# Assessment of Technical, Economic and Market Potential of Shallow Geothermal Energy in Portugal

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## Energy Engineering and Management

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# Abstract

Ground-source heat pumps (GSHP) are low energy consuming and low environmental impact application of shallow geothermal energy (SGE). This thesis presents an assessment of the technical, economic, and market potential for SGE with focus on GSHP systems in residential, office spaces, and hotel sectors in Portugal. The assessment of technical potential is based on review of energy consumption needs, available literature regarding borehole heat exchanger length, and current GSHP projects in Portugal. The economic and market potential assessments are based on energy consumption and real estate data available from public as well as corporate sector. The economic potential of these systems was estimated at €16 billion corresponding to approximately 6.5 GW for the three sectors mentioned above. The thesis also includes an assessment to compare net present value (NPV) and carbon emissions from GSHP systems for residential sector with other competing technological options. The market potential was estimated at €5.2 billion for residential sector corresponding to 1.87 MW of installed capacity. It was concluded that GSHP systems have potential to play a significant role in satisfying the requirements of EU Directive 2018/2001.

*Keywords: Shallow geothermal energy, ground-source heat pumps, technical potential, economic potential, market potential*

# Resumo

As bombas de calor de fonte subterrânea (GSHP) têm baixo consumo de energia e baixo impacto ambiental, aplicação de energia geotérmica superficial (SGE). Esta tese apresenta uma avaliação do potencial técnico, econômico e de mercado da SGE, com foco nos sistemas GSHP nos setores residencial, escritório e hotelaria em Portugal. A avaliação do potencial técnico é baseada na análise das necessidades de consumo de energia, literatura disponível sobre o comprimento do trocador de calor de poço e os projetos atuais do GSHP em Portugal. As avaliações de mercado e potencial econômico são baseadas em dados de energia e imóveis disponíveis nos setores público e corporativo. O potencial econômico desses sistemas foi estimado em 16 bilhões de euros, correspondendo a aproximadamente 6,5 GW para os três setores mencionados acima. A tese também inclui uma avaliação para comparar o valor presente líquido (VPL) e as emissões de carbono dos sistemas residenciais do GSHP com outras opções de tecnologia concorrentes. O potencial de mercado foi estimado em € 5,2 bilhões para o setor residencial, correspondendo a 1,87 MW de capacidade instalada. Verificou-se que os sistemas GSHP têm o potencial de desempenhar um papel significativo no atendimento aos requisitos da Diretiva da UE 2018/2001.

*Palavras-chave: Energia geotérmica superficial, bombas de calor de fonte subterrânea, potencial técnico, potencial econômico, potencial de mercado*

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# List of symbols

| | |
|---|---|
| $\delta$ | Annual fractional growth in the early years in Fisher-Pry diffusion model |
| $f$ | Fraction of the market substituted |
| $t_0$ | Time at which fraction of the market substituted is 50% |
| $N(t)$ | Cumulative number of adopters at time t |
| $\acute{N}(t)$ | Population of potential adopters at time t |
| $a$ | Coefficient of innovation |
| $b$ | Coefficient of imitation |
| $Q_{usable}$ | Estimated heat delivered by heat pumps |
| SPF | Average seasonal performance factor or the average COP over summer or winter |
| $E_{res}$ | Amount of energy captured by GSHP system |

## List of acronyms

| | |
|---|---|
| BHE | Borehole heat exchanger |
| BTU | British Thermal Units |
| COP | Co-efficient of performance |
| DHW | Domestic hot water |
| DGEG | Direcção-Geral de Energia e Geologia/ Directorate-General of Energy and Geology |
| EBM | Energy per Borehole Meter |
| EU | European Union |
| FV | Future value |
| GSHP | Ground source heat pump |
| hGSHP | Horizontal ground source heat pump |
| H&C | Heating and cooling |
| HVAC | Heating, ventilation and air conditioning |
| NPV | Net Present Value |
| NOx | Nitrogen dioxide emissions |
| OECD | Organization for Economic Cooperation and Development |
| PV | Photovoltaic |
| SGE | Shallow geothermal energy |
| SOx | Sulphur dioxide emissions |
| UTES | Underground Thermal Energy Storage |
| vGSHP | Vertical ground source heat pump |
| SUHI | Sub-surface Urban Heat Islands |

# Chapter 1: Geothermal energy and ground-source heat pumps – Technology in brief

### *1.1 Introduction*

In developed countries, buildings account for 20 – 40% of the final energy consumption [1]. The majority of this energy is used in heating and cooling (H&C) applications. Heating accounts for 42 EJ or 36% of the total energy consumption by buildings worldwide while cooling applications use 7 EJ [2]. In the EU, around half of energy consumption is by buildings. Out of the 192.5 Mtoe (8.05 EJ) final energy consumed by households in the EU, 79% was used up for heating and DHW applications. These figures for industrial sector stood at 193.6 Mtoe (8.1 EJ) and 70.6% respectively [3]. Moreover, fossil fuels contribute to 84% of H&C and the rest is generated using renewable energy [3]. H&C applications for residential and commercial buildings, as well as in the industrial sector contributes significantly to electricity consumption. The International Energy Agency (IEA), reports that combustible substances (coal, natural gas, biomass) accounted for 66.8% of the total electricity generation in 2017 [4]. Thus, it can be said that space conditioning inside a building contributes significantly towards carbon emissions. To reduce carbon emissions, electricity consumption must either reduce, higher energy efficiency must be achieved, or less fossil fuels must be used for power generation. Ground source heat pumps (GSHP) systems which utilize the geothermal energy represent space conditioning alternatives which reduce the average electricity consumption and hence carbon emissions.

### *1.2 Geothermal energy*

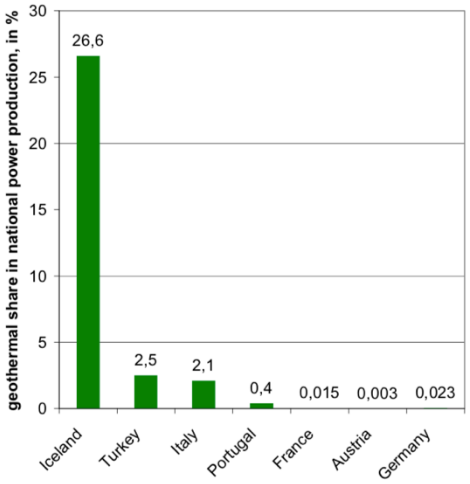
Geothermal energy is the thermal energy available below the surface of the Earth. It can be classified as high, medium or low-enthalpy resource with temperatures >225°C for high, 125 to 225°C for medium and less than <125°C for low-enthalpy resources [5]. The high and medium temperature resources can be utilized for power generation and direct heating. Low-temperature resources are available at shallower depths. Direct heating is one of the oldest applications of low-temperature geothermal resources [5]. Apart from direct heating, it can be also utilized for space heating and cooling (H&C), aquaculture, and in agricultural applications.

Geothermal energy is a renewable form of energy. Geothermal energy technology is cleaner and has a low carbon-footprint compared to the other renewable energy technologies [6].

### *1.2.1 Current status of geothermal energy*

There are three geothermal sub-sectors in Europe: electricity, direct-use and shallow (GSHP systems). In 2015, power generation using geothermal energy was approximately 2050 $MW_{el}$ [7]. In Portugal, 182 GWh electricity is produced per year. The share of geothermal energy in total energy production is only 0.4%. The power generation facility is located at San Miguel islands in the Azores archipelago. Geothermal energy is also used directly in district heating on a smaller scale, greenhouse heating applications, and thermo-mineral balneological activities [7].

Shallow geothermal energy is harnessed for space conditioning by installation of GSHP systems and Underground Thermal Energy Storage systems (UTES). In the EU, more than 1.7 million installations produced at least 22,900 $MW_{th}$ of shallow geothermal capacity by the end 2015 [7]. In addition to power generation and GSHP applications, geothermal energy can be directly used in applications like balneology, agriculture, aquaculture, and spa treatments [7]. Figure 1 [7] shows the share of geothermal energy in the national energy production. and Figure 2 [7] shows the percentage breakdown of the installed capacity in shallow, direct and electricity sub-sectors in the EU.



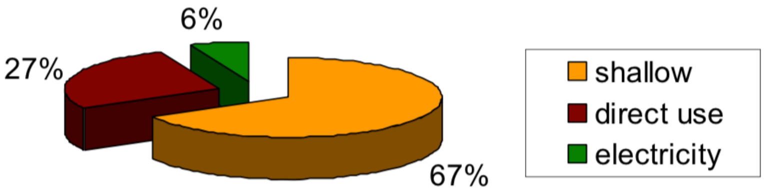


*Figure 1: Share of geothermal energy in national energy production, 2015 [7]*

*Figure 2: Share of installed capacity in the three sub-sectors, 2015 [7]*

The average number of GSHP systems installed within European countries is just over 57,000 per country with a capacity to produce 49,366 $GWh_{th}$/ year, and an average output of 22.2 $kW_{th}$ per installed unit. However, there is a significant difference between the number of GSHP systems installed in different countries. Sweden has the highest number of installations (540,000) followed by Germany (325,000) and France (200,000). Albania (106) and Iceland (70) have very low number of installations. Portugal has the lowest number of installations (54) within the entire European Union as per data from [7][13].

### *1.3 Shallow geothermal energy (SGE)*

In European Union (EU) Directive 2009/28/EC there is no legal differentiation between shallow and deep geothermal energy sources [8]. Different EU countries have different definitions for shallow geothermal energy (SGE) which is primarily based on either depth (e.g. Slovenia, Austria, Germany, Switzerland) or temperature (e.g. Slovakia).

For the purpose of this thesis, shallow geothermal energy (SGE) is defined as the thermal energy available within the surface of the Earth at depths not more than 400 m.

SGE can be utilized in aquaculture, agricultural applications, spa treatments and heating and cooling (H&C) applications. It can be used in domestic as well as in the industrial applications. However, due a lack of data the present thesis is focused on the utilization of SGE for H&C and domestic hot water (DHW) applications in residences, office spaces and hotel industry in Portugal.

#### *1.3.1 Advantages of shallow geothermal energy*

SGE is available locally and its utilization does not involve any flammable fuel, fuel transportation, or additional energy storage mechanisms [9]. All of this contributes to a lower carbon footprint. Moreover, its usage decreases the consumption of fossil fuels. This, in turn, reduces a country's dependence on fossil fuel imports, resulting in saving of foreign reserves.

#### *1.3.2 Ground-source heat pumps (GSHP)*

The ground temperature near the surface of the Earth varies due to solar radiation, wind, presence of vegetation and moisture. However, it remains fairly constant throughout the year as the depth increases (after 5 to 30m) [10]. Figure 3 [10] shows the ground temperature variation with depth for Nicosia in Cyprus. This temperature difference between the surface and ground can be utilized for heating purposes in winter and for cooling purposes in summer by employing a ground coupled heat exchanger and a heat pump. The heat pump extracts heat from the relatively hotter sub-surface area and exchanges it with the cooler area in the winter and in summer the heat is extracted from relatively cooler subsurface and exchanged with hotter area [9]. To accomplish this, fluid is circulated through the length of a borehole heat exchanger (BHE) by utilizing electrical energy.

The various components (eg. heat pump, heat exchanger) are collectively referred to as a “GSHP system” in the subsequent text. The main components of a GSHP system are briefly discussed in Section 1.5.

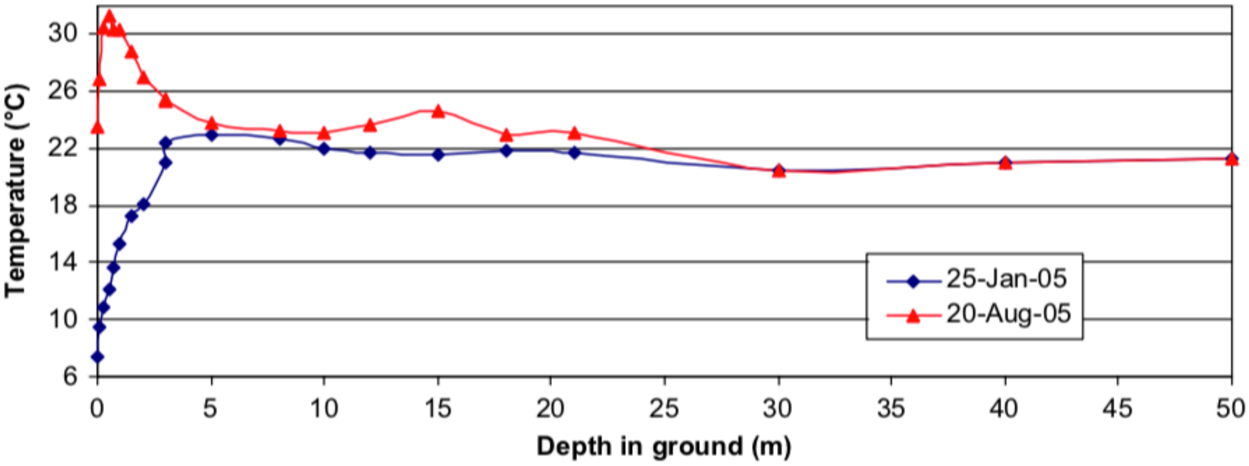


*Figure 3: Ground temperature variation with depth for (Nicosia, Cyprus) [10]*

For heating applications, GSHP systems do not combust fuel but rather use the solar energy stored in the ground. If the temperature difference between the ground and building is higher, then more work is required to operate the heat pump. This reduces the coefficient of performance (COP) of the system [11] which can be defined as the ratio of the thermal energy produced to the input driving energy. Typically, the COP for GSHP ranges from 3 to 6. COP is site specific due to fluctuations in the ground temperature as well as due to the effect of sub-surface urban heat islands (SUHI). Since the depths involved in shallow geothermal resources are much smaller than deep geothermal resources, it is relatively easier to extract and utilize thermal energy with the help of a GSHP system. As discussed above, the temperature of the ground remains constant (after certain depths) all around the year, unlike the air temperature, making the GSHP system highly efficient. It is possible to extract thermal energy from lower temperatures which can be obtained in shallow rock formations (less than 200 m) [12] with the help of advanced heat pump technology.

Thermal conductivity and thermal diffusivity of the rock or the soil are two properties that greatly affect the design of a GSHP system since the available geothermal energy depends on the rock and soil types [10]. The average temperature gradient in the ground is approximately 3°C per 100 meters depth. In addition to the rock and soil properties, the temperature below the surface of the Earth is affected by the seasonal temperature variation as seen in Figure 3. To appropriately size a GSHP system, the building space conditioning demands and building insulation must be considered. All these factors differ for different locations and buildings. Thus, designing GSHP system correctly can be considered site specific as well as demand specific.

### *1.3.3 Components of GSHP*

The main components of a GSHP system are heat exchangers that enable the exchange of heat with the ground and the heat exchange medium, a heat pump system that moves the heat to and from the ground to the building, and indoor units that condition and distribute heat [13], [11]. Compression and absorption heat pumps are employed for space heating and cooling applications although common types of heat pump operate based on the vapour compression cycle [12] [11]. Heat pumps come with a rating for heating as well as cooling. In the heating mode, heat exchangers act as evaporators, absorbing heat from the ground, and the building heat exchangers act as condensers, passing heat to the structure. The heat pump itself comprises (See Figure 4) five main components, namely, a compressor and expansion valve to control temperature and pressure, a reversing valve and two heat exchangers, along with accessories like tubing, fans, and controls [11]. The reversing valve is used to provide cooling to the building by reversing the flow of the fluid. In this mode, the earth connection heat exchangers assume the role of the condenser and the building heat exchangers become the evaporators [11].

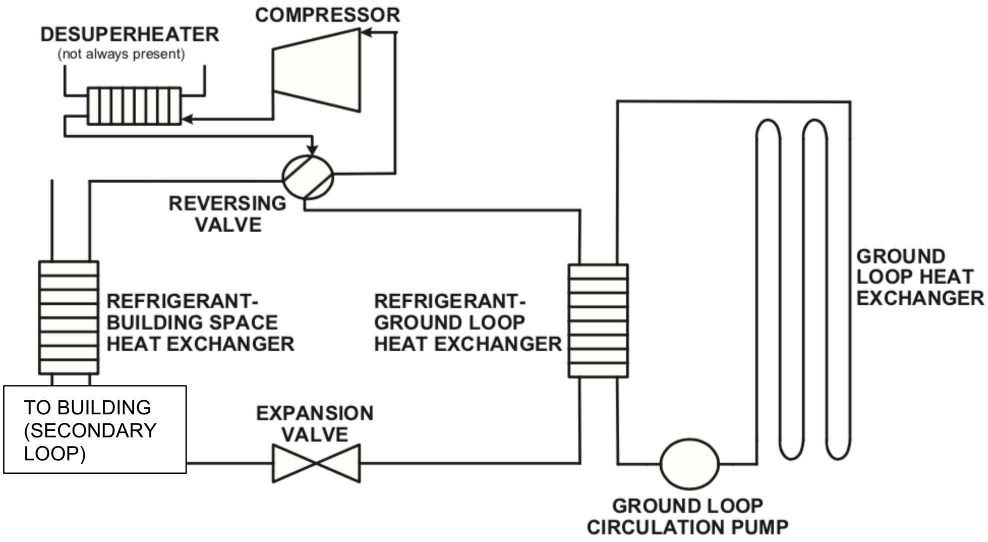


*Figure 4: Basic layout of the heat pump system [11]*

### *1.3.4 Types of GSHP system*

There are two types of circulation systems: open loop and closed loop. Open loop systems exploit groundwater through wells dug at depths less than 100 m. Closed loop systems are used to extract heat from the ground and can be installed to depths up to 200 m [12], [13]. There are two configurations for an open loop system: (a) extraction and reinjection, and (b) extraction and surface water systems; out of which configuration (a) is most common. In this configuration, which is shown in Figure 5 [10], the water is extracted from the well, passed through the heat exchanger and then released back into the ground via an injection well. Open loop systems work well with shallower wells. However, maintaining water quality is a challenge. If the water is not neutral and contains minerals, e.g. iron, more maintenance is required due to the problems of scaling, fouling, and corrosion [11].

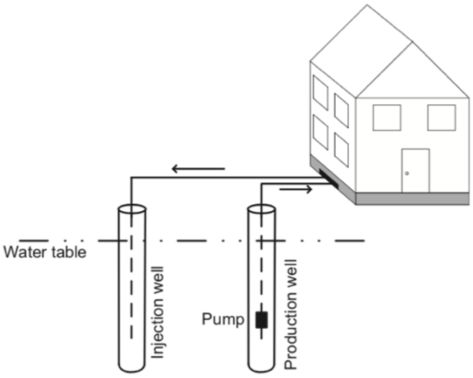
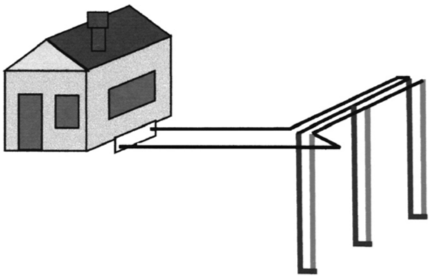


*Figure 5: Open loop system with extraction and injection configuration [10]*

In closed-loop systems (see Figure 6) [10], the heat exchanging medium is re-circulated and it remains enclosed in the system. Several runs of pipes are used to exchange heat with the ground. Both, open and closed-loop, systems utilize an efficient heat exchanging material, typically, polyethylene or copper tubes, and water or antifreeze solutions that are environmentally friendly [10]. The number of loops depends on the heating and cooling load, geological conditions, depth, the average ground temperature, local climate pattern, among other parameters[10].

Closed-loop systems can be installed in different configurations as shown in Figure 6. The pipes (heat exchangers) can be configured vertically or horizontally, and also in series or in parallel. Horizontal configurations (hGSHP) use relatively more space than the vertical configurations (vGSHP) and are suitable for smaller installations [12]. Vertical configurations require less piping and pumping energy. There could be a limitation on the depth to which vertical wells can be dug due to the presence of impermeable rock and potable water aquifer and increased pumping energy. A vertical well is typically backfilled with grout or soil cuttings to enhance heat transfer between pipes and borehole walls, support the pipe, and to prevent leakage due to defective joints [12], [14]. Grout is the filling material between the pipe and the ground.



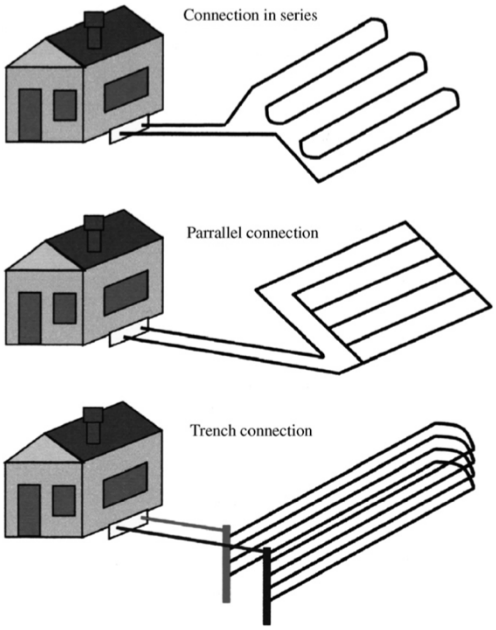


*Figure 6: Closed loop systems in different configurations [10]*

The drilling method depends on the type of ground, e.g. its consistency (soft, medium, hard), and make up (granular, rock). Typically, the drilling equipment and methods used for geothermal pumps are simpler than drilling for water [12] [7].

Water is widely used as a circulating fluid to exchange heat; most of the times with anti-freeze agents and inhibitors. Ideal properties for the circulating fluid are long life, being safe to handle, non-corrosive, low viscosity for better flow, and good heat transfer properties for heat exchange. In Europe, use of 20-30% aqueous solutions of glycols is common. The common anti-freeze agents are Calcium Chloride (CaCl2), Sodium Chloride (NaCl), Potassium Carbonate ($K_2CO_3$), Ethylene Glycol ($HOCH_2CH_2OH$), Propylene Glycol ($CH_3CHOHCH_2OH$), Methanol ($CH_3OH$), Ethanol ($C_2H_5OH$) and Potassium Acetate ($CH_3CHOOK$) [7].

### *1.3.5 Advantages of GSHP system*

a. *Low energy consumption*: The biggest advantage of a GSHP system is the saving in electricity consumption for its operation which is in the range of 25-50%[9].
b. *Low environmental impact*: Employing GSHP systems for heating applications uses less energy and thus reduces the consumption of fossil fuels. Compared to conventional space heating and cooling (gas and electric applications), GSHP systems can reduce greenhouse gas emissions by more than 66% [14].
c. *Low maintenance*: Owing to fewer moving parts, high reliability, and use of non-corrosive fluids, the operation, and maintenance cost for GSHP system is lower. This translates to significant savings over long

period, say, 20 years or more, and low life-cycle cost. The maintenance cost for GSHP is negligible. [9], [15].

d. *Safe and comfortable operation*: GSHP system has a quiet and comfortable operation. Additional fuel is not required, nor does it produce energy by any combustion process. Thus, it is safe to operate.[9], [15]

e. *Three-in-one system*: Installing a single GSHP system instead of two or more (for heating, cooling and DHW applications), is advantageous and convenient.

f. *Visual impact*: GSHP systems have low impact on the aesthetics of the environment where they are installed.

### *1.3.6 Disadvantages of GSHP*

GSHP systems are expensive to install largely owing to the drilling cost. A vGSHP installation is more expensive than hGSHP but requires less space than a hGSHP. A hGSHP system typically requires 140 – 280 $m^2$ of area per ton (~3.5 kW) of H&C. Difficult geological formations might increase the initial cost of a GSHP system due to problems encountered while drilling [16].

The sizing of GSHP systems has to be accurate or near-accurate. Underestimation of the size will result in an under-performing system while overestimation of the size will increase the initial cost of the project. Good understanding of the movement of sub-surface heat energy and accurate estimation of H&C requirements of the building under consideration is important. Unlike conventional HVAC systems, GSHP systems are not easily replaceable; in case of incorrect sizing.

### *1.3.7 Market figures*

In the EU, total investment in the geothermal sector was €4.53 billion in the year 2015. The SGE sector saw a significant amount of investment which fell just short of €4 billion. However, this investment is less than anticipated due to major players like Germany and Italy not reporting their investment numbers along with other 11 countries. It was estimated that the investment in Europe (including the countries that did not report) will increase to €7.17 billion [7]. The total investment figure and information on GSHP projects, especially for the residential sector is unavailable for Portugal.

## *1.4 Objective and thesis layout*

The present thesis attempts to find the technical, economic and market potential for SGE in Portugal. The assessment has been limited to SGE harnessed by GSHP systems. Moreover, it was assumed that all the GSHP systems that can be potentially installed, are vGSHP systems since they require smaller installation space. The thesis is divided in to five (5) chapters. While the first chapter gives brief introduction of geothermal energy and GSHP system, the second chapter describes the approach used to accomplish investigation of the technical, economic and market potentials. In the third chapter, investigation into technical potential has been conducted based on climactic and ground conditions. In the fourth chapter, real estate data has been estimated in the three market segments – residences, office space, and hotel to estimate the economic potential and deployment rate. This chapter also compares carbon emissions and net present value (NPV) for over 30-year project between GSHP systems and its competing technologies in residential sector. The final chapter discusses the market potential in the residential sector as installed capacity and possible revenue as well as penetration of GSHP projects based on Fisher-Pry model as well as renewable energy targets met these installations as per EU Directive 2008/2001.

Due to lack of data, industrial, aquaculture, balneology and other applications of SGE were excluded from the study. There have not been many targeted studies to find out the potential of this technology in Portugal. Thus, some assumptions were necessary in order to proceed and to “fill the gaps” in estimating the technical, economic and market potential. The difference between various potentials have been discussed in the subsequent chapter. Prior to estimating the market potential of technology, the theoretical, technical and economic potential should be known.

## *1.5 Conclusion*

GSHP systems utilizing SGE for space conditioning applications is a clean and proven technology. Ground heat exchangers can be installed in various configurations (vertical or horizontal and open loop or closed loop). Installation of GSHP is site-specific and demand specific. The decision to install a GSHP system and its configurations may depend on some or all of the following parameters: presence of ground water, availability of the capital, H&C and DHW requirements, local ground thermal properties, annual mean temperature at the installation site and availability of space.

Closed loop hGSHP systems require large area for installations. Installation of open-loop systems with extraction and injection depend on the aquifer conditions at the site, and regulations around its utilization. Thus, it is extremely difficult to determine the permissible installation sites. Vertical closed-loop BHE, on the other hand, require less space, are costlier than horizontal systems but can be installed without disturbing groundwater resources.

In the EU, the GSHP sector makes up a huge portion of the total investment within the SGE market and it is projected to increase in the future. But, in Portugal the penetration of this technology has been limited. There is no market data or project data from the installed GSHP systems for residences. In the present thesis, the potential for GSHP system will be explored assuming only vGSHP systems are installed.

# Chapter 2: Literature review and methodology

## *2.1 Literature review*

GSHP systems exploit SGE. Thus, determining SGE potential at the given site can provide insights into the potential for GSHP system installation. Over last few years, several studies have been conducted around the world to analyse the suitability of the ground temperature for application of GSHP system at a block, district, city, and regional levels, as well as savings in future energy cost and $CO_2$ emissions due to its installations.

For the Iberian Peninsula, Chamorro et al [17], estimated the technical potential for the geothermal energy systems but for the depths from 3 km to 10 km. This depth is outside the definition of the SGE proposed in Section 1.2. Detailed prediction of very shallow geothermal potential was performed at 14 different sites across Europe by utilizing harmonized and standardized data [18]. None of the 14 case study locations were in Portugal.

Various approaches are employed by researchers for the mapping of the shallow geothermal potential. Casasso and Sethi [19] describe the development of a mathematical model called G.POT that can be employed to determine the potential for utilization of SGE based on the thermal properties of the ground, operational and design parameters of the borehole heat exchanger (BHE), heating and cooling (H&C) duration and operation time. But such studies were not performed for Portugal or the Iberian Peninsula.

A three-step methodology was employed to estimate the geothermal potential for a parcel in the urban area of Switzerland by Miglani et al [20]. The three steps comprised an estimation for the energy demand of each type of building, sizing of the borehole and lastly simulation of long-term operation to find out the effect on performance. The paper presents a good overview of the procedure and factors to be considered to design a borehole heat exchanger. De Carli, et al [21], give a methodology to determine the H&C requirements for a small residential district. It aims to find an optimum solution for satisfying the H&C needs for a given density of buildings in a district or a sub-district. The study aims to understand if the application of GSHP technology at district level is more energy efficient and less costly than installing it for individual houses and/ or apartment buildings. It compares the energy consumption and payback time for a heat pump systems and hybrid systems comprising a GSHP coupled with solar PVs, heat pump and solar thermal collectors, heating with boilers. It was observed that GSHP coupled with solar PV saves 70-80% compared to a traditional system comprising boilers for DHW and heating, and split system for cooling. Also, the study in Europe by Rivoire et al [22] and in ten (10) different cities in the Indian Himalayas which fall in a similar climate zone was undertaken by Sivasakthivel et al [23] with these same objectives.

While most of the studies focus on energetic requirements and economic analysis, Schiel et al [24] focused on proposing a spatial method to determine if $CO_2$ emissions can be reduced by using SGE. The method takes into account the DHW and H&C requirements of each building and finds out the percentage of energy demand that shallow geothermal can provide. As per Bayer et al [25], there is no consistent way to determine the capacity of SGE for urban areas. The presence of SUHI makes such an exercise even harder. Bayer et al [25] used power density as reference to indicate the technical potential of geothermal energy and normalized its values obtained from different case studies for 100 m BHE length, 7 m spacing between BHE, and 2400 hours of annual operation. The power density values ranged from less than 50 $W/m^2$ to more than 400 $W/m^2$ indicating that there are inconsistencies in the methodologies as well as differences in the climatic conditions and geological variations.

In the USA, Liu et al [26] undertook a study to update a previous assessment of the technical potential of GSHP applications by taking into consideration the energy savings, $CO_2$ reduction, and savings in consumer spending. For Portugal, no such study regarding GSHP system use has been found.

The 2019 geothermal energy country update for Portugal [27] describes how geothermal energy is utilized on mainland Portugal and on the islands of Madeira and Azores. It gives an overview of the electricity generation projects and direct use projects that include district heating, greenhouse heating, and balneology applications. However, it gives few details of the GSHP applications which are not sufficient to draw any conclusions about the market potential or nor does it mention any strategies that might help promote this technology.

There have been studies that aimed at finding an efficient geothermal energy usage plan before the construction of specific buildings. Kim et al [28] compared the energy cost and energy consumption of a building prior to utilizing geothermal energy. For more reliable economic feasibility analysis, lifecycle analysis was also conducted that included maintenance costs and construction cost. Bayer et al [25] discussed the different ways in which researchers have estimated the theoretical and technical potential in urban areas. It presents the economic potential as a subset of technical potential. There is no widely accepted method to determine the technical potential. In addition, there is acceptable potential which is a fraction of economic potential due to regulatory restrictions, lack of experience and expertise, public interest and environmental considerations.

Some of the studies conducted to analyze the effect of GSHP installations on carbon emissions show that carbon emissions decrease over time, for example, Sivasakthivel et al [23] and Schiel et al [24]. Yousefi et al [29] designed a heating and cooling system for a medium-sized building based on the GSHP and an electric chiller and a boiler. Two objective functions, namely, net present cost and carbon emission of the system were minimized to determine the optimum sizing for the hybrid system. It was seen that as the share of GSHP increases, the net present value (NPV) increases but the carbon emissions go down. This system is also more efficient than the conventional HVAC system.  The energy performance of ground heat exchangers and a ground source heat pump system installed in Aveiro in Portugal was analysed by Pinto et al [30]. It was observed that the GSHP system with 33 boreholes is more efficient in winter and summer than the conventional HVAC system fitted with a boiler and chiller. A project of sizing the length of the borehole heat exchanger (BHE) and their configuration was undertaken in Coimbra in Portugal by Coelho et al [31] based on the building properties and soil characteristics. It was observed that four boreholes configured in parallel, with a total length of 611m satisfy the 81.8 kW cooling and 53.9 kW heating requirements. The importance of adding mono-ethylene glycol to prevent the water (heat exchanging medium) from freezing was also reaffirmed in this study.

It can be concluded that there is availability of literature which provides models to assess the geothermal potential, and also models and analyses to determine if it can be employed to satisfy the H&C needs of cities, districts and blocks within different climatic zones. Several assessments have been performed to evaluate the energetic, economic and environmental performance of GSHP system in different climatic zones. Most of these studies are site-specific and demand specific, thus they can be replicated to specific projects, but they cannot be replicated for region within country or a country as a whole. Also, there has been an attempt to quantify GSHP system's financial performance and $CO_2$ emissions by few authors. However, there has not been any published assessment of the market potential to estimate the total sales volume and sales revenue for GSHP system in any city, region or country. SGE is a relatively untapped energy source. It is not only a cleaner alternative, but it is also an attractive option for consumers due to its low energy and maintenance requirements. Estimating its market potential may be a good way to determine if it is indeed worth investing in this energy application from market perspective. However, market potential cannot be determined without investigating the technical and economic potential.

Following chapters attempt to determine the technical, economic and market potential for GSHP systems in Portugal assuming all installed systems are vGHSP systems. Thus, in the following text, GSHP system indicates a vGHSP system. The analysis includes residential, hotel and office space market segments. For the market potential analysis, only residential sector is considered. It excludes commercial spaces (e.g. malls, gyms), public buildings (e.g. museums, bus stations) and industrial sector.

### 2.2 Methodology

Figure 7 highlights the major steps taken in the evaluation of the technical, economic and market potential.

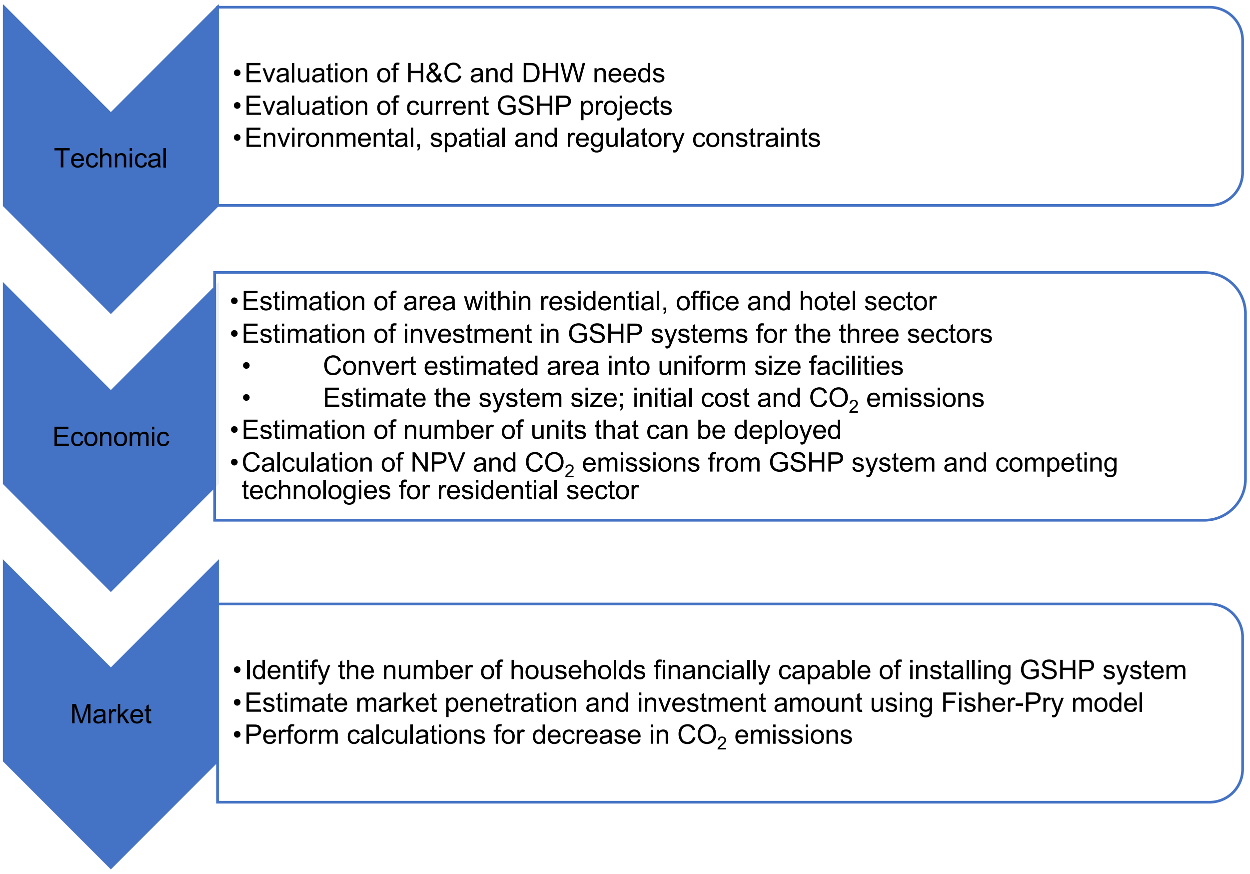


*Figure 7: Methodology*

#### *2.2.1 Technical Potential*

The first step to estimate the economic and market potential of GSHP systems in Portugal, will be to understand if there is any technical potential. The climatic conditions, ground conditions, and current projects have been evaluated to examine if the H&C and DHW requirements in residential, hotel and office space market segments can be satisfied. This assessment was limited to determining the technical potential as either affirmative or negative instead of computational work.

Depending on the space conditioning and DHW requirements, an estimate for the size of the heat pump system and average length of the BHE can be obtained for different market segments considered. Size of the system will determine the installation cost. The real estate data, environmental, spatial and regulatory constraints and cost will help in the further analysis for economic and market potential.

### *2.2.2 Economic Potential*

To estimate the economic potential, firstly, total area was estimated for dwellings, hotel and office spaces which was then converted into multiple facilities of uniform sizes. The size of the equipment was chosen to sufficiently cover the H&C and DHW energetic demands within these uniform spaces. The total investment cost for GSHP systems was estimated by multiplying the number of uniform facilities (dwellings, hotel, offices) with present value of the capital cost required.  To consider constraints, a factor called "spatial constraint factor" was defined and used as a multiplier for the total investment cost. The product is the estimated economic potential.

Financial and carbon emission performance of GSHP systems installed inside residences has been compared against the current technological options for space conditioning and DHW for 30-year project life to identify the technology option that can be displaced by GSHP system. Different indicators were taken into consideration, for example, net present value, payback time as compared to a reference system, fixed, operations and maintenance cost, and, affordability of the technology to the consumer [25]. From these options, net present value (NPV) was chosen. Three costs were considered for computing the net present value: capital cost, maintenance cost and fuel cost. Maintenance cost, operation cost and replacement costs for new equipment have been discounted in the future by using 2% as rate of inflation.  For example, if an equipment costing €600 would be replaced after, say, 10 years, then the present value of the equipment was adjusted to the future value (FV). For calculating the net present value and future value, the in-built functions "NPV" and "FV" were used.

$CO_2$ emissions were calculated by multiplying the amount of fuel required to satisfy the energy demands with the emissions factor assuming 1600 hours of operation (see Section 4.4.1) at rated power for all the cases for consistency. For all DHW applications except GSHP systems, three (3) hours operation was assumed per day throughout the year.

### *2.2.3 Market Potential*

For determining the market potential, the total number of dwellings that have financial capability to install GSHP systems was identified. The investment cost required was calculated by multiplying the investment cost for single unit with the number of dwellings. Fisher-Pry diffusion model was applied to estimate the displacement of the competing technology by GSHP systems and its impact on carbon emissions was also determined. Additionally, the percentage share of GSHP systems as renewable energy source in meeting the requirements of the EU Directive 2018/2001 for space conditioning was estimated. The computations were performed using MS Excel.

# Chapter 3: Investigation of Technical Potential

This chapter is broadly divided into two parts. Sections 3.1, and 3.2 aim to examine the climatic conditions, geology, current GSHP projects, space conditioning and DHW requirements in Portugal. Sections 3.3 and 3.4, and 3.6 discuss the real estate data from residential, hotel and office space sectors, as well as the environmental, regulatory, and spatial constraints.

## *3.1 Environmental considerations*

### *3.1.1 Classification of potential*

The useable potential for a given energy source depends on multiple factors like regulations, investor interest, technical and ecological constraints, to name few. The generation potential for renewable energy sources can be classified in to five distinct categories (see Figure 8) [32].

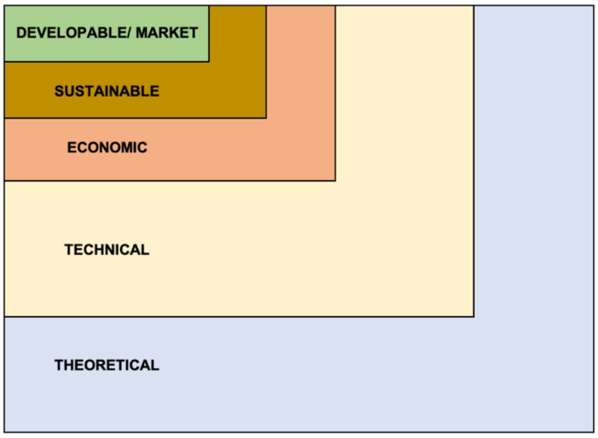


*Figure 8: Potential definition for renewable energy [32]*

Theoretical potential is the fraction of usable energy from a given energy source. For geothermal energy, all of the energy or heat-in-place can be considered as the theoretical potential. The potential of GSHP in 19 European countries is estimated to be at 100,000 TJ [33]. Limitations of the technology, utilization of land, environmental factors and regulations around harnessing the energy lead to utilization of a lesser amount of energy than the theoretical potential. This fraction is called the technical potential. GSHP technology is simple and gives high performance. Most of the available energy at a site which is identified for installation of the GSHP can be utilized. The technical potential then depends on the local environmental factors and regulations. Economic potential is the fraction of technical potential that can be utilized economically. It depends on the fixed cost (cost of drilling, equipment, installation and labour), operation and maintenance cost, decommissioning cost [34] as well as costs of the competing systems [35]. Sustainable potential is the fraction of economic potential that can be utilized using sustainable production methods [35]. Developable potential can be determined as a sub-category of the economic potential that can be developed under realistic conditions.

From a market economics perspective, market potential is the potential sale of a given product or service. It can be measured in sales revenue or number of units sold. Market potential depends on the attractiveness of the technology to the consumer, consumer preferences, consumer spending capacity and competition from similar technologies, products or services. If a consumer is attracted to a certain technology by virtue of its appearance, ease of use, popularity, affordability, environmentally friendliness or any other reason, then, given the product is within consumer's budget, there is a higher probability that they will consider buying it.

GSHP systems are durable consumer products. Unlike, deep geothermal energy that is widely used to generate power to be supplied to the grid, the developable potential of SGE for GSHP systems will depend on consumer preferences including their budget. Thus, for GSHP technology, which is based on the exploitation of SGE, market potential is same as the developable potential. Moreover, it is assumed that drilling and installation activities will be accomplished in sustainable manner. Thus, there was no separate attempt to determine sustainable potential.

### *3.1.2 Climatic and ground conditions in Portugal*

The design of a GSHP system mainly depends on climatic conditions and ground thermal conductivity (which are site specific), grout thermal conductivity, and maximum drilling depth [36] subject to building H&C and DHW requirements. The technology does not change with the size of the system.

The amount of heating or cooling required for a building or house depends on the climatic zone and building insulation [37]. Since Portugal has milder climate, the H&C and DHW load can be assumed to be not as demanding as North European countries e.g. Sweden which has the maximum number of GSHP systems installed [7]. Figure 9 shows the comparison for annual mean temperatures in Sweden and Portugal.

The ground thermal conductivity helps in determining the length of the borehole heat exchanger. Rocks generally have higher values of thermal conductivity than soil [38]. Thermal conductivity and thermal diffusivity of the soil and rock at a given site affect the design of the length of the BHE for the given thermal load of the building. Thermal conductivity (W/mK) of the rocks or soil is its ability to conduct heat. Thermal diffusivity ($m^2/s$) is thermal conductivity of a material divided by the product of its specific heat and density (at constant pressure). It measures the ability of a substance to conduct thermal energy due to temperature difference.

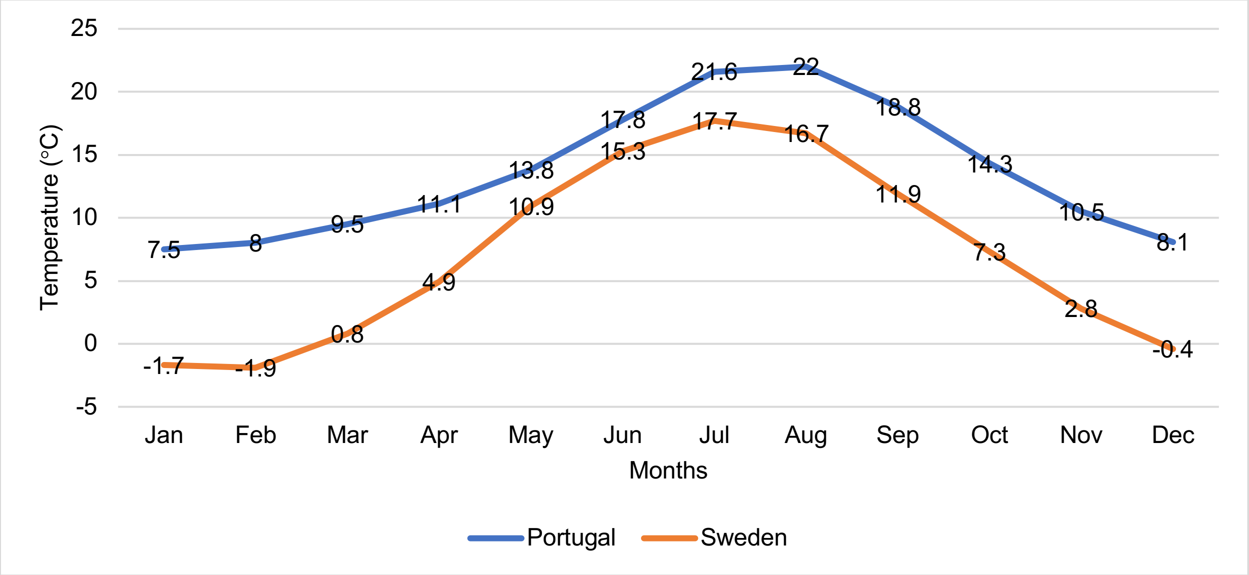


*Figure 9: Comparison for monthly mean temperatures in Sweden and Portugal [39]*

Some software, e.g. Ground Loop Design (GLD) have built-in values of the sub-surface thermal properties for some cities. These can be selected directly in the design of the BHE. To obtain more accurate values, it is appropriate to undertake a geotechnical survey [38].

Furthermore, if the heat extraction rate is higher than the heat deposition rate then the available geothermal energy-in-place will be eventually exhausted making the system unsustainable. Thus, there may be a maximum limit on the heat that can be extracted.

Table 1 gives values for rock types in Portugal and their values were obtained from 2015 study [40], which were extracted from Ground-loop Design software (GLDesign2009). The values of thermal diffusivity have been averaged from minimum and maximum values.

| *Rock type* | *Thermal conductivity ($Wm^{-1}K^{-1}$)* | *Thermal diffusivity ($m^2$ $day^{-1}$)* |
|---|---|---|
| Granite | 2.6 | 0.097 |
| Granodiorite | 2.5 | 0.092 |
| Basalt | 2.2 | 0.093 |
| Gabbaro | 2.3 | 0.089 |
| Limestone | 2.4 | 0.094 |
| Sandstone | 2.5 | 0.084 |

*Table 1: Rock properties*

In Sweden which has maximum GHSP system penetration, the main rock types are gneiss, granite, granodiorite, sandstone and marble [41]. The average thermal conductivity for gneiss type rock is 2.91 $Wm^{-1}K^{-1}$ and average thermal diffusivity is 0.127 $m^2$ $day^{-1}$ [42]. The average thermal conductivity for marble ~1.8 $Wm^{-1}K^{-1}$ and average thermal diffusivity is quite similar to limestone [43].

Comparing the climate and rock properties of Portugal and Sweden, it can be concluded that the make-up of the geology of Sweden and Portugal is quite similar, but the energy demands for space conditioning in Sweden are more demanding than they are for Portugal. Sweden has the highest number of GSHP system installations while Portugal is among one of the lowest. Thus, it can be said that if GSHP system can be installed in Sweden for a given facility, then it is feasible to install such system for the same facility (same size, shape, energy demands, building efficiency) in Portugal.

### *3.1.3 Design temperatures*

The entering temperature of the circulating media in the heat pump is important. Many software are available to design vertical bore system. They use different values for entering temperature as well as the leaving temperature. Typically, the GSHP system is designed such that the heat pump entering water temperature is 10°C above the outside air temperature for heating and 10°C below the outside air temperature for cooling. These values were obtained by studying the features of software – "GSHPCalc" [44].

## ***3.2 Heating and cooling requirements***

As per the ODYSEE report [45], natural gas provides most of the energy to households in the EU, followed by electricity (25% in 2015). The share of space heating within the household consumption was 67% in 2015. According to the 2015 Portuguese Directorate-General of Energy and Geology (DGEG) data, electricity usage by households was 42.6% of the total consumption [46]. The total electricity consumed by Portuguese households stood at 14.442 GWh. It includes electricity to run electrical appliances and for comfort (space conditioning) and excludes the use of electricity as vehicle fuels.

DGEG published a comprehensive report on the end-user energy usage statistics in its 2011 report [46] which is helpful from the perspective of this thesis. Table 2 data for occupancy and space conditioning was taken from same report. Table 3 data was populated on the basis of the information obtained in this report. The average occupancy in Portugal as per 2010 data is 2.7 individuals per dwelling. The average size of a dwelling is 107 $m^2$. It is lower for the mainland (106 $m^2$/ dwelling) in comparison with Azores and Madeira islands where it is 114 and 110 $m^2$/ dwelling respectively.

| *Individual/ dwelling* | *Avg. area per dwelling, $m^2$* | *Space heating, $m^2$* | *Space cooling, $m^2$* |
|---|---|---|---|
| 2.7 | 107 | 50.6 | 35.2 |

*Table 2: Average occupancy, area and space conditioning statistics for one dwelling*

| | *Heating requirement* | *Cooling requirement* | *DHW requirement* |
|---|---|---|---|
| toe/ $m^2$ [43] | 0.0037 | 0.0004 | NA |

| | | | |
|---|---|---|---|
| kWh/ m$^2$ | 43.03 | 4.65 | NA |
| kWh/ dwelling | 2177.32 | 163.75 | 1988.05 |
| kWh/ per capita | 806.43 | 60.65 | NA |

*Table 3: Annual space conditioning requirements in a household (2010) derived from DGEG report.*

*NA: Not applicable*

The average consumption of energy was about 0.724 toe (8,420 kWh) inside dwelling per year which corresponds to a spending of €840 per year. This does not take into account the energy consumed by vehicles. Inside a dwelling, energy is utilized for six different purposes: H&C, DHW, kitchen, lighting and to run electrical equipment. Referring to Table 3, in Portugal, majority of the energy consumed in a dwelling is used for water heating (23.5%) closely followed by space heating (21.5%). Space cooling accounts for only 0.5% of the total energy consumption [46].

Although space heating consumes relatively higher amount of energy (21.5%), it corresponds to 10.7% of the total energy expenditure. The average energy consumption for space heating was 0.0037 toe/ m$^2$ (2177.32 kWh) and for space cooling, it was 0.0004 toe/ m$^2$ (163.75 kWh). In a dwelling, the entire space is not subject to heating or cooling applications but only part of it. As per the same report, for space heating, 50.6 m$^2$/ dwelling and for space cooling 35.2 m$^2$/ dwelling is subjected to space conditioning applications. The final energy consumption (energy usage by end-consumer) declined at an average rate of 1.8% from 2006 to 2016 primarily due to higher efficiency in the end-use [47]. Final energy is utilized for six purposes mentioned above which includes space conditioning applications. Looking at the sources of energy and their consumption as per DGEG data [46] given in Table 4, electricity constitutes lower share as compared to heating oil, firewood and gas. It is assumed that the fuel sources and their contribution remained constant or near constant till present date since 2010.

For domestic hot water application, which is considered under kitchen applications, total of 583,040 toe (6,781GWh) of energy was consumed annually. The main sources of energy for DHW were natural gas, piped LPG and LPG bottle, which is mixture of butane and propane.

| Source | Space heating (toe) | Space cooling (toe) | DHW (toe) |
|---|---|---|---|
| Electricity | 0.036 | 0.015 | 0.037 |
| Firewood | 0.287 | NA | 0.272 |
| Gas* | 0.246 | NA | 0.591 |
| Heating Oil | 0.569 | NA | 0.46 |
| Thermal Solar | 0.206 | NA | 0.255 |
| Coal | 0.064 | NA | NA |
| *Total* | *1.408* | *0.015* | *1.615* |

*Table 4: Annual energy consumption per dwelling in toe*

**Gas includes LPG Butane, LPG Propane, Natural gas, piped GPL. NA: Not applicable*

### *3.2.1 Sizing of the borehole heat exchanger (BHE)*

In the 2015 study [40], to assess potential of BHE systems, twelve (12) cities across Portugal were selected for determination of BHE length, the relationship between the BHE length and thermal conductivity, and correlation between the design temperatures of the Portuguese cities and the energy per borehole meter (EBM). For the purpose of the current thesis, the BHE length and the correlation is of primary importance since the former affects the technology cost and the latter determines potential of SGE for GSHP technology in Portugal. Longer BHE length implies either deeper drilling or more boreholes or both, as well as equivalent length of pipe as ground collector. This increases the system cost significantly. Cost to customer is an important criterion in the evaluation of market potential and economic potential.

The built-in data from RETScreen Expert software for different cities was utilized in the study to obtain the monthly heating and cooling data for the buildings and the software Ground Loop Design (GLD) was used in the study to determine the length of the BHE required for each of the twelve cities. Uniform technical parameters were selected for all the cities in the study which can be seen in Table 5.

| | |
|---|---|
| Pipe specifications | SDR 11 pipe with 33.40 mm nominal OD and turbulent flow with 100% water. Double-U. |
| Borehole parameters | Separation 7m. Grout thermal conductivity: 2.09 W/mK. |
| Expected COP | 4.0 |
| Mode of distribution | Heated floors and cooled ceilings |

*Table 5: Uniform technical characteristics selected for all the cities*

The total estimated BHE length for different cities at the end of the study, for average thermal conductivity, varied between 277.6 m to 516.6 m. Number of boreholes were selected such that the individual length of the borehole is as close to 100 m as possible. The shallowest individual borehole depth was calculated at 93 m and the deepest individual borehole was calculated at 120 m. The minimum number of boreholes (with double-U pipe) was determined as three (3) and the maximum as six (6). Based on the EBM values for different cities given the geology (granite, limestone, sandstone), it was concluded that mainland Portugal has moderate to high potential for shallow geothermal energy applications (i.e. GSHP).

### *3.2.2 Current GSHP projects in Portugal*

Table 6 shows the current GSHP projects in Portugal for commercial properties taken from [48], [27]. The heating and cooling requirements range from approximately 33 – 330 kWh/yr/m$^2$ for heating and 31 – 244 kWh/yr/m$^2$ for cooling for commercial properties. It must be noted that these properties are used for different purposes namely, offices, living quarters, laboratory, classrooms and hotel, spa, and villas. Thus, the large discrepancy is due to the nature of the building which in turn determines the H&C and DHW requirements for the facility. For entries 1 through 6 and 23, 1600 hours of operation per year for H&C was assumed and multiplied with the size of the system. Then, it was divided by the area to compute the kWh/yr/m$^2$ requirement. For entries through 7 to 22, kWh/yr/m$^2$ requirement was computed by dividing the annual H&C needs provided in the original text [27] by the area. It can also be noted that most of the entries are complemented mostly by solar panels for possibly DHW and heating requirements. No data is currently available for GSHP systems installed for residential properties.

| No. | Location | Size | | Area (m$^2$) | Number of boreholes and each BHE length | kWh/m$^2$/yr heating | kWh/m$^2$/yr cooling | Complement |
|---|---|---|---|---|---|---|---|---|
| | | Heating | Cooling | | | | | |
| 1 | Superior School of Technology Setubal | 15 kWt | 12 kWt | 7 office rooms with area between 12 and 17 m$^2$ Two classrooms with 63 and 65 m$^2$ | Five (5) vBHE with each = 80m | 104.58 | 83.66 | No |
| 2 | Military Academy Amadora Quartering | 27.83 MWh/ yr | 25.76 MWh/ yr | 839 | 529[49] [46] | 33.17 | 30.70 | No |
| 3 | Regional administrative office Coimbra | 56 kWt | 61 kWt | 600 | Seven (7) double-U and vBHE = 125 m | 149.33 | 162.67 | No |
| 4 | New building - Sines Technopol | 24.5 kWt | 18.4 kWt | 251 | 2 simple U vBHE = 150 m | 156.18 | 117.29 | No |
| 5 | Laboratory - Sines Technopol | 50.8 kWt | 38 kWt | 534 | 3 simple U vBHE = 150 m | 152.21 | 113.86 | No |
| 6 | Office building - Sines Technopol | 76 kWt | 115.5 KWt | 1,286 | 10 simple U vBHE = 150 m | 94.56 | 143.70 | No |
| 7 | ESSUA Campus de Crasto Aveiro University (AU) | 612,800 kWh | 383,000 kWh | 7,660 | 22 double U vBHE = 150 m | 80.00 | 50.00 | No |
| 8 | CICFANO Campus de Santiago, AU | 284,800 kWh | 178,000 kWh | 3,560 | No information | 80.00 | 50.00 | Thermal energy from waste water |
| 9 | ESAN Santiago de Riba- Ul, AU | 327,040 kWh | 204,000 kWh | 4,088 | 34 double U vBHE = 150 m | 80.00 | 50.00 | Solar panels |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| 10 | ECOCRR Campus de Santiago, AU | 179,000 kWh | 112,000 kWh | 2,240 | 22 double U<br>vBHE = 120 m | 80.00 | 50.00 | No |
| 11 | CCCI Campus de Santiago, AU | 264,000 kWh | 165,000 kWh | 3,300 | 42 double U<br>vBHE = 130 m | 80.00 | 50.00 | Solar panels |
| 12 | EB23 Mortágua | 344,000 kWh | 215,000 kWh | 4,300 | 50 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 13 | Hotel Aqua Village | 480,000 kWh | 300,000 kWh | 6,000 | 33 U vertical<br>vBHE = 150 m | 80.00 | 50.00 | Solar panels |
| 14 | Hotel Stroganov | 78,600 kWh | 48,000 kWh | 960 | 10 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 15 | CE Lorvão | 104,000 kWh | 65,000 kWh | 1,300 | 10 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 16 | CE Santa Comba Dão 1 | 176,000 kWh | 110,000 kWh | 2,200 | 15 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 17 | CE Santa Comba Dão 2 | 256,000 kWh | 160,000 kWh | 3,200 | 18 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 18 | CE Santa Comba Dão 3 | 336,000 kWh | 210,000 kWh | 4,200 | 20 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 19 | Centro Balmar | 208,000 kWh | 130,000 kWh | 2,600 | 14 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 20 | APPC Viseu | 100,000 kWh | 62,500 kWh | 1,250 | 10 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 21 | M. Coruche | 224,000 kWh | 140,000 kWh | 2,800 | 18 U vertical<br>vBHE = 100 m | 80.00 | 50.00 | Solar panels |
| 22 | APPC Castelo Branco | 176,000 kWh | 110,000 kWh | 2,200 | 10 U vertical<br>vBHE = 130 m | 80.00 | 50.00 | Solar panels |
| 23 | Ombria Resort | 2,370 kW | 1,100 kW | 17,200 | 40x vBHE= 100 m<br>60x vBHE= 125 m<br>144x vBHE= 115 m | 220.47 | 102.33 | Solar panels |

*Table 6: Shallow geothermal projects in Portugal*

*NA: Data unavailable*

### *3.3 Real estate data*

*3.3.1 Housing*

As per Organisation for Economic Co-operation and Development (OECD) [50], *"a conventional dwelling is a room or suite of rooms and its accessories in a permanent building or structurally separated part… Examples of dwellings are houses, flats, and suites of rooms and so forth."* This data does not differentiate between family homes and vacation homes or the size of the dwellings (number of bedrooms).

Definition of "dwelling" as per OECD [50] is *"a room or suite of rooms and its accessories in a permanent building or structurally separated part that is intended for private habitation."* The definition further clarifies that detached rooms for habitation to be used as part of a dwelling should be counted as part of the dwelling.

The total number of conventional dwellings in Portugal were marginally less than 6 million (Table 7) and number of buildings with only one dwelling were 70.75% of the total number of dwellings as per 2011 data. If we assume this percentage to be the same for 2011 and 2017, then it implies that there were (5,942,131*0.7075) 4,204,058 detached or separate family houses and the remaining were apartments or flats used for dwelling (1,738,073).

| *Geographic location* | *Conventional dwellings (Data reference period 2017)* | *Percentage of buildings with one dwelling (Data reference period 2011)* |
|---|---|---|
| Mainland Portugal | 5,699,329 | 68.90 |
| Madeira | 130,980 | 91.58 |
| Azores | 111,822 | 89.30 |
| *Portugal (total)* | *5,942,131* | *70.75* |

Table 7: Number of conventional dwellings

### *3.3.2 Office space*

Most of the office space in Portugal is concentrated in two cities, namely, Lisbon and Porto. In Lisbon, available office space in the year 2018 was approximately 4.6 million m$^2$. [51] and for the same year in Porto it was 1.5 million m$^2$ [52]. No such information is available for rest of the country as per 2018 report [51] referred.

Lisbon and Porto are the two major commercial hubs in Portugal. Due to lack of data for office space and the city-wise or territory-wise number of registered companies, only office space in Lisbon and Porto was considered which total to 6.1 million m$^2$.

### *3.3.3 Hotels*

The total number of rooms in hotel establishments in Portugal stood at 184,435 within 6,868 hotel establishments [53]. It can be assumed that each hotel establishment has 27 rooms. This includes all types of lodging services like hotels, guest houses, tourist villages, motels, inns. As per [53], the total bed capacity was 423,152 which translates to 2.3 occupants per room. Also, the occupancy rate for the hotels was 51.9%. This data has been summarized in Table 8 below.

| | *Rooms in hotel establishments* | *Lodging capacity (persons)* | *Number of establishments* | *Occupants per room* | *Occupancy rate* |
|---|---|---|---|---|---|
| Portugal | 184,435 | 423,152 | 6,838 | 2.3 | 51.9 |

Table 8: Lodging statistics for tourism industry

The average size of a hotel room as per 2016 data [54] for Italy which sees comparatively more tourist traffic than Portugal was 32.9 sq. m. To be conservative, it is assumed that the average dwelling size for hotel in Portugal to be 30 sq. m. The H&C requirement for hotel rooms can be assumed to be consistent with the residential requirements assuming similar level of comfort although the estimated level of occupancy is slightly different (refer Tables 2 and 8). Since the travelers use hotel rooms for lodging only, it can be assumed that the DHW requirements will be 50% of the requirements within dwellings (994 kWh per dwelling). The analysis for hotel establishments excludes the space conditioning requirements in the common areas, kitchens, receptions, dining area, and cafeteria.

Using the information presented in Tables 2, 7, 8 and Section 3.7.2, Table 9 provides approximate area requiring space conditioning and total H&C for dwellings, hotels and office spaces in Portugal. In addition, it also shows an estimate for DHW requirements in dwellings and hotels.

The H&C requirements for offices can be estimated by taking an average of the corresponding values for entry 3 and 6 in Table 6. The average heating requirement can be estimated at 122 kWh/m$^2$/yr and average cooling requirement can be estimated at 153 kWh/m$^2$/yr. These projects (entry 3 and 6) were chosen because they were developed specifically for office buildings and they do not use complementary technology (eg. Solar panels) to satisfy space conditioning needs. Although this data is insufficient to estimate the actual H&C requirements in an office, these are the only two (2) data points available at the time of this analysis and hence have been considered to continue with the assessment. There is no data available regarding the average size or number of offices contained within the total available office space and the DHW requirements.

| | *Approx. area needing space conditioning (10$^6$ m$^2$)* | *Total estimated H&C needs (10$^6$ kWh)* | *Total estimated DHW requirements (10$^6$ kWh)* | *Sum (10$^6$ kWh)* |
|---|---|---|---|---|
| Dwellings | Heating: 300.7 | Heating: 12,939.1 | 11813 | 25,724 |
| | Cooling: 209.16 | Cooling: 972.6 | | |
| Hotels | Heating and cooling: 5.53 | Heating: 238.0 | 183.33 | 447 |
| | | Cooling: 25.71 | | |
| Office space* | Heating and cooling: 6.1 | Heating: 743.86 | NA | 1,678 |
| | | Cooling: 934.42 | | |

*Table 9: Approximate area requiring conditioning and total annual estimated H&C and DHW needs*

NA: Data unavailable. **Only Lisbon and Porto*

### *3.4 Constraints*

As discussed in Section 3.1, the technical potential is limited by space, environmental considerations and regulatory compliance.

### *3.4.1 Environmental considerations*

The presence of GSHP gives rise to localized anomalies under the ground or within the groundwater in the form of cold or heat plumes. Changes in the sub-surface and/ or ground water temperature can have negative impact on the chemical and physical properties and microbiology, with bacteria growth at higher temperature one of the main concerns. There have not been sufficient studies to quantify the impact of the geothermal applications on the groundwater ecosystem. [55]

### *3.4.2 Space*

For hGSHP systems the space requirements are higher than vGSHP systems. The pipes are usually laid at least 1.5 m below the ground [38] for the hGSHP systems. vGSHPs are more suitable in urban areas due reduced availability of land as compared to rural areas. The space required for vGSHP installation depends on the number of boreholes required. Minimum distance criterion can be defined for adjacent GSHPs based on the distance between the BHEs, water aquifer, and adjacent property. It is of interest since the criterion is easier to define, control and communicate [55]. Recommended distance between the boreholes for closed loop vGSHP is at least 7m (21 ft) to avoid thermal interference [38]. Until 2010, only four (4) countries in Europe made the minimum distance legally binding while three (3) countries made recommendations to regulate the distance for closed loop vGSHP. The maximum distance between the boreholes will depend on the space availability and budget for the addition piping. To make an estimation regarding availability of space for vGSHP installations in Portugal, GIS data will be required. Since the installations are site-specific and demand specific, the space evaluation needs to be performed on project-by-project basis. An example of such an approach could be found in [24] where the space for BHE installation per parcel was determined using GIS data.

### *3.4.3 Current regulations*

The current Portuguese law from 1990 is applicable to high and medium temperature resources and regulates its use for direct applications and power generation. It does not regulate low temperature, closed loop SGE systems [55] however, a working group was assembled in 2018 to recommend legislative solution targeted towards inclusion of SGE in the national legislative framework [56]. Portuguese national law recognizes environmental impact around the exploitation of geothermal resources. It guarantees against the deterioration of ground water quality and changes in the ground temperature due to heat extraction, and, promotes restoration of landscape. But this legislation does not apply to GSHP systems since the law fails to bring it under the definition of “geothermal resource” [56].

### *3.5 Conclusions*

Reviewing – the climactic and ground conditions in Portugal and Sweden, the study done for the twelve cities from the conceptual study [40] which is representative of Portugal, and, the existing GSHP projects across Portugal, it can be concluded that the ground thermal properties and ground temperature make it possible to exploit the shallow geothermal source for the existing climatic conditions of Portugal with varying degree of technical potential. [40] assumes uniform technical parameters, but in reality, they will differ for each project. Table 6 enumerates GSHP projects for different facilities, namely, classrooms, living quarters, hotel, spa, office spaces, and laboratory. This indicates that there is sufficient SGE potential in Portugal to be exploited by GSHP systems. The climate and ground conditions in Portugal allow GSHP systems to be used for heating, cooling and DHW applications. Moreover, 15 out of the 23 known projects used other technology, mostly solar panels, to complement the GSHP systems. This indicates that for non-residential projects investors prefer to install a “hybrid” of two or more technologies, out of which one is GSHP system.

Unlike other renewable energy sources like solar and wind, the theoretical and technical potential of SGE to be harnessed by GSHP systems is extremely challenging to put in numbers because the application is site-specific and demand specific. Thus, the focus of the above assessment was to quantify the total space conditioning and DHW requirements that can be satisfied by GSHP systems rather than the total availability of SGE across Portugal, and proceed under the paradigm that these requirements can be met technically but with varying capital costs depending on the size of the system.

Table 9 shows the approximate area requiring space conditioning and total annual estimated H&C and DHW needs for dwellings, hotels and office spaces in Portugal. In total, GSHP systems can be installed to satisfy at least 28.84 GWh of space conditioning requirements. This is a conservative estimate since these figures (Table 9) do not include DHW needs for offices, and H&C and DHW needs for commercial properties (eg. Mall, gymnasium, theatre) and public spaces (e.g. Metro stations, museums); due to lack of data.

To get a complete picture of the technical potential, further assessment of the currently identified constraints (environmental, space and regulations) and future constraints needs to be understood. This exercise is challenging due to insufficient installation data and lessons learned, and, lack of projects for district H&C. Further assessment can be carried out assuming deployment will primarily depend on the cost of technology instead of these constraints.

The biggest challenge to the penetration of this technology for heating may come from the traditional and cheap fuel sources (Table 4), namely, oil, firewood (biomass) and gas which constitute majority of the total energy consumed for heating, and also from thermal solar which is a relatively newer technology that has gotten cheaper and more accessible in the recent years. However, as mentioned above, solar energy is the preferred complementary technology to be used in conjunction with GSHP systems. This indicates that their combination probably provides cost and/ or performance advantage over a single GSHP system.

Referring to Table 4, it can be concluded that energy consumption for cooling is low, cooling systems are not as prevalent in Portugal as heating systems and they use electricity for their operation. This also indicates that a GSHP system installed to satisfy only cooling needs may not be the most economical choice given the high capital cost. Thus, its primary utilization could be for heating and DHW requirements.

Lack of regulations around use of shallow geothermal in Portugal offers great flexibility regarding installation of these systems on the given site. It implies that there are practically no limitations in the manner in which SGE can be utilized for GSHP systems and that all of the available heat-in-place can be extracted without restrictions. However, disregard to environmental and sustainability aspects may create hosts of issues.

Space limitations can be a big factor for not installing GSHP system in already existing buildings in the urban areas. The determination of space requirement can be evaluated on a project-by-project basis. Owing to the site-specific and demand specific nature of the GSHP technology, it is next to impossible to estimate the amount of land requirements to satisfy the H&C and DHW across Portugal. There is also a need to carry out studies to understand the long-term effects of GSHP systems on the sub-surface temperature distribution, microbiology and physical and chemical properties. It is outside the scope of the thesis to study the above-mentioned long-term effects as well as the environmental and sustainability aspects. In the subsequent chapters, it is assumed that the GSHP system installation will take place in a sustainable manner.

# Chapter 4: Economic Potential of GSHP systems

### *4.1 Overview*

This chapter is broadly organized in two parts. The first part consists of sections 4.2 to 4.8, in which the economic potential as well as the deployment rate required to replace the existing H&C and DHW applications with GSHP systems in residences, hotels, and offices is estimated. In the following sections, sections 4.9 to 4.11, the Net Present value (NPV) and $CO_2$ emissions from GSHP project is compared against the NPV and $CO_2$ emissions of the existing technologies for dwellings only. This is due to there being lack of data on the energy consumption for space conditioning and DHW requirements for hotels and office spaces.

Economic performances of technologies can be evaluated using standard cost measures like: NPV, internal rate of return (IRR), payback period and levelized cost of energy (LCOE). Out of these NPV was chosen because GSHP system is a consumer product. It uses energy for operation. In the absence of any qualitative studies to determine the factors affecting purchasing decision for GSHP systems, it can be assumed that the decision primarily depends on its initial cost and costs to own it over a period of time. IRR is the discount rate that makes the sum of all NPVs from the investment equal to zero. Payback period is the amount of time it takes to recover the investment. However, it neglects the time value of money. Also, consumers are less likely to evaluate a product based on payback period unlike investors. LCOE is the measure of all the costs associated with energy generation divided by the total energy produced over the length of the project. This measure more suitable to evaluate technologies that generate power.

As seen in Table 4, H&C and DHW requirements in Portugal are being satisfied by different energy sources, viz., electricity, firewood, gas, heating oil, thermal solar and coal. The technology applications utilizing these sources can be theoretically replaced by GSHP systems. However, practically, it may be impossible mainly due to the environmental, spatial, regulatory constraints as well as financial constraints of the buyer. Deeper depths will be able to provide greater heating or cooling potential, but it will increase the drilling and equipment cost considerably. For an existing property (stand-alone house or a building), there could be potential to utilize SGE by GSHP installation, but lack of space may not allow it. Application of GSHP systems will also depend on its economic performance compared to existing H&C and DHW technologies. GSHP systems emit less $CO_2$ as compared to technologies that use fuels like firewood and gas. However, the latter may be more attractive due to their affordability and convenience. In this chapter, the economic performance and $CO_2$ emissions of GSHP will be compared against its competition on the basis of NPV and tons of $CO_2$ emitted. NPV is the current value of the future cash flows discounted to present. Future value (FV) is the future value of current cash flow discounted in the future.

### *4.2 Lifetime costs of space conditioning and DHW applications*

Broadly three costs have been considered to assess the financial performance of all the space conditioning and DHW systems used in the analysis: capital cost, maintenance cost and the operation cost. Capital cost includes the cost of the equipment including the pipework and associated control systems, labour cost as well as installation cost. Maintenance cost includes inspection cost, cost to repair or replace any faulty component within the system as well as the labour cost for the rework. This cost has been annuitized over the length of the financial assessment. Operating cost includes the cost of fuel, e.g. electricity, firewood, gas. For the financial analysis, financial and product data has been taken from various sources available on the internet and academia. Data in a currency different than Euros was adjusted to Euros to facilitate realistic discussion.

For GSHP systems, the investment cost will primarily depend on number of boreholes, drilling cost, cost of equipment (includes heat pump, pipes), and labor cost. There is no data available on the investment and labour cost for the GSHP projects in Portugal. Figure 10 [37] shows the cost per installed kW output in Sterling. The capital costs per kW of installed capacity ranges from £400 to £1500 (€ 480 to € 1800 using exchange rate €1.2 to £1) for closed loop borehole system. These values have been obtained from different players (installers, consultants, manufacturers) in the UK shallow geothermal industry for projects that were executed at different times over last decade. This explains the large variation. The unit cost typically decreases with the size of the system [37]. This graph will be used in the subsequent texts to estimate the cost of the system.

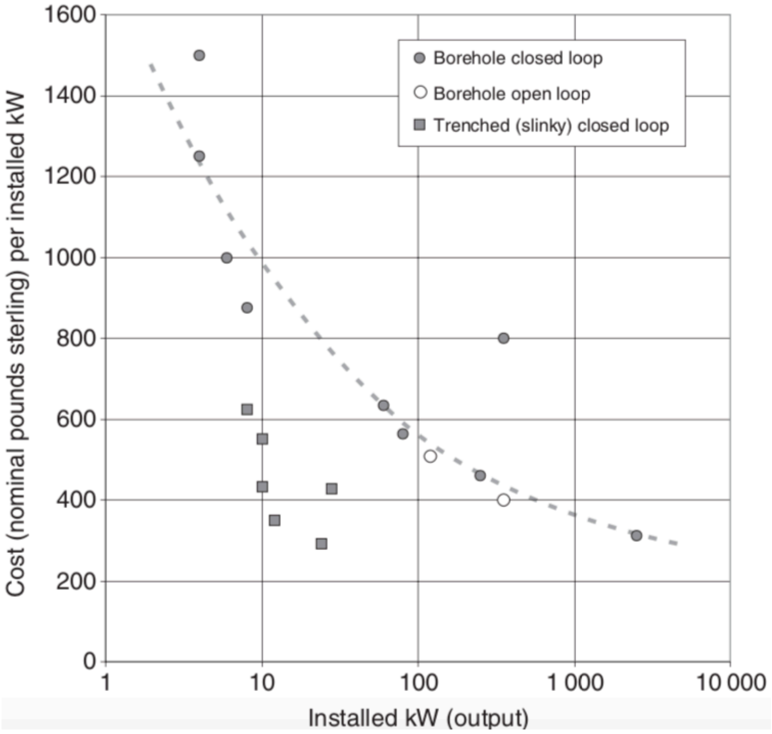


*Figure 10: Cost per installed kW output in UK Pounds [37]*

### *4.3 Emission factor and cost of fuel*

To estimate the $CO_2$ emissions from fuel consumption, emission factors for the given fuel can be used as a multiplying factor. Emission factor relates the quantity of pollutant released to the atmosphere due to any activity associated with the release of the pollutant. The $CO_2$ emission factor for Portugal is 0.369 $tCO_2$ per $MWh_e$ for consumed electricity as per document published by the Covenant of Mayors [57]. This value can be used as multiplying factor to estimate the amount of $CO_2$ released by utilizing GSHP pumps as well as HVAC and other heating, cooling and DHW applications that run on electricity. According to [57], natural gas has an emission factor of 0.202 $tCO_2$ per MWh. For wood, the emission factor varies between 0 to 0.403 $tCO_2$ per MWh, depending on how sustainably the wood was harvested. For the current analysis, a near mid-point value of 0.25 $tCO_2$ per MWh has been assumed. These values will be utilized in the subsequent text for performing analysis on $CO_2$ emissions. The fuel cost was taken from more than one source. Table 10 shows the emission factors and fuel costs used in calculations.

| *Fuel* | *Cost per unit (€/unit fuel)* | *Emission factor (*$tCO_2$ per MWh) |
|---|---|---|
| Electricity | 0.2293/ kWh [58] | 0.369 [57] |
| Gas | 21.1/ GJ [59] | 0.202 [57] |
| Firewood | 175/ ton[59] | 0.250 [57] |

*Table 10: Fuel cost and emission factor used for analysis*

### *4.4 Spatial constraint factor*

Major factors affecting the GSHP installations are availability of space, especially in urban areas, availability of a suitable location and presence of water aquifers, apart from regulatory and sustainability constraints. These constraints may significantly decrease the number of installations. It is assumed that the regulations are not a hurdle in extracting the heat-in-place and the installation, and, operation takes place in a sustainable manner.

Further, it is assumed that only 25% of the total identified sites will have sufficient space and a suitable location to install the GSHP system. Thus, a multiplying factor of 0.25, called the *'spatial constraint factor'*, have been used to predict the economic potential in this chapter. It must be noted that the value 25% is an arbitrary assumption. Real prediction is possible following GIS analysis or running appropriate tests at the proposed installation sites to understand the geology of the given area, but this is outside the scope of this thesis.

### *4.5 Economic potential in residential sector*

#### *4.5.1 Size of the system*

Referring to Table 7, the total number of dwellings in Portugal is just over 5.9 million. These dwellings include conventional houses and flats inside a building. There is lack of data on the average number of flats in a building. To include flats in the analysis, the total number of dwellings in Portugal can be converted into independent dwellings of uniform sizes depending on the population and occupancy level. The heating and cooling area can be adjusted as per the adjusted number of dwellings. Thus, for a project involving one dwelling (2.7 residents) heating and cooling area can be adjusted to 78.8 $m^2$ and 54.8$m^2$ respectively.

The total energy requirement for space conditioning and DHW per dwelling in Portugal can be added by summing the respective requirements from the kWh/ dwelling row (refer Table 3) which sums to 4,330 kWh. However, heating and cooling requirements will not be required simultaneously. Considering DHW requirements and higher of the heating and cooling requirements, the peak load can be estimated at 4,165 kWh (DHW and heating). This value can be assumed to be the minimum requirement. To account for losses, lack of proper insulation for the dwelling and to choose a standard product size available in the market, a 6-kW heat pump with COP of 4.0 can be chosen to sufficiently cover the above load. It is assumed that the system is designed such that the heat extraction rate is lower than or equal to heat deposition rate. Design of the system is outside the scope of this thesis. As per the latest update on the geothermal energy installations in Portugal, the installed capacity of shallow geothermal projects was approximately 0.65 MW with an average operating hour value 1,340 [27]. For further financial analysis, an operating hour value of 1,600 hours per year has been assumed to be conservative.

### *4.5.2 Cost of the system*

As per Figure 10, cost per kW of installed capacity for 6-kW closed loop system is approximately £1,300 or €1,560. This cost could be underestimated by up to 50% since it does not include commissions, consulting fees, and miscellaneous costs [37]. Assuming 25% underestimation, cost of €1,950/ kW can be assumed for 6-kW system which implies a total capital cost of €11,700. This cost includes cost of drilling the boreholes, cost of the heat pump and associated equipment like pipework, grout material. These values are more than 10 years old and must be adjusted to the average inflation rate for United Kingdom of 2.184% [60]. Assuming 15 years old values, the capital cost increases to €16,178 which can be rounded to €16,500 to account for miscellaneous costs. This capital cost can be taken as a reference for the further calculations for Portugal. The cost of electricity in Portugal as per the latest data was €0.2293/ kWh (Table 10). The typical life expectancy of a well-maintained heat pump is 30 years. This indicates that within 30 years of assumed project life, there will not be any replacement. GSHP systems including the heat pumps are reliable and robust systems. Thus, the maintenance cost is negligible and assumed to be zero per year. To calculate the NPV and FV, an in-built function within MS Excel was utilized.

### *4.5.3 $CO_2$ emissions*

The $CO_2$ emitted per room can be estimated using the emission factor of 0.369. Assuming 1600 hours of operation and COP of 4.0, approximately (0.369 x 6/4 x 1600/1000) 0.886 $tCO_2$ is emitted per year per dwelling.

*4.5.4 Summary*

The economic potential for residential sector can be summarized in Table 11 below. Availability of capital and competing technologies will play vital role in the possible installations. It will be discussed in the next chapter.

| | |
|---|---|
| Average area per dwelling in $m^2$ (Refer Table 2) | 107 |
| Number of individuals per dwelling (Refer Table 2) | 2.7 |
| Population | 10,300,000 |
| Number of dwellings of uniform size | 3,814,815 |
| Space heated, in mil. $m^2$ (Refer Table 9) | 300.7 |
| Space cooled, in mil. $m^2$ (Refer Table 9) | 209.16 |
| Adjusted space needing heating per dwelling (kWh) | 78.8 |
| Adjusted space needing cooling per dwelling (kWh) | 54.8 |
| Adjusted number of uniform sized dwellings | 3,814,815 |
| Size of the GSHP system for one dwelling, kW | 6 |
| Estimated capital cost per dwelling | €16,500 |
| Estimated $CO_2$ emissions per dwelling, per year | 0.886 $tCO_2$ |
| Total $CO_2$ emissions for all dwellings, per year | 3.378 million $tCO_2$ |
| Total $CO_2$ emissions after applying spatial constraint factor (See Section 4.3) for all dwellings, per year | 0.844 million $tCO_2$ |
| Economic potential | €62.9 billion |
| Economic potential after applying spatial constraint factor (See Section 4.3) | €15.7 billion |
| Estimated installed capacity | 5.72 GW |

*Table 11: Estimated economic potential in residential sector*

### 4.6 Economic potential in hotel industry

*4.6.1 Size of the system*

Referring to Table 8 and 9, the total estimated space conditioning needs in the hotel industry is 5.53 mil sq. m and the average number of rooms per hotel can be assumed to be 27. The occupancy level of hotels in Portugal is 51.9% [53] . This means that at any given time 52% (rounded value) of the total 184,435 rooms (rounded value) or 95,906 rooms are occupied. A 4-kW GSHP system per room is assumed to be sufficient to provide the space conditioning and DHW needs for an average of 2.3 occupants. The estimated size of the GSHP system per hotel building can be assumed to be 108 kW. It does not consider DHW as well as H&C requirements from common areas and facilities inside a hotel, e.g. kitchen, cafeteria, dining halls.

*4.6.2 Cost of the system*

Referring to Figure 10, the capital cost for 108 kW system will be approximately £550 or €660. Cost adjusted for 25% overestimation will be €825/ kW. These values are more than 10 years older. Assuming 15 years old values, the adjusted cost per kW, assuming 2.184% inflation, will be €1,141/ kW or €123,228, rounded to an investment of €124,000 for 108 kW GSHP system considering miscellaneous costs.

### *4.6.3 $CO_2$ emissions*

The $CO_2$ emitted per room can be estimated using the emission factor of 0.369. Assuming 1600 hours of operation and COP of 4.0, approximately (0.369 x 4/4 x 1600/1000) 0.5904 $tCO_2$ is emitted per year per room

### *4.6.4 Summary*

Table 12 summarizes the key statistics and economic potential for the hotel industry.

| | |
|---|---|
| Estimated hotel area | 5.53 mil. $m^2$ |
| Assumed size of one room | 30 $m^2$ |
| Total number of rooms | 184,435 |
| Room occupancy rate per year | 52% |
| Number of rooms using system per year | 95,906 |
| Number of hotel establishments | 6,868 |
| Number of rooms per building | 27 |
| Size of the GSHP system for one room (only space conditioning) | 4 kW |
| Size of GSHP system for one building | 108 kW |
| Estimated capital cost per room | €124,000 |
| Estimated $CO_2$ emissions per room, per year | 0.5904 $tCO_2$ |
| Total $CO_2$ emissions for hotels, per year | 108.9 $ktCO_2$ |
| Total $CO_2$ emissions savings for hotels after applying spatial constraint factor (See Section 4.3), per year | 27.2 $ktCO_2$ |
| Economic potential | €851.6 million |
| Economic potential after applying spatial constraint factor (See Section 4.3) | €212.9 million |
| Estimated installed capacity | 185.4 MW |

*Table 12: Estimated economic potential in the hotel sector*

## *4.7 Economic potential in office spaces*

### *4.7.1 Size of the system*

Office spaces are available in all sizes. It is nearly impossible to determine the average requirement for an office space since the number of people using the facility, type of operations, number of office equipment (printers, computers), number of restrooms (for DHW requirement), availability of kitchen facilities, will vary from office to office. This is also evident from the space heating and cooling requirements obtained in Table 6 for entry #3 and #6. For an office building in Sines, the heating and cooling requirements are approximately 94.56 $kWh/m^2/yr$ and 143.7 $kWh/m^2/yr$, respectively while for an office building in Coimbra the heating and cooling requirement are 149.3 kWh/m$^2$/yr and 162.7 kWh/m$^2$/yr, respectively. This estimation does not include DHW requirements.

However, to make an approximate estimate, above requirements have been averaged (122 kWh/m$^2$/yr for heating and 153 kWh/m$^2$/yr for cooling), and the total estimated office space 6.1 mil sq. m is divided by 943 m$^2$ (average of entry #3 and 6, Table 6) to convert it in to uniform office space. Thus, for space conditioning only, an office with above area will require approximately 144.3 MWh energy per year (cooling requirement considered since it is higher than heating requirement). Assuming 1600 hours of operation, at least 91-kW GSHP system will be needed for an office. If partial DHW demands are considered, the then at least 100-kW system can be chosen.

### *4.7.2 Cost of the system*

Capital cost of installing approximately 100-kW GSHP system is around UK pounds 550 (Figure 10) or €660. Since this cost is assumed to increase by 25%, the actual capital cost will be approximately €825/ kW. Since this value is assumed to be 15 years old, capital cost adjusted to inflation is €1,141/ kW. For a 100-kW system, the cost can be estimated at €114,100 which can be rounded to €114,000.

### *4.7.3 $CO_2$ of the system*

Assuming 1,600 hours of GSHP operation and COP 4.0, approximately (0.369 x 100/4 x 1600/1000) 14.76 $tCO_2$ is emitted per year per office.

### *4.7.4 Summary*

Table 13 summarizes the key statistics and economic potential for the office industry in Lisbon and Porto.

| | |
|---|---|
| Estimated office area (only Lisbon and Porto area) | 6.1 mil. m$^2$ |
| Assumed size of one office | 943 m$^2$ |
| Total number of uniform sized office buildings | 6,467 |
| Size of the GSHP system | 100 kW |
| Estimated capital cost per office | €114,000 |
| Estimated $CO_2$ emissions per office, per year | 14.76 $tCO_2$ |
| Total $CO_2$ emissions from all the offices, per year | 95.45 $ktCO_2$ |
| Total $CO_2$ emissions from all the offices after applying spatial constraint factor (See Section 4.3), per year | 23.86 $ktCO_2$ |
| Economic potential | €737 million |
| Economic potential after applying spatial constraint factor (See Section 4.3) | €184 million |
| Estimated installed capacity | 646.7 MW |

*Table 13: Estimated economic potential in office space sector (Lisbon and Porto)*

### *4.8 Deployment rate*

#### *4.8.1 Replacing current technology with GSHP systems*

Financial values from Table 11, 12 and 13, are subject to revision following a Portugal-wide GIS analysis and testing at project site to determine installation potential. The initial investment cost (~ €16,500) is prohibitive for many consumers considering the minimum wage in Portugal is €700 per month [61]. Thus, a sizeable proportion of population may not be willing to replace their current H&C and DHW system with a GSHP system. The decision regarding whether to replace current H&C and DHW technologies with GSHP systems may depend on their level of income and/ or government intervention.

#### *4.8.2 Deployment rate for GSHP system for new properties*

Assuming that the government offers subsidy schemes to an extent that mitigates the burden of the initial investment, then the maximum deployment rate can be assumed to be equal to the yearly growth in the three market segments considered.

In the year 2017, the number of licensed buildings for family housing across Portugal were 11,932 out of which 8,872 were new construction and the rest were reconstructions or refurbishments [62]. Additionally, there were 14,143 new construction licenses for family dwellings [62]. Thus, the total number of new licensed dwellings, (excluding reconstructions or refurbishments) for the year 2017 was 23,015 (8,872+14,143). The total area licensed for these new residences is not available. There was a decrease in number of new constructions from 2008-2014 due to economic crisis. Compared to the year 2016, the number of new constructions has shown a steady increase in 2017 [51]. Assuming that the average rate of increase remains the same for, say, next five (5) years (i.e. 23,015 new dwellings), the total yearly investment required in the residential sector can be estimated by assuming a 107 $m^2$ dwelling size and 6-kW per dwelling. This corresponds to an estimated potential installed capacity of, at least, 138 MW or €379.7 million per year (See Table 11).

The number of hotels has been increasing in four primary tourist markets in Portugal: Lisbon, Porto, Algarve and Madeira (Table 14). The total number of hotel rooms (only), available in Portugal in 2018 was close to 102,000. On an average a 4.2% increase in the number of rooms from the year 2015 to 2018 has been recorded in the hotel industry [63].

| Year | Number of hotels | Number of rooms |
|---|---|---|
| 2018 | 1,372 | 101,946 |
| 2017 | 1,309 | 98,960 |
| 2016 | 1,237 | 94,826 |
| 2015 | 1,164 | 90,148 |

*Table 14: Increasing trend in hotel industry*

Assuming that the average rate of increase remains the same for, say, next five (5) years there will be 4,300 new rooms. Since it assumed that each hotel building has 27 rooms, this corresponds to 160 new buildings with 108 kW GSHP systems each. Thus, the total yearly deployment possible in the hotel sector can be estimated at 17.3 MW/ yr or €19.84 million per year (over five years of assumed period).

In Lisbon, 21,000 m$^2$ of new office spaces was available in 2018 while in Porto the new office area stood at 11,000 m$^2$ [51]. This increase is not significant and there could be a scarcity of office space [51]. Thus, an increase in construction of new office space can be anticipated in the coming few years subject to the performance of the national economy. However, if the same rate of growth is assumed over next five (5) years in the office space, then there could be 34 new office buildings every year with uniform area of 943 m$^2$. Thus, the total installed capacity can be estimated at 3.4 MW per year with total market size of €3.9 million (per year). Table 15 shows the estimated deployment rate every year (for next five years) for residential, hotel and office space sector assuming all of the new constructions utilize GSHP system.

| Market segment | Estimated deployment rate in installed capacity/ year (MW/ yr) | Estimated deployment rate in market size/ year (million €/ yr) |
|---|---|---|
| Residential | 138 | 379.7 |
| Hotels | 17.3 | 19.8 |
| Office spaces | 3.4 | 3.9 |
| *Total* | *158.7* | *403.4* |
| Applying spatial constraint factor = 0.25 | *39.7* | *100.8* |

*Table 15: Estimated deployment rate every year (for five years)*

It must be noted that this is a conservative estimate given H&C and DHW for common areas is not included in the assessment for hotels. And for office spaces DHW requirement is not considered. DHW constitutes significant fraction of total energy demand for residences. If DHW is included for hotels and office spaces, then the estimate could be significantly higher for these two market segments. It is difficult to improve this estimate at this time due to lack of data and chosen configuration. It is possible to install GSHP systems in different configurations – one system for several rooms or, for a given floor/s or, for the entire building, or specific facility (eg. cafe inside an office, spa inside a hotel). Depending on the chosen configuration, the cost may vary significantly.

### *4.9 Competing technologies*

For a single dwelling, different technologies competing with GSHP systems were considered for comparison of NPV and $CO_2$ emissions. This excluded solar thermal collectors due to two reasons: firstly, the total installed capacity is low (0.1 m$^2$ per person) and secondly, the sale of solar thermal collector is declining in Portugal as per 2015 data [64]. Due to unavailability of more recent data (2016 – 2018), it is not possible to determine the current sales trend for solar thermal collectors.

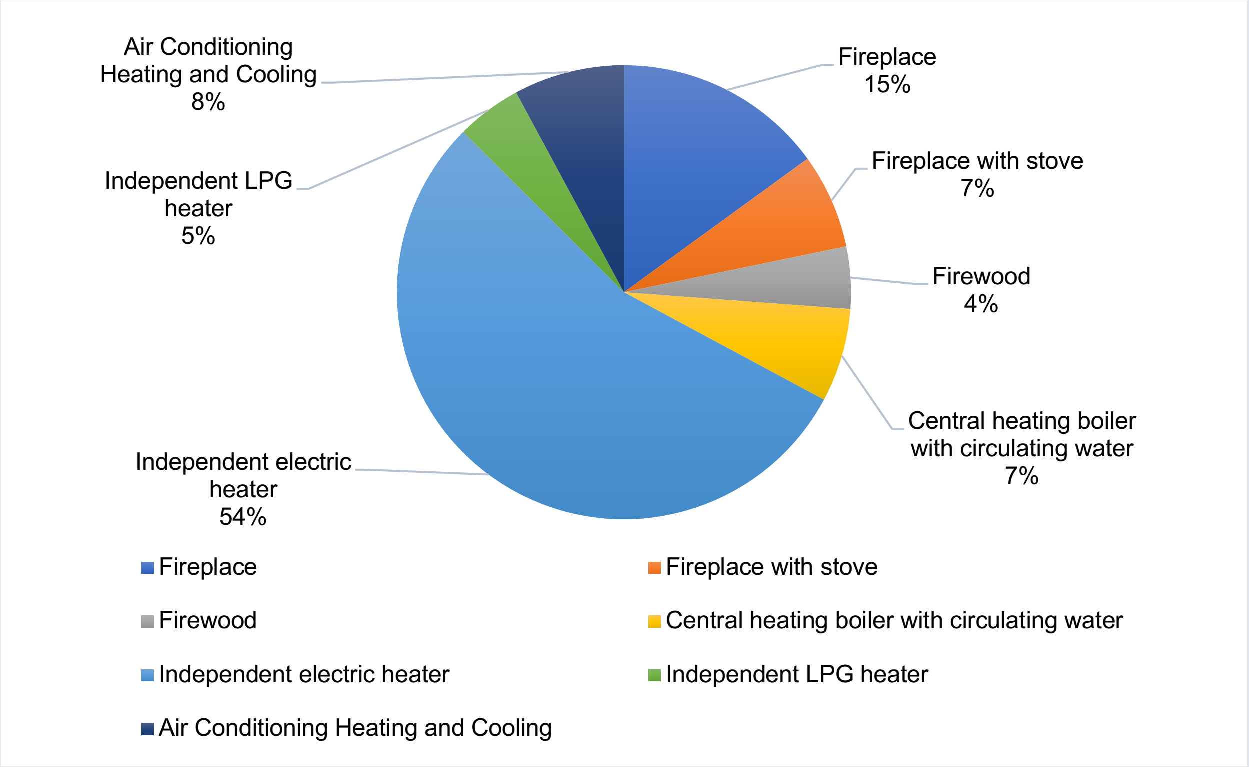


*Figure 11: Percentage market share of different heating technologies.*

Sample size: 3,953,710 dwellings with 5,114,134 equipment [46]

From the market data for 2010 (Figure 11), it can be observed that in the residential sector, for heating application, independent electric heater will be the main competitor for GSHP (54%) followed by fireplace (15%). For cooling application, fan is most widely used (61%) followed by HVAC system (33%). Gas heaters (71%) take up majority of the share for DHW followed by electric water heater (11%) as seen in Figure 13.

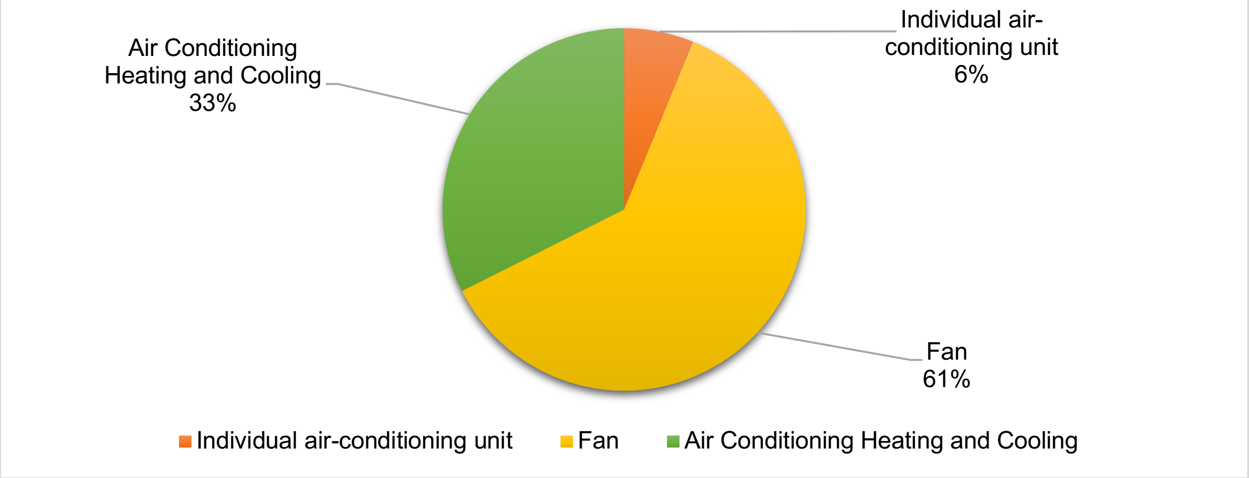


*Figure 12: Percentage market share of different cooling technologies*

Sample size: 909,290 dwellings with 1,231,975 equipment (Information extracted from [46])

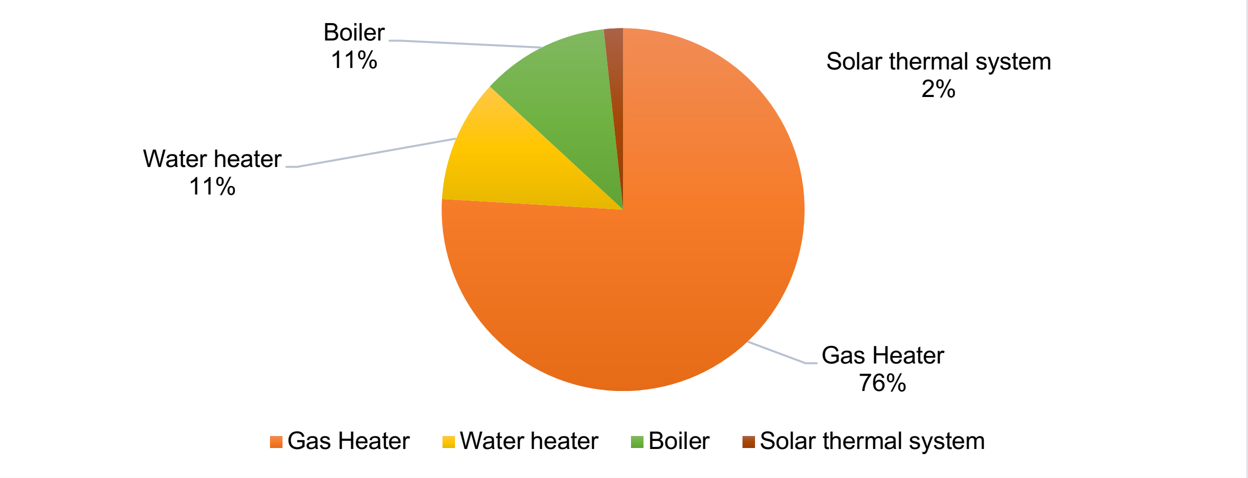


*Figure 13: Percentage market share of different DHW technologies.*

Sample size: 3,946,791 dwellings with 4,019,358 equipment [47]

### *4.10 NPV and $CO_2$ emission comparison*

#### *4.10.1 NPV and $CO_2$ of using only GSHP system for space conditioning and DHW requirements for one dwelling*

Referring to Section 4.4.1 and 4.4.2, the initial investment cost for a 6-kW GSHP system is €16,500 with low maintenance cost per year. The system can last for more than 30 years including the heat pump. The average cost of new heat pump is €5,100 [65]. Table 16 shows the costs for GSHP system for a dwelling and table 17 shows the NPV and $CO_2$ emissions over 30-year span.

| | |
|---|---|
| Capital cost for one dwelling (€) | 16,500 |
| Energy cost in Portugal (€/ kWh) [55] | 0.2293 |
| Life expectancy of GSHP system (years) | More than 30 |
| Life expectancy of heat pump (years) | More than 30 |
| Cost of replacement heat pump (€) | 5,100 |
| Maintenance cost (€/ year) | 50 |
| Inflation rate over next 30 years | 2% |
| Project duration (years) | 30 |

*Table 16: Capital, maintenance and operating costs for GSHP project for one dwelling*

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 16,176.5 | 26.57 |
| Maintenance cost | 1,470.6 | |
| Electricity consumption | 16,185.9 | |
| Total NPV | 33,832.9 | |

*Table 17: NPV and $CO_2$ emissions using GSHP system for one dwelling*

As seen in table 17, NPV of the project assuming only GSHP system is employed to satisfy space conditioning and DHW requirements for one dwelling of size 107 $m^2$. is marginally approximately €32,000 to 33,000 and the $CO_2$ emissions are 26.57 $tCO_2$ over 30 years period.

### *4.10.2 NPV of using only conventional HVAC and electric water heater for space conditioning and DHW requirements for one dwelling*

For conventional HVAC system, the fixed cost primarily will be the cost of the equipment and the associated duct system. One ton of HVAC system is equivalent to approximately 3.5 kW. To deliver 6 kW (same power as GSHP), a 1.7 tons HVAC system will be needed for space conditioning applications however it provides DHW needs too. Typically, up to 1.5 kW electric heater is sufficient to provide DHW needs for a dwelling with 2-3 people. This means 4.5 kW, or 1.29 tons will be used for space conditioning needs. Since 1.29 tons is not a standard size, 1.5 tons HVAC can be selected from the market which approximately costs €2,100 [59].

For DHW, an additional electric water heater will need to be installed. This value has been obtained by online browsing of products catalog. Approximate capital costs of residential 1- 1.5 KW water heater obtained by browsing through product catalogs online is approximately €800 [66], respectively (cost converted to Euros from USD) including installation charges. The maintenance cost is assumed to be €100 per year for both the equipment [67], [68]. The operational cost will include the cost of electricity. The maintenance cost for conventional HVAC is higher than GSHP system. Also, typically, a HVAC system needs to be replaced every 15 – 20 years. Since we chose project life as 30 years, there will be at least one replacement cycle. The average lifespan of water heater ranges from 8 to 12 years and requires minimal maintenance. Assuming good maintenance, a lifespan of 10 years can be considered which corresponds to two (2) replacement cycles assuming replacements occur at the end of the year. 1,600 hours of operation is assumed for the HVAC system which is same as GSHP system. 1,095 hours of operation have been assumed for water heater (3 hours per day). Table 18 shows costs associated with electrical technologies (HVAC and electric water heater) and Table 19 shows the NPV and $CO_2$ emissions over 30-year span.

| | |
|---|---|
| Capital cost for one dwelling (€) | 2,900 |
| Energy cost in Portugal (€/ kWh) [55] | 0.2293 |
| Life expectancy of HVAC unit replacement | 15 years |
| Life expectancy of water heater | 12 years |
| Maintenance cost (€/ year) | 200 |
| Inflation rate over next 30 years | 2% |
| Project duration | 30 years |

*Table 18: Capital, maintenance and operating costs for HVAC and electric water heater project for one dwelling*

The replacement cost has been assumed in the beginning of year 13 and 25 for water heater and beginning of year 16 for HVAC unit.

| | NPV (€) | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 6,470.6 | 111.17 |
| Maintenance cost | 5,882.4 | |
| Electricity consumption | 67,727.8 | |
| Total NPV | 80,080.7 | |

*Table 19: NPV and $CO_2$ emissions using HVAC and electric water heaters*

### *4.10.3 NPV of using ceiling fans for cooling requirements for one dwelling*

Assume minimum of three (3) ceiling fans will be required for cooling needs in the standard size dwelling. Cost of ceiling fan is typically €150 based on online browsing and output is typically 50 W. Ceiling fans require extremely low maintenance and last for about 10 years [69] which corresponds to two (2) replacements. For the analysis, 800 hours of operation is assumed.

Table 20 shows costs associated with ceiling fans and Table 21 shows the NPV and $CO_2$ emissions over 30-year span.

| | |
|---|---|
| Capital cost for one dwelling (€) | €450 |
| Energy cost in Portugal (€/ kWh) [55] | 0.2293 |
| Life expectancy of one fan | 10 years |
| Maintenance cost (€/ year) | Zero |
| Inflation rate over next 30 years | 2% |
| Project duration | 30 years |

*Table 20: Capital, maintenance and operating costs for three (3) ceilings fans for one dwelling*

The replacement cost has been assumed in the beginning of year 11 and 21 for all the ceiling fans.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 1,314.9 | 0.44 |
| Maintenance cost | 0.0 | |
| Electricity consumption | 269.8 | |
| Total NPV | 1,584.6 | |

*Table 21: NPV and $CO_2$ emissions using ceiling fans for cooling applications*

### *4.10.4 NPV of using only gas for heating and DHW requirements for one dwelling*

Gas (Natural gas, piped LPG and LPG bottle, which is mixture of butane and propane) is used as fuel for heating applications and DHW. Energy consumption for the heating and DHW (refer Table 3) for one dwelling sums up to 4,185 kWh. For further analysis the requirement is rounded to 4500 kWh to guarantee that the needs are met comfortably. This corresponds to 16.2 GJ of gas in Portugal. The cost of 1 GJ natural gas in Portugal is approximately €21.1 [70], making the total annual approximate operating cost of using gas for heating applications, €342. Online browsing suggests that for a family of 3, a simple gas water heater will cost at least, approximately, €600 including installation charges and around €50 maintenance cost per year spread over 30 years. The life of such heater is typically 8 to 12 years [71] [68]. For calculations, the life is assumed to be 10 years (two replacement cycles). The cost of installing residential gas furnace for heating, as per data available online, is approximately €3,000 including installation charges while the maintenance cost is higher for gas heater than electric heater at, approximately, €200 [72] The average life expectancy of gas furnace is 16-20 years [73]. For calculation, 18 years of life is assumed for calculations (one replacement cycle). Thus, the total capital cost for using gas heaters for heating and DHW applications is, approximately, €3,600. Table 22 shows costs associated with gas technologies and Table 23 shows the NPV and $CO_2$ emissions over 30-year span.

| | |
|---|---|
| Capital cost for one dwelling (€) | 3,600 |
| Gas price in Portugal (€/ GJ) [62] | 21.1 |
| Life expectancy of gas furnace unit | 18 years |
| Maintenance cost (€ / year) | 250 |
| Inflation rate over next 30 years | 2% |
| Project duration | 30 years |

*Table 22: Capital, maintenance and operating costs for gas technology for one dwelling*

The replacement cost has been assumed in the beginning of year 11 and 21 for gas water heater and beginning of year 19 for gas furnace.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 7,647.1 | 27.27 |
| Maintenance cost | 7,352.9 | |
| Fuel cost | 10,053.5 | |
| Total NPV | 25,053.5 | |

*Table 23: NPV and $CO_2$ emissions using gas technology*

For cooling, if it is assumed that such dwellings will use ceiling fans. Summing the values in Table 18 and 21, values in Table 24 can be obtained.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 8,961.9 | 27.71 |
| Maintenance cost | 7,352.9 | |
| Fuel cost | 10,323.3 | |
| Total NPV | 26,638.2 | |

*Table 24: NPV and NPV and $CO_2$ emissions using gas technology+ceiling fans*

#### *4.10.5 NPV of using only firewood for heating and DHW requirements for one dwelling*

A house using only firewood for heating and DHW applications will require a water boiler. The cost of an outdoor wood boiler can be assumed approximately € 8,000 [74]. The maintenance cost for the water boiler can be assumed to be approximately €250 [75]. Life expectancy for a wood boiler is assumed to be 15 years with proper maintenance. One tonne of fuelwood provides 0.3215 toe of energy [76] which corresponds to 3719 kWh. In the above section, it was seen that heating applications require 4500 kWh energy. Thus, to account for the lower efficiency, approximately two tonnes of firewood will be sufficient to run the heating applications which will cost approximately, €175 per tonne [77]. Table 25 shows costs associated with firewood technologies and Table 26 shows the NPV and $CO_2$ emissions over 30-year span.

| | |
|---|---|
| Capital cost for one dwelling (€) | 8,000 |
| Firewood cost in Portugal (€ / ton) [62] | 175 |
| Life expectancy of outdoor wood boiler | 15 |
| Maintenance cost (€/ year) | 250 |
| Inflation rate over next 30 years | 2% |
| Project duration | 30 years |

Table 25: Capital, maintenance and operating costs for using firewood for one dwelling

The replacement cost has been assumed in the beginning of year 16 for the boiler.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 16,960.8 | 27.83 |
| Maintenance cost | 7,352.9 | |
| Fuel consumption | 10,294.1 | |
| Total NPV | 34,607.8 | |

Table 26: NPV and $CO_2$ emissions using firewood

For cooling, if it is assumed that such dwellings will use ceiling fans. Summing the values in Table 26 and 21, values in Table 27 can be obtained.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 18,275.7 | 28.27 |
| Maintenance cost | 7,352.9 | |
| Fuel consumption | 10,563.9 | |
| Total NPV | 36,192.5 | |

Table 27: NPV and $CO_2$ emissions using firewood+ceiling fans

### *4.10.6 NPV of using only electric heaters for heating and DHW requirements for one dwelling*

The average price for electric heaters (wall-mounted and oil radiator) is €200 based online browsing. Typically, the maintenance cost for the electric heaters is minimal and for financial analysis purposes can be assumed to be zero. The typical size of the heaters is 2 kW. For Portugal, the average operating time can be assumed to be 800 hours/ year. The life expectancy for the electric heaters is approximately 10 years which corresponds to two (2) replacements over 30 years. For the dwellings utilizing electric heaters, let's assume that the DHW requirements are fulfilled using electric water heaters assuming 1,095 hours of operation. Thus, data from the section 4.5 can be used for the financial analysis and $CO_2$ emissions. Table 28 shows costs associated with electric heaters and Table 29 shows the NPV and $CO_2$ emissions over 30-year span.

| | |
|---|---|
| Capital cost for one dwelling (€) | €1,000 |
| Energy cost in Portugal (€ / kWh) | 0.2293 |
| Life expectancy of electric space heater | 10 |
| Life expectancy of electric water heater | 12 |
| Maintenance cost (€/ year) | 100 |
| Inflation rate over next 30 years | 2% |
| Project duration | 30 years |

Table 28: Capital, operating and maintenance costs for electric heaters and ceiling fans for one dwelling

The replacement cost has been assumed in the beginning of year 11 and 21 for the electric space heater and beginning of year 13 and 26 for the electric water heater.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 2,941.2 | 35.89 |
| Maintenance cost | 2,941.2 | |
| Fuel consumption | 21,867.8 | |
| Total NPV | 27,750.2 | |

*Table 29: NPV and $CO_2$ emissions using electric heaters for heating applications*

For cooling, if it is assumed that such dwellings will use ceiling fans. Summing the values in Table 29 and 21, values in Table 30 can be obtained.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 4,256.1 | 36.34 |
| Maintenance cost | 2,941.2 | |
| Fuel consumption | 22,137.6 | |
| Total NPV | 29,334.8 | |

*Table 30: NPV and CO2 emissions using electric heaters+ceiling fans*

### *4.10.7 NPV of Air to water heat pumps for DHW and heating applications for one dwelling*

Air-source heat pumps have performance comparable to GSHP systems and can be considered its competitor. Air source heat pumps are available in market, mainly as air-air and air-water variants. For the assessment, air to water heat pump has been considered since they can provide heating and hot water. Review of product line from at least one manufacturer suggested that cooling application is optional in air-to-water heat pumps [78]. For cooling applications, ceiling fans have been considered. The price for air to water heat pumps was approximately €7,000 based on catalogue released by a manufacturer for a 6-kW system in 2014 [46]. In addition to the pump cost, the capital cost will involve cost of ductwork, accessories and labour. Taking relevant values from, for 6-kW heat pump, the total capital cost can be estimated at €11,500, adjusted to inflation (2%). The maintenance cost for heat pumps is assumed to be similar to that of a HVAC system which is approximately €100/ year. It is assumed that the air to water heat pump will provide heating and DHW needs, only, and has a COP of 3.0. The annual time of operation will be 800 hours for heating and 1,095 hours (3 hours per day) for DHW. The life expectancy for the heat pump is approximately 20 years which corresponds to one replacement over 30 years. Thus, data from the section 4.5 can be used for the financial analysis and $CO_2$ emissions. Table 31 shows costs associated with electric heaters and Table 32 shows the NPV and $CO_2$ emissions over 30-year span.

| | |
|---|---|
| Capital cost for one dwelling (€) | 11,500 |
| Energy cost in Portugal (€ / kWh) | 0.2293 |
| Life expectancy of heat pump | 20 |
| Maintenance cost (€/ year) | 100 |
| Inflation rate over next 30 years | 2% |
| Project duration | 30 years |

*Table 31: Capital, operating and maintenance costs for Air to water heat pumps for one dwelling*

The replacement cost has been assumed in the beginning of year 21 for heat pump. Also, it is assumed that the cost of pump includes the replacement cost and the ductwork, accessories and other equipment will last for at least 30 years.

| | *NPV (€)* | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 18,137.3 | 41.96 |
| Maintenance cost | 2,941.2 | |
| Fuel consumption | 25,560.2 | |
| Total NPV | 46,638.6 | |

*Table 32: NPV and $CO_2$ emissions using electric heaters for heating applications*

It is assumed that such dwellings will use ceiling fans for cooling applications. Summing the values in Table 31 and 32, values in Table 33 can be obtained. Moreover, for the air-to-water heat pumps, even if ceiling fans are not considered for the cooling application, the difference in the NPV and $CO_2$ emissions are very small compared to the case where they are considered.

| | NPV (€) | *$CO_2$ emissions ($tCO_2$)* |
|---|---|---|
| Capital cost | 19,452.1 | 42.4 |
| Maintenance cost | 2,941.2 | |
| Fuel consumption | 25,830.0 | |
| Total NPV | 48,223.3 | |

*Table 33: NPV and $CO_2$ emissions using Air to water heat pumps+ceiling fans*

#### *4.11 Results*

Figure 14 shows NPV and $CO_2$ emissions for different technologies, namely, GSHP system, combination of HVAC with electric heaters, combination of gas technology with ceiling fans, combination of firewood with ceiling fans, and, combination of electric heaters with ceiling fans, and, combination of air to water heat pumps and ceiling fans. It can be seen that over the period of 30 years, the $CO_2$ emission values are almost similar for GSHP system, combination of gas technology with ceiling fans and, combination of firewood with ceiling fans. Combination of HVAC with electric water heaters has the highest NPV followed by combination of air to water heat pumps and ceiling fans, which is followed by GSHP systems. The lowest NPV is for the combination of gas systems and ceiling fans. Figure 15 shows the $CO_2$ emissions per €1,000 of NPV.

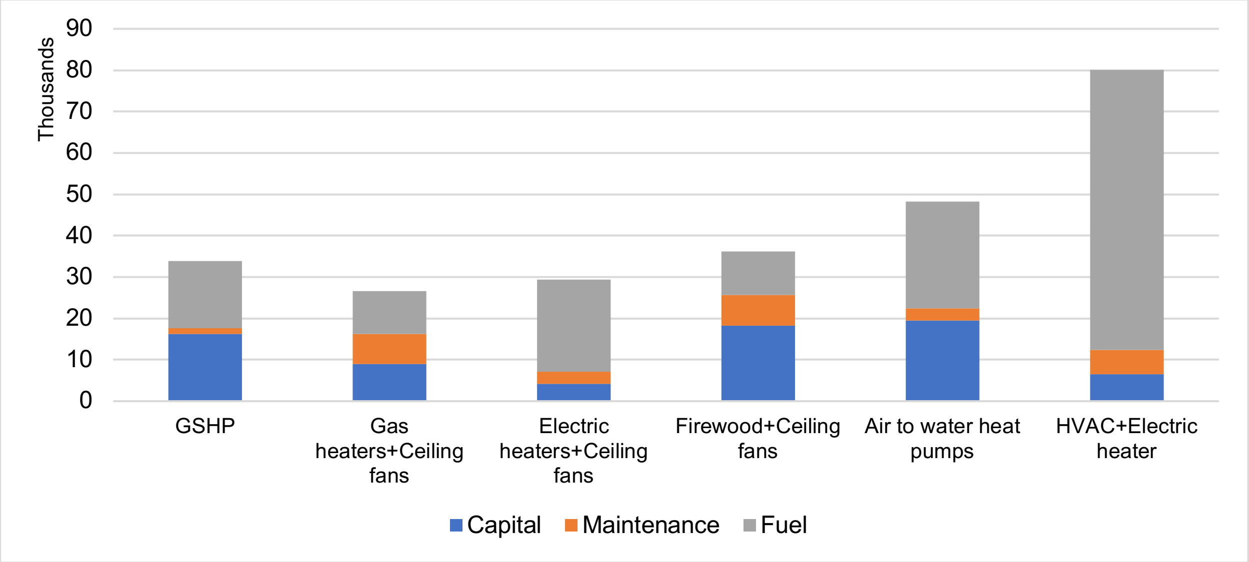


*Figure 14: Comparison of NPV and $CO_2$ emissions for different technologies*

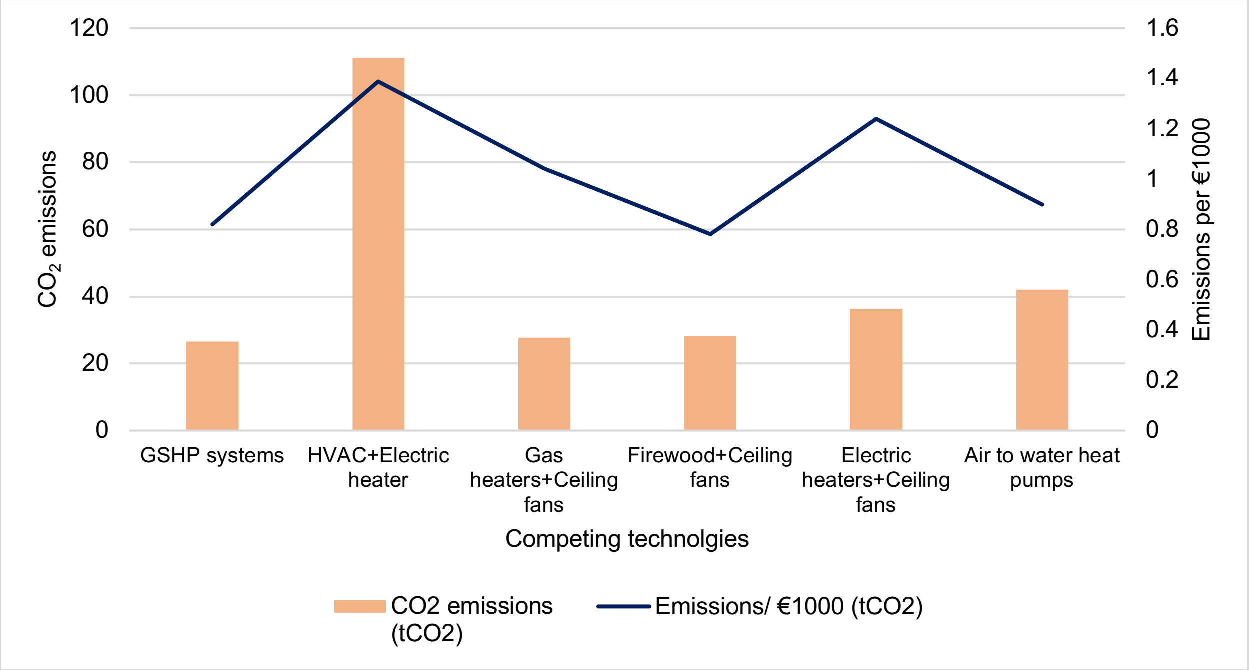


*Figure 15: Comparison of $CO_2$ emissions and $CO_2$ emissions/ €1,000 NPV for different technologies*

### *4.12 Conclusions*

The total estimated economic potential of GSHP systems in Portugal for current dwellings, offices and hotels places is approximately €16 billion corresponding to 6.5 GW of installed capacity (Refer Tables 11, 12, 13 and 34). This value is obtained using space constraint factor of 0.25. It does not include the DHW needs for offices and assumes conservative values for office spaces in the sizing of the GSHP system.

| *Market segment* | *Estimated economic potential (mil. €)* | *Potential installed capacity (GW)* | *$CO_2$ emissions ($ktCO_2$)* |
|---|---|---|---|
| Residential | 15,700 | 5.72 | 844 |
| Hotel | 212.9 | 0.185 | 27.2 |
| Office spaces | 184 | 0.647 | 23.8 |
| Total | 16,097 | 6.552 | 895 |

*Table 34: Summary of estimated market size, installed capacity and CO2 emissions in each market segment*

It can be concluded that the majority of the economic potential and $CO_2$ emission is concentrated in the residential sector. All the financial values are susceptible to significant changes due to the assumed arbitrary value for space constraint factor. Due to highly site-specific and demand specific application of this technology, a GIS survey as well as appropriate testing at the site under consideration will immensely help in estimating more reliable values. Due to lack of data, the labour cost (part of the capital cost) and the maintenance cost were obtained mostly from the UK, EU and USA and converted to Euro, where applicable. These costs will need to be adopted to Portuguese economy to carry out more realistic assessment of the total economic potential.

The values for estimated economic potential are based on an ideal situation which assumes that all the current technologies can be replaced with GSHP systems. But, 100% adoption is impossible due to economic constraints in addition to the spatial constraints. The decision to install GSHP systems on the current properties will depend, primarily, on the income and willingness of the property owner.

To predict growth of the market, it is assumed that the Government will provide sufficient subsidy to cover initial capital cost of the GSHP system, so that the maximum deployment rate is equal to the new properties licensed every year in residential, hotel and office market segments. This is an ideal scenario.

Fireplaces, fans, gas heaters, electric water heaters and electric space heaters have low NPV compared to GSHP systems. This may make them preferred technological options for heating, cooling and DHW requirements. Combination of HVAC systems with electric water heating system, on the other hand, has higher NPV and higher $CO_2$ emissions than GSHP systems. It can be assumed that replacing HVAC systems and electric (or gas) water heaters with GSHP systems should be initial focus since it offers price and technological advantages.

Referring to Figure 14, although the combination of gas technology with ceiling fans and combination of firewood with ceiling fans have $CO_2$ emissions comparable with GSHP systems, it must be noted that the emissions analysis does not consider emissions of harmful toxins (NOx and SOx) from the combustion of gas and firewood.

There are ongoing efforts to increase the share of renewable energy in the total energy mix. It is highly likely that over a decade or two, GSHP systems (as well as all electric devices) will be powered using renewable energy which will lower $CO_2$ emissions from these technologies. The cost of fuel (electricity, firewood, gas) will change at different rates in next 30 years. Thus, there could be significant difference between the predicted and actual fuel cost, and hence the results of the assessment.

If considered separately, the NPV and the $CO_2$ emissions for GSHP system is not the lowest however, GSHP has the lowest $CO_2$ emissions value per €1000 spent which makes it an attractive investment option for large scale projects, e.g. shopping mall, movie theatre, corporate parks, schools, hospitals and supermarkets.

# Chapter 5: Market Potential

As discussed in Section 3.1, market potential is the potential sale of a given product or service. It can be measured in sales revenue or number of units sold. From Section 4.7 above, it can be seen that residential sector has majority of market potential (~96%). Also, the initial focus should be to replace the existing HVAC system and electric (or gas) water heaters with GSHP systems since these are more expensive and carbon intensive. This chapter attempts to find residential market size that should be of interest to allow such replacement, the rate of replacement, and share of GSHP systems as renewable energy source in H&C solutions.

## *5.1 Market focus*

Referring to Figure 16, the combination of gas and electric heaters for heating and DHW application with ceiling fans is the main competitor of the GSHP with regards to cost and the carbon emissions. This combination is cheaper than GSHP systems and it has similar $CO_2$ emission values (SOx/ NOx not considered). Consumers will prefer GSHP systems over these systems either, (1) to benefit from the advantages of the GSHP systems (See Section 1.7), and/ or (2) if the government provides incentives to the GSHP system installers. There are no government schemes available at this moment for GSHP system installation in Portugal. Also, evaluation of advantages of one technology over the other is a subjective phenomenon. On the other hand, the combination of HVAC systems with electric water heater is more expensive and carbon intensive as compared to GSHP systems. Replacing this combination presents clear advantages. Thus, the initial focus should be replacing this combination. In the following text, this combination is termed as “Combination A”.

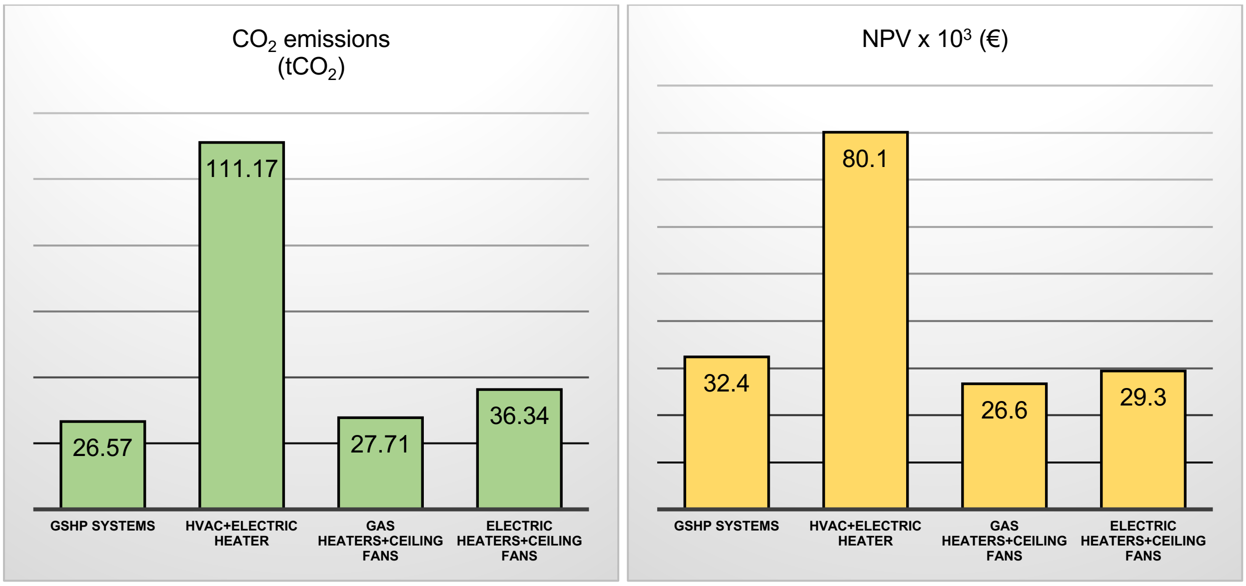


*Figure 16: Comparison of NPV and $CO_2$ emissions to determine market focus*

### *5.2 Number of HVAC systems in Portugal*

Referring Table 35 [46], the number of dwellings with HVAC installed for heating and cooling applications was approximately between 223,000 – 230,000 with approximately 400,000 sets of equipment. These figures are from 2010. For this analysis, it is assumed that the number of dwellings with HVAC systems remained constant until 2019 and a value of 225,000 has been used. In year 2019, the figures are likely to be higher thus estimates from Table 35 can be considered conservative. HVAC systems are capable of providing heating and cooling but there is a discrepancy between the number of HVAC equipment for heating and cooling. Since this discrepancy is less than 1% of the lower value, it can be neglected.

| | *No. of dwelling* | *No. of equipment* |
|---|---|---|
| HVAC for heating application | 223,429 | 402,664 |
| HVAC for cooling application | 230,063 | 399,432 |
| Electric water heater | 426,751 | 439,724 |

*Table 35: Number of HVAC for heating and cooling*

The number of electric water heaters in the country exceeds the number of HVAC as there is no breakdown regarding the source of heat for DHW supply, it is assumed in the thesis that all of these units utilize electric water heater.

### *5.3 Market size*

The number of new licenses for buildings and constructions for family houses declined from 2010 to 2014 before marginally picking up again from 2015 – 2017 [62]. If wealth is correlated with the size of the house as done by Tanguay [79], then people with bigger houses can be assumed to have sufficient spending capacity to install GSHP system in the absence of any subsidy. In this case, we can assume two market segments: people staying in T2 or bigger dwellings and people staying elsewhere. In 2018, the total number of licensed dwellings bigger than T1 (T2, T3, T4 or more) in new construction for family housings was 12,613 (rounded to 12,600) of which T3 has the biggest share (7,310 dwellings) [62].

Thus, it can be assumed that in 2018, the market potential of GSHP systems was, ideally, dwellings with Combination A to be replaced with GSHP system (225,000 units) plus newly licensed dwellings that can be fitted with GSHP systems (12,600), totaling to 237,600 in year 2018. This market will increase by 12,600/year assuming constant growth every year. Thus, making the number such of units – 250,200 in the year 2019. Here, a spatial constraint factor of 0.75 (See Section 4.3) is chosen to be higher than in the previous cases since family housing with size T2 or bigger can be assumed to have sufficient installation space.

A bigger house will have higher H&C and DHW requirements due to bigger area. The H&C demand depends on factors like – building material, insulation, number of occupants. Gouveia [80] conducted studies to get insights from the energy consumption in the residential sector. The trends originating from this case study suggested that for energy consumption, socio-demographic characteristics are more significant determinants than building construction characteristics. Consumers in bigger house can be assumed to have greater space conditioning needs. Thus, a bigger size GSHP system, say, 10-kW, can be chosen. It must be noted that same logic can be applied to dwellings with Combination A. The size of combination of these systems (and thus, the cost), will increase with the size of the dwellings. To be consistent, a 2-ton (~7 kW) HVAC system can be chosen to satisfy increased space conditioning needs. The DHW needs can be assumed to be constant since the average number of occupants will not change significantly.

Referring to Figure 10, the size of a 10-kW system is slightly less than 1,000 UK Pounds/ kW or €1,200/ kW installed capacity. This cost could be underestimated by up to 25% since it does not include commissions, consulting fees, and miscellaneous costs [37]. Thus, a cost of €1,500/ kW can be assumed for 10-kW system which implies a total capital cost of €15,000. These values are more than 10 years old and must be adjusted to the average inflation rate for United Kingdom of 2.184% [60]. Assuming 15 years old values, the capital cost increases to €20,741 which can be rounded to €21,000 to account for miscellaneous costs. This value is used in Table 36 to find the estimated market value of GSHP system.

| *Year* | *Number of dwellings* | *Spatial constraint factor* | *Installation cost* | *Estimated market value* | *Installed capacity (GW)* |
|---|---|---|---|---|---|
| 2019 | 250,200 | 0.75 | €21,000 | €5,254 million | 1.87 |

*Table 36: Upper limit of the market value of GSHP system (T2 and above)*

### *5.4 Diffusion model for market penetration*

Understanding the market penetration of the of new technology is interesting for entrepreneurs and government entities. There are many forecasting techniques available to predict market penetration of a given product. One of the widely used models is called the Diffusion model. This model predicts the market penetration by considering that acceptance of new product depends on the "adoption and imitation" process. Adopters or innovators are the people who buy the product and in turn influence the "imitators" to adopt it [81]. The basic model can be expressed mathematically as:

$$\frac{dN(t)}{dt} = a[N'(t) - N(t)] + b.N(t)\,[N'(t) - N(t)]$$

Where, $\frac{dN(t)}{dt}$ = rate of diffusion at time t, N(t) = cumulative number of adopters at time t, Ń(t) = population of potential adopters at time t (or maximum number of potential adopters), a = coefficient of innovation, and b = coefficient of imitation.

Various models have been developed for different types of product. The values of co-efficient "a" and "b" vary for different technologies and they are typically based on historic data.

### *5.5 Fisher and Pry diffusion model*

Fisher and Pry is a technological substitution model that attempts to forecast the rate of replacement technology that is superior to the older technology that it is attempting to replace. Here, GSHP system can be considered as a superior technology than Combination A. This method gives *"fractional rate of fractional substitution of the old technology by the new in terms of what is left to be substituted"* [82].

Fisher-Pry model can be mathematically expressed as:

$$\frac{f}{1-f} = \exp\ [\delta\ * (\mathrm{t} - \mathrm{t}_0)]$$

Where, f = fraction of the market substituted, $\delta$ = annual fractional growth in the early years, and $t_0$ = time at which f = 50%.

Fisher-Pry model can be used to predict the penetration of the GSHP system. Firstly, the number of years that will be required to replace half of the Combination A, will need to be estimated. The target carbon reduction from household sector compared to 2005 level is set at 15% in 2030 by the Portuguese government [83]. Thus, year 2030 can be chosen as the target year to replace 50% of the technology combination A with GSHP system. It is assumed that people are already utilizing combination A and with dwellings of size T2 or more can afford the GSHP system. Also, Portugal plans to become carbon neutral by the end of year 2050. Assuming that the energy mix for power generation remains fairly similar in year 2050, Fisher-Pry model can be used to compute the estimated annual fractional growth that can be targeted to achieve the 50% replacement by year 2030 and 100% replacement by end of year 2050.

Using the annual assumed growth rate of dwellings of size T2 or more as 12,600/ year there will be estimated 628,200 units in year 2050. Applying the space constraint factor (0.75) will decrease the growth rate to 9,450/ year and total number of units to 480,600 units at the end of year 2050. This aggregated value is used in the beginning of the analysis period as the market ceiling. In reality, the market ceiling will change every year. Figure 17 shows the assumed linear growth trend in the dwellings of size T2 or more, from 2020 until 2050.

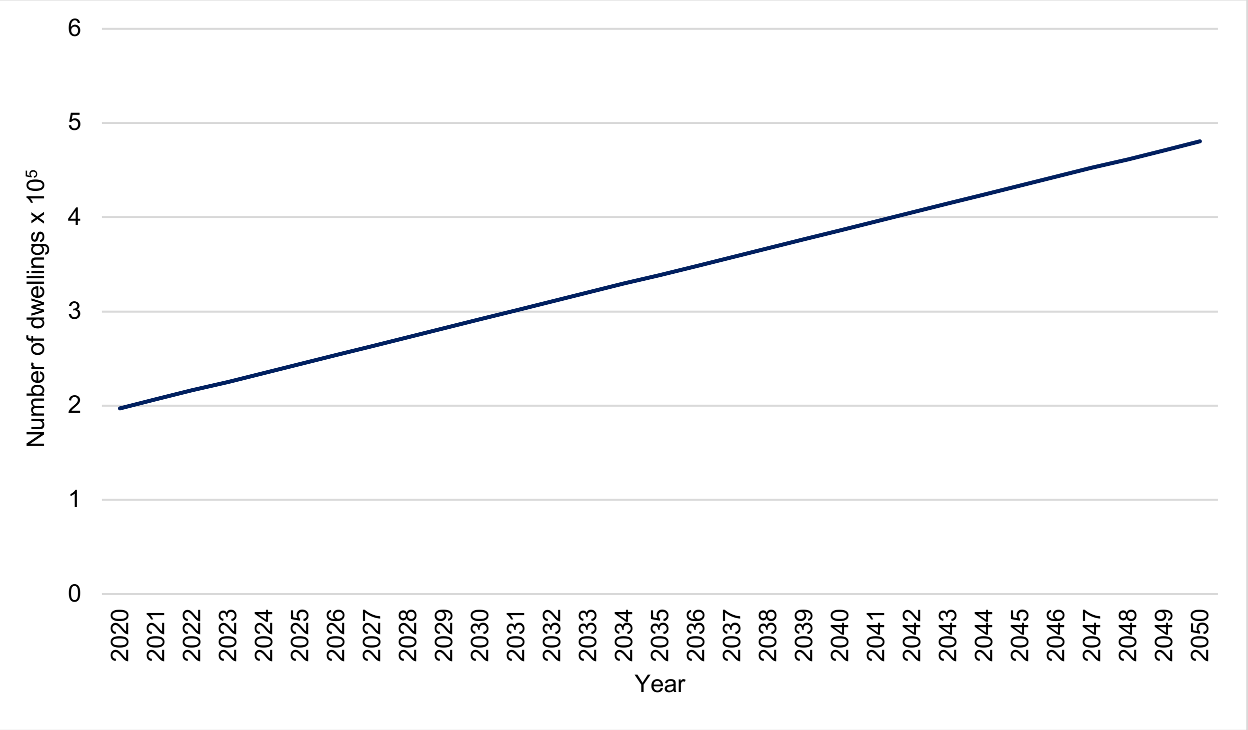


*Figure 17: Growth in number of dwellings (T2 or more)*

MS Excel was used to model the Fisher-Pry equation. The parameter $\delta$ was adjusted such that the penetration of GSHP in the first year is approximately 1/3rd of the new dwellings (T2 or higher) which is approximately 3,375 units. The logic being, if the government, through some mechanism (eg. incentives, tax breaks, subsidies) are successful in convincing at least 1/3rd new home buyers (adopters) to install GSHP systems in the first year and maintain the growth rate, then there will be an uptake of the GSHP technology, eventually, replacing all of the Combination A technology by the end of year 2050. It is expected that through sustained marketing campaigns, government incentives, and word of mouth, more people (imitators) would buy into the new technology. The parameter $\delta$, was found to be 0.405 corresponding to 3,375 newly installed GSHP units in the first year. Typically, the parameter $\delta$, is assumed based on sales data of similar product from the past. Due to unavailability of data, a reverse approach was utilized.

Above mentioned scenario is quite ideal. The number of installations will depend heavily on the infrastructure availability, namely, drill rigs, qualified labor, availability of equipment (interconnections, heat pump units, hoses, grout material) among other factors. No new GSHP system installation in residential sector was reported in Portugal in the last few years [57]. However, as per [84], 52 units of GSHPs were sold in Portugal in 2017. Thus, a significantly lower target should be set for the initial years assuming lack of sufficient infrastructure and/ or manpower to deliver 3,375 units in the first year. This means that by 2030, 50% replacements will be impossible. The Fisher-Pry model can be revised with some realistic assumptions. If 50% replacements are assumed in year 2040 with the same value for parameter $\delta$ i.e., 0.405, then the value obtained for the number of units replaced in 2020 stands at 59 units. This value can be considered as a fair representation of the current market. Figure 18 shows the number of units replaced every year for the ‘ideal’ situation where 50% replacements are taking place in 2030, and for ‘realistic’ situation where $t_0$ is in the year 2040 with $\delta = 0.405$, and t in the year 2050, being same for both the cases. Figure 19 shows the percentage penetration for both the cases. It can be seen that, in the ‘realistic’ scenario, above 90% penetration is possible in the year 2046. This corresponds to approximately 400,000 units being sold. There are total of 480,600 units to be installed by the end of 2050 corresponding to cumulative market value of approximately €10 billion in present Euro value, i.e., inflation is neglected.

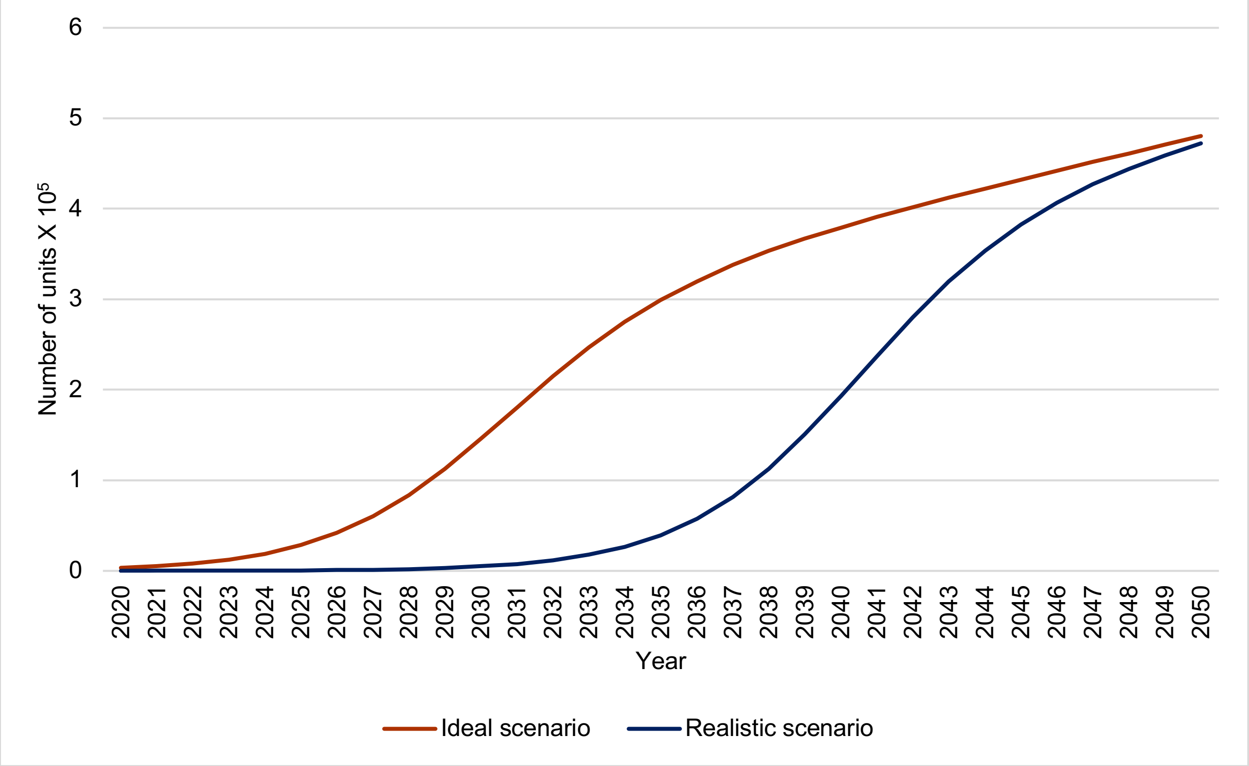


*Figure 18: Comparison of number of units replaced per year in ideal vs. realistic scenario*

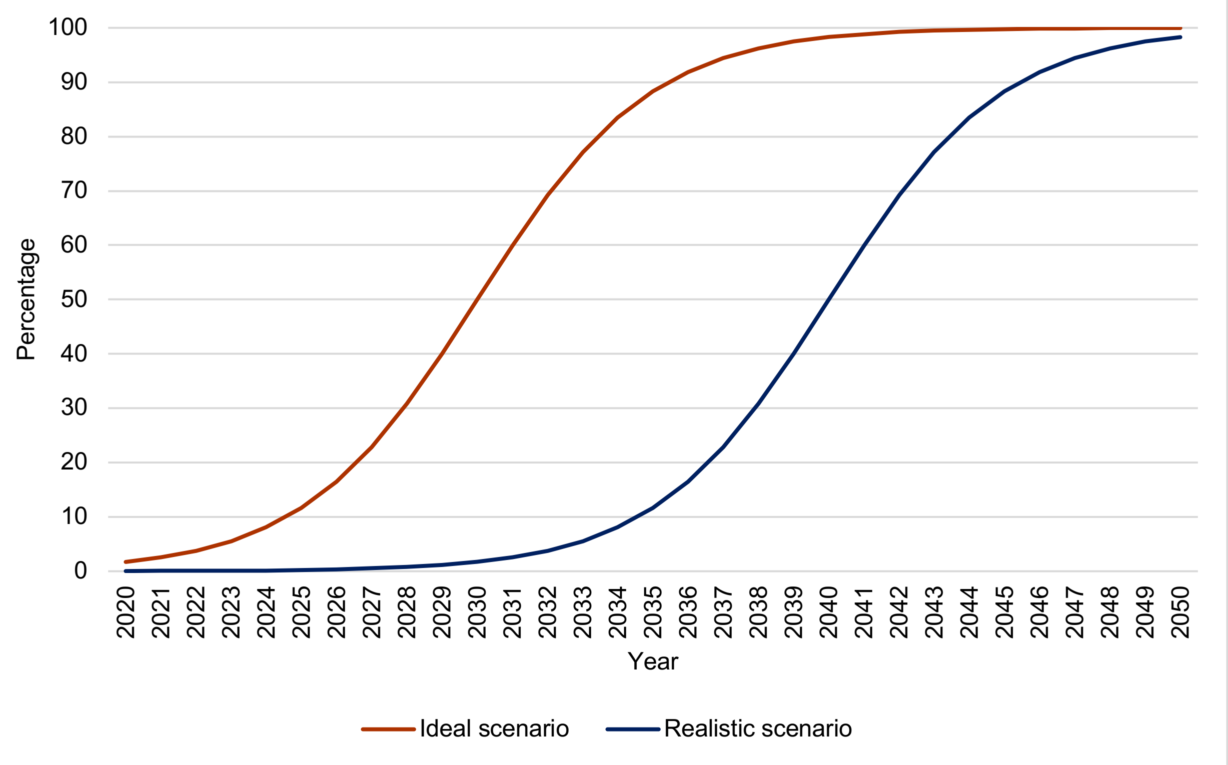


*Figure 19: Percentage penetration per year in ideal vs. realistic scenario*

### *5.6 Decrease in carbon emissions*

GSHP system installation will decrease carbon emissions as compared to Combination A technology. Table 37 below compares the $CO_2$ emissions from one dwelling in $ktCO_2$ and total $CO_2$ emissions at the end of 2050 from 480,600 dwellings, assuming all dwellings are fitted with Combination A or GSHP systems.

| | Assuming T2 and bigger size dwellings fitted with following technologies in year 2050 | |
|---|---|---|
| | Combination A | GSHP system |
| $CO_2$ emissions from one dwelling/ year ($tCO_2$) | 4.74 | 1.48 |
| $CO_2$ emissions from one dwelling for 30 years ($tCO_2$) | 142.17 | 44.28 |
| Projected number of dwellings at the end of year 2050 | 480,600 | |
| Total $CO_2$ emissions in the end of year 2050 ($ktCO_2$) | 2,278 | 711.3 |

*Table 37: Comparison of carbon emissions at the end of year 2050 assuming dwellings (T2 or bigger) are fitted with combination A or GSHP*

Figure 20 shows the comparison between $CO_2$ emissions between Combination A and GSHP system in the year 2050 and Figure 21 shows the graph of savings in $CO_2$ emissions per year, from 2020 to 2050, by using GSHP system over Combination A. Cumulatively, there is a potential savings of more than 1500 $ktCO_2$ by replacing the Combination A systems with GSHP systems.

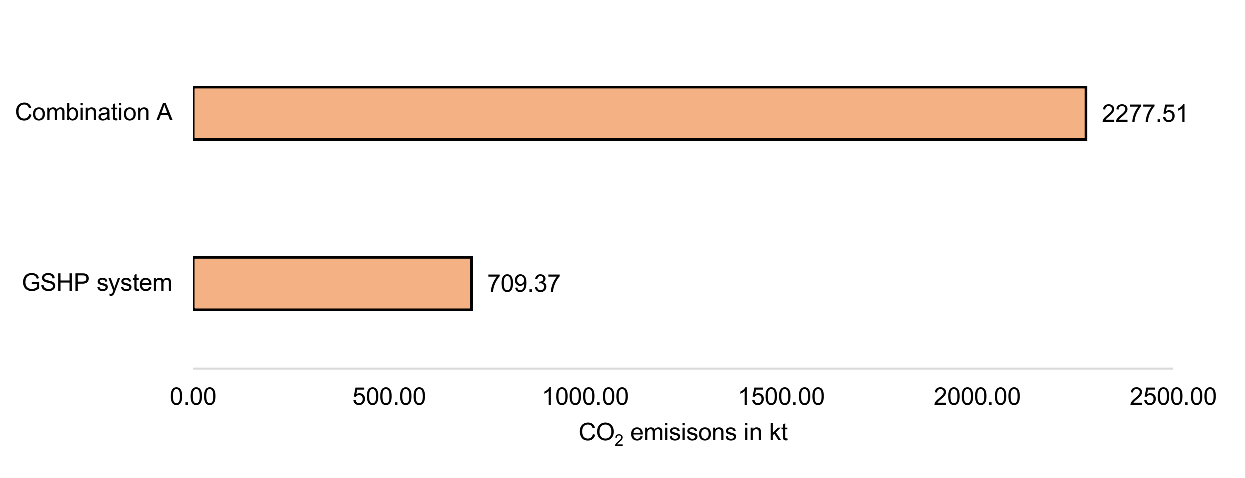


Figure 20: Comparison of $CO_2$ emissions between Combination A and GSHP in 2050

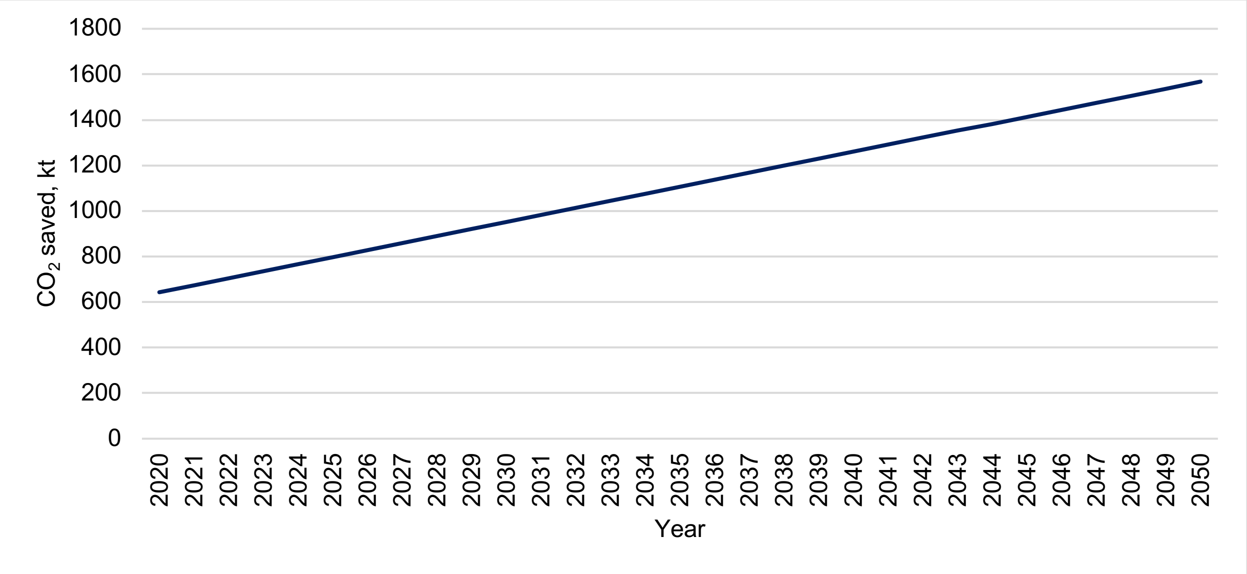


Figure 21: Savings in $CO_2$ by using GSHP systems over Combination A

### *5.7 Carbon mitigation potential as per EU Directive 2018/2001*

SGE is a renewable energy source. The potential SGE share for satisfying the H&C needs can be estimated by assuming that the market penetration is taking place as per the “realistic” scenario described in Section 5.5.

As per Article 23 of the EU Directive 2018/2001 [85] on the “*Promotion of the use of energy from renewable sources*”, which attempts to increase the share of renewable energy for H&C, *“…each Member State shall endeavour to increase the share of renewable energy in that sector by an indicative 1.3 percentage points as an annual average calculated for the periods 2021 to 2025 and 2026 to 2030 starting from the share of* *renewable energy in the heating and cooling sector in 2020, expressed in terms of national share of final energy consumption…*"

This can be interpreted as 1.3% increase in the share of renewable energy for H&C every year, to meet the average between 2021 – 2025 and 2026 – 2030 as compared to share in 2020. As per Annex VII [85], the amount of energy captured by GSHP can be calculated using following formula:

$$E_{res} = Q_{usable} * (1 - \frac{1}{SPF})$$

Where, $Q_{usable}$ is the estimated heat delivered by heat pumps; SPF = average seasonal performance factor or the average COP over summer or winter. The average SPF will be different for each GSHP installation. Thus, it is assumed to be 4.0 for simplicity. It is further specified that only heat pumps with SPF > (1.15 * 1/$\eta$) must be considered; where, $\eta$ is the average power plant efficiency in Portugal provided by Eurostat. To verify that the above condition is satisfied, a reverse approach can be used. For SPF = 4.0, the value of $\eta$ is 0.2875, which is below the 2011 $\eta$-value of 0.493 for Portugal [86]. This indicates that all of the GSHPs can be considered to calculate $E_{res}$. Energy consumption data obtained from [30] can be used obtain values in Table 38.

| | |
|---|---|
| Total energy consumed inside a dwelling | 0.742 toe or 8,629 kWh |
| Total percentage of energy consumption for space conditioning | 22.0 |
| Percentage of renewable energy used inside a dwelling | 25.1 |
| Total renewable energy consumed in a dwelling for space conditioning and DHW | 476.5 kWh |
| Total renewable energy consumed in 3,814,815 uniform dwellings for space conditioning and DHW | 1,817.7 GWh |
| 1.3% of total renewable energy consumed by all dwellings | 23,630 MWh |

*Table 38: Renewable and non-renewable energy share in space conditioning and DHW in accommodations*

Due to lack of recent data, it is assumed that the energy consumption values will be same in 2020 as they were in 2010. From Table 38, it can be estimated that the share of renewable energy for H&C needs, must increase by at least 23,630 MWh every year, until year 2030. From Table 3, it can be concluded that out of 4,329.1 kWh energy used in a dwelling for space conditioning and DHW, 54.1% or 2,341 kWh is utilized only for space conditioning. Thus, it can be assumed that out of the 10-kW installed power in T2 or bigger dwellings, 5.41 kW is utilized only for space conditioning needs.

Table 39 and Figure 22 shows the yearly goals achieved by GSHP systems (installed in T2 or bigger dwellings) against the target of 23,630 MWh/ yr renewable energy, based on the formula given in Annex VII of EU Directive 2018/2001, and 1,600 hours operation.

| End of year | Number of units replaced | Installed capacity (MW) | Utilization for space conditioning (MW) | $Q_{usable}$ (MWh) | $E_{res}$ (MWh) | Percentage of target amount of energy captured by GSHP (%) |
|---|---|---|---|---|---|---|
| 2021 | 93 | 0.93 | 0.50 | 805 | 604 | 2.6 |
| 2022 | 147 | 1.47 | 0.80 | 1272 | 954 | 4.0 |
| 2023 | 230 | 2.30 | 1.24 | 1991 | 1,493 | 6.3 |
| 2024 | 359 | 3.59 | 1.94 | 3108 | 2,331 | 9.9 |
| 2025 | 560 | 5.60 | 3.03 | 4847 | 3,636 | 15.4 |
| 2026 | 872 | 8.72 | 4.72 | 7548 | 5,661 | 24.0 |
| 2027 | 1,353 | 13.53 | 7.32 | 11712 | 8,784 | 37.2 |
| 2028 | 2,097 | 20.97 | 11.34 | 18152 | 13,614 | 57.6 |
| 2029 | 3,241 | 32.41 | 17.53 | 28054 | 21,041 | 89.0 |
| 2030 | 4,993 | 49.93 | 27.01 | 43219 | 32,415 | 137.2 |

*Table 39: Goals achieved by GSHPs installed in T2 or bigger dwellings*

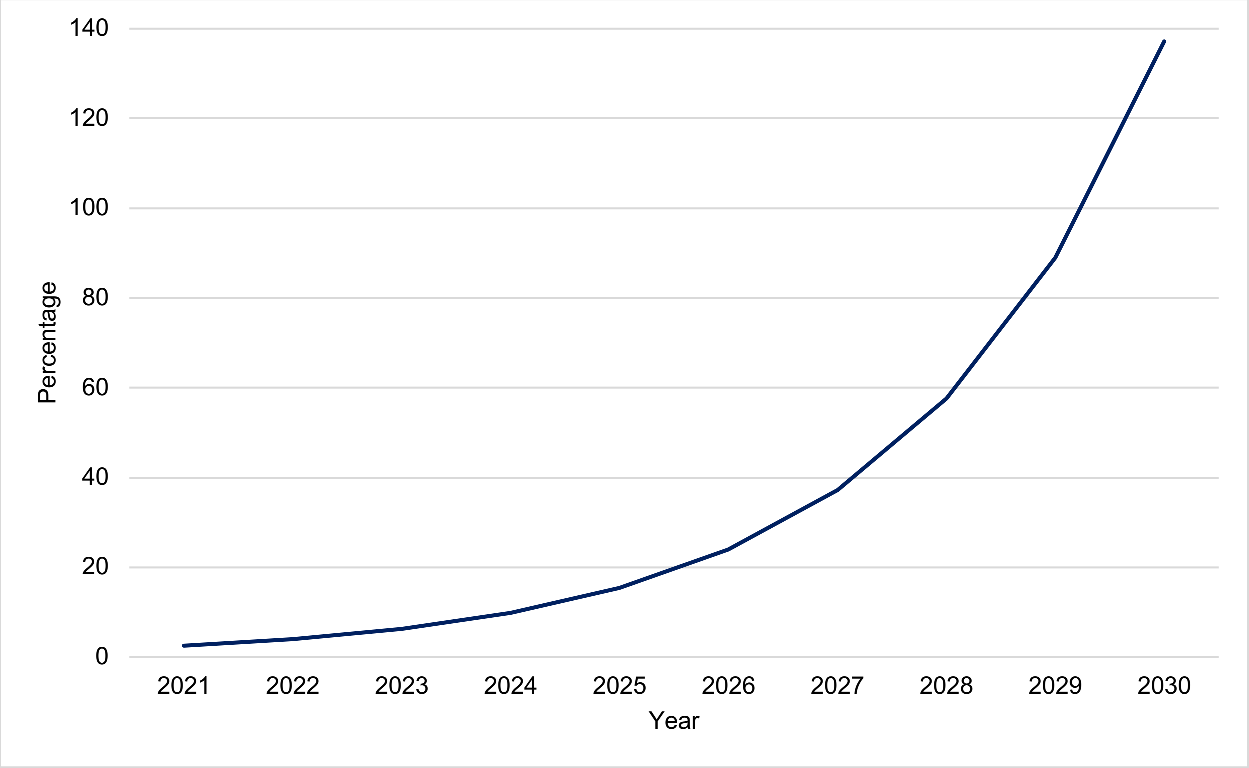


*Figure 22: Percentage of target amount of renewable energy captured by GSHP systems installed in T2 or bigger dwellings*

### *5.8 Survey*

A survey was designed and distributed to gain more insights on the status and perceptions towards GSHP systems and H&C preferences in the industrial and residential sector of the European Union, especially in Portugal. This survey was developed as part of the thesis. However, due to very low number of respondents, the results from this survey were inconclusive. The questions have been included in the Appendix for reference.

### *5.9 Conclusions*

The current market potential for GSHP systems in the residential sector can be estimated at approximately €5 billion corresponding to 1.87 GW of installed capacity. GSHP systems are more expensive than combination of gas technology and ceiling fans for H&C and DHW applications but they are cheaper than Combination A technology. Bigger dwellings can be considered as indicator of wealth. To promote the installation of GSHP systems, initial target should be family houses of size T2 or bigger. The predicted growth in this sector is 12,600 units/ year. The cumulative number of GSHP units available for new installation or displacement of Combination A technology until year 2050 is marginally less than half a million which corresponds to cumulative market size of approximately €10 billion.

If appropriate strategies are devised to promote installation of GSHP systems for the new homeowners, then owing to adopter-imitator phenomenon as per the Fisher-Pry model, by year 2040, it is possible to displace half of the total Combination A technology by GSHP systems. Some of these strategies may include targeted marketing campaigns, tax incentives, and subsidies.

Displacement of Combination A technology by GSHP technology reduces the carbon emissions by 3.26 $tCO_2$ per year from one dwelling (T2 or bigger) with the cumulative reduction of 34.3 $MtCO_2$ until year 2050, from 480,600 dwellings, assuming same energy mix and no improvement in the energy efficiency in either of the technologies. Thus, it can be considered a conservative estimate.

As per the EU Directive 2018/2001, it can be concluded that the share of renewable energy for H&C needs, must increase by at least 23,630 MWh every year, until 2030. Installation of GSHP systems in T2 or bigger dwellings as per the “realistic” scenario described in Section 5.5, can help to achieve 100% of this target by the end of year 2030. Although it must be noted that due to lack of data, certain assumptions were necessary to arrive at this conclusion. The actual numbers may vary greatly as and when new data becomes available. However, it can be said that GSHP (SGE) has potential to play a significant role in achieving the targets for renewable energy share in H&C, if potential for GSHP system installations are taken into consideration across different sectors like hotels, office, malls, and public buildings.

### *5.10 Final comments and future work*

It can be affirmed that SGE can be utilized in Portugal through GSHP applications. Instead of computing the total available potential, the easier approach will be to estimate the installation capacity since GSHP application is site-specific and demand specific. For these systems, the estimated economic potential in the residential, office and hotel sector, is approximately €16 billion corresponding to over 6 GW of installed capacity. It can be deployed at the rate of 39.7 MW/year corresponding to €100.8 million/year over the period of next five years starting from the beginning of 2020 assuming spatial constraint factor of 0.25.

Over 30 years of project life, GSHP systems were found to be more expensive but less carbon intensive than following technologies or combination of technologies for H&C and DHW: Gas technology and ceiling fans, electric heater with ceiling fans, firewood with ceiling fans, air-to-water air-source heat pumps with electric water heater. Combination A technology should be targeted first for replacement with GSHP systems since it is more expensive and carbon intensive than GSHP system. The estimated market size for the GSHP systems in the residential sector is approximately €5.2 billion corresponding to at least 187,000 units after applying spatial constraint factor of 0.75. As per Fisher-Pry model, under “realistic” scenario, it is possible to replace half of the Combination A technologies with GSHP systems by 2040 if the Government and private sector encourage approximately 93 homeowners to install GSHP system in the first year (2020). And subsequently maintain the growth rate as per the predictions by Fisher-Pry model. Results from the Fisher-Pry diffusion model can be improved if market data becomes available. These results can help the Government, legislators and investors to devise appropriate strategies that may help penetration of GSHP system.

Throughout the study there was lack of sufficient data to perform an accurate analysis. The technical, economical, and market analysis of SGE could have yielded better results if there was availability of data regarding office spaces in Portugal, number of office buildings, energy consumed inside office buildings including hot water requirements, energy usage inside hotels, to name few. Realistic results could be achieved by using energy usage data, and, GIS analysis to understand the geology and hence the rock/ soil properties. Studies should be conducted in Portugal to examine the long-term effects as well as the environmental and sustainability aspects of installing GSHP systems.

It is understood that some of this data might be difficult to gather like energy requirements of specific zones inside a building, e.g. kitchen inside a hotel. But efforts should be made to conduct surveys and perform assessments to obtain approximate values. Also, some of the data might be difficult to predict like fuel prices after ten years. This may considerably affect the conclusions from the current assessment. Portuguese SGE industry should make increased efforts to gather data from current and future installed GSHP systems. This will enable deeper and more insightful analysis of the size, feasibility, economics, performance and success or failure of these projects. Moreover, having specific data might help in identifying areas where energy use can be optimized, saved or efficient equipment can be used.

The present work can be improved upon to make realistic predictions regarding market size for GSHP systems. Future work may include examining the possibility of using GSHP systems for industrial applications and SGE applications in aquaculture, spa, balneology. To incorporate spatial constraint into the discussion, a parameter called ‘spatial constraint factor’ was defined and was given an arbitrary value. This parameter can be approximated as more data becomes available. It can be computed by dividing the number of sites suitable for GSHP system installation by the number of total sites surveyed for GSHP system installation.

During comparison of carbon emissions from different H&C and DHW technologies, life cycle assessment for each technology for $CO_2$ as well as NOx/ SOx/ greenhouse gases, is more pertinent in the discussion of carbon emissions. However, it will be nearly an impossible task since each product uses different materials, productions processes and supply chain.

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**Appendix**

| Type of Equipment | No. of dwellings | No. of equipment | No. of equipment/ dwellings | Percentage share [%] |
|---|---|---|---|---|
| Fireplace | 740,264 | 766,581 | 1 | 14.99 |
| Fireplace with stove | 340,498 | 346,204 | 1 | 6.77 |
| Firewood | 222,856 | 226,138 | 1 | 4.42 |
| Firewood with electric motor | | | | |
| Central heating boiler with circulating water | 323,520 | 340,904 | 1.1 | 6.67 |
| Independent electric heater | 1,884,850 | 2,794,054 | 1.5 | 54.63 |
| Independent LPG heater | 218,293 | 237,589 | 0.1 | 4.65 |
| Solar thermal collector | | | | |
| Air Conditioning Heating and Cooling (Heat Pump) | 223,429 | 402,664 | 1.8 | 7.87 |
| *Total* | *3,953,710* | *5,114,134* | | |

Table A1: Characterization of the equipment used for Environmental heating by type of equipment - Portugal, 2010 [29]

| Type of equipment | No. of dwellings | No. of equipment | No of equipment/ dwellings | Percentage share [%] |
|---|---|---|---|---|
| Individual air-conditioning unit | 64,099 | 76,435 | 1.2 | 6.20 |
| Fan | 615,128 | 756,108 | 1.2 | 61.37 |
| Air Conditioning Heating and Cooling (Heat Pump) | 230,063 | 399,432 | 1.7 | 32.42 |
| *Total* | *909,290* | *1,231,975* | | |

Table A2: Characterization of the equipment used for cooling of the environment by type of equipment - Portugal, 2010 [29]

| Type of equipment | No. of dwellings | No. of equipment | No. of equipment/ dwellings | Percentage share [%] |
|---|---|---|---|---|
| Gas Heater | 2,995,810 | 3,051,993 | 1 | 75.93 |
| Water heater | 426,751 | 439,724 | 1 | 10.94 |
| Boiler | 455,406 | 458,817 | 1 | 11.42 |
| Solar thermal system | 68,824 | 68,824 | 1 | 1.71 |
| *Total* | *3,946,791* | *4,019,358* |  |  |

Table A3: Characterization of the equipment used for Water heating by type of equipment - Portugal, 2010 [29]

**Calculations**

A. Calculations for NPV and carbon emissions for installing GSHP in one dwelling assuming project life = 30 years project

| | NPV (€) | $CO_2$ emissions ($tCO_2$) |
|---|---|---|
| Capital cost | 16,176.5 | **26.57** |
| Maintenance cost | 1,470.6 | |
| Electricity consumption | 16,185.9 | |
| **Total NPV** | 33,832.9 | |

| Year | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 16,500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maintenance cost | 50.0 | 51.0 | 52.0 | 53.1 | 54.1 | 55.2 | 56.3 | 57.4 | 58.6 | 59.8 |
| Electricity consumption | 550.3 | 561.3 | 572.6 | 584.0 | 595.7 | 607.6 | 619.7 | 632.1 | 644.8 | 657.7 |

| Year | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maintenance cost | 60.9 | 62.2 | 63.4 | 64.7 | 66.0 | 67.3 | 68.6 | 70.0 | 71.4 | 72.8 |
| Electricity consumption | 670.8 | 684.3 | 697.9 | 711.9 | 726.1 | 740.7 | 755.5 | 770.6 | 786.0 | 801.7 |

| Year | Year 21 | Year 22 | Year 23 | Year 24 | Year 25 | Year 26 | Year 27 | Year 28 | Year 29 | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maintenance cost | 74.3 | 75.8 | 77.3 | 78.8 | 80.4 | 82.0 | 83.7 | 85.3 | 87.1 | 88.8 |
| Electricity consumption | 817.7 | 834.1 | 850.8 | 867.8 | 885.2 | 902.9 | 920.9 | 939.3 | 958.1 | 977.3 |

B. Calculations for NPV and carbon emissions for installing HVAC system for heating and cooling and electric water heaters for DHW requirements in one dwelling assuming project life = 30 years project

| | NPV (€) | $CO_2$ emissions ($tCO_2/MWh$) |
|---|---|---|
| Capital cost | 6,470.6 | **111.17** |
| Maintenance cost | 5,882.4 | |
| Electricity consumption | 67,727.8 | |
| **Total NPV** | **80,080.7** | |

| Year | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 2900.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 200.0 | 204.0 | 208.1 | 212.2 | 216.5 | 220.8 | 225.2 | 229.7 | 234.3 | 239.0 |
| Electricity consumption | 2302.7 | 2348.8 | 2395.8 | 2443.7 | 2492.6 | 2542.4 | 2593.3 | 2645.1 | 2698.0 | 2752.0 |

| Year | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 0.0 | 0.0 | 1014.6 | 0.0 | 0.0 | 2826.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 243.8 | 248.7 | 253.6 | 258.7 | 263.9 | 269.2 | 274.6 | 280.0 | 285.6 | 291.4 |
| Electricity consumption | 2807.0 | 2863.2 | 2920.4 | 2978.8 | 3038.4 | 3099.2 | 3161.2 | 3224.4 | 3288.9 | 3354.7 |

| Year | Year 21 | Year 22 | Year 23 | Year 24 | Year 25 | Year 26 | Year 27 | Year 28 | Year 29 | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 0.0 | 0.0 | 0.0 | 0.0 | 1286.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 297.2 | 303.1 | 309.2 | 315.4 | 321.7 | 328.1 | 334.7 | 341.4 | 348.2 | 355.2 |
| Electricity consumption | 3421.8 | 3490.2 | 3560.0 | 3631.2 | 3703.8 | 3777.9 | 3853.5 | 3930.5 | 4009.1 | 4089.3 |

### C. Calculations for NPV and carbon emissions for installing gas systems for heating and cooling and gas water heaters for DHW requirements in one dwelling assuming project life = 30 years

| *Gas* | NPV (€) | $CO_2$ emissions ($tCO_2/MWh$) |
|---|---|---|
| Capital cost | 7,647.1 | **27.27** |
| Maintenance cost | 7,352.9 | |
| Fuel cost | 10,053.5 | |
| **Total NPV** | **25,053.5** | |

| Year | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 3600.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 250.0 | 255.0 | 260.1 | 265.3 | 270.6 | 276.0 | 281.5 | 287.2 | 292.9 | 298.8 |
| Electricity consumption | 341.8 | 348.7 | 355.6 | 362.7 | 370.0 | 377.4 | 384.9 | 392.6 | 400.5 | 408.5 |

| Year | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 731.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4284.7 | 0.0 |
| Maintenance cost | 304.7 | 310.8 | 317.1 | 323.4 | 329.9 | 336.5 | 343.2 | 350.1 | 357.1 | 364.2 |
| Electricity consumption | 416.7 | 425.0 | 433.5 | 442.2 | 451.0 | 460.0 | 469.2 | 478.6 | 488.2 | 498.0 |

| Year | Year 21 | Year 22 | Year 23 | Year 24 | Year 25 | Year 26 | Year 27 | Year 28 | Year 29 | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 891.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 371.5 | 378.9 | 386.5 | 394.2 | 402.1 | 410.2 | 418.4 | 426.7 | 435.3 | 444.0 |
| Electricity consumption | 507.9 | 518.1 | 528.4 | 539.0 | 549.8 | 560.8 | 572.0 | 583.4 | 595.1 | 607.0 |

### D. Calculations for NPV and carbon emissions for installing firewood systems for heating and for DHW requirements in one dwelling assuming project life = 30 years

| | NPV (€) | $CO_2$ emissions ($tCO_2/MWh$) |
|---|---|---|
| Capital cost | 16,960.8 | **27.83** |
| Maintenance cost | 7,352.9 | |
| Fuel consumption | 10,294.1 | |
| **Total NPV** | **34,607.8** | |

| Year | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 8000.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 250.0 | 255.0 | 260.1 | 265.3 | 270.6 | 276.0 | 281.5 | 287.2 | 292.9 | 298.8 |
| Electricity consumption | 350.0 | 357.0 | 364.1 | 371.4 | 378.9 | 386.4 | 394.2 | 402.0 | 410.1 | 418.3 |

| Year | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10766.9 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 304.7 | 310.8 | 317.1 | 323.4 | 329.9 | 336.5 | 343.2 | 350.1 | 357.1 | 364.2 |
| Electricity consumption | 426.6 | 435.2 | 443.9 | 452.8 | 461.8 | 471.1 | 480.5 | 490.1 | 499.9 | 509.9 |

| Year | Year 21 | Year 22 | Year 23 | Year 24 | Year 25 | Year 26 | Year 27 | Year 28 | Year 29 | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 1931.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 371.5 | 378.9 | 386.5 | 394.2 | 402.1 | 410.2 | 418.4 | 426.7 | 435.3 | 444.0 |
| Electricity consumption | 520.1 | 530.5 | 541.1 | 551.9 | 563.0 | 574.2 | 585.7 | 597.4 | 609.4 | 621.5 |

### E. Calculations for NPV and carbon emissions for installing electric heaters for heating and for DHW requirements in one dwelling assuming project life = 30 years

| | NPV (€) | CO$_2$ emissions (tCO$_2$/MWh) |
|---|---|---|
| Capital cost | 2,941.2 | **35.89** |
| Maintenance cost | 2,941.2 | |
| Fuel consumption | 21,867.8 | |
| **Total NPV** | **27,750.2** | |

| Year | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 1000.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 100.0 | 102.0 | 104.0 | 106.1 | 108.2 | 110.4 | 112.6 | 114.9 | 117.2 | 119.5 |
| Electricity consumption | 743.5 | 758.4 | 773.5 | 789.0 | 804.8 | 820.9 | 837.3 | 854.1 | 871.1 | 888.6 |

| Year | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 243.8 | 0.0 | 1014.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 121.9 | 124.3 | 126.8 | 129.4 | 131.9 | 134.6 | 137.3 | 140.0 | 142.8 | 145.7 |
| Electricity consumption | 906.3 | 924.5 | 942.9 | 961.8 | 981.0 | 1000.7 | 1020.7 | 1041.1 | 1061.9 | 1083.1 |

| Year | Year 21 | Year 22 | Year 23 | Year 24 | Year 25 | Year 26 | Year 27 | Year 28 | Year 29 | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 297.2 | 0.0 | 0.0 | 0.0 | 0.0 | 1312.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 148.6 | 151.6 | 154.6 | 157.7 | 160.8 | 164.1 | 167.3 | 170.7 | 174.1 | 177.6 |
| Electricity consumption | 1104.8 | 1126.9 | 1149.4 | 1172.4 | 1195.9 | 1219.8 | 1244.2 | 1269.1 | 1294.5 | 1320.3 |

F. Calculations for NPV and carbon emissions for installing three (3) ceiling fans for cooling requirements in one dwelling assuming project life = 30 years

| | NPV (€) | $CO_2$ emissions ($tCO_2/MWh$) |
|---|---|---|
| Capital cost | 1,314.9 | **0.44** |
| Maintenance cost | 0.0 | |
| Electricity consumption | 269.8 | |
| **Total NPV** | **1,584.6** | |

| Year | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 450.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity consumption | 9.2 | 9.4 | 9.5 | 9.7 | 9.9 | 10.1 | 10.3 | 10.5 | 10.7 | 11.0 |

| Year | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 537.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity consumption | 11.2 | 11.4 | 11.6 | 11.9 | 12.1 | 12.3 | 12.6 | 12.8 | 13.1 | 13.4 |

| Year | Year 21 | Year 22 | Year 23 | Year 24 | Year 25 | Year 26 | Year 27 | Year 28 | Year 29 | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 668.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity consumption | 13.6 | 13.9 | 14.2 | 14.5 | 14.8 | 15.0 | 15.3 | 15.7 | 16.0 | 16.3 |

G. Calculations for NPV and carbon emissions for installing air-source heat pumps (air to water) for cooling requirements in one dwelling assuming project life = 30 years

| | NPV (€) | $CO_2$ emissions ($tCO_2/MWh$) |
|---|---|---|
| Capital cost | 18,137.3 | **41.96** |
| Maintenance cost | 2,941.2 | |
| Electricity consumption | 25,560.2 | |
| **Total NPV** | **46,638.6** | |

| Year | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 11500 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 100.0 | 102.0 | 104.0 | 106.1 | 108.2 | 110.4 | 112.6 | 114.9 | 117.2 | 119.5 |
| Electricity consumption | 869.0 | 886.4 | 904.2 | 922.2 | 940.7 | 959.5 | 978.7 | 998.3 | 1018.2 | 1038.6 |

| Year | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 121.9 | 124.3 | 126.8 | 129.4 | 131.9 | 134.6 | 137.3 | 140.0 | 142.8 | 145.7 |
| Electricity consumption | 1059.4 | 1080.6 | 1102.2 | 1124.2 | 1146.7 | 1169.6 | 1193.0 | 1216.9 | 1241.2 | 1266.0 |

| Year | Year 21 | Year 22 | Year 23 | Year 24 | Year 25 | Year 26 | Year 27 | Year 28 | Year 29 | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital cost | 10401 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maintenance cost | 148.6 | 151.6 | 154.6 | 157.7 | 160.8 | 164.1 | 167.3 | 170.7 | 174.1 | 177.6 |
| Electricity consumption | 1291.4 | 1317.2 | 1343.5 | 1370.4 | 1397.8 | 1425.8 | 1454.3 | 1483.4 | 1513.0 | 1543.3 |

| Licensed dwellings in new constructions for family housing | |
|---|---|
| T4 | 2,336 |
| T3 | 7,310 |
| T2 | 2,967 |
| *Total* | *12,613* |
| | *12,600 (rounded value)* |

Table A4: Licensed dwellings in new constructions for family housing

| *Annual projected growth 12,600 unit* | | *$CO_2$ emissions (ktCO$_2$/MWh)* | | *Annual projected growth 12,600 units* | | *$CO_2$ emissions (ktCO$_2$/MWh)* | |
|---|---|---|---|---|---|---|---|
| *Year* | *Number of units* | *Combination A* | *GSHP* | *Year* | *Number of units* | *Combination A* | *GSHP* |
| 2018 | 237,600 | 1140.7 | 263.0 | 2035 | 451,800 | 2169.1 | 500.1 |
| 2019 | 250,200 | 1201.2 | 277.0 | 2036 | 464,400 | 2229.5 | 514.1 |
| 2020 | 262,800 | 1261.7 | 290.9 | 2037 | 477,000 | 2290.0 | 528.0 |
| 2021 | 275,400 | 1322.2 | 304.9 | 2038 | 489,600 | 2350.5 | 542.0 |
| 2022 | 288,000 | 1382.7 | 318.8 | 2039 | 502,200 | 2411.0 | 555.9 |
| 2023 | 300,600 | 1443.2 | 332.8 | 2040 | 514,800 | 2471.5 | 569.9 |
| 2024 | 313,200 | 1503.6 | 346.7 | 2041 | 527,400 | 2532.0 | 583.8 |
| 2025 | 325,800 | 1564.1 | 360.7 | 2042 | 540,000 | 2592.5 | 597.8 |
| 2026 | 338,400 | 1624.6 | 374.6 | 2043 | 552,600 | 2653.0 | 611.7 |
| 2027 | 351,000 | 1685.1 | 388.6 | 2044 | 565,200 | 2713.5 | 625.7 |
| 2028 | 363,600 | 1745.6 | 402.5 | 2045 | 577,800 | 2774.0 | 639.6 |
| 2029 | 376,200 | 1806.1 | 416.5 | 2046 | 590,400 | 2834.5 | 653.6 |
| 2030 | 388,800 | 1866.6 | 430.4 | 2047 | 603,000 | 2895.0 | 667.5 |
| 2031 | 401,400 | 1927.1 | 444.3 | 2048 | 615,600 | 2955.4 | 681.5 |
| 2032 | 414,000 | 1987.6 | 458.3 | 2049 | 628,200 | 3015.9 | 695.4 |
| 2033 | 426,600 | 2048.1 | 472.2 | 2050 | 640,800 | 3076.4 | 709.4 |
| 2034 | | 439,200 | | 2108.6 | | 486.2 | |

Table A5: Annual projected growth and $CO_2$ emissions in dwellings (T2 or more) for Combination A and GSHP systems

| *Year* | *Projected number of dwellings (T2 and more)** | *δ* | *t* | *t0* | *Exp [-δ * (t-t0)]* | *f(t)* | *Percentage penetration* | *Number of units replaced* | *Cumulative market size in mil. € (inflation neglected)* |
|---|---|---|---|---|---|---|---|---|---|
| 2020 | 197,100 | 0.405 | 1 | 11 | 57.40 | 0.02 | 1.71 | **3,375** | 101 |
| 2021 | 206,550 | 0.405 | 2 | 11 | 38.28 | 0.03 | 2.55 | 5,258 | 158 |
| 2022 | 216,000 | 0.405 | 3 | 11 | 25.53 | 0.04 | 3.77 | 8,140 | 244 |
| 2023 | 225,450 | 0.405 | 4 | 11 | 17.03 | 0.06 | 5.55 | 12,503 | 375 |
| 2024 | 234,900 | 0.405 | 5 | 11 | 11.36 | 0.08 | 8.09 | 19,006 | 570 |
| 2025 | 244,350 | 0.405 | 6 | 11 | 7.58 | 0.12 | 11.66 | 28,491 | 855 |
| 2026 | 253,800 | 0.405 | 7 | 11 | 5.05 | 0.17 | 16.52 | 41,928 | 1,258 |
| 2027 | 263,250 | 0.405 | 8 | 11 | 3.37 | 0.23 | 22.88 | 60,236 | 1,807 |
| 2028 | 272,700 | 0.405 | 9 | 11 | 2.25 | 0.31 | 30.79 | 83,961 | 2,519 |
| 2029 | 282,150 | 0.405 | 10 | 11 | 1.50 | 0.40 | 40.01 | 112,891 | 3,387 |
| **2030** | **291,600** | **0.405** | **11** | **11** | **1.00** | **0.50** | **50.00** | **145,800** | **4,374** |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2031 | 301,050 | 0.405 | 12 | 11 | 0.67 | 0.60 | 59.99 | 180,596 | 5,418 |
| 2032 | 310,500 | 0.405 | 13 | 11 | 0.44 | 0.69 | 69.21 | 214,900 | 6,447 |
| 2033 | 319,950 | 0.405 | 14 | 11 | 0.30 | 0.77 | 77.12 | 246,739 | 7,402 |
| 2034 | 329,400 | 0.405 | 15 | 11 | 0.20 | 0.83 | 83.48 | 274,981 | 8,249 |
| 2035 | 338,850 | 0.405 | 16 | 11 | 0.13 | 0.88 | 88.34 | 299,339 | 8,980 |
| 2036 | 348,300 | 0.405 | 17 | 11 | 0.09 | 0.92 | 91.91 | 320,117 | 9,604 |
| 2037 | 357,750 | 0.405 | 18 | 11 | 0.06 | 0.94 | 94.45 | 337,908 | 10,137 |
| 2038 | 367,200 | 0.405 | 19 | 11 | 0.04 | 0.96 | 96.23 | 353,361 | 10,601 |
| 2039 | 376,650 | 0.405 | 20 | 11 | 0.03 | 0.97 | 97.45 | 367,061 | 11,012 |
| 2040 | 386,100 | 0.405 | 21 | 11 | 0.02 | 0.98 | 98.29 | 379,488 | 11,385 |
| 2041 | 395,550 | 0.405 | 22 | 11 | 0.01 | 0.99 | 98.85 | 391,006 | 11,730 |
| 2042 | 405,000 | 0.405 | 23 | 11 | 0.01 | 0.99 | 99.23 | 401,885 | 12,057 |
| 2043 | 414,450 | 0.405 | 24 | 11 | 0.01 | 0.99 | 99.49 | 412,318 | 12,370 |
| 2044 | 423,900 | 0.405 | 25 | 11 | 0.00 | 1.00 | 99.66 | 422,443 | 12,673 |
| 2045 | 433,350 | 0.405 | 26 | 11 | 0.00 | 1.00 | 99.77 | 432,355 | 12,971 |
| 2046 | 442,800 | 0.405 | 27 | 11 | 0.00 | 1.00 | 99.85 | 442,121 | 13,264 |
| 2047 | 452,250 | 0.405 | 28 | 11 | 0.00 | 1.00 | 99.90 | 451,787 | 13,554 |
| 2048 | 461,700 | 0.405 | 29 | 11 | 0.00 | 1.00 | 99.93 | 461,385 | 13,842 |
| 2049 | 471,150 | 0.405 | 30 | 11 | 0.00 | 1.00 | 99.95 | 470,935 | 14,128 |
| 2050 | 480,600 | 0.405 | 31 | 11 | 0.00 | 1.00 | 99.97 | 480,454 | 14,414 |

Table A6: Ideal scenario for Fisher Pry analysis with *δ = 0.405*. *Spatial constraint factor = 0.75

| *Year* | *Projected number of dwellings (T2 and more)** | *δ* | *t* | *t0* | *Exp [-δ * (t-t0)]* | *f(t)* | *Percentage penetration* | *Number of units replaced* | *Cumulative market size in mil. € (inflation neglected)* |
|---|---|---|---|---|---|---|---|---|---|
| 2020 | 197,100 | 0.405 | 1 | 21 | 3294.47 | 0.00 | 0.03 | 59 | 2 |
| 2021 | 206,550 | 0.405 | 2 | 21 | 2197.33 | 0.00 | 0.05 | 93 | 3 |
| 2022 | 216,000 | 0.405 | 3 | 21 | 1465.57 | 0.00 | 0.07 | 147 | 4 |
| 2023 | 225,450 | 0.405 | 4 | 21 | 977.50 | 0.00 | 0.10 | 230 | 7 |
| 2024 | 234,900 | 0.405 | 5 | 21 | 651.97 | 0.00 | 0.15 | 359 | 11 |
| 2025 | 244,350 | 0.405 | 6 | 21 | 434.85 | 0.00 | 0.23 | 560 | 17 |
| 2026 | 253,800 | 0.405 | 7 | 21 | 290.03 | 0.00 | 0.34 | 872 | 26 |
| 2027 | 263,250 | 0.405 | 8 | 21 | 193.45 | 0.01 | 0.51 | 1,353 | 41 |
| 2028 | 272,700 | 0.405 | 9 | 21 | 129.02 | 0.01 | 0.77 | 2,097 | 63 |
| 2029 | 282,150 | 0.405 | 10 | 21 | 86.06 | 0.01 | 1.15 | 3,241 | 97 |
| 2030 | 291,600 | 0.405 | 11 | 21 | 57.40 | 0.02 | 1.71 | 4,993 | 150 |
| 2031 | 301,050 | 0.405 | 12 | 21 | 38.28 | 0.03 | 2.55 | 7,663 | 230 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2032 | 310,500 | 0.405 | 13 | 21 | 25.53 | 0.04 | 3.77 | 11,702 | 351 |
| 2033 | 319,950 | 0.405 | 14 | 21 | 17.03 | 0.06 | 5.55 | 17,745 | 532 |
| 2034 | 329,400 | 0.405 | 15 | 21 | 11.36 | 0.08 | 8.09 | 26,652 | 800 |
| 2035 | 338,850 | 0.405 | 16 | 21 | 7.58 | 0.12 | 11.66 | 39,510 | 1,185 |
| 2036 | 348,300 | 0.405 | 17 | 21 | 5.05 | 0.17 | 16.52 | 57,540 | 1,726 |
| 2037 | 357,750 | 0.405 | 18 | 21 | 3.37 | 0.23 | 22.88 | 81,859 | 2,456 |
| 2038 | 367,200 | 0.405 | 19 | 21 | 2.25 | 0.31 | 30.79 | 113,057 | 3,392 |
| 2039 | 376,650 | 0.405 | 20 | 21 | 1.50 | 0.40 | 40.01 | 150,702 | 4,521 |
| 2040 | 386,100 | 0.405 | 21 | 21 | 1.00 | 0.50 | 50.00 | 193,050 | 5,792 |
| 2041 | 395,550 | 0.405 | 22 | 21 | 0.67 | 0.60 | 59.99 | 237,285 | 7,119 |
| 2042 | 405,000 | 0.405 | 23 | 21 | 0.44 | 0.69 | 69.21 | 280,304 | 8,409 |
| 2043 | 414,450 | 0.405 | 24 | 21 | 0.30 | 0.77 | 77.12 | 319,616 | 9,588 |
| 2044 | 423,900 | 0.405 | 25 | 21 | 0.20 | 0.83 | 83.48 | 353,869 | 10,616 |
| 2045 | 433,350 | 0.405 | 26 | 21 | 0.13 | 0.88 | 88.34 | 382,820 | 11,485 |
| 2046 | 442,800 | 0.405 | 27 | 21 | 0.09 | 0.92 | 91.91 | 406,971 | 12,209 |
| 2047 | 452,250 | 0.405 | 28 | 21 | 0.06 | 0.94 | 94.45 | 427,167 | 12,815 |
| 2048 | 461,700 | 0.405 | 29 | 21 | 0.04 | 0.96 | 96.23 | 444,299 | 13,329 |
| 2049 | 471,150 | 0.405 | 30 | 21 | 0.03 | 0.97 | 97.45 | 459,156 | 13,775 |
| 2050 | 480,600 | 0.405 | 31 | 21 | 0.02 | 0.98 | 98.29 | 472,370 | 14,171 |

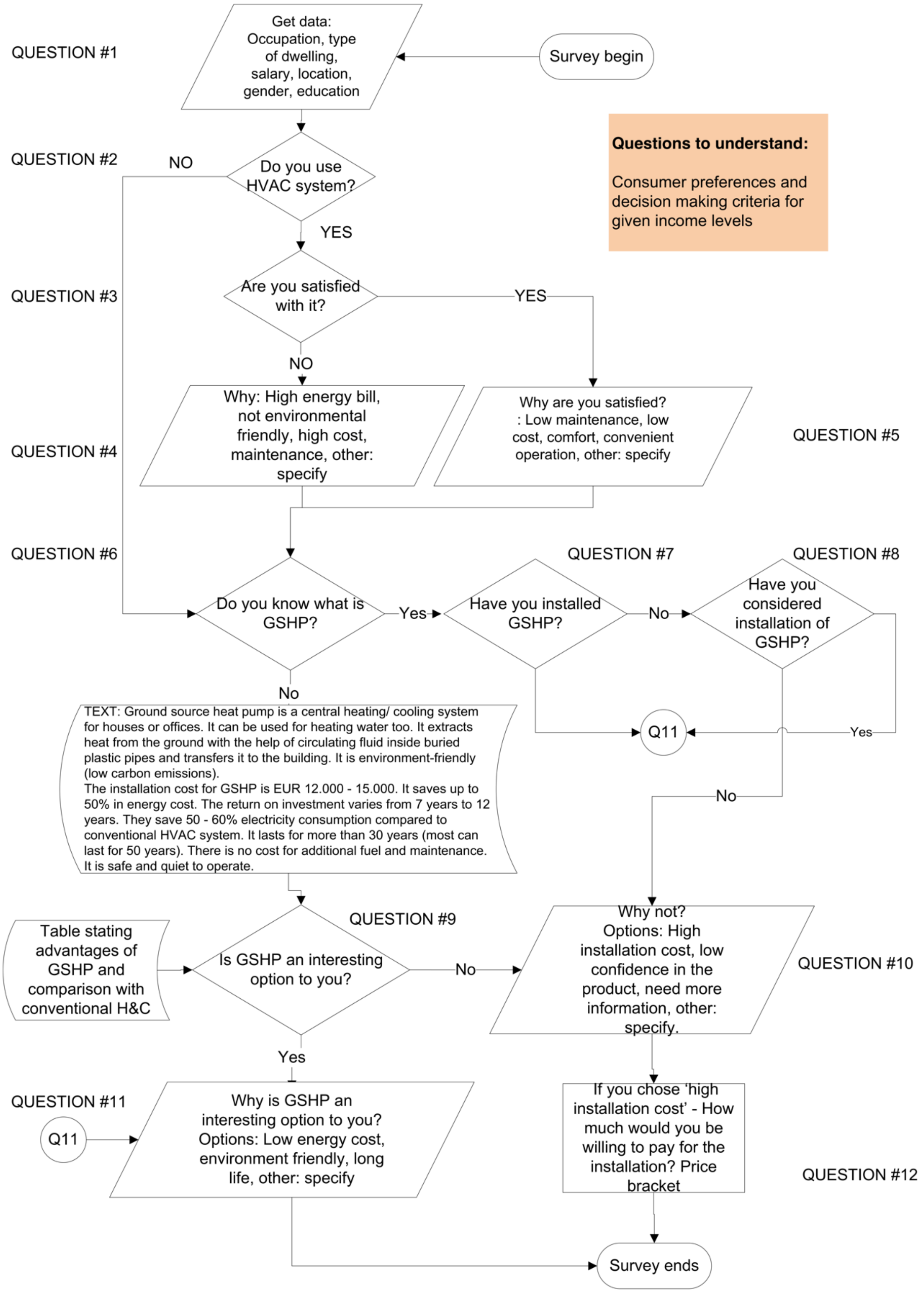
Table A7: Realistic scenario for Fisher Pry analysis with $\delta$ = *0.405*. *Spatial constraint factor = 0.75

| Year | Number of units | $CO_2$ emissions (kt) | | |
|---|---|---|---|---|
| | | Combination A | GSHP system | Difference |
| 2020 | 262,800 | 934.0 | 290.9 | 643.1 |
| 2021 | 275,400 | 978.8 | 304.9 | 673.9 |
| 2022 | 288,000 | 1023.6 | 318.8 | 704.8 |
| 2023 | 300,600 | 1068.4 | 332.8 | 735.6 |
| 2024 | 313,200 | 1113.2 | 346.7 | 766.5 |
| 2025 | 325,800 | 1157.9 | 360.7 | 797.3 |
| 2026 | 338,400 | 1202.7 | 374.6 | 828.1 |
| 2027 | 351,000 | 1247.5 | 388.6 | 859.0 |
| 2028 | 363,600 | 1292.3 | 402.5 | 889.8 |
| 2029 | 376,200 | 1337.1 | 416.5 | 920.6 |
| 2030 | 388,800 | 1381.9 | 430.4 | 951.5 |
| 2031 | 401,400 | 1426.6 | 444.3 | 982.3 |
| 2032 | 414,000 | 1471.4 | 458.3 | 1013.1 |
| 2033 | 426,600 | 1516.2 | 472.2 | 1044.0 |
| 2034 | 439,200 | 1561.0 | 486.2 | 1074.8 |
| 2035 | 451,800 | 1605.8 | 500.1 | 1105.6 |

| | | | | |
|---|---|---|---|---|
| 2036 | 464,400 | 1650.6 | 514.1 | 1136.5 |
| 2037 | 477,000 | 1695.3 | 528.0 | 1167.3 |
| 2038 | 489,600 | 1740.1 | 542.0 | 1198.1 |
| 2039 | 502,200 | 1784.9 | 555.9 | 1229.0 |
| 2040 | 514,800 | 1829.7 | 569.9 | 1259.8 |
| 2041 | 527,400 | 1874.5 | 583.8 | 1290.6 |
| 2042 | 540,000 | 1919.2 | 597.8 | 1321.5 |
| 2043 | 552,600 | 1964.0 | 611.7 | 1352.3 |
| 2044 | 565,200 | 2008.8 | 625.7 | 1383.1 |
| 2045 | 577,800 | 2053.6 | 639.6 | 1414.0 |
| 2046 | 590,400 | 2098.4 | 653.6 | 1444.8 |
| 2047 | 603,000 | 2143.2 | 667.5 | 1475.6 |
| 2048 | 615,600 | 2187.9 | 681.5 | 1506.5 |
| 2049 | 628,200 | 2232.7 | 695.4 | 1537.3 |
| 2050 | 640,800 | 2277.5 | 709.4 | 1568.1 |
| | | Cumulative savings in CO$_2$ emissions | | 34,274.5 |

Table A8: CO$_2$ emissions saving per year until 2050

## Survey questions for house owners



## Survey questions for professionals