UNIVERSITY OF ICELAND

Master's Thesis
in Environment and Natural Resources

The Environmental and Socio-economic Benefits of Geothermal District Heating

Meiting Qin

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FACULTY OF LIFE AND ENVIRONMENTAL SCIENCES

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Preface

I am grateful for the opportunity to pursue my master's study at the University of Iceland and to enroll in the Environment and Natural Resource program. I would like to thank my supervisor, Professor Brynhildur Davíðsdóttir for the time she devoted to this master's thesis. Her extensive expertise, as well as the constructive criticism, were the best support I could have asked for. Also, I would like to thank my colleagues as well as my supervisor Páll Valdimarsson at Arctic Green Energy (AGE) for the amazing job opportunity and for their support during my studies. Finally, I want to thank my parents and friends, especially Alice Walsh, Elias Weltert, Lijing Zhou and Snæfríður Guðmunds Aspelund for their strong support and inspiration, and my little cute hamster Gustina Nevæhsdóttir, who encouraged me with her Viking spirit throughout the writing of my thesis. I could not have finished this thesis without their generous support and patience.

Abstract

Geothermal energy is derived from hot underground reservoirs and is a greener alternative to using fossil fuels for heating. The development of geothermal energy also contributes to sustainable development globally and contributes to several United Nations Sustainable Development Goals (UN SDGs) like SDG 3, SDG 7, SDG 8 & SDG 13. According to Eurostat, Russia supplied roughly one-third of the EU's total crude oil (34.5%) and natural gas (31.5%) imports in 2010. Approximately 75 % of this gas is used for heating. Geothermal energy has the potential to replace a large portion of that fuel and can be used for district heating. The purpose of this thesis is to identify the environmental and socio-economic benefits of geothermal energy for district heating, as well as identify and implement indicators to measure those benefits. To realise this challenge, a benefits calculation tool was developed, which helps to quantify the potential benefits of geothermal energy. The benefits calculation tool was implemented in a case study of Budapest, Hungary. The results show that by replacing 40% of the natural gas heating system with geothermal based district heating in Budapest, at least 4.6% of the total GHG emission is reduced in Hungary in addition to other benefits. The results also indicate that the benefits calculation tool can be applied elsewhere to evaluate the benefits of geothermal district heating and thereby contribute to the development of geothermal energy.

Útdráttur

Jarðvarmi er fenginn úr heitum neðanjarðarlindum og er grænni valkostur en að nota jarðefnaeldsneyti til hitunar húsa. Nýting jarðhita stuðlar einnig að sjálfbærri þróun á heimsvísu og þá hefur sérstaklega áhrif á nokkur heimsmarkmið Sameinuðu Þjóðanna (SDG 3, SDG 8 og SDG 13). Samkvæmt Eurostat uppfyllti Rússland árið 2010 um 1/3 af eftirspurn Evrópusambandsins eftir hráolíu (34,5%), og 31,5% af eftirspurn eftir jarðgasi. Um 75% af því jarðgasi er notað til hitunar húsa. Mögulegt er að nýta jarðvarma til að uppfylla stóran hluta þessarar eftirspurnar með notkun jarðvarma í hitaveitum. Tilgangur þessarar ritgerðar er að komast að því hver umhverfis- og félagshagfræðilegur ávinningur er af því að nota jarðvarma fyrir hitaveitur auk þess að skilgreina og útfæra mælikvarða á þann ávinning. Reiknivél var þróuð til að sýna fram á hugsanlegan ávinning á megindlegan hátt. Reiknivélin var síðan prófuð í tilviksrannsókn fyrir Búdapest, Ungverjalandi þar sem ávinningur aukinnar nýtingar jarðvarma í hitaveitu var metinn. Niðurstöðurnar sýna að með því að skipta út 40% af jarðgasi fyrir jarðvama í hitaveitu Búdapest dregur úr losun gróðurhúsalofttttegunda um 4,6% í Ungverjalandi, dregur úr loftmengun í Búdapest og kostnaði við hitaveitu auk annars ávinnings. Niðurstöður benda einnig til að hægt sé að nýta reiknivélina til að leggja mat á ávinning nýtingar jarðvarma til hitaveitu annars staðar, og þar með stuðla að aukinni nýtingu jarðvarma.

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List of Abbreviations

AGE	Arctic Green Energy
AQI	Air Quality Index
AGECC	Advisory Group on Energy and Climate Change
CO_2	Carbon Dioxide
EPA	Environmental Protection Agency
GHG	Global Greenhouse Gas
GDH	Geothermal District Heating
GBD	Global Burden of Disease
H2S	Hydrogen Sulphide
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ILO	International Labour Organization
IEA	International Energy Agency
IETA	International Emissions Trading Association
IHME	Institute for Health Metrics and Evaluation
NOx	Nitrous Oxide
PM 10	Particulate Matter
QALY	Quality Adjusted Life Year
SDG	Sustainable Development Goals

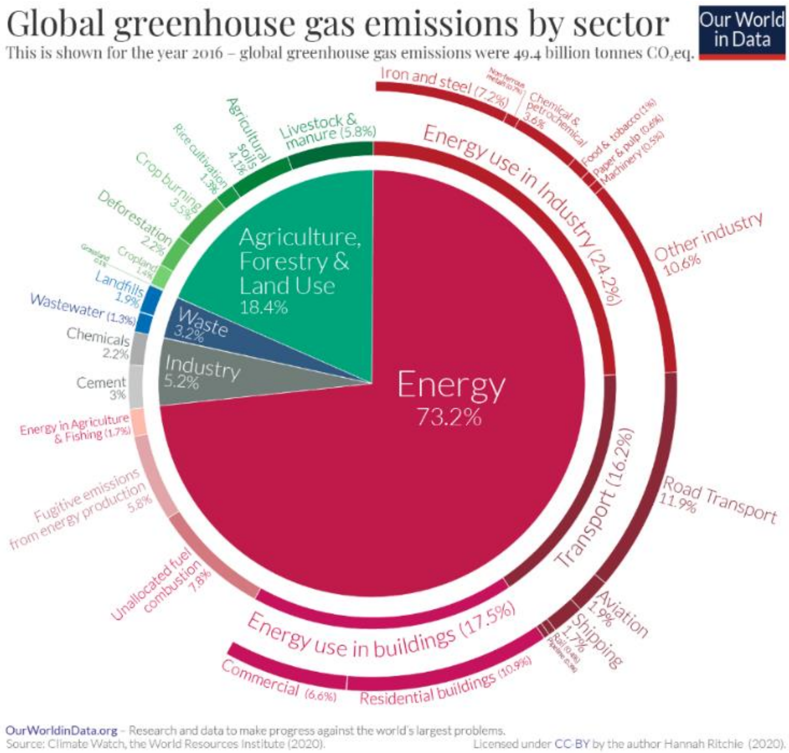
TSP	Suspended Particles
VSL	Value of Statistical Life
WHO	World Health Organization

1 Introduction

1.1 Motivation

Renewable energy plays a key role in the decarbonization of the energy sector and the resulting mitigation of climate change. It also plays an important role in enhanced energy security by reducing reliance on finite fossil fuels. A big global concern regarding fossil fuels is the negative impacts on the environment such as from CO_2 emissions leading to climate change and poor air quality. The Intergovernmental Panel on Climate Change (IPCC) has pointed out that the burning of fossil fuels contributes greatly to GHG emissions (IPCC, 2022). As Figure 1 shows, greenhouse gas (GHG) emissions can be split down by the economic activities that lead to their production. Among them all, energy is responsible for 73.2% of the GHG emissions, making it the major contributor. Also, an important point here is that the energy use in buildings (17.5%), such as heating and electricity, is the second-largest single source of GHG emissions. With increasing global energy demand and consumption, geothermal energy usage for district heating, as well as electricity generation, may increase significantly worldwide in the future and thereby contribute to reduced GHG emissions (Lund et al., 2021).

Figure 1. Global Greenhouse Gas Emissions by Sector



Source: Ritchie, Roser & Pablo, 2020

Several studies have shown that the use of geothermal energy contributes to the reduction of GHG emissions which is one of the most important environmental benefits of utilising geothermal energy (Soltani, et al., 2021; Rybach, 2008; Zhang et al., 2020). Moreover, positive impacts of geothermal energy´s direct use, e.g., for district heating include reduced air pollution when compared to fossil fuels (Pan et al., 2019). With the rapid increase in global air pollution, geothermal district heating (GDH) systems can provide a sustainable heating solution to cities covered in smog. Air quality problems such as haze and smog are found in many Chinese and Western cities, and they are at least partially caused by burning fossil fuels for household space heating (Zhang & Samet, 2015). Poor air quality is then one of the main causes of several health-related issues (Centre for Research on Energy and Clean Air, 2020).

Many countries have made renewable energy development a top priority, not just to cut emissions and meet international climate goals, but also to achieve broader socio-economic benefits. Higher renewable energy usage is predicted to have positive effects on economic growth, employment and other welfare indicators including public health (IRENA, 2016). Figure 2 provides an overview of the total employment figures in the renewable energy sector by technology and indicates the fast net job growth from investing in renewable energy, including geothermal energy. In 2020, there were 12 million renewable energy jobs worldwide with 32% of renewable energy jobs held by women (IRENA & ILO, 2021). The Geothermal Energy Association (GEA) suggests that the development of geothermal energy materially contributes to the global job market through direct and indirect employment (GEA, 2005). The possible significant environmental and socio-economic benefits of utilizing geothermal energy for district heating, call for investigation and quantification of these possible benefits, and if confirmed to apply such benefit assessments to further the development of geothermal energy. Thus, this thesis aims to contribute to such research.

Figure 2. Global Renewable Energy Employment by Technology 2012-2020

Source: IRENA Jobs database, 2021

1.2 Research Aim, Questions and Methods

The overall research aim is to identify and measure the environmental, and socio-economic benefits of geothermal district heating particularly focused on GDH systems. Despite the importance of transitioning to renewable geothermal energy for district heating, a practical tool is missing that enables quantification of the benefits of transitioning from fossil fuel-based heating systems to geothermal heating systems. Therefore, an added aim of this research is to develop a generic benefits calculation tool in order to easily quantify those benefits from environmental and socio-economic perspectives.

The research questions are:

1. What are the environmental and socio-economic benefits associated with GDH?

2. How can we measure or quantify those benefits? What are the metrics that can be used?

The findings will be applied to the city of Budapest, Hungary to answer the following question:

3. How can Budapest benefit from replacing natural gas heating systems with GDH systems?

The benefits analyzed are:

Environmental:

1. Annual avoided CO_2 emissions by using geothermal: assessed by each fossil fuel emissions factor and its usage, minus the CO_2 emissions released by geothermal.

2. Avoided air pollution: the sum of avoided air pollutants, assessed by the quantity of fossil fuels used and the emission factors of the pollutants minus emissions derived from geothermal energy.

3. Annual deaths avoided as a result of improved air quality: assessed by reduced number of deaths due to improvements in air quality.

Socio-economic:

1. Carbon credits gained: One ton of CO_2eq emission saved is equal to one carbon credit gained, priced by the price of carbon quotas from the EU ETS system.

2. City management improvement: assessed by equivalents of 1-million-ton CO_2 emission avoided by replacing fossil fuels with geothermal means in terms of other emitting sectors.

3. Value of life saved: based on the annual premature deaths avoided by improved air quality and the statistical value per life.

4. Affordability - energy cost saved: Assessed by the levelized cost of heat and the energy cost saved as a result of using GDH instead of fossil fuels.

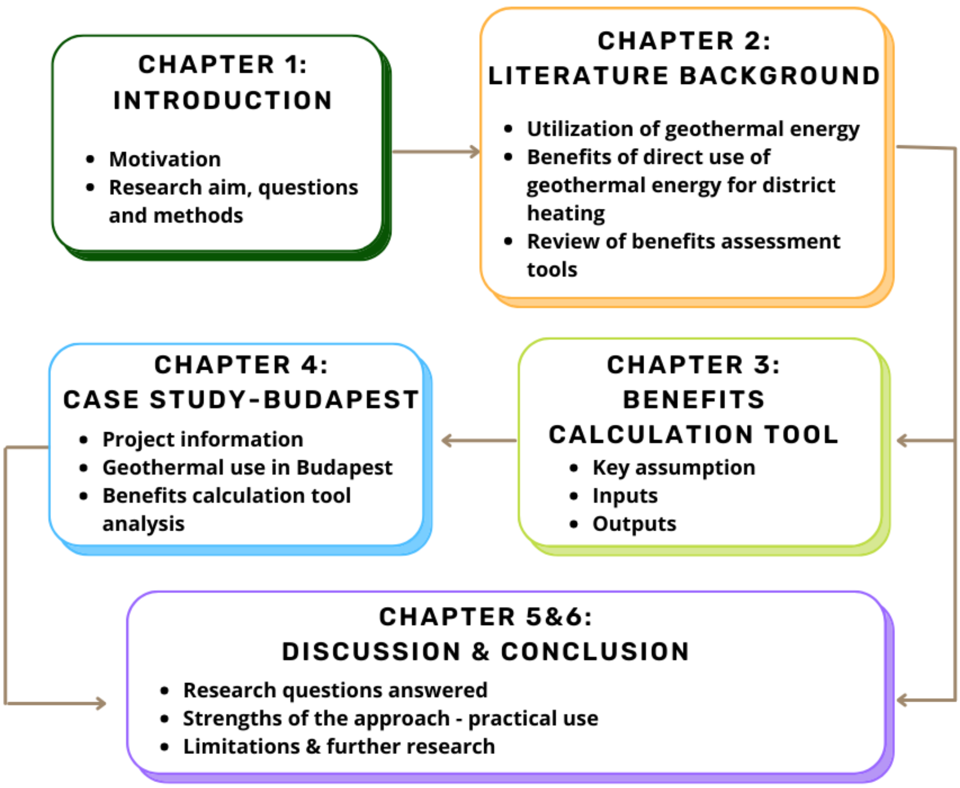
5. Net job growth from investing in GDH systems: assessed by net job growth per TJ from GDH systems.

Data from relevant sources are applied to evaluate and quantify the benefits of GDH systems.

1.3 Structure

The structure of this thesis is as follows (see Figure 3): First, the study reviews the relevant existing research on the development of geothermal district heating and their potential benefits, from environmental and social-economic perspectives. In chapter three, the measurement tool is introduced, followed by its methodology, key assumptions, inputs, and outputs. Chapter four provides a case study of applying this measurement tool to the geothermal heating project in Budapest, Hungary. Finally, the thesis concludes with a discussion and a conclusion.

Figure 3. Thesis Structure

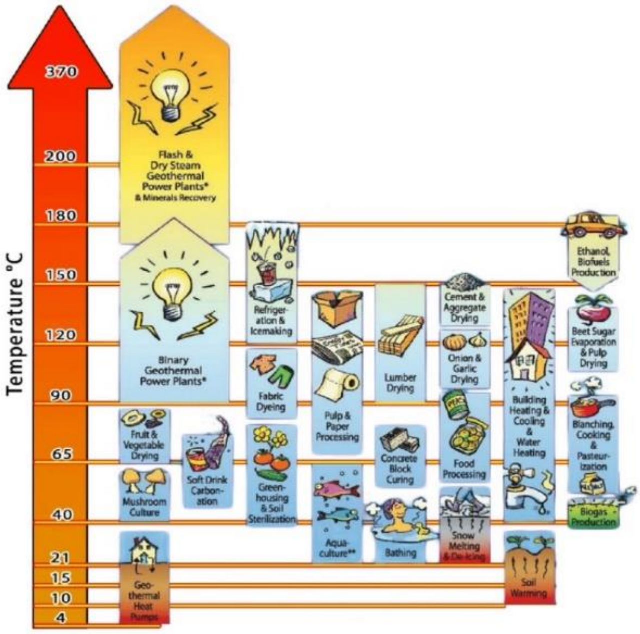


2 Literature Background

2.1 The Utilization of Geothermal Energy

Geothermal energy is the thermal energy that comes from the earth’s core and has been utilized for a long time (Stober & Bucher, 2013). The use of geothermal energy can be divided into two categories: electricity production and direct application (Mburu, 2009). As the Lindal diagram reveals (see Figure 4), geothermal energy resources can be applied to a range of applications based on the different temperatures, reusing the heat for more than one application (Stefansson, 2000).

Figure 4. The Lindal Diagram



Source: Geothermal Education Office, 2005

Low (<150°C at 1 km) and medium temperature (150-200°C) geothermal fields can be found in most countries around the globe making them rather accessible (Saemundsson et al., 2011). Resources with temperatures above 200°C are defined as high-temperature fields and they can be used for conventional power production (ibid). Direct geothermal energy usage is one of the oldest, most versatile, and widely used methods of utilizing geothermal energy (Dickson & Fanelli, 2003). Compared to using geothermal energy for electricity generation, direct use of geothermal energy for heating is more efficient and has lower temperature requirements (Lund, 2010). With an efficiency up to 70%, direct use of geothermal energy has a considerably greater efficiency than geothermal power generation (12%) and internal combustion engines (54%) not the least when used in a cascade (EPA, 2006). The use of geothermal energy in a cascade has also been proposed as a strategy to maximize the use of medium and low enthalpy resources, both for electricity generation and direct use (Rubio-Maya et al., 2015). The advantages of using geothermal energy in cascade mode are maximising the utilization of the resource, reducing harmful gas emissions, reducing the use of primary energy derived from fossil fuels as well as increasing the profitability of the facility (ibid).

Low-temperature resources are used for direct use and as Figure 4 shows there is the significant scope for diverse direct use of geothermal energy. One example for the direct use of geothermal is heating houses through district heating systems, or Geothermal District Heating (GHD) systems. GDH systems are extensively used in some countries such as Iceland where the main heating source is provided by geothermal energy (Sander, 2016). Other examples include the Danish city Frederikshavn where low-temperature geothermal energy is being used for district heating in the city that once relied primarily on fossil fuels, making the transition to using their locally available renewable energy sources instead (Østergaard & Lund, 2011). District heating, as part of space heating, has increased 68.0% in installed capacity and 83.8% in annual energy use in 2021 compared to 2014 (Lund & Toth, 2021). The installed capacity totals 12 768 MWt and the annual energy use is 162 979 TJ/yr and in comparison, 91% of the installed capacity and 91% of the annual energy use is in district heating among 29 countries by 2021 (ibid). The academic literature on the utilization of the geothermal system in South-East Hungary also has revealed the huge, but only partially exploited geothermal potential in Hungary (Szanyi & Kovács, 2010).

In the next section, selected benefits linked to the use of geothermal energy are discussed with a particular focus on the direct usage of geothermal energy for district heating.

2.2 Benefits of Direct Use of Geothermal Energy for District Heating

Geothermal energy in theory is perpetual, in many cases with low CO_2 emissions, can be harnessed at a competitive price and has a high security of continuous delivery of heat at a steady temperature if used sustainably (Stober & Bucher, 2013). In this section, the environmental and socio-economic benefits of geothermal district heating are discussed and categorized into four themes as displayed in Table 1. Furthermore, each of the benefits listed is discussed in some detail below.

Table 1. Summary of the Environmental and Socio-economic Benefits of Geothermal District Heating by Theme.

Theme	Benefits
Environmental	• Avoidance of CO_2 emissions • Reduced air pollution
Social issues: poverty and living conditions	• Affordable energy supply for all: GDH is more cost-effective • Improved living conditions
Social issues: health	• Improved outdoor air quality and lower indoor air pollution

	• Costs saved in healthcare for air pollutants-related diseases • Therapeutic usage • Improved mental health level
Economic development	• Carbon credits gained • Improved energy security due to lower dependence on fossil fuels • Direct, indirect jobs created • Stable energy prices

2.2.1 Environmental Benefits

The environmental benefits of GDH include reduced GHG emissions and reduction in air pollution which translates to reduced health risks due to air pollution. Compared to geothermal power plants GDH systems have a very low environmental impact as they use relatively shallow geothermal resources (Lake et al., 2017). Compared to using the high-temperature source (>200°C) of geothermal energy to generate electricity, the direct use from a lower temperature source (<150°C) is more environmentally friendly since it is a natural hot water source extracted from the earth without burning fossil fuels and it produces practically no CO_2 emission beyond background emissions (Rybach, 2010).

As mentioned above, one of the environmental benefits is reduced GHG emissions. Compared to fossil-fired heating systems, a GDH system has a great advantage in reduced GHG emissions. As heating accounts for 50% of global final energy consumption in 2018 and it contributes 40% of global CO_2 emissions (IEA, 2019), using geothermal district heating systems can help reduce global CO_2 emissions in particular as direct CO_2 emissions from direct use applications are negligible (Rybach, 2000). A case study of Tianjin indicates that shallow geothermal energy has garnered widespread attention in China, and it is viewed as a vital means of relieving strain on energy supplies, meeting greenhouse gas reduction targets, and establishing a low-carbon economy system (Fu & Zhang, 2012). A recent study shows that in China, where coal is mainly used for heat generation, geothermal heating can lead to the reduction of carbon emissions in the space heating sector by 76% and a reduction in particulate matter (PM) formation by 77%, based on on-site data collected from two geothermal wells, four geothermal heating sites and ten coal-fired heating sites in China (Zhang, et al, 2020). Moreover, research shows that it is possible to use GDH to replace fossil fuel heating systems in several Eastern European countries such as Hungary and Poland with a significant reduction in GHG emissions (Pálvölgyi & Buzási, 2021; Wachowicz-Pyzik et al., 2022; Pająk et al., 2020).

Table 2 below displays the CO_2 emissions of fossil fuels that occur from their combustion. Such emissions can be largely avoided when a GDH system is used instead of fossil-fuelled systems.

Table 2. CO_2 Emissions of Fossil Fuels

Fuel	CO_2 emission (t CO2/TJ)
Lignite/Brown Coal	95.81
Residual Fuel Oil	79.30
Natural gas	55.80

Source: EFDB IPCC, 2016

Another significant environmental benefit is the improvement of air quality. The air quality index (AQI) is widely used to measure how much the air is currently polluted and its yardstick ranges from 0 to 500. As Table 3 illustrates, the lower the AQI value, the better the air quality is in a certain area at a certain time.

Table 3. AQI Categories

US AQI Level		PM2.5 (μg/m³)	Health Recommendation (for 24 hour exposure)
Good	0-50	0-12.0	Air quality is satisfactory and poses little or no risk.
Moderate	51-100	12.1-35.4	Sensitive individuals should avoid outdoor activity as they may experience respiratory symptoms.
Unhealthy for Sensitive Groups	101-150	35.5-55.4	General public and sensitive individuals in particular are at risk to experience irritation and respiratory problems.
Unhealthy	151-200	55.5-150.4	Increased likelihood of adverse effects and aggravation to the heart and lungs among general public.
Very Unhealthy	201-300	150.5-250.4	General public will be noticeably affected. Sensitive groups should restrict outdoor activities.
Hazardous	301+	250.5+	General public at high risk of experiencing strong irritations and adverse health effects. Should avoid outdoor activities.

Source: U.S. Environmental Protection Agency (EPA), 2022

EPA has established five major air pollutants regulated by the Clean Air Act to measure AQI, they are: 1) ground-level ozone, 2) particle pollution (also known as particulate matter, including PM2.5 and PM10), 3) carbon monoxide (CO), 4) sulphur dioxide (SO_2), 5) nitrogen dioxide (NO_2). The burning of fossil fuels creates air pollutants like sulphur dioxide (SO_2), nitrogen oxides (NO_2), particulates emissions and other emissions, leading to poor air quality and having negative impacts on human health (EPA, 2022). There are other pollutants such as lead (Pb) can affect air quality. However, the five criteria pollutants mentioned above by EPA are deemed relevant for this research.

Table 4 below compares the lifecycle emissions of different energy sources (except for GHG emissions as they are compared in Table 3). As Table 4 shows, GDH systems produce much less air pollution than fossil fuels, apart from H_2S in the case of using high enthalpy geothermal resources for electricity generation. However, GDH systems produce much lower emissions in all cases than the use of fossil fuel-fired systems.

Table 4. Lifecycle Emissions of Various Energy Sources

Emission	SO_2 [kg/MWh]	NOx [kg/MWh]	Particulate Matter [kg/MWh]	Reference
Coal	4.71	1.955	1.012	DiPippo (2016)
Oil	5.44	1.814	Not included	DiPippo (2016)
Natural Gas	0.0 998	1.343	0.0 635	DiPippo (2016)
GDH systems	3.67[1]	NA	NA	Carbfix (2022) Ivarsson and Klüpfel (2021)
Biomass	0.0 083	0.02	0.13	Galbraith, D. et al. (2006)

[1] In the year 2020, the maximum capacity of GDH produced by the Hellisheiði power plant was 900 liters/second, which corresponds to 150 MW (assuming temperature is 40°C) and the utilization time is 4 876 (15 800 000 m^3 of water / 0.9 m^3 per second / 3 600 seconds) hours per year utilization time (Ivarsson and Klüpfel, 2021). Therefore, the annual GDH production at the Hellisheiði power plant is estimated to be 731 400 MWh (150 MW*4 876 hours per year utilization time). The Hellisheidi geothermal power plant emits around 9 500 tons of H_2S every year and is subject to environmental regulations. The current Sulfix system captures roughly 85% of the H_2S and injects it underground where it rapidly mineralizes into pyrite mostly (Carbfix, n.d.-a). Based on the information above, the H_2S emissions attributed to the GDH at the Hellisheidi geothermal power plant are estimated to be 1.95 kg/MWh (9 500 tons H_2S * (1-0.85) *1 000 / 731 400 MWh).

Moler mass of Sulphur is 32, Hydrogen is 1 and Oxygen is 16.

1 mole of H_2S = 1 * 2 + 32 = 34

1 mole of SO_2 = 32 + 16 * 2 = 64

Both chemicals have one molecule of S, so the number of moles in one kg of H_2S is 1 / 34 and the number of moles in one kg of SO_2 is 1/64. Therefore, 1 kg of H_2S will therefore create 1.88 kg of SO_2 when it gets oxidized with air. Therefore, SO_2 emissions attributed to the GDH at the Hellisheidi geothermal power plant are estimated to be 3.67 kg /MWh (1.95 kg/MWh* 1.88).

				EMEP/EEA (2013)

Therefore, by transferring from fossil fuel-based heating systems to GDH systems, the air quality is estimated to improve. For example, an increasing number of people in northern China now use geothermal energy, replacing coal for heating in winter. Geothermal energy provides heating for the people living in the eleven villages in Xiong'an, cutting 150 000 tons of coal consumption annually which reduces GHG emissions and air pollution indoors and outdoors in rural China (Hong, 2019). Another study conducted in Xi'an China also indicates that environmental and economic benefits such as reducing diverse pollutant emissions resulting in improved air quality and decreasing the cost of urban heating are associated with geothermal energy (Yan & Qin, 2017). The World Health Organization (WHO) estimated that ambient and household air pollution kills an estimated seven million people worldwide every year, making it a major threat to health (WHO, 2022). Negative impacts due to poor air quality on a global scale can be found in a report by the Centre for Research on Energy and Clean Air (CREA, 2020): "

- Approximately 40 000 children died before their 5th birthday because of exposure to PM2.5 pollution from fossil fuels every year.
- NO_2 pollution from fossil fuels is linked to roughly four million new cases of asthma in children each year, with approximately 16 million children worldwide living with asthma as a result. Exposure to PM2.5 and ozone from fossil fuels is
- Fossil fuel PM2.5 pollution was responsible for 1.8 billion days of work absence every year."

The statistical value of life (VSL) and value of a Quality-Adjusted Life-Year (QALY) are used to measure the monetary cost due to the impact of air pollution on human health

(Muller & Mendelsohn, 2007). The value of life is an economic value used to quantify the benefit of avoiding a fatality (Department of the Prime Minister and Cabinet of Australia, 2021). Both measures are used in cost-benefit analyses as a method of assigning a monetary value to better or worse living conditions. While QALY measures the quality of life ranging from 0–1, VSL monetizes the values using willingness-to-pay (Viscussi, 2005). A study shows that PM2.5 (Particulate Matter), NH_3 (Ammonia), SO_2 (Sulfur Dioxide), and VOC (Volatile Organic Compounds) pollutants are the greatest damage contributors and the gross annual cost ranges from $71 billion (0.7% of GDP) to $277 billion (2.8% of GDP) per year in the US (Muller & Mendelsohn, 2007). By using this concept, it is possible to measure how many fatalities can be avoided and their worth by reducing the use of fossil fuels and increasing the use of geothermal energy.

2.2.2 Socio-Economic Benefits

Geothermal energy, if used in a sustainable way, has a huge potential for contributing to social and economic development (Soltani, 2021). The possible socio-economic benefits from using geothermal energy include enhancing energy affordability due to lower costs, stimulating net job creation, improvement of residents' happiness level as well as quality of life, improvement of the public health level and saved lives due to less air pollution (Shortall et al., 2015).

2.2.2.1 Poverty

Energy affordability implies an affordable energy supply for all, namely that people of all income levels should be able to obtain the energy they require to live comfortably (Dubois & Meier, 2016). According to the Advisory Group on Energy and Climate Change (AGECC), the energy supply is considered affordable if the cost to end-users is compatible with their income levels and no higher than the cost of traditional fuels and should not be more than a reasonable fraction of their income (10–20%) (AGECC, 2010). Geothermal energy, especially for direct use, is providing affordable clean energy and improving living conditions for many people (Goldemberg & Johansson, 2004). A study by Energiforsk shows the average geothermal energy heating price in all EU countries is 18.1 €/MWh (Energiforsk, 2016). Table 5 compares the prices of different energy sources for heating confirming the large advantage in cost when compared to fossil fuels and most other types of renewable energy (Hansen, 2019).

Table 5. Comparison of Levelized Cost of Heat for Different Kinds of Energy

Energy Type	Cost ($/ MWh)
Geothermal	26
Natural gas	53
Oil boiler	92
Solar heating	139
Biomass boiler	106

Source: Hansen, 2019

Moreover, the energy costs of GDH systems are not subject to fluctuations, unlike fossil fuels (Ölz et al., 2007). Also, unlike wind and solar resources, which are more dependent on external factors such as weather fluctuations and climate change, geothermal resources, as the heat of the earth, are available 24 hours a day, 7 days a week which contributes to energy security (Kagel et al., 2005). As a result, geothermal resources not only contribute to improved energy security due to reduced use of fossil fuels, they also are more stable than other more climate dependent renewable energy resources. Energy security and its impact on economic security is seen as an integral part of sustainable development. A nation's energy independence can greatly improve its energy and economic security level (UNDP, 2004).

2.2.2.2 Economic Development

Geothermal developments contribute to economic development for example through employment and reduced GHG emissions which can create economic benefits through sales of carbon emissions permits (carbon credits gained), as well as through lower and more stable energy prices.

One of the economic benefits is the carbon credits gained because of CO_2 emissions saved by using GDH to replace fossil fuel heating. The definition of carbon credit is a "generic term to assign a value to a reduction or offset of greenhouse gas emissions usually equivalent to one ton of carbon dioxide equivalent (CO_2e)", according to the Environment Protection Authority of Victoria (EPAV, 2008). The IPCC has pointed out that "Policies that provide a real or implicit price of carbon could create incentives for producers and consumers to significantly invest in low-GHG products, technologies and processes" (IPCC, 2007). The EU-ETS system is a system that was created to enable trading in carbon emissions permits, creating a price on carbon. According to a survey by the International Emissions Trading Association (IETA), the members expect carbon prices of any ETS in different periods and it will be at least €47.25/tCO_2 (IETA, 2021). Ember provided the latest data on EU ETS carbon prices (Figure 5) illustrating that prices are above €80/tCO_2

by the 10th of May, 2022 and are expected to remain high into the foreseeable future. The latest data are used for the estimation in this research.

Figure 5. EU ETS Prices

Source: Ember, 2022

Geothermal developments stimulate economic growth through both direct and indirect employment in areas such as construction, operation, maintenance and research. However, the duration and the quality of the work must be considered. The International Renewable Energy Agency (IRENA)'s latest estimate of direct and indirect jobs in the geothermal sector was 96 000 in 2021 globally (IRENA, 2021). Furthermore, a study conducted by the European Geothermal Energy Council indicates that a geothermal power plant with a capacity of 50 MW will engage up to 862 employees (see Table 6) in the process of design, construction, operation, and maintenance. Moreover, when compared to other energy technologies, geothermal energy usually creates a large number of jobs (Jennejohn, 2010). For example, geothermal energy creates more jobs per megawatt than natural gas, as indicated in Table 7 below.

Table 6. Jobs Created in Geothermal Development (50 MW)

Development Stage	Numbers of Job Created (persons-years)
Project starting	10 - 13
Exploration	11 - 22
Plant design and construction	383 - 489
Drilling	91 - 116
Operation and maintenance	10 - 25
System manufacturing	192 - 197
Total	697 - 862

Source: Jennejohn, 2010

Table 7. Jobs Creation Comparison

Energy Type	Construction Employment (jobs/MW)	O&M Employment (jobs/MW)	Total Employment for 500 MW Capacity (person-years)	Total Employment per TJ (person-years)[2]
Geothermal	4.0	1.7	27 050	7
Natural Gas	1.0	0.1	2 460	0.44

Source: Jennejohn, 2010

2.2.2.3 Health Benefits: Better Air Quality, Higher Happiness, Mental Level and Therapeutics Use

Health benefits such as better air quality, improved mental health level, and improved life quality are associated with geothermal development. Geothermal heating and cooling improve both outdoor and indoor air quality. Because there is no combustion to produce the heat, there are no indoor air pollutants (as shown earlier). Health benefits may also arise from reducing the indoor emissions from polluting energy sources such as firewood for heating (Ogola, et al., 2011). Air quality is an important factor that affects public health

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[2] The average work hours in a calendar year are 2 080 hours. Therefore, 500 MW = 1 040 000 MWH (2 080 hours * 500 MW). 1 MWh = 0.0 036 TJ. 1 TJ = 277.7 MWh.
1 040 000 MWH = total employment per TJ = 3 744 TJ (1040000 MHH * 0.0 036 TJ).
Therefore, total employment per TJ (geothermal) = 7 (27 050 / 3744). Total employment per TJ (natural gas) = 0.44 (2460 / 3744).

as well as the quality of life. The cases from different geographical areas in Europe and China indicate a positive or linear relationship between local air quality and individual happiness. Consequently, better air quality indicates a higher level of individual happiness, life quality as well as satisfaction (Huete-Alcocer et al., 2022; Zhang et al., 2016). Furthermore, in the example study in China, a monetary value was used to confirm the existence of a positive relationship between air quality and happiness level (Zhang et al., 2016). Many studies have reported that air pollution is a significant risk factor for human health and provide evidence that air pollution is a moderate risk factor for human health and quality of life: about 5 % of the disease burden of lung cancer has been attributed to outdoor air pollution (WHO, 2002); exposures to outdoor air pollution accounted for approximately 2% of the global cardiopulmonary disease burden (Cohen et al., 2005; WHO, 2002); outdoor PM air pollution is estimated to be responsible for about 3 % of adult cardiopulmonary disease mortality; about 5% of the trachea, bronchus, and lung cancer mortality; and about 1% of mortality in children from acute respiratory infection in urban areas worldwide (Cohen et al., 2005). It is estimated that the global cost of health damages caused by PM2.5 in 2019 is $8.1 trillion, approximately 6.1% of global GDP (World Bank, 2022). In Europe, the average European city inhabitant pays €1 276 per year for air pollution (Delft, 2020).

Another health issue affected by air pollution is mental health level. The WHO defines mental health as "a state of well-being in which the individual realizes his or her own abilities, can cope with the normal stresses of life, can work productively and fruitfully, and can make a contribution to his or her community" and the three factors, economics, stress level and air quality are amongst other factors affecting the level of mental health (WHO, 2002). Recent research has shown that exposure to air pollutants like SO_2 and NOx is linked to increased severity of mental illnesses such as schizophrenia, depression, and anxiety (Newbury, 2021).

Another application of geothermal water is for therapeutic uses, specifically, “spas” (Lund & Boyd, 2016). In different locations and cultures in the world, geothermal energy has been used for therapeutic purposes. The use of geothermal water and steam for bathing and health care has had a long tradition in many regions of the world. Examples include Japanese Onsen in Hokkaido, Gellért baths in Budapest, Hungary as well as the Blue Lagoon spa in Iceland. The geothermal brine of the Blue Lagoon is the effluent water from the nearby Svartsengi geothermal plant, enriched with silica, algae, and minerals that contribute to the health of the skin (Blue lagoon, 2022). For example, a study shows that bathing in the Blue Lagoon, with the addition of ultraviolet B (UVB) light, has positive effects on psoriasis treatment and is better than UVB treatment given alone (Ólafsson, 1996).

2.2.3 Negative Aspects of Geothermal Energy

Despite the environmental and socio-economic benefits of renewable geothermal systems as discussed above, there are negative aspects too. These negative impacts and how to deal with them must be considered. An example is health risks associated with geothermal effluent, especially for geothermal power plants. One study shows that hydrogen sulphide (H_2S) is frequently emitted at a higher rate to the environment when geothermal sites are developed than before (Ólafsdóttir et al., 2010). H_2S is toxic and it can affect different body systems, especially the nervous system. Lower levels of H_2S can cause irritation of the eyes, a sore throat and cough, nausea, shortness of breath, and fluid in the lungs (Lindenmann et al., 2010). However, with appropriate removal technologies, such as amine gas treating technologies, those risks can be lowered. Another risk is noise pollution (Berglund et al 1999). Despite the land use of geothermal energy being relatively small compared to other energy sources, conflict with other land uses and habitat loss still exists (Edenhofer et al., 2011). Furthermore, it can cause negative impacts on the local ecosystem and biodiversity. There is a risk related to the drilling process such as causing earthquakes (Baer et al., 2008). Wastewater from GHD can also become secondary pollution to the local environment and degrade water quality (Wetang'ula, 2004). To eliminate or minimize those negative impacts, precautionary measures such as H_2S removal technologies need to be taken in advance.

2.2.4 Aligning with the UN SDGs

The utilization of geothermal energy can also be aligned with the United Nations SDGs (Figure 6).

Figure 6. The 17 Sustainable Development Goals

Source: The United Nations, 2022

It is expected that the utilization of geothermal energy will contribute to the SDGs directly and indirectly. For example:

- *SDG1: End poverty in all its forms everywhere*

Geothermal development contributes to energy accessibility by bringing energy to more people. In return, economic opportunities will increase, and poverty will reduce. Such opportunities may arise because of more reliable access to electricity, direct utilization of geothermal resources in specific areas, such as GDH, aquaculture, bathing and tourism (Ogola et al., 2012).

- *SDG 3: Ensure healthy lives and promote well-being for all at all ages*

Increased availability of geothermal energy is expected to improve opportunities for healthier lives (Georgsson & Haraldsson, 2019). One example is the possibility of changing from fossil fuels heating systems to renewable geothermal energy for district heating, with improved and more reliable access to heat, which has the potential of reducing air pollutant emissions and improving happiness levels (Zhang et al., 2016).

- *SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all*

As stated in SDG 7, the UN has committed to ensuring access to affordable, reliable, sustainable, and modern energy for all by 2030. Geothermal energy is considered a renewable energy resource and is usually produced and used domestically. Geothermal energy is also a climate independent energy source, it is not subject to fluctuations. Access to energy is necessary but not sufficient since the targeted population must be able to afford the energy. Geothermal energy is affordable since it is largely competitive with electricity generation using coal or oil (Black & Veatch, 2008). Low-enthalpy geothermal energy is a clean, reliable, and affordable energy source that can be used to provide environmental-friendly district heating solutions to urban district heating systems (Pálvölgyi & Buzási, 2021; Pająk et al., 2020).

- *SDG 8: Promote inclusive and sustainable economic growth, employment and decent work for all.*

Economic growth goes hand in hand with access to energy. Access to affordable, reliable, sustainable heating solutions are crucial to meeting the SDG 8 (UN, 2021). This in turn links to SDG 1. Increasing geothermal development contributes to the progress of SDG 8. For example, a study in the US provides an estimation of green jobs created through geothermal development (Jennejohn, 2010).

- *Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation.*

Geothermal aim to engage the construction of energy utilization systems, such as GDH, which transport heat to various houses (Georgsson & Haraldsson, 2019). Residents have also benefited from water supply systems designed with the primary goal of delivering water for geothermal drilling and power plant operations (ibid).

- *Goal 13: Take urgent action to combat climate change and its impacts.*

It is well acknowledged that greenhouse gas emissions from fossil fuels are in most cases much higher than emissions related to the use of geothermal energy. Therefore, the utilization of geothermal energy contributes to GHG mitigation. Geothermal energy may also be used to assist with adaptation where the effects of climate change are unavoidable and negative. For example, a study found that thanks to geothermal district heating, Reykjavik is one of the cleanest cities in the world and about 100 million tonnes of CO_2 emissions have been avoided yearly by replacing coal and oil heating by geothermal in Iceland (Fridleifsson et al., 2008).

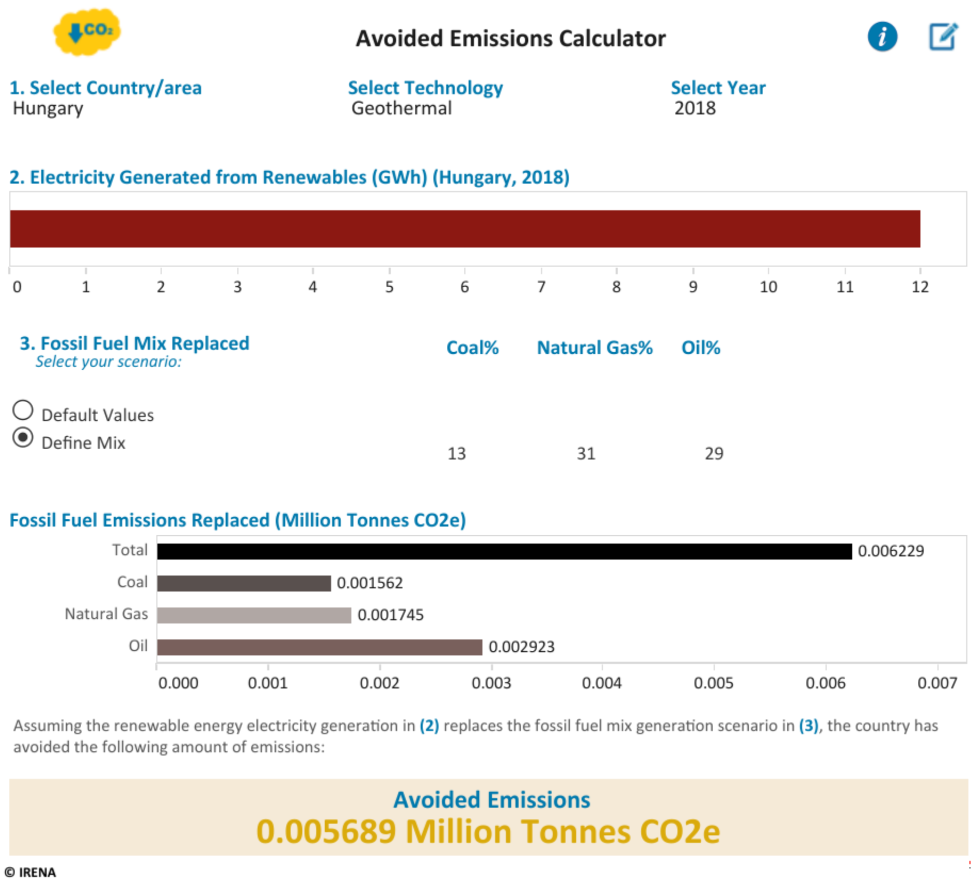
2.3 Review of Benefit Assessment Tools

As the aim of this thesis is to quantify the benefits associated with geothermal development, this section reviews other benefit assessment calculation tools, focusing on the general idea behind the calculations, their strengths and limitations. Firstly, the IRENA avoided emissions calculator is reviewed. It is a tool used to estimate the potential impacts of renewables. Secondly, the Greenhouse Gas Equivalencies calculator is reviewed. It provides an estimation of the equivalent amount of carbon dioxide (CO_2) emissions that can be translated to the terms used in city management. Thirdly, the Global Burden of Disease (GBD) tool is reviewed, and its use for death rate estimation. In total, three calculation tools are reviewed in this section. At the end of this entire section, a summary statement is given to state how these tools are applied in this research work. The three tools were chosen for the review as 1) they are the most relevant tools to this research which were identified and 2) the data source behind them are widely recognized.

2.3.1 IRENA Avoided Emissions Calculator

IRENA avoided emissions calculator is used to estimate the greenhouse gas emissions avoided as a result of a country's renewable energy deployment and compared to fossil fuel (IRENA Data Centre, 2021). This tool helps to illustrate the potential impacts of renewables. The data sources of this tool are from the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Knowing the fossil fuel mix of a country (default values or define mix) and the alternative technology (one or multiple), the avoided emissions in the selected year can be estimated. The calculator interface is shown in Figure 7 with the example of Hungary. First, the country, technology, and year were selected. Then according to IRENA's data, the electricity generated from geothermal in Hungary is 12 GWh in 2018. The percentages of coal, gas and oil in the total primary energy supply in Hungary respectively are 13%, 31% and 29% in 2018 (IRENA, 2018). By replacing the fossil fuel mix generation in the scenario above, Hungary has avoided 0.005 689 million tonnes CO_2e (Figure 7).

Figure 7. Country Assessment – Hungary



Source: IRENA Data Centre, 2021

Strengths:

This tool provides a quick overlook of avoided emissions estimation due to a country's uptake of renewables. The tool is user-friendly and the define mix option allows users to develop their own fossil fuel use scenario. Users might build a scenario in which countries use other technologies with minimal lifecycle emissions, such as solar, to reach a total fossil fuel mix of less than 100%. Additionally, it is an authoritative tool since it is developed by IRENA which acts as an authenticator of the various data sources. Another strength of the tool is the visualization of the estimated emissions replaced.

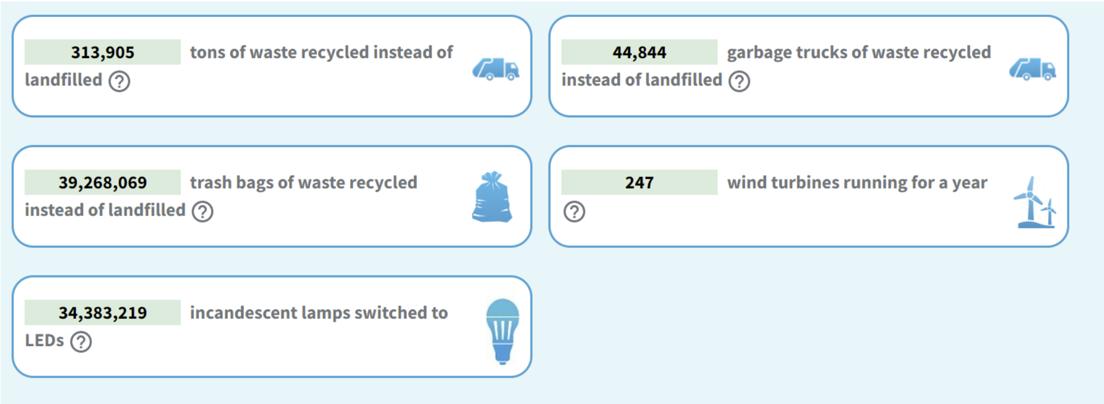
Limitations:

The estimation greatly depends on the fuel mix replaced by renewables. Therefore, this tool is only used to provide a general avoided emissions estimation in a certain scenario rather than an absolute number which will require further information on baseline electricity use and technology displacement options (IRENA, 2021). However, only the country and the electricity generated from renewables is considered in this tool. In addition to that, in some cases, the country data is missing such as for Lichtenstein. More importantly, decision-makers such as mayors would need more specific information to consider the issues in smaller regions such as cities, and residential areas rather than the whole country. Therefore, the lack of smaller regions such as cities and focus on GDH systems limits the use of this tool in this study.

2.3.2 Greenhouse Gas Equivalencies Calculator

The greenhouse gas equivalencies calculator developed by the United States EPA is used to communicate the benefits of greenhouse gas reduction targets by translating abstract numbers to concrete terms such as tons of waste recycled instead of landfilled with the associated GHG emissions (EPA, 2022). The tool contains two steps. The first step is to enter and convert the data (energy or emission data). The second step is to see the equivalent amount CO_2 emissions from using that amount translated to known entities. For example, the equivalents of one million-ton CO_2 emission avoided are shown in Figure 8.

Figure 8. Equivalent of One Million-ton CO_2 Emission Avoided



Source: EPA tool, 2022

Strengths:

This calculation tool translates abstract emissions or energy data to concrete terms that city managers and policy makers can easily understand. It is an effective tool for presenting the city's greenhouse gas reduction plan, targets, and other actions aimed at lowering greenhouse gas emissions (EPA, 2022).

Limitations:

These are rough estimates that should not be used for emission inventories or formal carbon emissions assessments (EPA, 2022). Therefore, the estimation can be taken as a reference for city management but cannot be counted as a formal emissions assessment.

2.3.4 GBD Results Tool

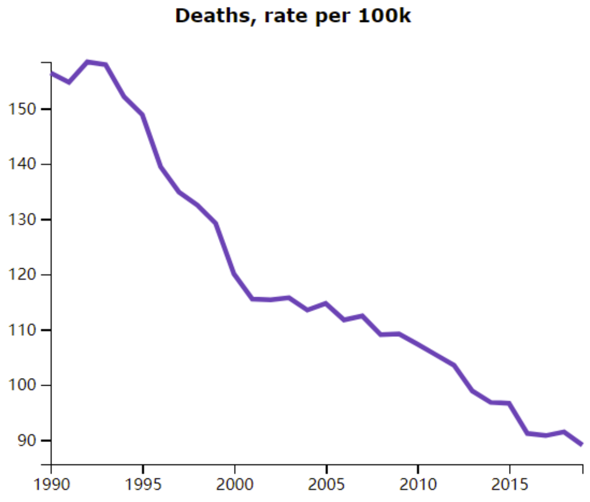
Everybody deserves to live a long and healthy life. To aspire towards this goal, a comprehensive picture of what disables and causes death across countries, time, age, and gender is needed. The Global Burden of Disease (GBD) tool is used to estimate health loss from hundreds of diseases, injuries, and risk factors to improve health systems and eradicate inequities (IHME, 2022). The first step to use this tool is to query the data by specifying the query parameters using the tool's controls. Once the query parameters are identified, then click the search button to execute a query (Figure 9).

Figure 9. GBD Results Tool User Interface: Drop-down Menus

Source: IHME, 2022

For instance, by querying the location (Hungary), year (2019), risk (air pollution), cause (all-cause), sex (both), and age (standardized) of Hungary, there are 43.76 deaths per 100 000 population due to air pollution in Hungary (see Figure 10).

Figure 10. Death Rates from Air Pollution in Hungary, 2019



Source: IHME, 2022

Strengths:

The GBD results tool is a useful calculator for querying and obtaining GBD data. IHME has distilled large volumes of information into a set of interactive data visualizations that allow individuals to make sense of over one billion data points collected. It makes these results more accessible and valuable. Another strength of this tool is the variety and complexity of data. The data are collected and analysed by a consortium of over 7000 researchers from 156 countries and territories, capturing premature death and disability from more than 350 diseases and injuries in 195 countries, by age and gender, from 1990 to the present, allowing comparisons over time, across age groups, and among populations (IHME, 2022). The GBD machinery's adaptable design allows for regular updates as new data and epidemiological studies become available. As a result, the tools may be used at the global, national, and local levels to study health patterns over time (ibid). Moreover, the tool can return results both as a visualization (a web-based data table with line charts) and as a CSV (comma-separated values) file. The CSV file is downloadable from the tool's user interface.

Limitations:

A limit of this tool is that queries with massive parameters can sometimes result in files that omit some results specified in the query – certain age groups, years, etc. Another limitation is that the tool does not work with Internet Explorer versions 10 and earlier which limits its users.

2.3.3 Summary Statement

Based on the review of the tools above, the tools are taken into consideration in this research work. IRENA avoided emissions calculator is used as an inspiration to calculate avoided emissions. Due to the fact that IRENA avoided emissions calculator calculates the emission saved from electricity generated by geothermal rather than the emission saved from GDH. Additionally, the emissions from GDH are much lower than the emissions from geothermal power plants for electricity generation. Therefore, the emissions from IRENA tool do not apply to GDH. However, it can be used as an inspiration for the author to develop the GDH benefits calculation tool. The greenhouse gas equivalencies calculator can be for illustrative purposes in the context of city management in the benefits calculation tool to translate one million-ton CO_2 emission to understandable entities. Since the part of the main audience of the research work might be policymakers and city managers this tool is considered as a side calculation to show what replacing fossil fuels with geothermal means in terms of other emitting sectors associated with city management. As for the GBD results tool, the results of death rate are applied in the calculation of output 5: the annual premature deaths avoided due to poor air quality.

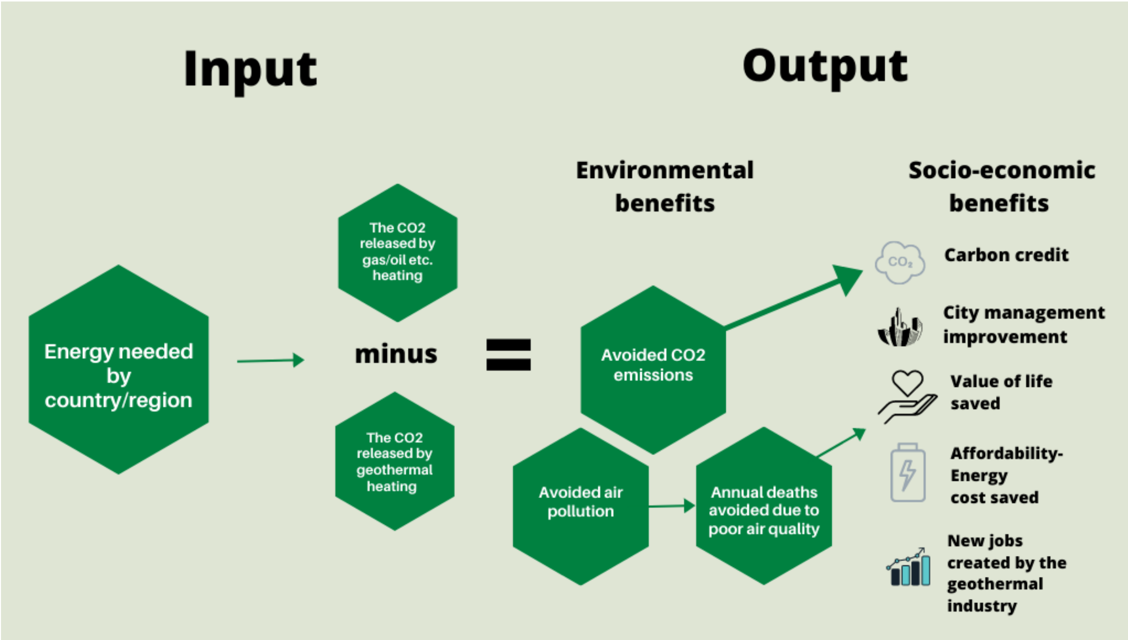
3 The Measurement Tool: The Benefits Calculation Tool

3.1 The Introduction of the Benefits Calculation Tool

In the previous section, the environmental and socio-economic benefits of geothermal district heating have been discussed to address the first research question. In this section, the aim is to provide a quantitative measurement of those benefits mentioned and simultaneously the benefits calculation tool is introduced. First, the overall methodology is presented. Then, each calculation is described and explained.

The methodology of the benefits calculation tool is illustrated in Figure 11. The calculation tool contains two parts: inputs and outputs. The input part includes the energy needed by a certain country; the CO_2 emissions released by the fossil fuel as well as the CO_2 emission released by the GDH. Given the energy needed by a certain country or region and the emission factors of the fossil fuel used, the CO_2 emission released by the fossil fuel can be calculated. The CO_2 emission released by GDH is calculated based on the emission factor. The output part contains the environmental benefits and the socio-economic benefits. The avoided CO_2 emissions are a calculated result of the CO_2 emission released by the fossil fuel minus the CO_2 emission released by GHD. The carbon credit gained is then derived from the avoided CO_2 emission. As other air pollutants derived from GHD are non-existent, the avoided air pollution can be assessed directly from expected emissions from fossil fuels. This is translated to annual deaths avoided due to poor air quality and the value of life saved is estimated.

Figure 11. The Benefits Calculation Tool



3.2 Key Assumptions

The key assumptions and their sources in the benefits calculation tool are listed in Table 8.

Table 8. Key Assumptions of the Benefits Calculation Tool

<table>
<tr><th>Assumption</th><th>Content</th><th>Reference</th></tr>
<tr><td>Emission Released by Fossil Fuels per TJ (tonne CO_2/TJ)</td><td><table><tr><th>Fossil Fuels</th><th>Emission Factor (tCO_2/TJ)</th></tr><tr><td>Natural gas</td><td>56.00</td></tr><tr><td>Hard coal</td><td>95.81</td></tr><tr><td>Residual fuel oil</td><td>79.30</td></tr></table></td><td>IPCC, 2016</td></tr>
<tr><td>Emission Released by GDH per TJ (tonne CO_2/TJ)</td><td>3.67[3]</td><td>EFLA, 2020</td></tr>
<tr><td>Carbon Credit (€/tonne of CO_2)</td><td>88.19 (EU ETS)</td><td>Ember, 2021</td></tr>
<tr><td>Air Pollution Emission Factors – Natural Gas</td><td><table><tr><th>Pollutant</th><th>Emission Factor (kg/TJ)[4]</th></tr><tr><td>N_2O-Uncontrolled (Nitrous Oxide)</td><td>0.95</td></tr></table></td><td>EPA, 2020</td></tr>
</table>

[3] Please note that the number might be different from source to source. The number is based on data collected in Reykjavik and the estimated emission released as a byproduct of the electricity generation is 226,2 g CO_2eq/m3(or 1.57 tCO_2/TJ) of water (31.5 °C) in the district heating system. However, in Table 4, the water temperature is 40 °C. Therefore, a temperature drop in the water is expected. If it is only from low-enthalpy resources, the emissions are usually considered zero.

[4]Unit conversions: 1 lb = 0.454 kg, 10^6 scf =1.02 TJ

For example, Emission Factor of SO_2 (kg/TJ) = (0.6 Ib/10^6 scf *0.454 kg)/1.02 TJ = 0.27 kg/TJ

	PM (Total): 3.38 SO_2: 0.27[5] TOC (Total Organic Compounds): 4.90 VOC (volatile organic compounds): 2.45	
Implicit value of a statistical life	International: 0.2 - 74.1 (millions 2000 US$)[6] Hungary: 2.32 (year 2015 US$) or 2.15 (year 2015 €)	Viscusi & Aldy, 2003 WHO OECD (2015).
Equivalents of 1-million-ton CO_2 Emission Avoided	**Item** / **Equivalent** Tons of waste recycled instead of landfilled: 313 905 Garbage trucks of waste recycled instead of landfilled: 44 844 Wind turbines running for a year: 247	EPA, 2022

[6] Please note the big range is due to the differences in income levels, mean risks, nonfatal risk and workers' comp. Therefore, for accurate estimation, a specific value for each country is required.

<table>
<tr><td>Geothermal Energy Heating Price</td><td>18.1 €/MWh = 5 027.82 €/TJ (18.1* 277.7[7])
All EU countries, average: 18.1 €/MWh
Iceland: 15.84 €/MWh = 4 398. 77 €/TJ (15.84*277.7)
Hungary: 43 €/MWh = 119 41.1 €/TJ (43*277.7)</td><td>Energiforsk, 2016</td></tr>
<tr><td>Job Creation by Energy Type</td><td><table><tr><th>Energy Type</th><th>Total Employment per TJ (person-years)</th></tr><tr><td>Geothermal</td><td>7</td></tr><tr><td>Natural Gas</td><td>0.44</td></tr></table></td><td>Jennejohn, 2010</td></tr>
</table>

[7] 1 TJ = 277.7 MWh

3.3 Inputs

3.3.1 Input 1: Annual Energy Consumption per Capita (TJ/per person)

Estimated annual national residential use of specific heating energy in one nation in a specific year. The data of annual national residential use of fossil fuels is provided by the International Energy Agency (IEA). For example, the natural gas final consumption in residential sector in Hungry is 129 926 TJ in 2019 (IEA, 2022). The energy consumption per capita in a specific year can be calculated in the equation below:

Annual fossil fuel consumption per capita (TJ/per person) = Annual national residential use of fossil fuel / National population

3.3.2 Input 2: Annual Regional Residential Use of Fossil Fuel (TJ)

Estimated annual regional residential use of specific heating energy in one region in a specific year. Knowing the energy consumption per capita in a certain country and the regional population, the annual regional residential use of specific heating energy can be calculated as below (assume homogeneity in energy used):

Annual regional residential use of fossil fuel = Annual energy consumption per capita* Regional population

3.3.3 Input 3: Annual Total CO_2 Released by Fossil Fuels (ton CO_2)

The annual total amount of CO_2 released depends on the type of fossil fuel. The emission factors of different fossil fuels can be found in Table 8. Therefore, the annual total CO_2 released by fossil fuels can be calculated as:

Annual total CO_2 released by fossil fuels= Emission factor*Annual regional residential use of fossil fuel

3.3.4 Input 4: Percentage of Geothermal in the Total Energy Consumption (X%)

The percentage of geothermal energy in the total energy consumption (X%). The energy transition is usually taken step by step, therefore, how much CO_2 emission can be saved depends on the percentage of geothermal energy in the total energy consumption.

3.3.5 Input 5: Annual Regional CO_2 Released by GDH (tons CO_2)

Please note that the number might be different from source to source. The number is based on the data collected in Reykjavik and the estimated emission released as a byproduct of the electricity generation is 1.57 tCO_2/TJ (or 226.2 g CO_2eq/m3) of water in the district heating system (EFLA, 2020). If it is only from low-enthalpy resources, the emissions are usually considered zero. Therefore, the annual regional CO_2 released by GDH systems is estimated in the equation below:

Annual CO_2 released by geothermal (tons CO_2) = Emission released by geothermal per TJ * Annual national residential use of fossil fuel * Percentage (0% - 100%) of geothermal in the total energy consumption

3.4 Outputs

3.4.1 Output 1: Annual Avoided CO_2 Emissions by Using Geothermal (Million-ton CO_2)

The equation to calculate the annual avoided CO_2 emissions by using geothermal is shown below:

Annual avoided CO_2 emissions by using geothermal (Million-ton CO_2) = The annual CO_2 emission released by fossil fuels * Percentage of geothermal in the total energy consumption - The annual CO_2 emission released by geothermal

3.4.2 Output 2: Carbon Credits Gained

One ton of carbon emission saved is equal to one carbon credit. According to the latest data on EU ETS carbon prices (Figure 6), the EU ETS price is €88.19/tCO_2 by the 10th of May, 2022 (Ember, 2022). Therefore, €88.19/tCO_2 is used in this calculation tool. The calculation formula is:

Carbon Credits gained (euro) = €88.19 * Annual avoided CO_2 emissions by using geothermal

3.4.3 Output 3: Equivalents of 1-million-ton CO_2 Emission Avoided

This is a side calculation to show what replacing fossil fuels with geothermal means in terms of other emitting sectors in the context of city management. Based on the key assumptions in Table 8, the calculation equations are:

- ***Tons of waste recycled instead of landfilled = Annual CO_2 emissions avoided by using geothermal *313 905***

- ***Garbage trucks of waste recycled instead of landfilled = Annual CO_2 emissions avoided by using geothermal *44 844***

- ***Wind turbines running for a year = Annual avoided CO_2 emissions by using geothermal * 247***

3.4.4 Output 4: Annual Air Pollution Saved (ton/year)

Natural gas is widely used for residential heating. For example, natural gas is used for space heating for more than half of the homes in the US (U.S. Energy Information Administration, 2022). In this study, the annual air pollution saved is based on transferring from natural gas to geothermal energy for heating (see case study for Budapest, below).

The emission factor of each pollutant of natural gas is shown in Table 8. Therefore, the equation to calculate the annual air pollution saved is as below:

- ***Annual air pollution saved (ton/year) = Sum of air pollutants from fossil fuel - SO_2 emissions from geothermal (substituted by H_2S)***
- ***Sum of air pollutants from fossil fuel = N_2O emissions + PM (total) emissions + SO_2 emissions + TOC emissions + VOC emissions***
- ***N_2O emissions (ton) = Annual regional residential use of fossil fuel * Percentage of geothermal in the total energy consumption *0.95***
- ***PM (total) emissions (ton) = Annual regional residential use of fossil fuel * Percentage of geothermal in the total energy consumption *3.38***
- ***SO_2 emissions (ton) = Annual regional residential use of fossil fuel * Percentage of geothermal in the total energy consumption *0.27***
- ***TOC emissions (ton) = Annual regional residential use of fossil fuel * Percentage of geothermal in the total energy consumption *4.90***
- ***VOC emissions (ton) = Annual regional residential use of fossil fuel * Percentage of geothermal in the total energy consumption *2.45***

3.4.5 Output 5: Annual Premature Deaths Avoided Due to Poor Air Quality

The WHO estimates that around 8 million people die every year from exposure to fine particles in polluted air that penetrate deep into the lungs and cardiovascular system, causing diseases including strokes, heart disease, lung cancer, chronic obstructive pulmonary diseases and respiratory infections, including pneumonia (WHO, 2022). However, air pollution is not the same everywhere. Pollutants are emitted into the environment from a range of both man-made and natural sources, including industry, transportation, agriculture, waste management, burning of fossil fuels in households and natural sources like volcanic eruptions (European Environmental Agency, 2021). For example, residential space heating is a major contributor to PM2.5 emissions in the EU (IEA, 2016).

Death rates from air pollution change due to the change in air pollutant levels. In this thesis, the data of death rates are retrieved from Institute for Health Metrics and Evaluation (IHME), GBD. Death rates are measured as the number of deaths per 100 000 population from both outdoor and indoor air pollution (IHME, 2019). Rates are age-standardized, meaning they assume a constant age structure of the population to allow for comparisons between countries and over time (IHME, 2019). The percentage distribution of air pollutant emissions from household heating depends on the country. For example, in 2017 in Hungary, 87% of the PM 2.5 emissions, 63% of the PM 10, 21% of the NOx emissions, 85% of the CO emissions and 29% of the CO2 emissions were derived from heating in households (Mentes et al., 2019). The average percentage of pollutants from household heating is assumed to be 57%[8]. Therefore, the annual premature deaths avoided due to poor air quality can be estimated as:

Premature death rate due to pollution = The number of deaths of a given country or region

[8] 57% = (87%+63%+21%+85%+29%)/5

Annual premature deaths avoided = Percentage of distribution of air pollutant emissions from household heating* Geothermal percentage* Regional population* Death rate

3.4.6 Output 6: Value of Life Saved ($ million)

Due to the use of geothermal energy for heating, the air quality can be significantly improved. Therefore, we can assume fewer people would get sick or even die due to poor air quality. The purpose of this calculation is to put a monetary value to the death caused by air pollution from fossil fuel heating. The estimated life value can be referred to Table 8. Therefore, according to the annual deaths avoided due to poor air quality, the value of a life saved can be calculated as:

Value of life saved = Annual death amount* Estimated life value

3.4.7. Output 7: Affordability - Energy Cost Saved ($ million)

The use of GDH promotes energy affordability. The energy cost saved because of using GDH can be calculated as:

Energy cost saved ($ million) = (Fossil fuel energy heating unit cost – geothermal heating unit cost) * Annual regional residential use of fossil fuel * Percentage of geothermal in the total energy consumption

3.4.8 Output 8: Job Growth by Geothermal Development (person-years)

Geothermal development contributes to job growth. Therefore, the job growth by geothermal development per TJ can be calculated as:

Job growth by geothermal development per TJ = Annual regional residential use of fossil fuel*Percentage of geothermal in the total energy consumption*Total Employment per TJ of geothermal (Table 8)

4 Case Study: Budapest, Hungary

4.1 Project Information

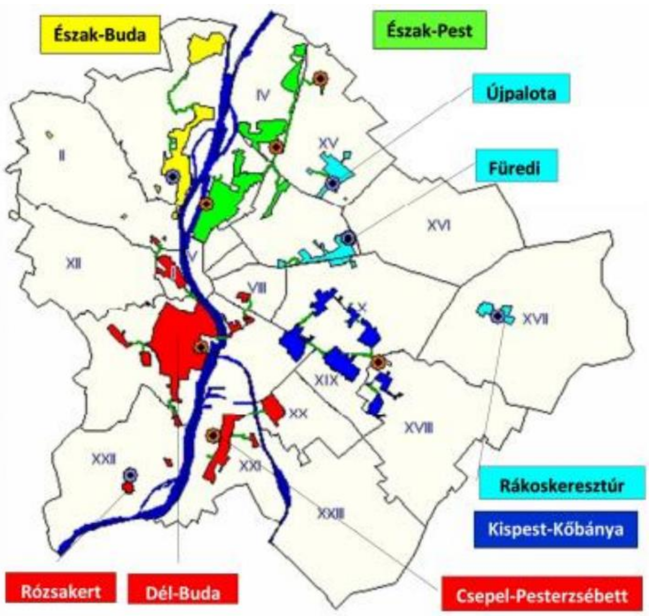
4.1.1 Geothermal Use in Budapest

Hungary has significant geothermal potential. Thermal baths can be found in any part of the country, and Budapest is known as the city of baths. The thermal water temperature in Hungary is normally 80-120°C which can be perfectly used for geothermal heating (Aniko, David & Attila, 2020). Geothermal power generation is more limited in the country because this medium-range temperature is hardly suitable for industrial power generation, but in some places, higher temperatures can be found. District heating supplied by geothermal energy is working in numerous locations in the country and a geothermal power plant is in operation in Tura (50 km from Budapest). However, until today, the production for heating purposes is still at the early phase in Budapest. Some small systems are working with few blocks of flats to be heated by the Paskál well. A larger system was built for the heating of the zoo by well of the Széchenyi spa.

4.1.2 District Heating System in Budapest

A significant part of the district heat production in Budapest is carried out by independent companies based on contractual relationship with FŐTÁV. Currently the main heat source is natural gas burned in different heat plants and power plants in the city. This dependence is also reinforced by FŐTÁVs existing district heating infrastructure, consisting of independent heat islands. The district heating system could not be considered as a connected, unified system as the FŐTÁV operates eight hydraulically independent heat islands. However, a large-scale development project aiming to connect the major systems are already under execution in the city. The heat islands are represented in Figure 12.

Figure 12. **Territorial Coverage of the Főtáv District Heating System**



Source: Főtáv Zrt, personal communication, 2021

The Budapest District heating faces many new challenges, including changes in the socio-economic and regulatory environment, the variable heat consumption habits of consumers, the revitalization of the financing environment of building HVAC (Heating, ventilation, and air conditioning) renovations and the renewal and repositioning of the producer market.

4.1.3 Proposed Project Areas in Budapest

Arctic Green Energy (AGE) and FŐTÁV intend to work together to explore and utilize the geothermal district heating possibilities in Budapest. The aim is to explore and present the potential geothermal district heating connection possibilities to the FŐTÁV district heating system. The main goal of AGE in Budapest is to build up a capacity of 200 MW with baseload built for a population of approx. 800 000, which is approximately 40% of the population in "big Budapest" (FŐTÁV, 2021). The area in question is in the east-south-eastern part of Budapest, 15 km distance E-SE from the Danube. The following four project areas are proposed (Mannvit, personal communication, 2021):

1. Rákoskeresztúr heat island: the geothermal reservoir is located at -1500 m below the heat plant. At that depth, the calculated reservoir temperature is estimated to be between 85°C to 95°C. Outflow temperature is estimated to be 80°C to 90°C.
2. Kőbánya-Kispest heat island: the geothermal reservoir is located at -2000 m depth at the south-eastern end of the heat island with a temperature of 105°C to 120°C. Outflow temperature is estimated to be higher than 100°C, possibly 110°C. The production rate estimate is 25 –50 l/s.
3. Csepel (North-Csepel-Olympic village): the geothermal reservoir is located at -5-600 m depth at the site of the Olympic village, which sits on the top of Csepel island. Outflow temperature is estimated to be ~ 55°C. Production rate estimate is 25 –30 l/s.
4. Dürerpark: the geothermal reservoir is located at -1300 m below the Project site. At that depth, the calculated reservoir temperature is estimated to be between 75°C –80°C. Outflow temperature is estimated to be 75°C. Production rate estimate is 25 –50 l/s.

4.2 Benefits Calculation Tool Analysis

Below the benefits calculation tool is applied for the case described above, incorporating current conditions in Budapest. According to the data from IEA, currently natural gas is the main fuel used for heating purposes in Hungary and especially in the residential sector (IEA, 2022). Therefore, in this case study, natural gas is considered as the fuel to be replaced. A total of 40% of the use of natural gas is assumed to be replaced by geothermal energy.

In 2019, the residential use of natural gas was 129 926 TJ-gross in Hungary (IEA, 2022). Given the population of 9 778 371 in the whole country with a population of 1 752 286 in Budapest (the Hungarian Central Statistical Office, 2021). The natural gas consumption per capita is calculated as 0.01 TJ per year in Hungary and the annual regional residential use of natural gas (TJ) in Budapest (Table 9) is 23 283 TJ. The estimated annual total CO_2 released is 1 303 835 tons (Table 9) when natural gas is used for residential heating.

Table 9. Benefits Calculation Tool Analysis of Budapest – Inputs

Region	Budapest, Hungary
Year	2019
Annual national residential use of natural gas (TJ)	129 926
Energy consumption per capita (TJ/per person)	0.01
Regional population	1 752 286
Annual regional residential use of natural gas (TJ)	23 283
Fossil fuel type	Natural gas
Emission released by natural gas per TJ (ton CO_2/TJ)	56.00
Annual total CO_2 released by natural gas (ton CO_2)	1 303 835
Percentage of geothermal in the total energy consumption	40%
Emission released by geothermal per TJ (tnCO_2/TJ)	Zero
Annual CO_2 released by geothermal (ton CO_2)	Zero

Please note that the emission factor of geothermal in this case isn't the same from the assumption in Table 8. Since it is the direct use of low enthalpy geothermal sources and doesn't involve electricity production in the project areas in Budapest, the emission factors of CO_2 and H_2S should be lower (nearly zero) than in Reykjavik. Therefore, the estimated CO_2 and H_2S emissions released by geothermal in this case are assumed as zero.

Table 10 presents the results from the benefits assessment tool and the environmental and socio-economic benefits of replacing natural gas with geothermal energy. The annual CO_2 emissions avoided by using geothermal are estimated to be 0.52 million tons amounting to €46 million carbon credits. The relevance of the avoided emissions is shown in the context of city management improvement as the annual CO_2 emissions avoided are equal to 163 712 tons of waste recycled instead of landfilled, 23 388 garbage trucks of waste recycled instead of landfilled and equal to the emissions saved using 108 wind turbines running for a year.

In Hungary, the amount of gas and air pollutants from solid fuel combustion used by the public during the heating season represents a significant percentage of the total amount of air pollution. In 2017 in Hungary, 87% of the PM 2.5 emissions, 63% of the PM 10, 21% of the NOx emissions, 85% of the CO emissions and 29% of the CO_2 emissions were derived from heating in households (Mentes et al., 2019). The average percentage of pollutants from household heating is assumed to be 57%. Switching to geothermal will accordingly improve air quality, and avoid deaths. The death rate from air pollution in Hungary was 43.76 deaths per 100 000 population in 2019 (IHME, 2019). Therefore, the annual deaths avoided due to improved air quality in Budapest is estimated to be 175 and the value of life saved per year is 376 million € (in 2015 €). Also, by replacing natural gas with GDH, the heating energy cost saved is €26 million annually contributing to the affordability of heating energy prices. Finally, the assessment shows that 65 192 new jobs (without considering job lost in the natural gas sector) will be created in a long term as a result of the geothermal development in Budapest stimulating economic growth in Budapest, particularly in the project area.

Table 10. Benefits Calculation Tool Analysis of Budapest – Output

Annual avoided CO2 emissions by using geothermal (million-ton CO_2)	0.52
Carbon credits gained (million euro)	46
Avoided emissions equal to tons of waste recycled instead of landfilled	163 712
Avoided emissions equal to garbage trucks of waste recycled instead of landfilled	23 388
Avoided emissions equal to wind turbines running for a year	108
N_2O (uncontrolled) emission saved (ton/year)	9
PM (total) emission saved (ton/year)	31
SO_2 emission saved (ton/year)	3
TOC emission saved (ton/year)	49
VOC emission saved (ton/year)	23
Annual total air pollution saved (ton/year)	112
Annual deaths avoided due to improved air quality	175
Value of life saved (2015 €)	376
Affordability - energy heating saved (€ million)	26
Job growth by geothermal development (person-years)	65 192

5 Discussion

This thesis has investigated the benefits of geothermal district heating in the environmental, social and economic dimensions of sustainability and aimed to quantify those benefits. For this purpose, a benefits calculation tool was created. The benefits calculator was applied in a specific case for the city of Budapest, Hungary to figure out how the city can benefit from replacing natural gas heating systems with GDH systems. The findings illustrate that this is a complex multidisciplinary subject. In section 5.1, the most important findings for the three research questions are discussed in accordance with the relevant literature. After that, section 5.2 highlights the strengths of the approach. Finally, section 5.3 discusses the limitation of this study and the directions for future research.

5.1 Research Questions Answered

In this thesis, possible environmental and socio-economic benefits as a result of GDH development worldwide were reviewed. The indicators of each benefit were analysed and, as part of the research results, the benefit calculation tool was developed to provide quantitative measurement of the benefits.

1) What are the environmental and socio-economic benefits associated with GDH?

The results of this study indicate a range of benefits associated with GDH, among them there are seven key environmental and socio-economic benefits associated with GDH replacing natural gas heating. Those are: 1) annual avoided CO_2 emissions by using geothermal, 2) air pollution avoided, 3) annual deaths avoided as a result of higher air quality, 4) carbon credit gained, 5) the value of life saved, 6) energy cost saved, 7) job growth from investing in GDH systems. The key benefits described in this research are largely in line with the existing literature on GDH. The research found out the most significant benefits identified are the affordability of GDH compared to fossil-fuels heating systems (Energiforsk, 2016; Goldemberg & Johansson, 2004), CO_2 emissions reduction as a result of replacing fossil fuels with GDH (Oktay & Aslan, 2007; Ruirui, et al., 2020; Fridleifsson et al., 2008; Pálvölgyi & Buzási, 2021; Wachowicz-Pyzik et al., 2022; Szanyi & Kovács, 2010), air quality improvement (World Bank, 2022; Delft, 2020; Ogola et al., 2011;), higher level of happiness as well as better living conditions (Huete-Alcocer et al., 2022; Zhang et al., 2016) and economic growth stimulation through e.g., job creation (IRENA, 2021; Jennejohn, 2010). Moreover, the research also investigated how geothermal energy development is aligned with the UN SDGs (Figure 6) and thereby fulfilled the three dimensions of sustainable development. For the environmental dimension, geothermal energy development contributes greatly to SDG7 (Pálvölgyi & Buzási, 2021; Pająk et al., 2020) as well as SDG 13 (Fridleifsson et al., 2008). By providing environmental-friendly district heating solutions to urban district heating systems (Pálvölgyi & Buzási, 2021; Pająk et al., 2020; Zhang, et al., 2016), geothermal energy is used to improve living conditions and promote well-being (SDG3), therefore, it progresses the development in the social dimension. It is proven that one of the most significant inputs for economic development is energy (Sharma, 2010). Therefore, geothermal energy development is aligned with SDG1 (Ogola et al., 2012) and SDG 8 (Jennejohn, 2010) by stimulating economic growth and creating green job opportunities. However, the environmental and socio-economic benefits associated with GDH vary, depending on the conditions in each region. In this study, the author chose to focus on the key benefits mentioned, as they appear most frequently in the literature mentioned above, and they are applicable to most of the countries that have the need for heating and potential geothermal sources for GDH. Additionally, it is worth mentioning that even though GDH systems are extensively used in some countries like Iceland, they are scarcely applied in other countries. To further elaborate, despite the fact that geothermal potential exists worldwide, and population density and outdoor temperatures necessitate the deployment of a GDH system, the small number of systems implemented poses the question that why only a few cities utilise GDH systems. One possible explanation might be the lack of incentive policies to promote the use of GDH systems. Another explanation might be the lack of awareness and knowledge of how beneficial it is to utilize GDH systems.

2) How to measure or quantify those benefits? What are the applicable indicators and metrics?

Based on the literature review, the research results suggest that the indicators and metrics needed to reveal the value of the chosen benefits are: 1) the CO_2 emissions factors of different energy sources (EFDB IPCC, 2016; EFLA, 2020), 2) the air pollutions emission factors such as PM10, SO_2, NOx etc. of natural gas and geothermal energy (EPA, 2020; Aradóttir et al., 2015), 3) CO_2 emission avoided (EPA, 2022) and air pollution avoided, 4) changes in death rates and thereby the number of deaths due to reduced air pollution (IHME, 2019), 5) the value of life (Nils, 2016), 6) carbon pricing – derived from EU ETS (IETA, 2021), 7) levelized cost of heat by geothermal energy compared to fossil fuels (Earl & Ghanashyam, 2017) and 8) net job growth from geothermal (Jennejohn, 2010).

Existing research recognises the critical role played by GHD systems in realizing the energy transition and proposes the possible indicators to quantify those benefits GHD can bring. Nevertheless, when reviewing the literature, a clear path was not found in order to quantify those benefits to see a better picture and no applicable benefit calculation tool was found that captured the necessary benefits. Thus, a new approach was needed which resulted in the benefits calculation tool which was developed to gather all the measurement indicators collected in the research into one assessment. This tool can then be used to provide an estimation to illustrate the potential benefits of utilizing renewable geothermal energy for district heating in a certain region. The main advantage of this tool is its ability to provide a general quantitative estimate of the benefits of GDH in a certain region without investing a big amount of time and energy. Furthermore, the case study of Budapest presents the use experience of this tool and can be easily duplicated elsewhere.

3) Case study - How can Budapest benefit from replacing natural gas heating systems with GDH systems?

The case study in Budapest is an example of the practical use of the tool and shows the benefits of transferring from natural gas to renewable GDH systems in Budapest. According to Table 10, the annual avoided CO_2 emissions by using GDH is 0.52 million tons and that is 0.2 968 tCO2e reduction per capita in the project area. The average Hungarian GHG emission was 6.5 tCO2e per capita in 2018 (OECD, 2021). Even though the scale of this project is rather small, the CO_2 emissions avoided from this project can reduce at least 4.6% of the total GHG emissions in Hungary. The CO_2 emissions avoided can be counted as €46 million carbon credit gained.

All of 100% of the Hungarian population were exposed to concentrations above the various WHO-recommended thresholds for air pollution in 2019 (OECD, 2021). Hungary has the world's second highest air pollution death rate, only behind China (Euronews, 2019). Each year, up to 10 000 individuals in Hungary die prematurely as a result of diseases linked to air pollution (ibid.). The annual cost of air pollution for Budapest residents is around HUF 677 000 (€1 773) (Nicholas, 2020). In the case study, it is estimated that the annual deaths avoided due to air pollution from fossil fuels heating are 175. Then if a monetary value of life (Hungary: €2.15 million) is assigned to each death avoided, then the total value of life saved in this case is €376 million. In addition, this energy transition brings economic benefits as well. Firstly, the annual heating energy cost saved is estimated to be €26 in total. Moreover, the number of job creations is expected to be 65 192 person-years. That is 61 094 more than the jobs created in the natural gas heating sector (4 089 person-years).

Overall, given the small scale of the project, a 4.6% reduction in GHG emissions for the nation is significant, as are the health and economic benefits. For the authorities in Budapest, the results of the case study imply that GHD brings significant benefits and can be used to showcase a green development concept and contribute to the Hungarian target to realize net-zero emissions by 2050. The case study also illustrates that the tool is useful in practice and can be used in other locations.

5.2 Strengths of the Approach – Practical Use

This thesis provides a general overview of the utilization of geothermal energy, with a focus on geothermal district heating. It covers the three dimensions of sustainable development, and the evidence of the five SDGs was discussed based on the relevant literature. By translating all benefits identified into the universal language of data, a benefit assessment tool was created to enhance the understanding of GDH benefits. The tool is fundamental to simplifying the assessment of the environmental and socio-economic benefits helping to illustrate the advantages of GDH.

In addition, the findings in this thesis help to create business value for AGE and to close a market gap by presenting the benefits calculation tool. To this author´s knowledge, there is no such tool on the market that specially focuses on the estimation of the environmental and socio-economic benefits of geothermal district heating. The tool can be considered to be a geothermal promotion tool and can play a key supporting role by supporting informed and verified decisions.

Moreover, the case study in Budapest is an example of the practical use of the tool and demonstrates the potential of transferring from natural gas to renewable GDH systems in the context of the project. It can be easily duplicated for other regions when a new GDH project arises. The tool is convenient to use and can be used by stakeholders with different backgrounds and positions. The results of this study may benefit national and regional authorities, companies, institutions and organizations conducting policy- and decision-making regarding geothermal district heating development. Specifically in Hungary but also in other countries. These entities can both take advantage of the knowledge shared by the study as well as the methodology if they intend to carry out a similar benefits estimation of geothermal district heating developments. Conclusively, the tool provides the most intuitive user experience and helps turn insights into action, cut down analysis time and change behaviours that help everyone be more data-driven across the sectors.

5.3 Limitations of the Approach and Further Research

While this approach has several strong advantages, there are also limitations which must be considered. One of the limitations is that the research does not include all potential benefits such as an increase in energy security. Another limitation is the general value used in some of the benefits calculations such as output 5: the annual deaths avoided due to poor air quality and employment created pleasured by person-years. For the job creation assessment, the value is very high and there is uncertainty regarding this value, but no better data have been found. However, the point is to prove that the development of geothermal generates a lot more jobs than natural gas. A general value is used due to the fact that the benefits calculation tool is designed to be applied to more than one case. However, the estimation results might not be fully accurate in all cases because of regional differences such as different death rates in different regions. Therefore, it is an approximation of the annual death amount avoided and it is a limitation in this research. If air pollution deaths in Budapest are higher than on average, the avoided deaths assessed by the benefits assessment tool are undervalued. The same applies to for example assessments of air pollution, and thereby air pollution avoided. Therefore, the benefits calculation results provide a fairly general estimation rather than an absolutely accurate assessment. Also, the relationship between pollution and the number of premature deaths is complex and the pollution level is changing due to several factors such as wind speed. Therefore, in the calculation Output 5: Annual Premature Deaths Avoided Due to Poor Air Quality, the air pollutant is considered as compartmentalized, i.e., the pollution switched off in one compartment while remaining in another. That is one way to provide the estimation in an ideal situation and regardless of the factors such as wind speed that might affect the air quality. Therefore, it is one of the limitations of the approach.

In further research, it would be interesting to research the benefits of replacing other energy types with geothermal district heating in addition to more benefits categories. For instance, the replacement of traditional biomass with geothermal energy, an increase in energy security, and reduced land use compared to other energy sources. Also, it would be interesting to explore the visualization possibilities of the tool, for example, to use the Tableau software to create a web-based data table with line charts to provide a better interface for users.

6 Conclusion

The study identified and assessed the environmental and socio-economic benefits of establishing geothermal district heating and the results suggest that in general GDH is beneficial and important. GDH has the potential to provide a clean, affordable and reliable heating solution to meet the heating needs in many countries. Moreover, by developing a benefit calculation tool, this thesis helps to quantify the benefits associated with the development of GDH.

Based on a case application of the benefits tool for the development of GDH in Budapest, it can be concluded that district heating based on a geothermal system is a relatively clean heating solution that contributes to the progress of sustainable development. The main outcomes of the case study were: 1) by replacing 40% of the natural gas heating system with GDH, at least 4.6% of the total GHG emission is avoided in Hungary, 2) the practical application of the benefits calculation tool developed can be duplicated to another city and 3) the results can raise awareness of the benefits of developing GDH in Budapest.

To conclude, this study established a quantitative framework, a benefits assessment tool, for quantifying the environmental, and socio-economic benefits associated with GDH systems. Hopefully, the results and further use of the benefits tool might raise awareness of the significant benefits associated with replacing fossil fuel heating with GDH.

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