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

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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 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 Article 23 of EU Directive 2018/2001.

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

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. Out of the 192.5 Mtoe (8.05 EJ) final energy consumed by households in the EU, 79% was used up for heating and domestic hot water (DHW) applications. These figures for industrial sector stood at 193.6 Mtoe (8.1 EJ) and 70.6% respectively [2]. Moreover, fossil fuels contribute to 84% of H&C and the rest is generated using renewable energy [2]. H&C applications for residential and commercial buildings, as well as in the industrial sector contribute significantly to electricity consumption. To reduce carbon emissions, electricity consumption must either reduce, higher energy efficiency must be achieved, or more renewables must be introduced in the energy mix. Ground source heat pumps (GSHP) systems which utilize the geothermal energy represent space conditioning alternatives that reduce the electricity consumption inside household and hence carbon emissions.

2. Shallow Geothermal Energy (SGE) and its current status

Geothermal energy is a renewable form of 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 [3]. Since there is no legal differentiation between shallow and deep geothermal energy sources [4], 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.

Direct heating is one of the oldest applications of low-temperature geothermal resources obtained at shallower depths [3]. Apart from direct heating using geothermal energy, it can be also utilized for H&C, aquaculture, and in agricultural applications.

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. Sweden has the highest number of installations (540,000) followed by Germany (325,000) and France (200,000). Comparatively, Albania (106) and Iceland (70) have low number of installations. Portugal has the lowest number of installations (54) within the entire European Union as per data from [5].

2.1 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) [6]. This temperature difference between the surface of the Earth and the 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 [7]. To accomplish this, fluid is circulated through the length of a borehole heat exchanger (BHE) by utilizing electrical energy.

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 [8], [9].

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 [10], [8]. In closed-loop systems (Figure 1) [6], the heat exchanging medium is re-circulated and it remains enclosed in the system. Closed-loop systems can be installed in different configurations. 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 [10]. 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 [6]. In addition, the temperature below the surface of the earth is affected by the seasonal temperature variation. To appropriately size a GSHP system, the building space conditioning demands and building insulation must also 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.

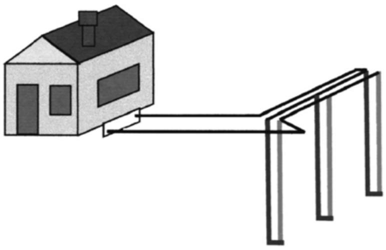


Figure 1: Closed-loop system

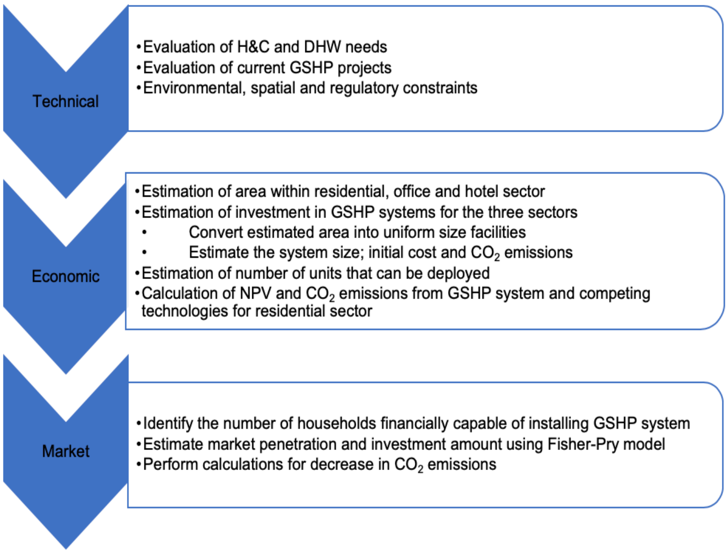


Figure 2: Methodology in brief

2.2 Thesis objective

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 vertical GSHP systems since they require smaller installation space. The thesis is divided in to five (5) parts. While the Part 1 and 2 give brief introduction of geothermal energy and GSHP system, in Part 3, investigation into technical potential has been conducted based on climatic and ground conditions. In Part 4, 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. In Part 5 attempt has been made to find the market potential as installed capacity and possible revenue as well as penetration of GSHP projects in the residential market segment based on Fisher-Pry diffusion model and renewable energy targets met by these installations as per Article 23 of EU Directive 2008/2001. Due to lack of data, industrial, aquaculture, balneology and other applications of SGE were excluded from the study. Figure 2 highlights the major steps taken in the evaluation of the technical, economic and market potential.

3. Investigation of Technical Potential

3.1 Classification of potential

Theoretical potential is the fraction of usable energy from a given energy source. 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. Economic potential is the fraction of technical potential in which profitable investments are possible. 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.

3.2 Heating and cooling requirements

DGEG published a comprehensive report on the end-user energy usage statistics in its 2011 report [11] which is helpful from the perspective of this thesis. Table 1 data for occupancy and space conditioning was taken from same report. Table 2 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 OECD definition of 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 1: Residential occupancy data

	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 2: H&C and DHW requirements

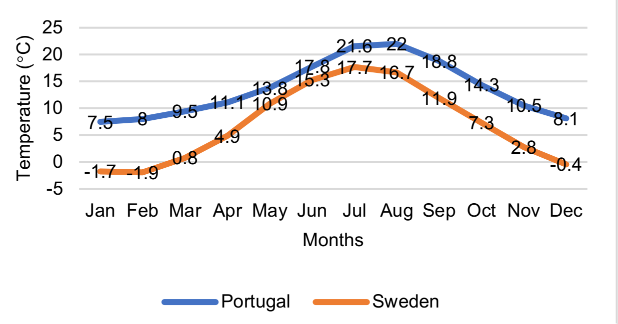


Figure 3: Comparison for annual mean temperatures in Sweden and Portugal

3.3 Climatic and ground conditions in Portugal

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 [5]. Figure 3 shows the comparison for annual mean temperatures in Sweden and Portugal.

Table 4 gives thermal conductivity and thermal diffusivity values for rocks in Portugal which were obtained from 2015 study [12], which were extracted from Ground-loop Design software (GLDesign2009). In Sweden, which has maximum GHSP system penetration, the main rock types are gneiss, granite, granodiorite, sandstone and marble [13]. 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} [14]. The average thermal conductivity for marble ~1.8 $Wm^{-1}K^{-1}$ and average thermal diffusivity is quite similar to limestone [15].

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 4: Rock properties

Fuel	*Cost per unit (€/unit fuel)*	*Emission factor* (tCO_2 per MWh)
Electricity	0.2293/ kWh [16]	0.369 [17]
Gas	21.1/ GJ [18]	0.202 [17]
Firewood	175/ ton[18]	0.250 [17]

Table 3: Fuel cost and emission factors

	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	11,813	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 5: Area and its estimated H&C and DHW requirements potentially met by GSHP systems

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.

3.3.1 Borehole heat exchanger (BHE) length for Portugal

In the 2015 study [12], 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). 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 was as close to 100 m as possible. The minimum number of boreholes was computed at three (3) and the maximum as six (6). The shallowest individual borehole depth was calculated at 93 m and the deepest individual borehole was calculated at 120 m. 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).

3.3.2 Current GSHP projects in Portugal

Current GSHP projects in Portugal for commercial properties published in [19], [20] were reviewed to obtain estimate on the borehole length, H&C and DHW requirements in different kinds of facilities (offices, laboratories, dormitories) as well as to affirm that there GSHP systems can be installed in Portugal which are capable of meeting space conditioning and DHW requirements of various facilities.

3.4 Real estate data

Table 5 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 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. 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. [21], [22], [23], [24].

3.5 Constraints

There are three (3) primary constraints for GSHP installations: environmental, space and regulations around utilization of geothermal resources. The presence of GSHP gives rise to localized anomalies under the ground or within the groundwater in the form of cold or heat plumes. This can have negative impact on the chemical and physical properties and microbiology, with bacteria growth at higher temperature [25]. Minimum distance criterion can be defined for adjacent GSHPs based on the distance between the BHEs, water aquifer, and adjacent property [25]. For hGSHP systems the space requirements are higher than vGSHP systems. Recommended distance between the boreholes for closed loop vGSHP is at least 7m (21 ft) to avoid thermal interference [26]. 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. 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.

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 [25]. Portuguese national law recognizes environmental impact around the exploitation of geothermal resources. However, this legislation does not apply to GSHP systems since the law fails to bring it under the definition of “geothermal resource” [27].

3.6 Conclusions

Reviewing – the climactic and ground conditions in Portugal and Sweden, the study done for the twelve cities from the conceptual study [12] 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. In total, GSHP systems can be installed to satisfy at least 28.84 GWh space conditioning requirements. This is a conservative estimate since these figures (Table 5) do not include DHW needs for offices, and H&C and DHW needs for commercial properties (e.g. Mall, gymnasium, theatre) and public spaces (e.g. Metro stations, museums); due to lack of data.

4. Economic Potential of GSHP systems

4.1 Cost

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. Figure 4 [28] shows the cost per installed kW output in Pound Sterling, which was converted to Euro for further analysis.

4.2 Emission 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 [17]. Table 3 shows the emission factors and fuel costs used in calculations.

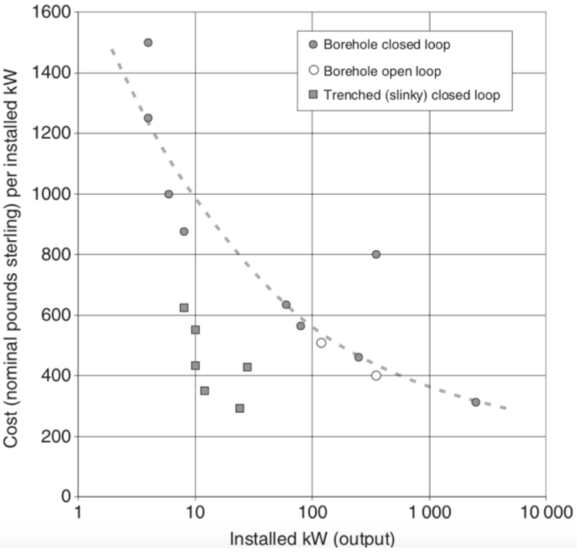


Figure 4: Cost per installed kW output in Sterling Pounds

4.3 Spatial constraint factor

Due to unavailability of suitable location for GSHP system installations due to constraints, it is assumed that only 25% of the total identified sites will be favorable for installations. Thus, a multiplying factor of 0.25, called the *'spatial constraint factor'*, have been used to predict the economic potential. 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.

4.4. Economic potential in residential sector

Table 6 summarizes the economic potential for residential sector.

Population	10,300,000
Number of dwellings of uniform size	3,814,815
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
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 after applying spatial constraint factor (See Section 4.3)	€15.7 billion
Estimated installed capacity	5.72 GW

Table 6: Economic potential for residential sector

4.5 Economic potential in hotel industry

Table 7 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
Total CO_2 emissions savings for hotels after applying spatial constraint factor (See Section 4.3), per year	27.2 $ktCO_2$
Economic potential after applying spatial constraint factor (See Section 4.3)	€212.9 million
Estimated installed capacity	185.4 MW

Table 7: Economic potential for the hotel industry

4.6 Economic potential in office spaces

Table 8 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
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 after applying spatial constraint factor (See Section 4.3)	€184 million
Estimated installed capacity	646.7 MW

Table 8: economic potential for the office spaces (Lisbon and Porto only)

Thus, the total estimated economic potential is just over €16 billion in all the three sctors combined with total installed capacity of approximately 6.5 GW.

4.7 Deployment rate

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. Thus, the total number of new licensed dwellings, (excluding reconstructions or refurbishments) for the year 2017 was 23,015 [29]. It can be assumed that the average rate of increase will remain the same for, say, next five (5) years. The total number of hotel rooms (only), available in Portugal in 2018 was close to 102,000.

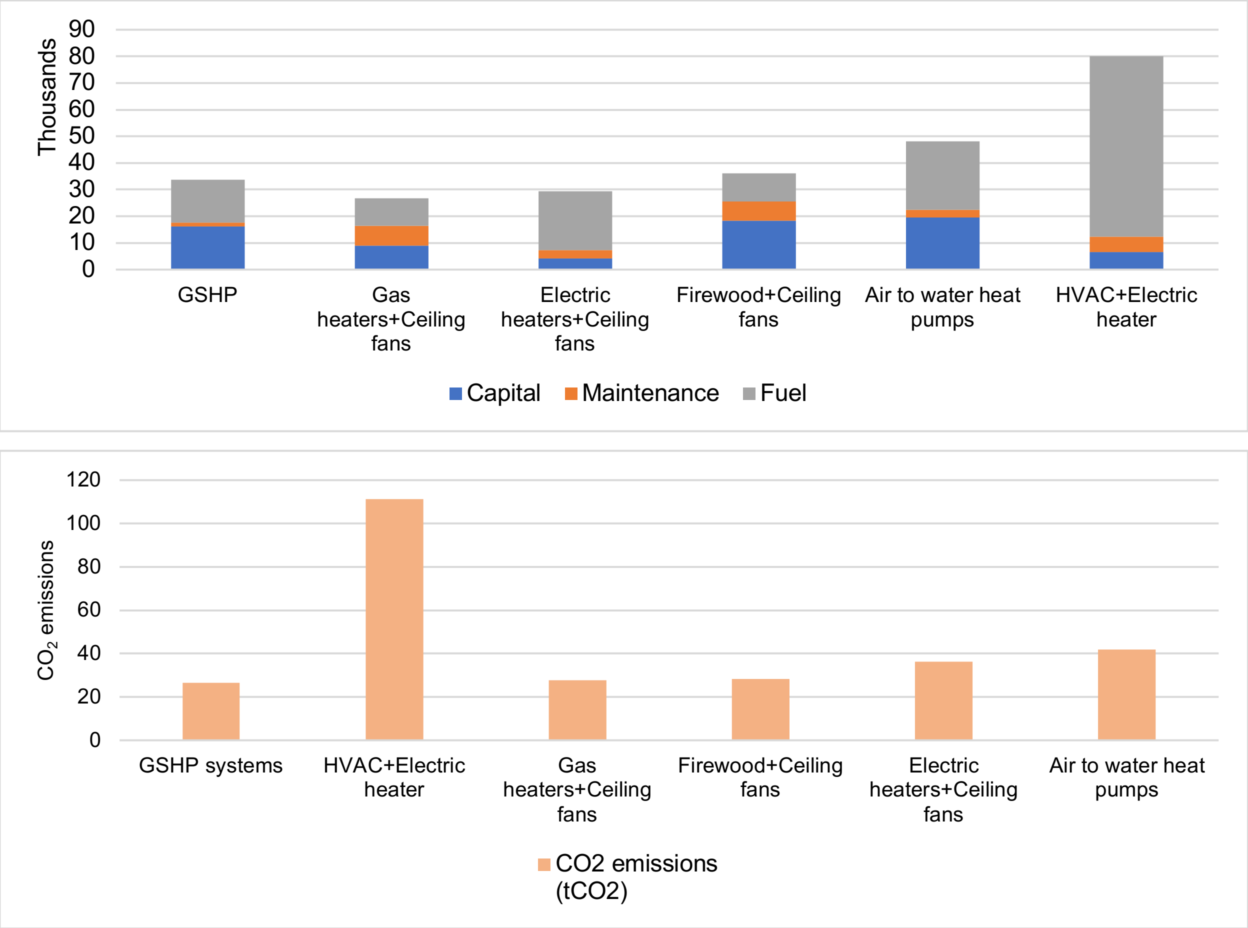
Market segment	Estimated deployment rate in installed capacity/ year (MW/ yr)	Estimated deployment rate in market size/ year (million €/ yr)
Residential	138	379.7
Hotels	17.3	19.8
Office spaces	3.4	3.9
Total	*158.7*	*403.4*
Spatial constraint factor = 0.25	*39.7*	*100.8*

Table 9: Deployment rate

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 [30]. Assuming that the average rate of increase remains constant for, say, next five (5) years there will be 4,300 new rooms. 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 [21]. 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. Table 10 shows the estimated deployment rate every year (for next five years) for residential, hotel and office market assuming all of the new constructions utilize GSHP system.

4.8 NPV and CO_2 emission comparison with competing technologies

From the market data for 2010 [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%). Other competitors include independent electric heaters, independent gas heaters, air conditioning heating (HVAC) For cooling application, fan is most widely used (61%) followed by HVAC system (33%). Gas water heaters (71%) take up majority of the share for DHW followed by electric water heater and boiler, each 11%. In addition, air-to-water heat pumps were also considered in this assessment since their economic and emission performance is comparable with GSHP systems. To calculate the NPV, capital cost, maintenance cost and operation cost were considered for each competing technology or combination of technologies. These costs were obtained from various sources on the internet and where possible converted to Euros for uniform comparison. Operation cost included the cost of the fuel while maintenance cost covered any replacement/ repair cost. CO_2 emissions were computed assuming that system is performing at maximum rated capacity. Figure 5 shows the Comparison of NPV and CO_2 of different technologies.



4.9 Conclusions

It can be concluded that the majority of the economic potential and CO_2 emission is in the residential sector. All the financial values are susceptible to significant changes due to the assumed arbitrary value for spatial constraint factor. Fireplaces, fans, gas heaters, electric water heaters and electric space heaters have lower 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 advantages. There could be significant difference between the predicted and actual fuel cost in the future as well as increase of renewable energy in the mix, and hence the results of the assessment might change significantly.

5. Market Potential

5.1 Market focus

The combination of HVAC systems with electric water heater is more expensive and carbon intensive as compared to GSHP systems as per Figure 5. 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”.

5.2 Market size

The number of dwellings with HVAC installed for H&C applications was approximately between 223,000 – 230,000 with approximately 400,000 sets of equipment [11]. It is assumed that the number of dwellings with HVAC systems remained constant until 2019 and a value of 225,000 has been used. The number of electric water heaters (439,724) 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.

If wealth is correlated with the size of the house as done by Tanguay [31], 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 in smaller than T2 dwellings. 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) [29]. 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. Thus, a bigger size GSHP system, say, 10-kW, can be chosen. Table 10 gives the estimated market value of GSHP system.

Year	*Number of dwellings*	*Size of installed system*	*Spatial constraint factor*	*Installation cost*	*Estimated market value*	*Installed capacity (GW)*
2019	250,200	10 kW	0.75	€21,000	€5,254 million	1.87

Table 10: Estimated market value of GSHP systems

5.3 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. Mathematically, it can expressed as:

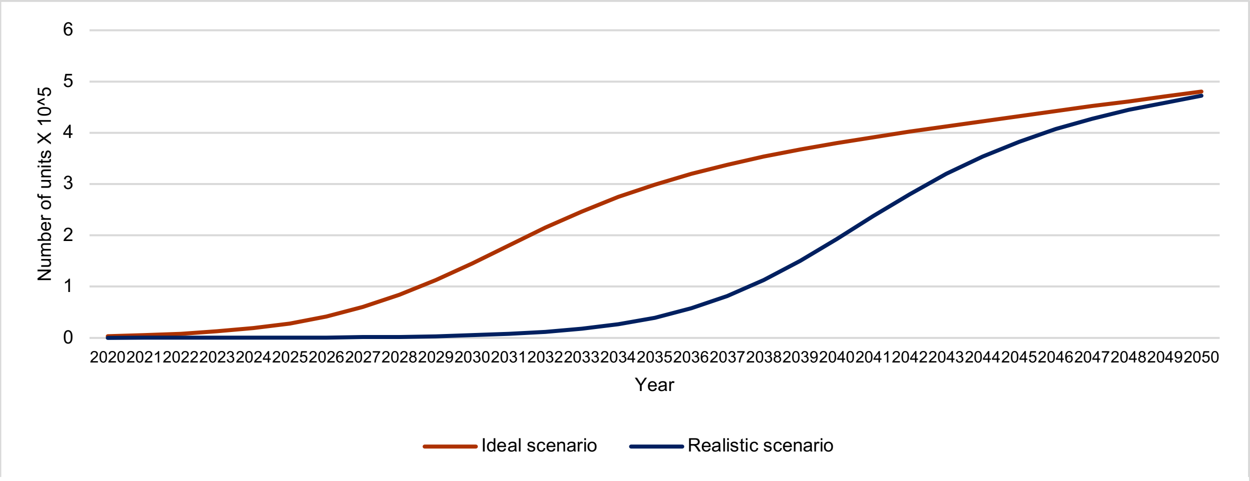


Figure 5: Number of units replaced every year

$$\frac{f}{1-f} = \exp\ [\delta * (t - t_0)]$$

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

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. Two scenarios were considered: “ideal” and “realistic”. For the ideal scenario, the parameter δ 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. No new GSHP system installation in residential sector was reported in Portugal in the last few years [17]. Thus, a significantly lower target should be set for the initial years assuming lack of sufficient infrastructure to deliver 3,375 units in the first year. This means that by 2030, 50% replacements will be impossible. As per [32], 52 units of GSHPs were sold in Portugal in 2017. If 50% replacements are assumed in year 2040 with the same value for parameter δ 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 6 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 δ = 0.405, and t in the year 2050, being same for both the cases.

5.4 Carbon mitigation potential as per EU Directive 2018/2001

Article 23 of the EU Directive 2018/2001 can be interpreted prescribe 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. Current energy consumption data obtained from [33] can be used obtain values in Table 11. Figure 7 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, 1600 hours operation, assumed seasonal performance factor of 4.0 and η = 0.493 for Portugal [34].

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 11: Energy consumption data inside a dwelling

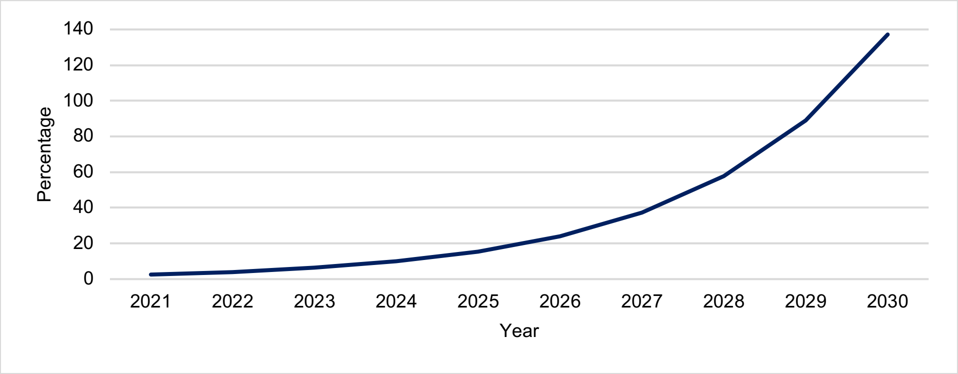


Figure 6: Percentage of yearly goals achieved by GSHP systems for renewable source in H&C

5.5 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. To promote the installation of GSHP systems, initial target should be family houses of size T2 or bigger. 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. 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. Article 23 of EU Directive 2018/2001 can be interpreted to read that the share of renewable energy for H&C needs, must increase by at least 1.3% from 2021 until 2030 which corresponds to 23,630 MWh/ year for Portugal assuming energy mix and energy efficiency remains constant. Installation of GSHP systems in T2 or bigger dwellings as per the "realistic" scenario can help to achieve 100% of this target by the end of year 2030.

5.6 Final comments and future work

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 and hot water needs inside office buildings, energy usage inside hotels. Realistic results could be achieved by using amount of 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. Future work may include examining the possibility of using GSHP systems for industrial applications and SGE applications in aquaculture, spa, balneology. To incorporate the constraints 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.

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