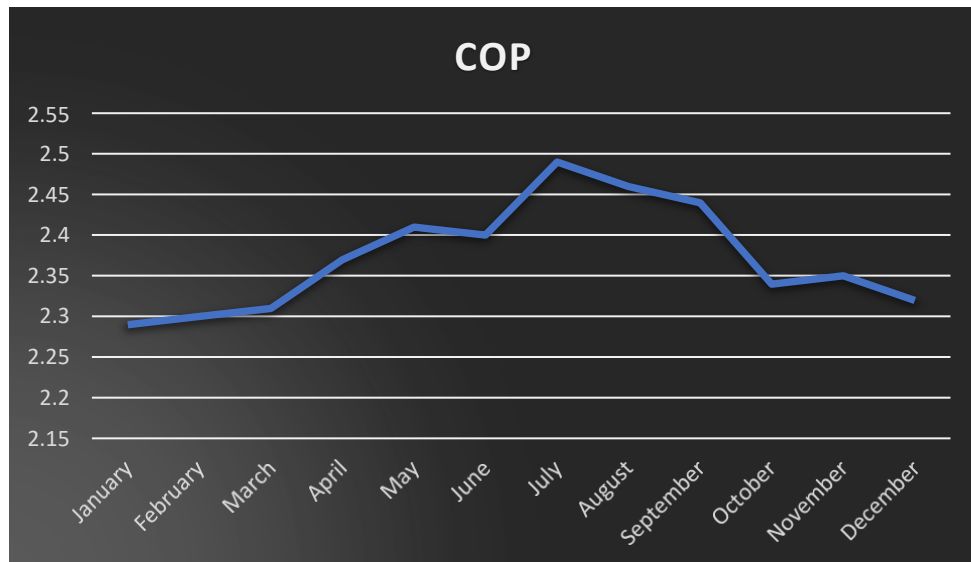


Figure 43 - Coefficient of performance

It is also interesting to analyse the input and output of the water (brine) temperature of the borehole heat exchanger. This is where geothermal energy comes into the game of renewable energies, as it takes advantage of the small constant temperature jump of the earth that heats up before entering the heat pump, as can be seen in the Figure 45. Bearing in mind that the temperature can reach negative values, brine is used which has a freezing point of approximately -20 degrees, so it can flow and absorb all the heat available from the earth.

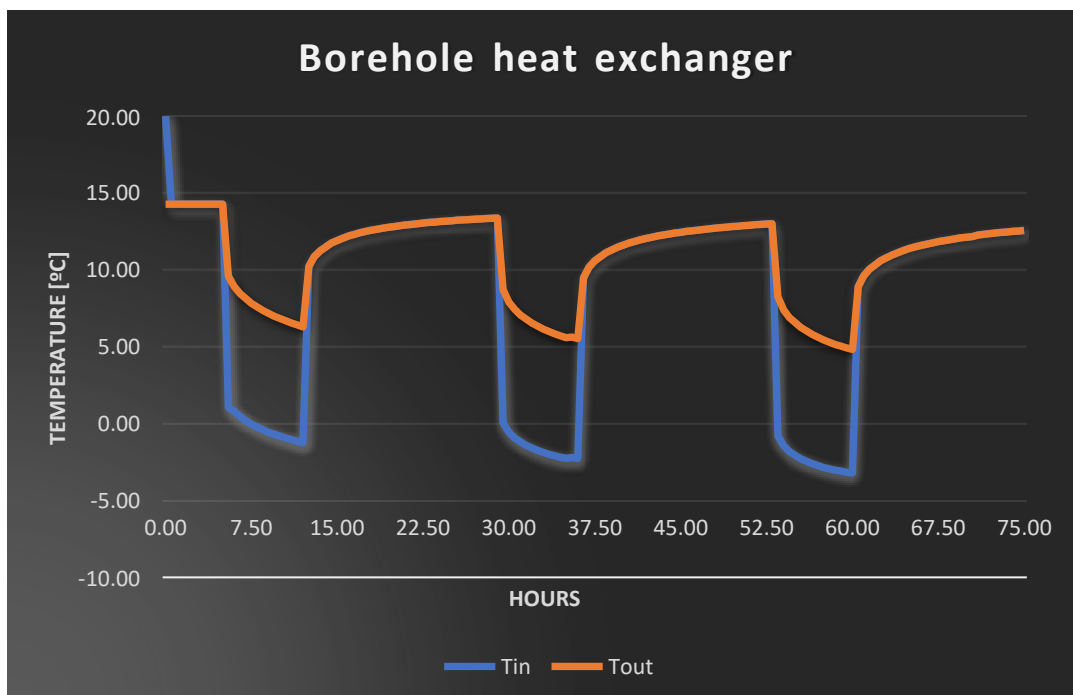


Figure 44 - Borehole heat exchanger (BHE)

The same procedure done with the gas boiler was done with the heat pump system, realizing to what extent electrical consumption and thermal response could improve. The values of Figures 46 and 47 show much more promising results, although they are not achievable due to the condition of the building. It should also be noted that the heat pump on very cold days

cannot respond to the required thermal needs. One of the coldest days of the simulation was purposely chosen to understand how the heat pump would behave. The results speak for themselves. The indoor temperature barely reaches 18 degrees, and the minimum temperature reaches 6 degrees at night. This is critical for churches that have valuable content that could be spoiled. Temperatures below 10 degrees are therefore not recommended.

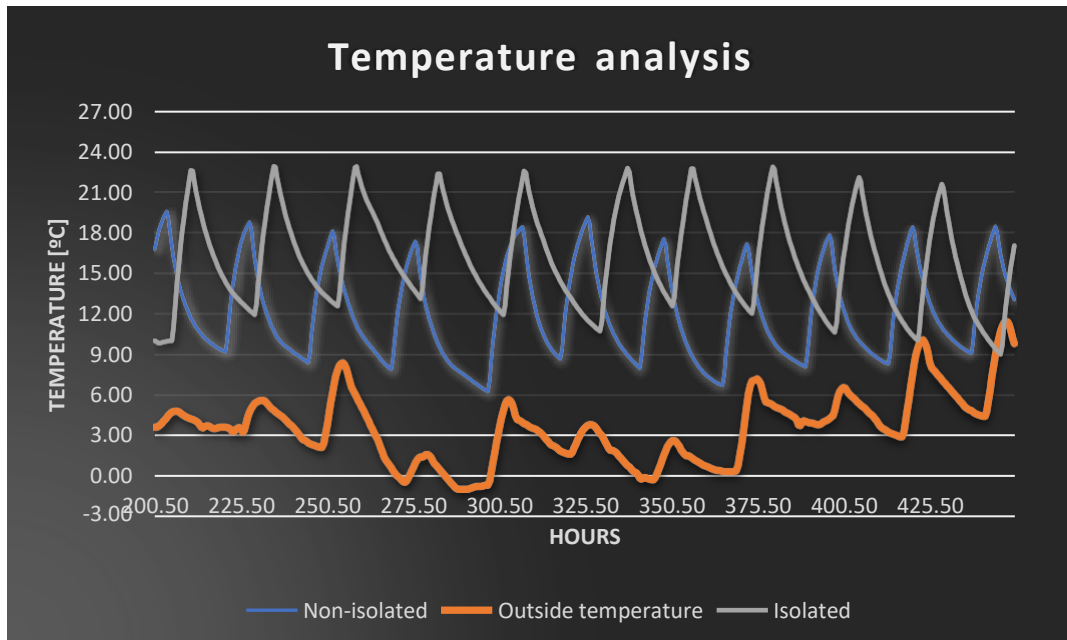


Figure 45 - Insulation effect HP

The energy consumption results are also influenced by thermal insulation as in the case of the heat pump. Figure 47 shows an identical behaviour. Tables 17 and 16 show the expenditure on electrical energy with and without insulation. Only insulation itself can save until 2 770 € and 5 t of CO₂ emissions. Note that the annual bills are higher than the solution with the gas boiler. This is due to the big difference between prices per kWh in Ireland and the fact that the heat pump is not efficient enough. The boiler has a performance of 92% which represents a very efficient heat source and difficult to overcome. However, it is always possible to save on the ecological footprint, assuming that a large part of grid energy is generated through renewable sources.

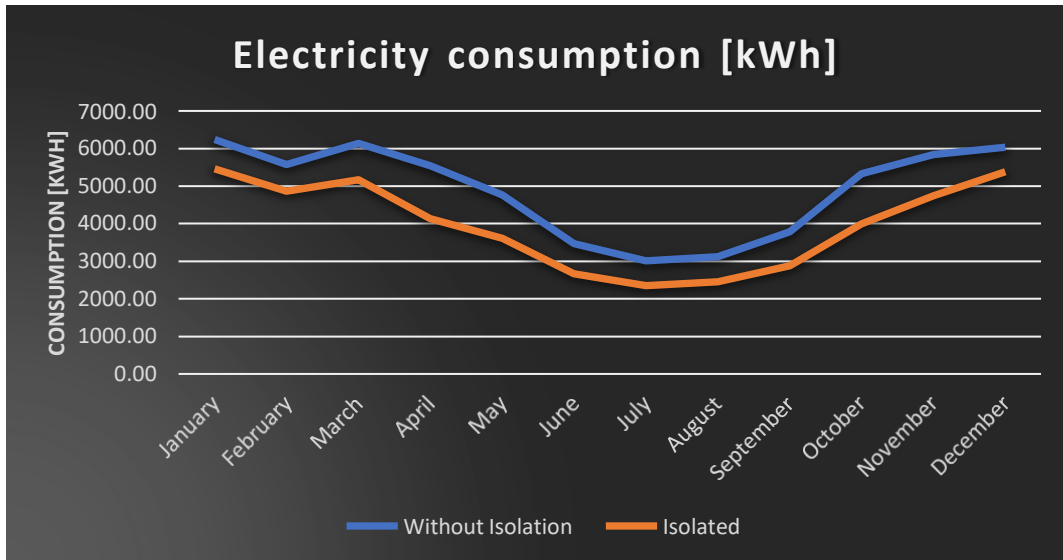


Figure 46 - Electricity consumption

Table 16 - Electric consumption and CO2 emissions

	Electric Consumption [kWh/year]	Price [€/kWh] [6]	CO2 emissions [kg/kWh] [43]
Non-Insulated	58 800	0.2495	0.468
Insulated	47 695	0.2495	0.468

Table 17- Annual Costs and emissions for the second simulation

ANNUAL COSTS	ANNUAL CO2 EMISSIONS
$58\,800\text{ kWh} * 0.2495 \frac{\text{€}}{\text{kWh}} = 14\,670\text{ €}$	$58\,800\text{ kWh} * 0.468 \frac{\text{kg}}{\text{kWh}} = 27\,518\text{ kg}$
$47\,695\text{ kWh} * 0.2495 \frac{\text{€}}{\text{kWh}} = 11\,900\text{ €}$	$47\,695\text{ kWh} * 0.468 \frac{\text{kg}}{\text{kWh}} = 22\,321\text{ kg}$

After analysing the results, one decided to implement a photovoltaic system on the roof of the church, to reduce part of the grid's electricity consumption. Figures 48 and 49 show how much electrical energy can be generated by the proposed solution, knowing that for the operation of the heat pump it will consume alternating current.

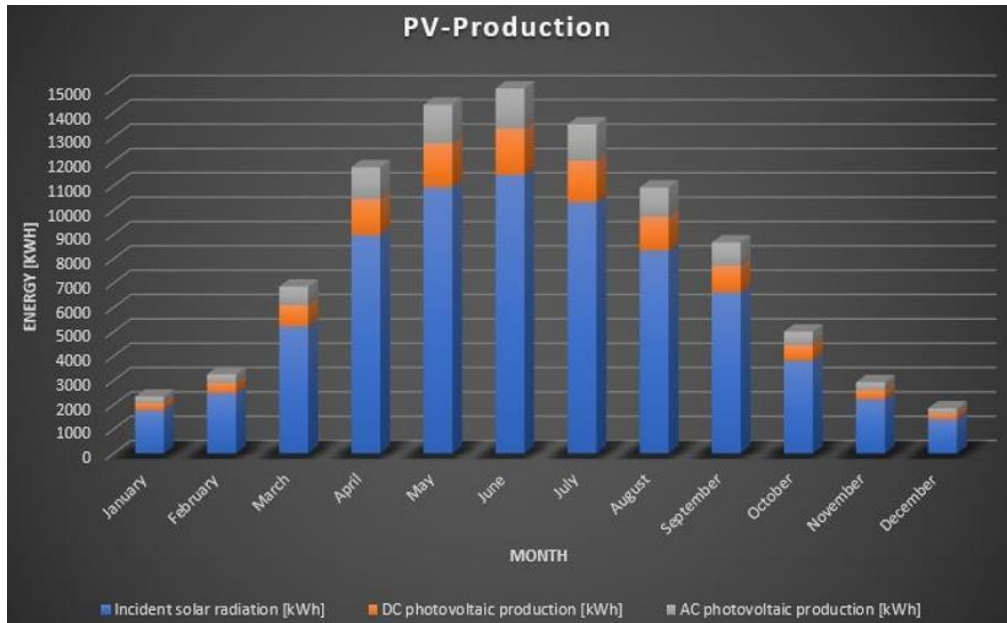


Figure 47 - PV production

To simplify the calculations in this case study, it was assumed that the photovoltaic production will be stored in its own batteries so that they can be used whenever necessary, thus, all the energy generated in DC can be converted to AC respectively and totally consumed by the heat pump. For this module, an average of 14% of the radiation is converted into electric energy as one can see in Figure 49.

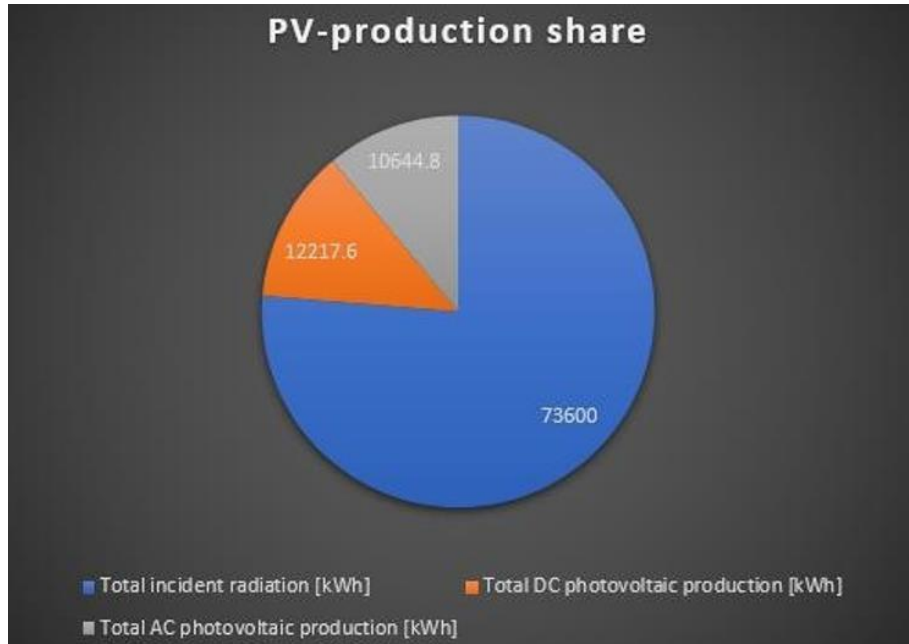


Figure 48 - PV-share

As expected, electrical production is higher in months with the highest solar incidence. Although the climate of Cork is very cloudy, much of the absorbed radiation is diffuse, which means that even with rain, it is possible to produce electricity. This fact combined with the moderate temperatures throughout the year allows the photovoltaic cells to maintain a good and stable performance. Figure 44 shows the daytime temperatures of the modules, and we can see

that its maximum average temperature reaches almost 30°C. This is a suitable temperature and won't have an impact in the performance of the PV-system.

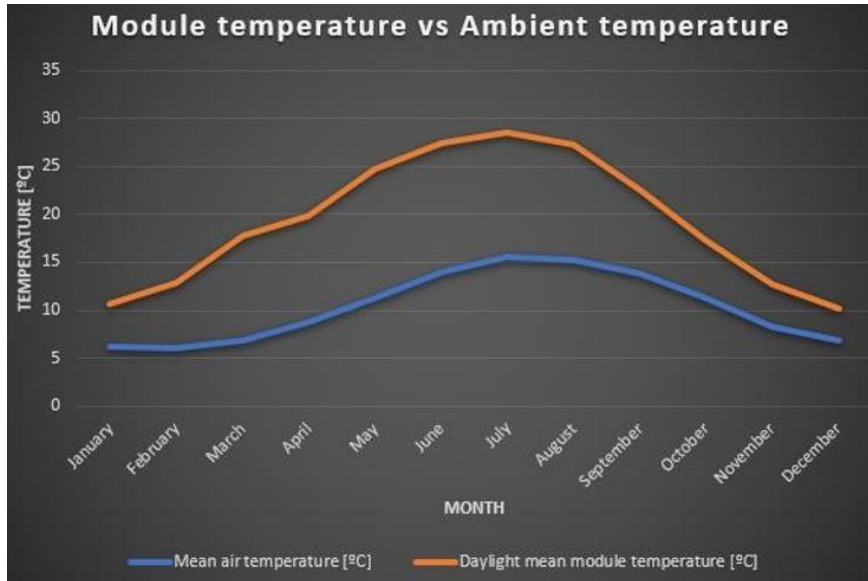


Figure 49 - Module temperature

Finally, making the proper calculations and assuming a final AC consumption of 10 645 kWh per year, it is established that the building could benefit greatly from the combination between insulation and PV-modules, saving almost 2,500 euros per year compared to the current system (gas boiler). Without the insulation, the bills would be practically the same, but with a saving of up to 8t of CO2 emissions, which is a considerable value.

Table 18- Annual Costs and emissions with PV-gains

ANNUAL COSTS	ANNUAL CO2 EMISSIONS
$(58\,800 - 10\,645) kWh * 0.2495 \frac{\text{€}}{kWh}$ = 12 014 [€]	$(58\,800 - 10\,645) kWh * 0.468 \frac{kg}{kWh} = 22$ 536 kg
$(47\,695 - 10\,645) kWh * 0.2495 \frac{\text{€}}{kWh}$ = 9 244 €	$(47\,695 - 10\,645) kWh * 0.468 \frac{kg}{kWh} =$ 17 339 kg

5.4 Solution with GSHP, radiant floor and PV-System

After analysing the heat pump with the current radiator system, it was intended to find the best possible solution for the use of this heat pump. This solution is the combination of a heat pump with a low temperature heating system plus photovoltaic modules and insulation. To

know what the costs, the thermal response as well as the ecological footprint would be, simulations were made using a new component in *TRNSYS*, namely *Type 653* (radiant floor).

Before being able to analyse the interior temperature of the church, using underfloor heating, it is necessary to consider that the church has an average height of 7 meters. *TRNSYS* temperature sensor analyses the average of the entire volume. Thus, knowing that the radiant floor evens the temperature close to the height of a human being (2m), we must assume that although in the graph of figure 51, only a maximum of 18 degrees appears, in fact, it will be more than this value. This does not happen with conventional radiators, bearing in mind that the heat is expelled upwards (glued to the walls) causing this temperature to be lower in the middle of the church volume as explained in Figure 50.



Figure 50 - Radiant floor heating vs radiators [50]

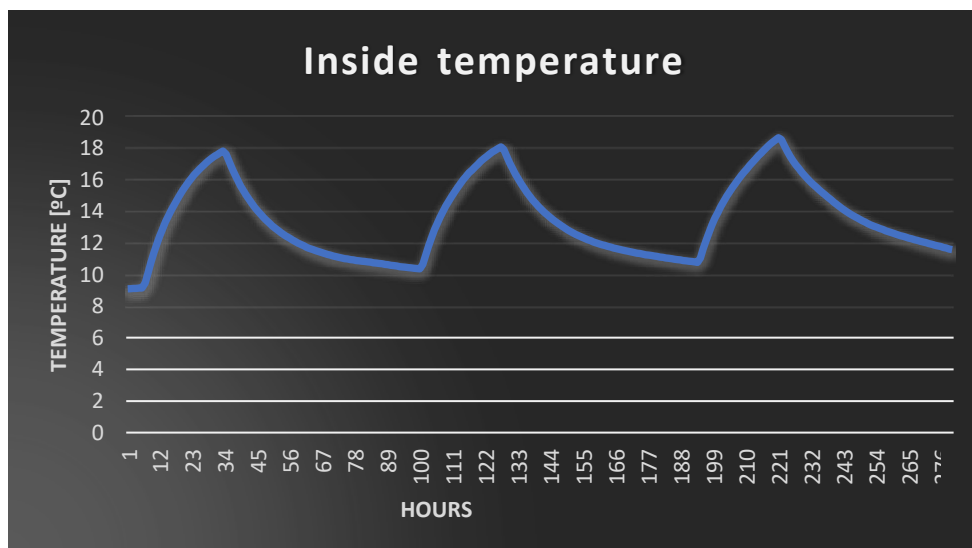


Figure 51 - Inside temperature (radiant floor)

As the church has a very large area for heating, a temperature of 55 degrees was chosen for the entrance to the slab. If it was a house, the temperature varied between 35-45 degrees, but as it is a building with a very large volume, we opted for a higher temperature, thus transferring more heat.

In Figure 53 it is possible to check the output and return temperature of the heat pump, with a typical difference of 20 degrees. The heat pump feels comfortable in this range of temperatures, as one can see by the increase of one unit of the coefficient of performance thus being much

more efficient. The same effect regarding the COP of the previous simulation is also visible in this case. Although it does not vary much, due to the constant temperature of the soil, it is possible to notice a certain difference in the hottest months.

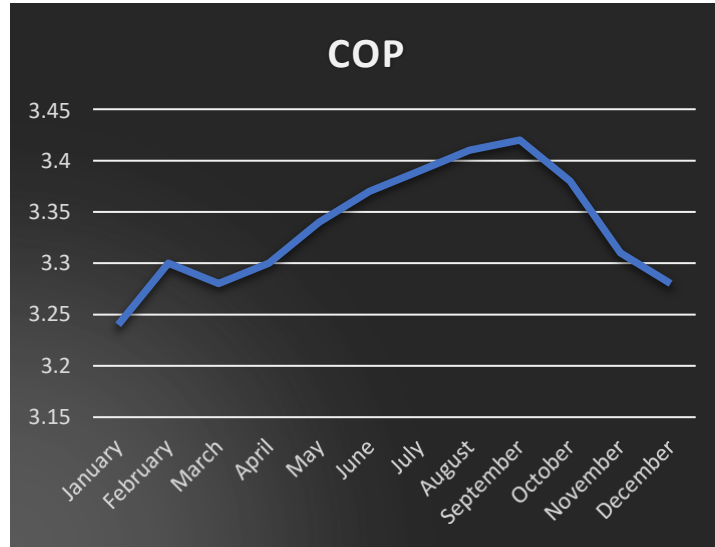


Figure 52 - COP (radiant floor)

The high COP causes the electrical consumption to be reduced considerably. With the help of the photovoltaic system (the same used in the previous simulation) it is possible to inject electrical energy directly into the heat pump, reducing the same costs as before. Since the outlet temperature is 15 degrees lower than that of the radiators, the temperature inlet to the underground heat exchanger increases considerably as can be seen in Figure 53. These two factors are closely linked to the performance of a geothermal heat pump.

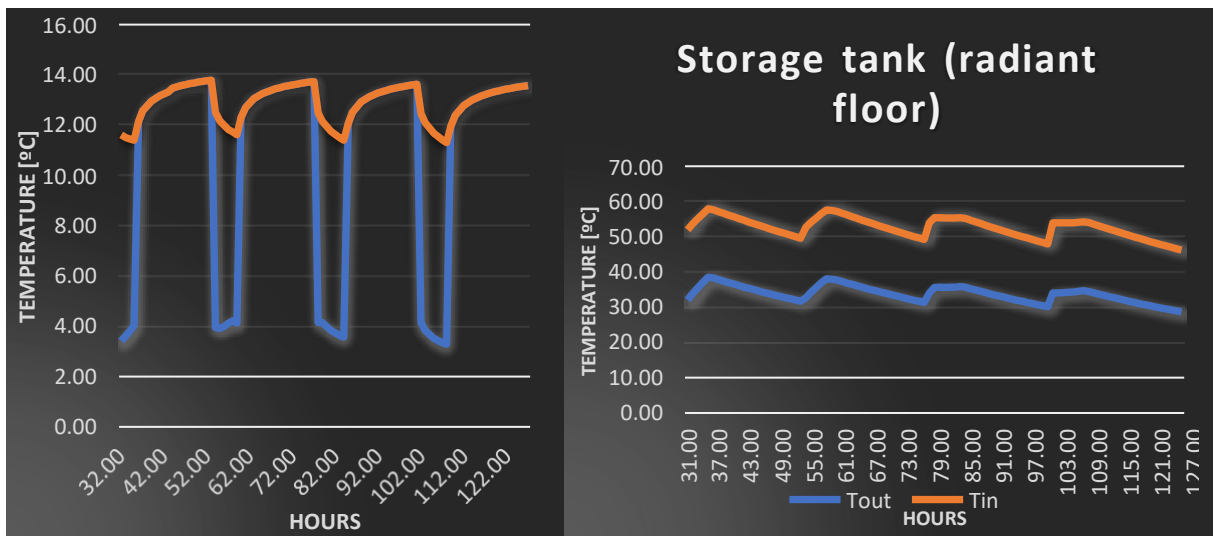


Figure 53 - Borehole heat exchanger and storage tank temperatures

The profile of electricity consumption for a year remains the same, due to the same climate. However, because of the more efficient system, consumption is much lower. We can see its behaviour in the figure 54, and in table 19 the final calculations for consumption and emissions expelled into the environment with this solution. The final cost has greatly reduced, as have the CO2 emissions.

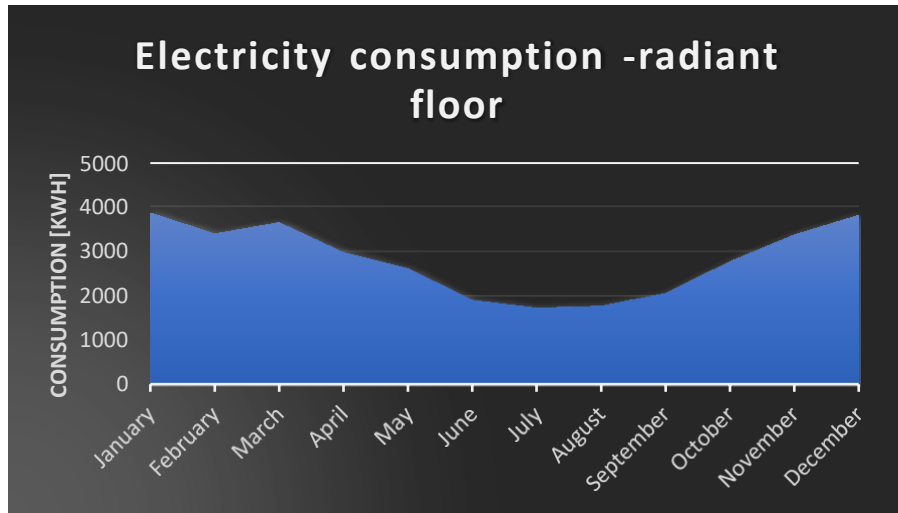


Figure 54 - Electricity consumption for the radiant floor solution

Table 19 - Final calculations for the radiant floor solution

ANNUAL COSTS	ANNUAL CO2 EMISSIONS
$(33\ 844 - 10\ 645) \text{ kWh} * 0.2495 \frac{\text{€}}{\text{kWh}}$ = 5 788 €	$(33844 - 10\ 645) \text{ kWh} * 0.468 \frac{\text{kg}}{\text{kWh}} = 10\ 857 \text{ kg}$

5.5 Return-on Investment

After having made all the simulations proposed for this work, it will be necessary to make a summary of all the important aspects analysed. Figure 55 precisely compares these values. For the investment calculation, the considerations were summarized in table 20. Depending on the type of contract and the legislation of the country in question, an investment in renewable energy may have benefits/discounts. In this way today's governments try to persuade people to embrace clean and renewable energy.

It should be noted that a high investment is required for any of the proposed solutions, but always with positive results in terms of saving emissions and consumption. The solution that is intended to be implemented in the church, takes at least 70 years to recover the investment, without isolation. This last factor influences the annual electricity consumption bills much more (3.5 times higher the price per kWh) reducing the return on investment by 50 years. This is explained by the reduction of peaks in energy demand, and the better functioning of the heat pump, making it more efficient. It is important to notice that maintenance costs were not regarded.

Table 20 - Calculation details

Geothermal heat pump + vertical installation [50]	450 €/kW * 89.1 kW = 40 095 €
PV-System + inverter + installation [51]	330 €/module * 60 = 19 800 €
Insulation [52]	10 €/m ² * 1456 m ² = 14 560 €
Radiant floor [53]	100 €/m ² * 260 m ² = 26 000 €

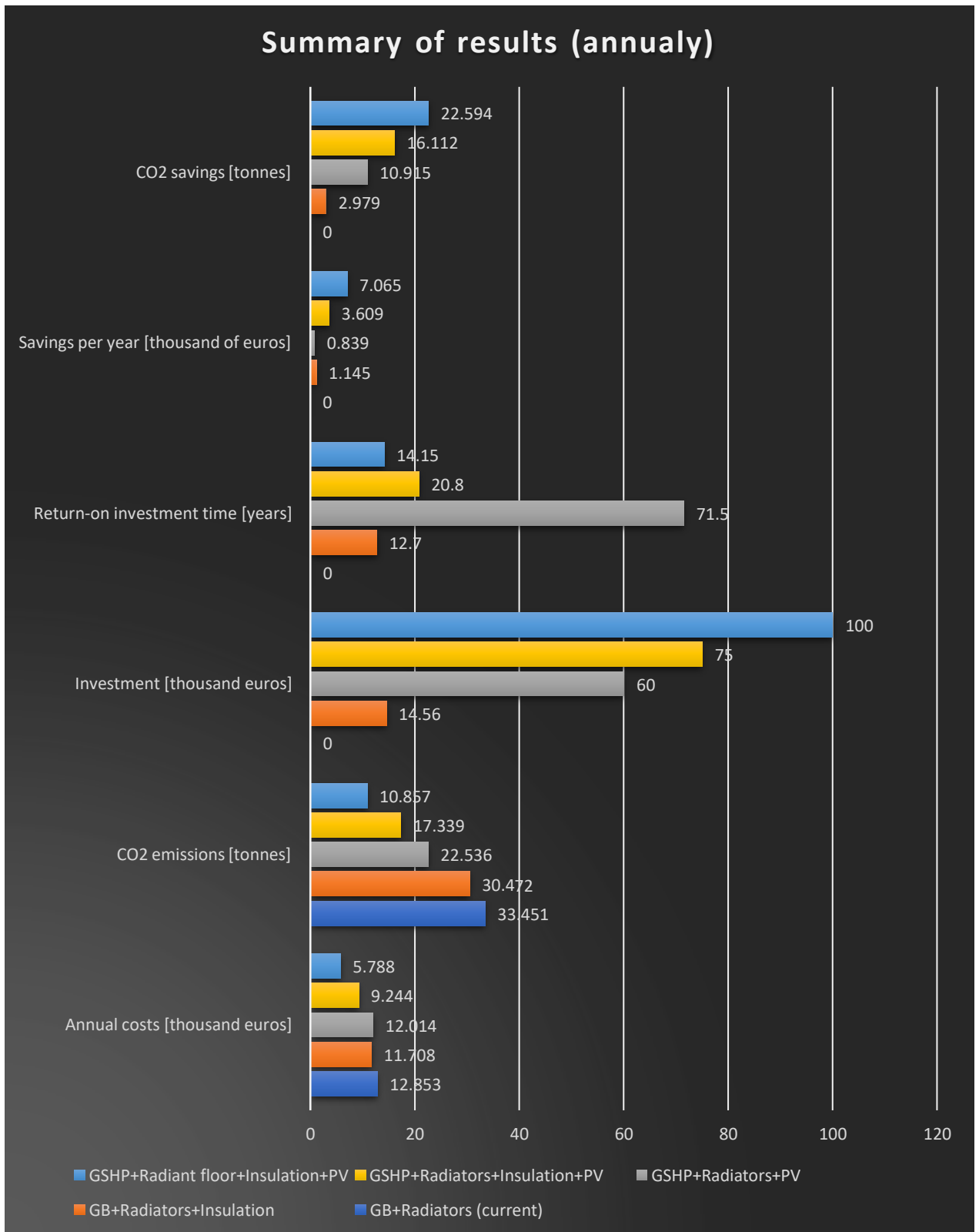


Figure 55 - Summary of results

6. Conclusions

Using *TRNSYS* as the software chosen for the simulations, it was possible to achieve the intended objectives. The simulation in this program and in all others that simulate HVAC installations, require a lot of attention and technical data, not only of the building parameters, but also of the climate, the desired temperature profile, and the technical details of the equipment. Before introducing the components in the simulation mode, it is always necessary to make a pre-dimensioning to be able to get closer to the objective. When the equipment has been chosen, we introduce it as external files in the simulation, as there is many equipment that is not in the *TRNSYS* bookstore, so that it is possible to simulate the chosen component with greater precision (normalized data).

As it is a very old building, and it was not possible to obtain exact details about its entire structure, many assumptions have been made. Therefore, the results obtained can vary a lot depending on its user. The many considerations that have been made in this project, turns this work more subjective and therefore they need to be explained accordingly as the project progresses.

The study tried to understand to what extent it would be feasible to replace a gas boiler with a geothermal heat pump, and for that it was necessary to simulate both systems. For a more complete study, several hypotheses were studied in addition to the current system. Not only was a photovoltaic system analysed, but also something very important that people usually forget when it comes to saving the planet, namely insulation. This is a parameter perhaps as important as the replacement of the energy source itself, because as we saw in the results presented in the previous section, it is possible to save both in annual costs and in expelled emissions. The thermal insulation means that the gas boiler can be dimensioned 20 kW below the current level and an additional 3000 € per year as well as 6 tonnes of *CO2* can be saved.

The first big challenge was choosing an appropriate heat pump, since the necessary condition was that the GSHP needed to reach temperatures of 75 °C. This condition was not easy to overcome, because even managing to get a high heat power, most of the pumps found on the market only guaranteed maximum temperatures around 60 °C. This would represent a great loss of energy compared to the existing gas boiler. As the heat pump would be connected to the radiators, and if we wanted to maintain the same heat performance, we would have to guarantee the same outlet temperature. Since this temperature is quite high for the use of heat pumps, very low performance values (COP) have been obtained compared to other applications. To take advantage of the full potential of these devices, the heat pump must be connected to medium temperature emitters between 40-60 °C (like underfloor radiating), as it is in this range that the COP values are higher.

The study revealed that it is possible to retrofit an old building with heat pumps using the current hot water distribution system, without major problems. Since the building requires high thermal loads, all equipment must be oversized. This over-dimensioning is desirable, as it manages to have a greater margin of manoeuvre if necessary. It is important to consider that if we want to have a good performance/cost ratio, we need a large initial investment especially in large and old buildings.

Although it is not possible to use underfloor heating in the church, as well as insulation, this would be by far the best possible solution for our case study. It is also important to point out that the photovoltaic system brings an added value to the system, as it manages to produce 10 645 kWh of energy converted into AC. This translates into an annual saving of 2660€ which, in conjunction with the heat pump, leads to a saving of 8 tonnes of *CO2* a year. Finally, the best solution, although impractical in this case, could save 22 tonnes of *CO2* and 7000€ per year. In an ecological and realistic analysis, replacing a boiler with a heat pump is, despite the

high investment, feasible, even with 70 years of ROI. Being a protected building that will exist for many more years, that time will eventually come, and till then it will save many tons of *CO2*. An alternative would be to get an agreement with the Irish government and be able to add thermal insulators without damaging/changing the building, for example on the inner side of the roof. A small change in legislation could help a lot in fighting climate change.

It is difficult for personal homes or even in public buildings, to start changing the way we heat our spaces. In fact, natural gas is much cheaper than electricity in Ireland and boilers can achieve yields of up to 90% not requiring a large investment. It is understandable that not everyone has the possibility to invest in renewable energies, however there are other alternatives that can be equally advantageous for saving energy, reducing bills and emissions. There are more and more incentives on the part of governments to call on people to be part of this much needed change, which is a great indicator and gives us hope for a cleaner and more sustainable world.

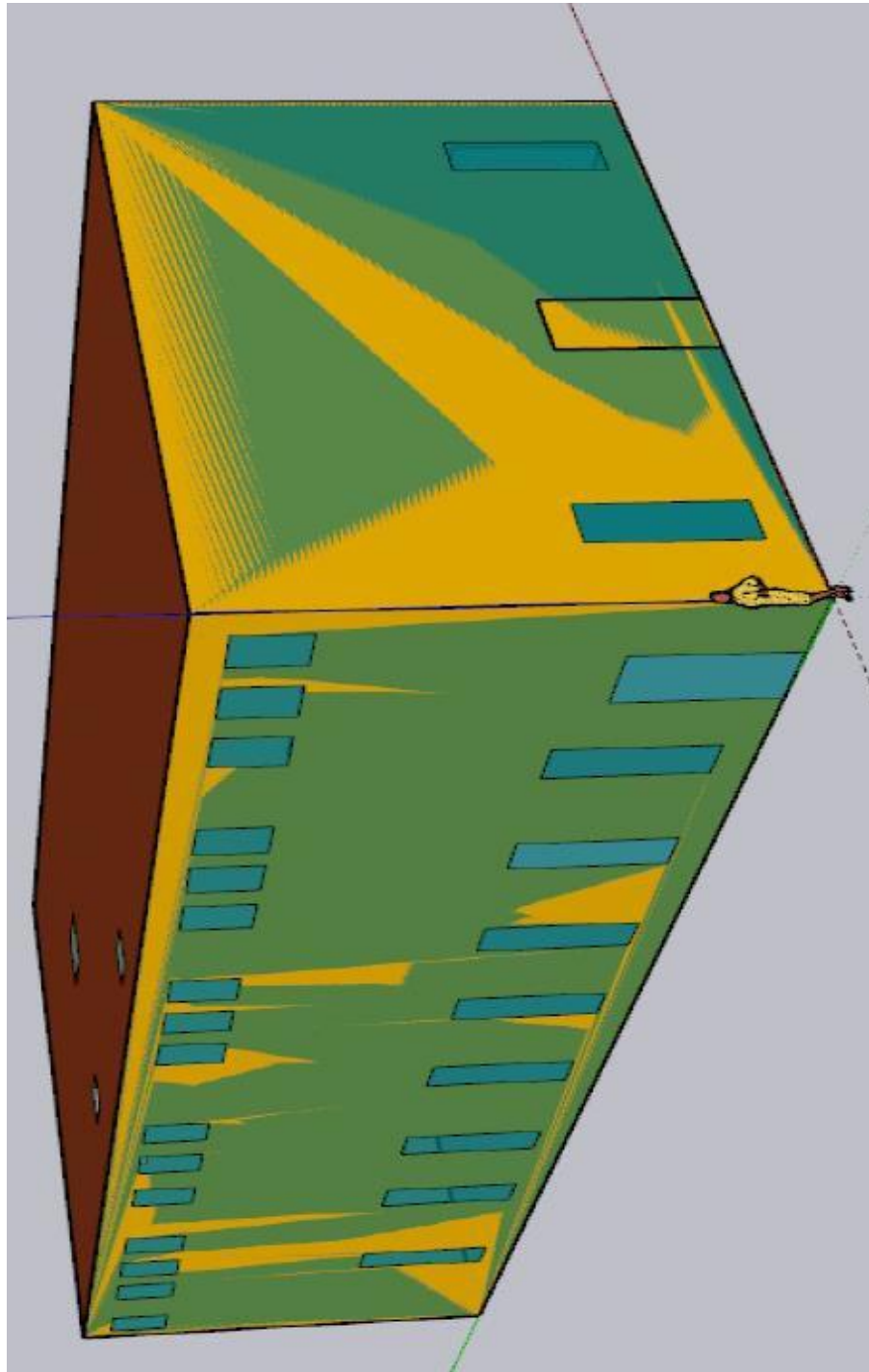
References

1. C.L, Ana Luísa, 2009 “Os actuais desafios da energia. Implementação e utilização das energias renováveis. Ciências Faculdade de. n.d. “UNIVERSIDADE DE LISBOA.:” Repositorio.Ul.Pt. [Accessed January 16, 2021].
2. Eurostat (2020) “Share of energy from renewable sources” n.d. Europa.Eu. [Accessed January 16, 2021]
3. EUROPEU, P. & da União Europeia, C. Directiva 2009/28/CE do Parlamento Europeu e do Conselho de 23 de Abril de 2009, relativa à promoção da utilização de energia proveniente de fontes renováveis. *Jornal Oficial da União Europeia*, 2009.
4. Mohrbacher, Hardy, 2012 “Molybdenum in Iron and Steels for Clean and Green Power Generation”. [Accessed January 16, 2021b].
5. UNIÃO EUROPEIA. Directiva 2010/31/UE, de 19 de Maio 2010. *Jornal oficial da União Europeia*, 18 de Junho 2010
6. Sustainable Energy Authority of Ireland. (2020, December). *Energy in Ireland*. <https://www.seai.ie/publications/Energy-in-Ireland-2020.pdf> [Accessed January 17, 2021]
7. GeoAtlantic - Un proyecto para promover la eficiencia de los recursos | Otro sitio realizado con WordPress. (2020, September 20). GeoAtlantic. <http://geoatlantic.eu/?lang=en>
8. Scholz, S. (2019). NABU | Erneuerbare Energien | Geothermie | Energie aus der Tiefe. NABU - Naturschutzbund Deutschland e.V. <https://www.nabu.de/umwelt-und-ressourcen/energie/erneuerbare-energien-energie-wende/geothermie/10643.html>
9. Richter, A. (2020, February 5). *The Top 10 Geothermal Countries 2019 – based on installed generation capacity (MWe)*. Think GeoEnergy - Geothermal Energy News. <https://www.thinkgeoenergy.com/the-top-10-geothermal-countries-2019-based-on-installed-generation-capacity-mwe/>
10. Guo, X., Du, L., Sun, P., Zhang, J., Shi, X., & Song, H. (2019). *An integrated approach to sustainable heat recovery in a sedimentary geothermal reservoir considering surface energy demands*. *Energy Procedia*, 158, 6003–6008. <https://doi.org/10.1016/j.egypro.2019.01.519>
11. Pinto, A., Rodrigues, F., & Mota, A. (2017). *Geothermal contribution on southern Europe climate for energy efficiency of university buildings. Winter season*. *Energy Procedia*, 134, 181–191. <https://doi.org/10.1016/j.egypro.2017.09.556>
12. Tinti, F., Kasmaee, S., Elkarmoty, M., Bonduà, S., & Bortolotti, V. (2018). *Suitability Evaluation of Specific Shallow Geothermal Technologies Using a GIS-Based Multi Criteria Decision Analysis Implementing the Analytic Hierarchic Process*. *Energies*, 11(2), 457.
13. Enx & Geysir Green Energy (2008) “Geothermal Utilisation in Europe” stjornarradid.is/media/atvinnuvegaraduneyti-media/media/frettir/080119_geothermal_europe_memo_for_ossur.pdf
14. BP Statistical Review of Global Energy (2020), <https://ourworldindata.org/grapher/installed-geothermal-capacity?tab> [Accessed January 20, 2021]
15. Pasquali, R., Jones, G. L., Burgess, J., & Williams, T. H. (2016). *Geothermal Energy Use, Country Update for Ireland*. Geothermal Association of Ireland, c/o SLR Consulting, 7 Dundrum Business Park, D14 N2Y7, Ireland, 1–13. [Accessed January 21, 2021] http://geoatlantic.eu/portfolio/wp-content/uploads/2019/02/ref.-20_EGC2016-Country-Update-Ireland.pdf
16. Department of the Environment, Climate and Communications. (2020). *Geothermal Energy in Ireland - A roadmap for a policy and regulatory framework*.

17. S.I. No. 147/2011 - European Communities (Renewable Energy) Regulations 2011. (C) Houses of the Oireachtas Service.
18. Wu, S., Dai, Y., Li, X., Oppong, F., & Xu, C. (2018). A review of ground-source heat pump systems with heat pipes for energy efficiency in buildings. *Energy Procedia*, 152, 413–418. <https://doi.org/10.1016/j.egypro.2018.09.167>
19. Petr Stefan . (2019). *Water2Energy - References*. *Water2Energy*. <http://www.veoliawater2energy.com/en/references/heat-pumps> [Accessed January 26,2021]
20. *Geothermal Home Heating And Cooling - Thermal Systems*. (2014, March 18). MC Williams&Son. <http://me1065.wikidot.com/geothermal-home-heating-and-cooling>
21. *Stuff.co.nz*. (2016, May 3). *Let your dirt warm your home - the magic of geothermal heating*. *Stuff*. <https://www.stuff.co.nz/life-style/home-property/78678179/let-your-dirt-warm-your-home--the-magic-of-geothermal-heating> [Accessed January 26,2021]
22. *Mean Annual Air Temperature | MATT | Ground temperature | Renewable Energy | Interseasonal Heat Transfer | Solar Thermal Collectors | Ground Source Heat Pumps | Renewable Cooling*. (2018). *Icax*. https://www.icax.co.uk/Mean_Annual_Air_Temperature.html [Accessed January 27,2021]
23. *De Kleijn Energy Consultants & Engineers*. (2018). *Refrigerants*. *Industrial Heat Pumps*. https://industrialheatpumps.nl/en/how_it_works/refrigerants/[Accessed January 27,2021]
24. Eslami-Nejad, P., Nguyen, A., Cimmino, M., Bastani, A., & Badache, M. (2020). *Performance comparison of a vertical direct expansion geothermal evaporator: Part I, single U-pipe using different refrigerants*. *International Journal of Refrigeration*, 116, 119–128. <https://doi.org/10.1016/j.ijrefrig.2020.03.024>
25. *Google Earth*. (2020). *Google Earth*. <https://earth.google.com/web/@51.89392618,-8.50357259,10.25105941a,79.14156442d,35y,-79.9862781h,60.72844862t,360r> [Accessed January 29, 2021]
26. Conner, T. (1989, November). *Comparison of Steady State Evaporation Models for Toxic Chemical Spills: Development of a New Evaporation Model*. https://www.researchgate.net/figure/Thermal-Properties-of-Different-Ground-Types_tbl1_235046768 [Accessed January 29, 2021]
27. *Cork's Climate*. (2020). *Climate Data*. <https://pt.climate-data.org/europa/irlanda/cork/cork-6019/#climate-graph>
28. *Church Building Projects - Welcome*. (2014, May 4). *5.5 Permissions – Historic Buildings | Church Building Projects - Welcome*. *Church Building Projects - Welcome | Making Church Buildings Missional*. http://www.churchbuildingprojects.co.uk/how-to/5-technical/5-5-permissions-historic-buildings/?doing_wp_cron=1612744360.3356668949127197265625
29. *Heat loss*. (2020, October). *Designing Buildings Wiki*. https://www.designingbuildings.co.uk/wiki/Heat_loss [Accessed January 29, 2021]
30. *Heat balance of a historical church - Transmission losses*. (2014, June). *Maidar Galarraga*.<https://www.diva-portal.org/smash/get/diva2:728969/FULLTEXT01.pdf>[Accessed February 02, 2021]
31. *Central Heating Systems - Diploma in Plumbing Studies*. (2015). https://www.pearsonschoolsandfecolleges.co.uk/FEAndVocational/Construction/Plumbing/Levels-2-and-3-Diploma-in-Plumbing-Studies/Samples/FreesamplechapterPlumbing/Level2_PLUMB_SB.pdf [Accessed 02 February, 2021]
32. *Maximum Flow Velocities in Water Systems*. (2020). *Engineering Tool Box*. https://www.engineeringtoolbox.com/flow-velocity-water-pipes-d_385.html [Accessed 02 February, 2021]

33. A. (2020, November 20). *One pipe system used in older central heating systems. Parkstone Yorkshire.* <https://www.parkstone-yorkshire.co.uk/one-pipe-system-used-in-older-central-heating-systems/> [Accessed 02 February, 2021]
34. *Installation and Service Instructions Buderus Logana.* (2000). Bosch. https://www.bosch-climate.us/files/6720817939_G315_Installation_Instructions_en_02.2017_US_1.pdf [Accessed February 03,2021]
35. Riello. (2015). Riello 40GS. <https://www.rielloburners.co.uk/images/content/downloads/RIELLO%2040%20GS.pdf> [Accessed February 03,2021]
36. HeatandPlumb.com. (2020). *MaxHeat Heritage Sectional Radiator | 4/95/20 | 960mm x 1200mm | Primer.* <https://www.heatandplumb.com/acatalog/maxheat-heritage-4-column-cast-radiator-4-95-20> [Accessed February 04,2021]
37. Sebarchievici, C., Dan, D., & Sarbu, I. (2015). *Performance Assessment of a Ground-coupled Heat Pump for an Office Room Heating using Radiator or Radiant Floor Heating Systems.* *Procedia Engineering*, 118, 88–100. <https://doi.org/10.1016/j.proeng.2015.08.407>
38. EN 442-1&2:2014 *Radiators and convectors* (2014)
39. Bordass, W., & Bemrose, C. (1996). *Heating Your Church.* Penguin Random House.
40. Solar Energy Laboratory, Univ. of Wisconsin-Madison, TRANSSOLAR Energietechnik GmbH, CSTB – Centre Scientifique et Technique du Bâtiment, & TESS – Thermal Energy Systems Specialists. (2018). *TRNSYS 18 - A Transient System Simulation program.*
41. *Heat Gain from People, Lights, and Appliances.* (2020, April 14). Engineer-Educators.Com.
42. Bergman, T. L., Lavine, A. S., Incropera, F. P., & DeWitt, D. P. (2011). *Fundamentals of Heat and Mass Transfer* (7th ed.). Wiley.
43. *Carbon tracker | Bulb.* (2020). *Join Bulb - Making Energy Simpler, Cheaper, Greener.* <https://bulb.co.uk/carbon-tracker/> [Accessed February 10,2021]
44. Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: *World Map of the Köppen-Geiger climate classification updated.* *Meteorol. Z.*, 15, 259-263. DOI: 10.1127/0941-2948/2006/0130.
45. Jones, G., Goodman, R., Pasquali, R., Kelly, J. G., O'Neill, N., & Slowey, E. (2007, May). *The Status of Geothermal Resource Development in Ireland.*
46. WAMAK heat pumps - WW SHR HeavyDuty 80 oC. (2018). WAMAK. <https://www.wamak.eu/en/heat-pumps/heavy-duty/ww-shr-heavyduty-80-%C2%BAC>
47. Luer, T., Boljevic, S., & Smolen, S. (2019). *Feasibility study for application of ground source heat pumps as a means of thermal energy supply for large shopping center.*
48. Ma, W., Keun Kim, M., & Hao, J. (2019). *Numerical Simulation Modeling of a GSHP and WSHP System for an Office Building in the Hot Summer and Cold Winter Region of China: A Case Study in Suzhou.*
49. Jian, Y., Yu, Z., Liu, Z., Li, Y., & Li, R. (2016). *Simulation Study of Impacts of Radiator Selection on Indoor Thermal Environment and Energy Consumption.* *Procedia Engineering*, 146, 466–472. <https://doi.org/10.1016/j.proeng.2016.06.430>
50. *How Much Will a Geothermal Heating and Cooling System Cost for My Home in 2021?* (2021, January 27). *Climate Master.*
51. *The Cost of a Solar PV System.* (2021, February 24). *TheGreenAge.*
52. Perry, C. (2021, May 11). *How Much Does Attic Insulation Cost? Forbes Advisor.* <https://www.forbes.com/advisor/home-improvement/attic-insulation-cost/>
53. Cernivec, S. (2021, August 2). *How Much Does Radiant Floor Heating Cost in 2021? WarmlyYours.Com.* <https://www.warmlyyours.com/en-US/posts/How-Much-Does-Floor-Heating-Cost-2574>

APPENDIX A - Building model in *Google Sketchup*



APPENDIX B - Gas boiler LOGANO G315

Logano G315						
Boiler capacity	Unit	105	140	170	200	230
Number of boiler sections	-	5	6	7	8	9
Nominal output	Btu/hr	293.500 - 358.000	362.000 - 477.800	481.000 - 580.200	583.600 - 682.600	686.000 - 794.990
	(kW)	(86 - 105)	(106 - 140)	(141 - 170)	(171 - 200)	(201 - 230)
Combustion output	Btu/hr	314.300 - 387.300	387.300 - 516.700	515.300 - 625.900	624.900 - 734.100	734.400 - 846.000
	(kW)	(92.1 - 113.5)	(113.5 - 151.4)	(151.0 - 183.4)	(183.1 - 215.1)	(215.2 - 247.9)
Boiler overall length (L)	inches	44-19/64	50-19/32	56-57/64	63-3/16	69-31/64
	(mm)	(1125)	(1285)	(1445)	(1605)	(1765)
Boiler block length (L _b)	inches	38-3/16	44-31/64	50-25/32	57-3/32	63-25/64
	(mm)	(970)	(1130)	(1290)	(1450)	(1610)
Fitting clearance, boiler section (width × height × depth)	inches (mm)	28-1/32 × 35-25/32 × 6-19/64 (712 × 934 × 160)				
Fitting clearance, boiler block (width × height × length)	inches (mm)	28-1/32 × 39-1/8 × L _b (712 × 994 × L _b)				
Combustion chamber length	inches	31-7/64	37-13/32	43-45/64	50	56-19/64
	(mm)	(790)	(950)	(1110)	(1270)	(1430)
Combustion chamber diameter	inches	15 3/4				
	(mm)	(400)				
Burner door thickness	inches	4-59/64				
	(mm)	(125)				
Vent connection diameter	inches	7"				
	(mm)	(178)				
Weight, net ¹⁾	lb.	1.20	1.395	1.59	1.78	1.975
	(kg)	(543)	(631)	(719)	(807)	(895)
Boiler water content	gal.	37.75	45.25	52.5	60	67.5
	(l)	143	171	199	227	255
Gas capacity	gal.	36.83	47.82	56.8	65.78	69.48
	(l)	147	181	215	249	263
Flue gas temperature, partial load (60 %)	°F	176.6	200.4	176.6	209.0	205.8
	(°C)	(137)	(138)	(136)	(132)	(141)
Flue gas temperature, full load	°F	323.6 - 365	309.2 - 359.6	321.8 - 356	316.4 - 348.6	334.4 - 374
	(°C)	(162 - 185)	(154 - 182)	(161 - 180)	(158 - 176)	(166 - 190)
Flue gas mass flow rate, oil, partial load (60 %)	lb./s	0.0524	0.0831	0.101	0.1188	0.1367
	(kg/s)	(0.0283)	(0.0377)	(0.0458)	(0.0539)	(0.0620)
Flue gas mass flow rate oil, full load ²⁾	lb./s	0.0862 - 0.1063	0.1063 - 0.1418	0.1413 - 0.1717	0.1713 - 0.2013	0.2013 - 0.2319
	(kg/s)	(0.0391 - 0.0482)	(0.0482 - 0.0643)	(0.0641 - 0.0779)	(0.0777 - 0.0913)	(0.0913 - 0.1052)
Flue gas mass flow rate, gas, partial load (60%)	lb./s	0.0326	0.0336	0.1014	0.1193	0.1371
	(kg/s)	(0.0284)	(0.0379)	(0.0460)	(0.0541)	(0.0622)
Flue gas mass flow, gas, full load NOT DEFINED	lb./s	0.0864 - 0.1067	0.1067 - 0.1422	0.1418 - 0.1722	0.172 - 0.2019	0.2022 - 0.2328
	(kg/s)	(0.0392 - 0.0484)	(0.0484 - 0.0645)	(0.0643 - 0.0781)	(0.0780 - 0.0916)	(0.0917 - 0.1056)
CO ₂ content, oil	%	13.0				
CO ₂ content, gas	%	10				
Required draft	PSI	0				
	(Pa)	(0)				
Fireside pressure drop	in. W.C.	0.117 - 0.165	0.185 - 0.317	0.285 - 0.522	0.538 - 0.715	0.530 - 0.711
	(mbar)	(0.26 - 0.41)	(0.46 - 0.75)	(0.71 - 1.30)	(1.34 - 1.78)	(1.32 - 1.77)

APPENDIX C - BURNER *RIELLO GS10*

One Stage Gas Burners RIELLO 40 GS SERIES

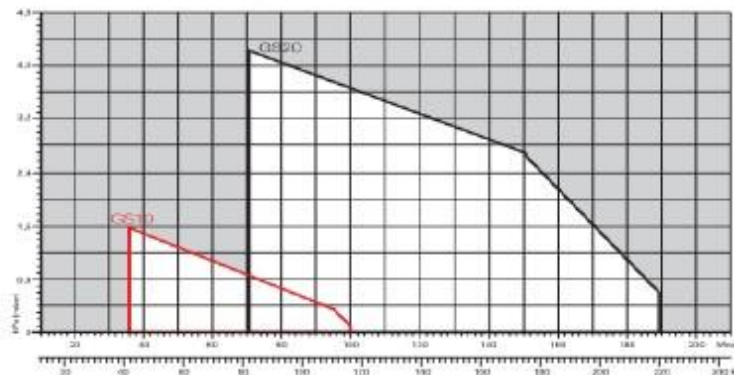
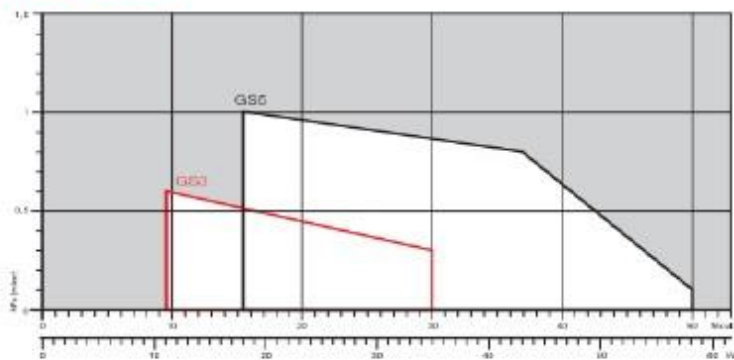
Available models

Burners

CODE	MODEL	HEAT OUTPUT		TOTAL ELECTRICAL POWER (kW)	CERTIFICATION	NOTE
		(kW)	NATURAL GAS (Nm ³ /h)			
3755119	GS3	11 - 35	1,1 - 3,5	0,100	CE - 0694 CN7B05	(1) (5)
3755219	GS5	18 - 58	1,8 - 5,8	0,110	CE - 0694 CN7B05	(1) (5)
3755281	GS5	23 - 65	2,3 - 6,5	0,180	-	(2) (4) (5)
3755426	GS10	42 - 116	4,2 - 11,6	0,130	CE - 0694 CN7B05	(1)
20034913	GS10 TL	42 - 116	4,2 - 11,6	0,130	CE - 0694 CN7B05	(1)
3755444	GS10	42 - 116	4,2 - 11,6	0,130	CE - 0694 CN7B05	(2) (3)
3755483	GS10	42 - 116	4,2 - 11,6	0,200	-	(2) (4)
20007527	GS10	42 - 116	4,2 - 11,6	0,200	-	(1) (4) (5)
3755616	GS20	81 - 220	8,1 - 22	0,250	CE - 0694 CN7B05	(1)
20033905	GS20 TL	81 - 220	8,1 - 22	0,250	CE - 0694 CN7B05	(1)
3755644	GS20	81 - 220	8,1 - 22	0,250	CE - 0694 CN7B05	(2) (3)
3755683	GS20	81 - 220	8,1 - 22	0,430	-	(2) (4) (5)

Net calorific value G20: 10 kWh/Nm³ - Density: 0,71 kg/Nm³
 The burners of GS series are in according to EN 676
 (1) With plug and socket
 (2) With terminal block
 (3) Belgium version
 (4) Korea version
 (5) With air damper opening motor inside the cover

FIRING RATES



APPENDIX D - RADIATOR FROM *MaxHeat*

MaxHeat Heritage 4/65/20 Column Radiator Features:

- Radiator Valves sold separately (See the You May Need)
- Air Vents and Retaining Stays need to be ordered separately (See the You May Need)
- Need to order optional Joining Key (on a sale or return basis) for radiator longer than 1200mm size (See the You May Need)
- For overall length you need to add an extra 20mm
- May require some assembly
- Can be ordered in a RAL colour at extra cost - please call if you require colour
- Primer paint dark grey primer RAL 7022 - suitable for re-painting
- Pressure tested to 10 bar / maximum working pressure 6 bar
- Integrated feet supplied as standard
- Supplied with a 10 year guarantee from the manufacturer

MaxHeat Heritage 4/65/20 Column Radiator Specifications:

Radiator Type	Sectional
Radiator Configuration	4 Column
Radiator Design	Column Tubes - Vertical
Radiator Sections	20
Radiator Height	660mm
Radiator Width	1200mm
Radiator Depth	144mm
Orientation	Horizontal
Fuel	Central Heating
Pipe Centres	1200mm + Valves
Wall to Pipe Centres	102 - 112mm
Material	Cast Iron
Colour	Dark Grey Primer
Output Watts	1860
Output BTUs	6340
Brand	MaxHeat
Collection	Heritage
Style	Traditional
Market	Domestic
EAN Barcode	5055601414122
Manufacturer Part Number	4/65/20

APPENDIX E - HEAT PUMP UNIT



WW 125 SHR HD Modul

Technical information - heat pump

Type :	WW 125 SHR HD Modul	latest data update :	2017-11-23 15:22:00
Article code :	WAM01408	Language :	English

Nominal performance data according to EN 14511

Heating capacity :	89.10 kW	Input :	21.21 kW
Refrigerating capacity :	67.89 kW	COP :	4.2

* Data at conditions W30°C/W70°C

Operating temperature limitations

Source temperature minimal :	-5°C	Flow temperature minimal :	+20°C
Source temperature maximal :	+45°C	Flow temperature maximal :	+82°C

Mechanical data

Width :	mm	Weight inside :	560 kg
Depth :	mm		
Height :	mm		

Noise emissions

Noise emissions inside Lp (1m) :	52 dB(A)
------------------------------------	----------

Refrigerant circle parameters

Refrigerant :	R134a	Orifice inside :	EEV
Refrigerant volume :	30 kg		

Pipe dimensions, flow rates, pressure drops

Connecting dimensions - primary side :	2.1/2 "	Pressure drop - primary side :	max 20 kPa
Connecting dimensions - secondary side :	2.1/2 "	Pressure drop - secondary side :	max 20 kPa
Flow - primary side :	19.58 m ³ /hour	Recommended ΔT source :	3 K
Flow - secondary side :	11.01 m ³ /hour	Recommended ΔT consumer :	7 K

Electrical parameters

Main connection cable - dimension :	5x10 mm ²	Current - nominal :	37.18 A
Primary side cable - dimension :	5x2.5 mm ²	Current - maximal :	52.80 A
Voltage :	3 x 400 V	Softstart :	MCD 201
Fuze :	63 A	Starting current :	100.39 A

Features

Condenser circulator installed :	No	Installed HP controller :	SIEMENS RVS 21
Source circulator installed :	No	Control of mixed heating circuit :	Yes
Bivalent heater installed :	No	Control of direct pump heating circuit :	Yes
Three way switching valve in delivery :	No	Active cooling :	optional



WW 125 SHR HD Modul

Source	Heating capacity / flow temperature (kW)			Power input / flow temperature (kW)			COP / flow temperature (-)		
	60	70	80	60	70	80	60	70	80
40	128,16	117,29	106,83	18,16	21,67	26,21	7,06	5,41	4,08
39	124,57	114,10	104,05	18,08	21,62	26,17	6,89	5,28	3,98
38	121,08	111,01	101,34	18,00	21,57	26,14	6,73	5,15	3,88
37	117,67	107,99	98,71	17,93	21,52	26,10	6,56	5,02	3,78
36	114,36	105,06	96,16	17,86	21,47	26,07	6,40	4,89	3,69
35	111,13	102,21	93,67	17,79	21,42	26,03	6,25	4,77	3,60
34	107,99	99,44	91,26	17,72	21,38	25,99	6,09	4,65	3,51
33	104,94	96,74	88,92	17,66	21,34	25,96	5,94	4,53	3,43
32	101,96	94,12	86,64	17,60	21,30	25,92	5,79	4,42	3,34
31	99,07	91,58	84,43	17,55	21,25	25,88	5,65	4,31	3,26
30	96,26	89,10	82,29	17,49	21,21	25,84	5,50	4,20	3,18
29	93,53	86,70	80,20	17,44	21,17	25,80	5,36	4,09	3,11
28	90,87	84,36	78,18	17,39	21,13	25,75	5,22	3,99	3,04
27	88,29	82,09	76,21	17,34	21,09	25,71	5,09	3,89	2,96
26	85,78	79,89	74,31	17,30	21,05	25,66	4,96	3,79	2,90
25	83,34	77,74	72,46	17,25	21,01	25,61	4,83	3,70	2,83
24	80,98	75,67	70,66	17,21	20,97	25,56	4,71	3,61	2,76
23	78,68	73,65	68,92	17,17	20,93	25,51	4,58	3,52	2,70
22	76,44	71,69	67,22	17,12	20,89	25,45	4,46	3,43	2,64
21	74,28	69,78	65,58	17,08	20,84	25,39	4,35	3,35	2,58
20	72,17	67,94	63,98	17,04	20,80	25,33	4,24	3,27	2,53
19	70,13	66,14	62,43	17,00	20,75	25,26	4,13	3,19	2,47
18	68,14	64,40	60,92	16,96	20,70	25,19	4,02	3,11	2,42
17	66,21	62,71	59,46	16,92	20,65	25,12	3,91	3,04	2,37
16	64,34	61,06	58,03	16,87	20,60	25,04	3,81	2,96	2,32
15	62,53	59,47	56,65	16,83	20,54	24,96	3,71	2,89	2,27
14	60,76	57,91	55,30	16,79	20,48	24,87	3,62	2,83	2,22
13	59,05	56,40	53,98	16,74	20,42	24,78	3,53	2,76	2,18
12	57,39	54,94	52,71	16,70	20,36	24,68	3,44	2,70	2,14
11	55,78	53,51	51,46	16,65	20,29	24,58	3,35	2,64	2,09
10	54,21	52,12	50,24	16,60	20,22	24,48	3,27	2,58	2,05
9	52,69	50,77	49,06	16,55	20,15	24,36	3,18	2,52	2,01
8	51,21	49,46	47,90	16,50	20,07	24,25	3,10	2,46	1,98
7	49,77	48,17	46,77	16,44	19,99	24,12	3,03	2,41	1,94
6	48,37	46,92	45,66	16,38	19,90	24,00	2,95	2,36	1,90
5	47,01	45,70	44,57	16,32	19,81	23,86	2,88	2,31	1,87

APPENDIX F - PV-module from SolarWorld

Sunmodule[®] Plus SW 280-290 MONO BLACK (5-busbar)



PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

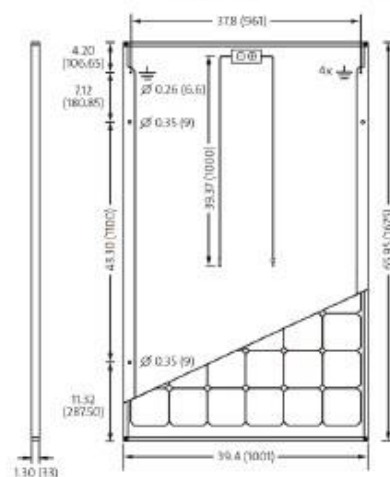
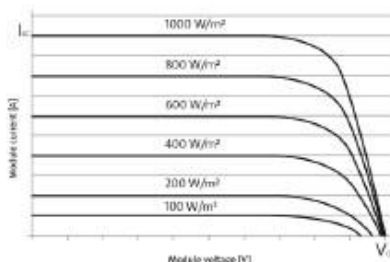
		SW 280	SW 285	SW 290
Maximum power	P_{max}	280 Wp	285 Wp	290 Wp
Open circuit voltage	V_{oc}	39.5 V	39.7 V	39.9 V
Maximum power point voltage	V_{mp}	31.2 V	31.3 V	31.4 V
Short circuit current	I_{sc}	9.71 A	9.84 A	9.97 A
Maximum power point current	I_{mp}	9.07 A	9.20 A	9.33 A
Module efficiency	η_{stc}	16.70 %	17.00 %	17.30 %

*STC: 1000W/m², 25°C, AM 1.5

PERFORMANCE AT 800 W/M², NOCT, AM 1.5

		SW 280	SW 285	SW 290
Maximum power	P_{noct}	207.2 Wp	211.1 Wp	215 Wp
Open circuit voltage	V_{oc}	35.8 V	36.0 V	36.2 V
Maximum power point voltage	V_{mp}	28.3 V	28.4 V	28.5 V
Short circuit current	I_{sc}	7.85 A	7.96 A	8.06 A
Maximum power point current	I_{mp}	7.33 A	7.43 A	7.54 A

Minor reduction in efficiency under partial load conditions at 25°C at 300 W/m², 100% of the STC efficiency (1000 W/m²) is achieved.



All units provided are Imperial. If units provided in parentheses.
SolarWorld AG reserves the right to make specification changes without notice.

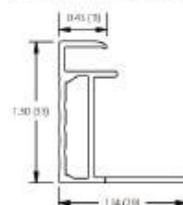
COMPONENT MATERIALS

Cells per module	60	Front	Low-iron empered glass with ARC (EN 12150)
Cell type	Mono crystalline 5-busbar	Frame	Black anodized aluminum
Cell dimensions	6.17 in x 6.17 in (156.75 x 156.75 mm)	Weight	39.7 lbs (18.0 kg)
THERMAL CHARACTERISTICS		ADDITIONAL DATA	
NOCT	48°C	Power sorting	-0 Wp/+5 Wp
TC _{sc}	0.044 %/C	J-Box	IP65
TC _{V_{mp}}	-0.31 %/C	Connector	PV wire per IUL4703 with H4/UTX connectors
TC _{P_{max}}	-0.43 %/C	Module fire performance	(UL 1703) Type I
Operating temp	-40 to +85 °C		

PARAMETERS FOR OPTIMAL SYSTEM INTEGRATION

Maximum system voltage SC II / NEC	1000 V	
Maximum reverse current	25 A	
Number of bypass diodes	3	
Design loads*	Two rail system	113 psf downward, 64 psf upward
Design loads*	Three rail system	178 psf downward, 64 psf upward
Design loads*	Edge mounting	178 psf downward, 41 psf upward

*Please refer to the Sunmodule installation instructions for the details associated with these load cases.



- Compatible with both "Top-Down" and "Bottom" mounting methods
- Grounding locations: - 4 locations along the length of the module in the extended flange.

SW-01-7515U5 16-0311