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Geothermal energy and sustainability: Economic, social and environmental life cycle analysis

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Abstract
This study is about the use of geothermal energy for electricity production, heating and cooling spaces and hot water supply. The technology and function of a geothermal plant is described, and the environmental, economic and social sustainability of geothermal energy is analysed. Furthermore, reference is made to Life Cycle Assessment, a method of environmental impact evaluation. Finally, the existing legislative framework of Greece, as well as previous forms of it is presented and the progress that has been made in favor of geothermal energy becomes apparent.

Περίληψη
Η παρούσα διπλωματική εργασία αφορά τη χρήση της γεωθερμίας και τις εφαρμογές της στην παραγωγή ηλεκτρικής ενέργειας, στη θέρμανση - ψύξη χώρων και στην παροχή ζεστού νερού. Γίνεται μια περιγραφή της τεχνολογίας και της λειτουργίας μιας γεωθερμικής εγκατάστασης και αναλύεται η βιωσιμότητα της γεωθερμίας σε περιβαλλοντικό, οικονομικό και κοινωνικό επίπεδο. Στη συνέχεια γίνεται αναφορά στην Ανάλυση Κύκλου Ζωής, μια μέθοδο αξιολόγησης περιβαλλοντικών επιπτώσεων και τέλος παρατίθεται το υπάρχον ρυθμιστικό / νομοθετικό πλαίσιο της Ελλάδας που αφορά στη γεωθερμία, αλλά και παλαιότερες μορφές αυτού και γίνεται εμφανής η πρόοδος που έχει συντελεστεί προς όφελος της γεωθερμίας.

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Contents

Abstract 2

Περίληψη 2

Acknowledgments 3

Contents 4

Nomenclature 6

1. Introduction to geothermal energy 8

2. Environmental Aspect 12

2.1: Life Cycle Assessment 12

2.1.1: Limitations 13

2.1.2: Sensitivity Analysis 13

2.1.3: Uncertainty analysis 14

2.1.4: Datasets and Software 14

2.2: LCA and geothermal energy 15

2.2.1: Environmental Impacts 15

2.2.2: Constraints 20

2.2.3: Life Cycle Assessment of various case studies 21

2.2.4: General Conclusions 31

3. Social Aspects 32

3.1 Public understanding 32

3.2 Energy consumption and household preferences 33

3.3 Energy poverty 34

3.4 Economic development- employment 35

3.5 Health and safety 35

3.6 Development of local infrastructure 36

3.7 Culture and Religion 36

4. Economic Aspects 38

4.1 Cost analysis of geothermal projects 38

4.1.1 Cost of GSHP systems for heating and cooling 38

4.1.2 Cost of geothermal power plants 38

4.1.3 Case studies in cost analysis of geothermal installations 39

4.2 Optimization of geothermal systems 45

4.3 General Conclusions 48
5. Legislative framework 49
5.1 Geothermal Energy regulations and policies in EU 49
5.2 Geothermal Energy Deployment in Greece 51
5.2.1 Objectives 51
5.2.2 Regulatory Framework 52
5.3 General Conclusions 54
6. Conclusions 55
Bibliography 57

Nomenclature

CarbFix: Carbon dioxide sequestration

CED: Cumulative energy demand

CEP: Clean Energy for All Package

CRES: Centre for Renewable Sources and Energy Saving

CSR: Corporate Social Responsibility

dB: DecibelE

DHS: District heating system

EED: Energy Efficiency Directive

ESS: European Social Survey

EU: European Union

GHG: Greenhouse gas

GHP: Groundwater heat pump

GWHP: Groundwater heat pump system

H&C: Heating and Cooling

HVAC: Heating, Ventilation, and Air Conditioning

HWCB: Hot water condensing boiler

INFORSE: International Network for Sustainable Energy

kW: Kilowatt

kWe: Kilowatt-electric

kWh: Kilowatt-hour

kWth: Kilowatt-thermal

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LCoE: Levelized Cost of Energy

LPG-HG: liquefied petroleum gas hot air generator

lt: litres

NCRE: Non-Conventional Renewable Energy

NECP: National Energy and Climate Plans

NPV: Net Present Value

O&M: Operating and Maintenance costs

PGE: Pertamina Geothermal Energy

PV-GHP: photovoltaic-geothermal heat pump

RD&I: Research, Development and Innovation (RD&I)

RES: Renewable energy sources

RES-HC: Renewable energy sources for heating and cooling

SGE: Shallow geothermal energy

SHW: Sanitary hot water

SulFix: Hydrogen sulphide gas removal

T: Temperature

Chapter 1

1. Introduction to geothermal energy

Geothermal energy is the power that derives from the subsurface. The continuous decay of radioactive particles, cause the earth to produce heat. This thermal energy is enclosed in the rocks and fluids beneath the surface and can be found from shallow ground to several kilometres depth, to the hot magma. As known, the earth's layers are not continuous but are formed of smaller pieces called tectonic plates, which are constantly moving. Through this movement, the plates either drift apart or collide, resulting earthquakes, that cause earth's crust to fracture or attenuate, allowing heat and hot magma to slip towards the surface and fluids, mostly rainwater, to penetrate from the surface to the subsurface. As surface water infiltrates at depth it exchanges heat with the hot rocks&, resulting in high-temperature underground ''ponds'', known as geothermal reservoirs. A reservoir that is by nature adequately hot and permeable is called hydrothermal. On the surface, these fluids that vary in temperature can be used to generate electricity, directly for applications that require thermal energy , or for geothermal heat pumps used in heating or cooling (H&C) applications that require lower temperature heat from shallow wells [1].

For thousands of years, humans exploited geothermal energy for bathing, cooking and therapeutic purposes. Until today, depending on geothermal waters temperature there are many applications that do not require the conversion of thermal energy to some other form but they use it directly. Main application areas are space heating and cooling, bathing and swimming (including bathing for therapeutic purposes), agriculture (greenhouses and soil heating), industrial processes (food and drink preparation), and aquaculture (mainly fish farming) [2].

For heating-cooling spaces and water heating besides an optimal location it is necessary to access and extract geothermal fluids, as well as reinject them back into the ground. The technology that is used for this process is called Ground Source Heat Pump (GSHP) or Geothermal Heat Pump (GHP) systems. Essentially, it is a circuit of underground water pipes and a heat pump that is placed at a ground level [2]. GSHP systems take advantage of the relatively stable temperatures of earth through seasons and the difference between the temperatures of above-ground air and the subsurface soil, using the physical property of liquids to absorb and release heat when they vaporize or condense. In details, when the pressure of a gas increases, the temperature also increases and vice versa as stated by the basic thermodynamic law where the heat is always transferred from a warmer object to a colder one. Furthermore, these systems require a small amount of electricity to run five times less than the energy they deliver, resulting in a net energy benefit. Their electricity source defines how environmentally clean and fossil-fuel free they are, but in general, GHSPs are highly efficient and one of the least environmentally harmful conditioning systems [3].

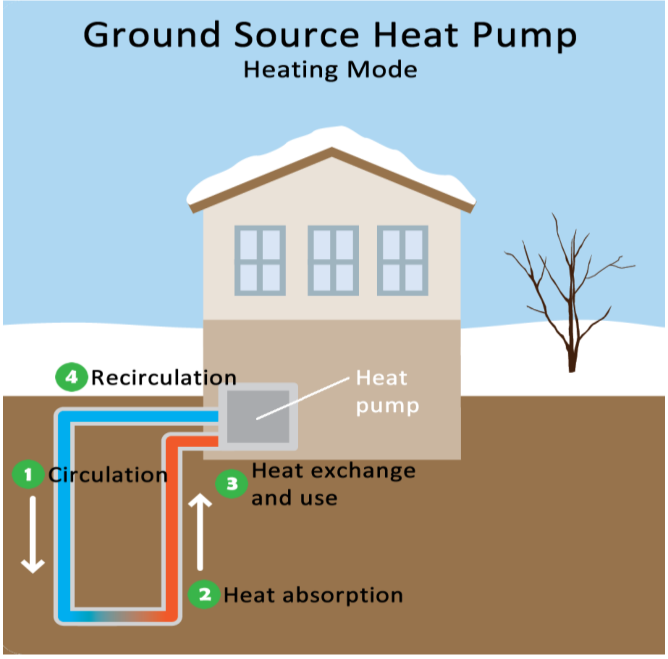

Figure 1 Illustration of a GSHP system for space heating purposes, takes heat from the ground, and delivers it to a building [3]

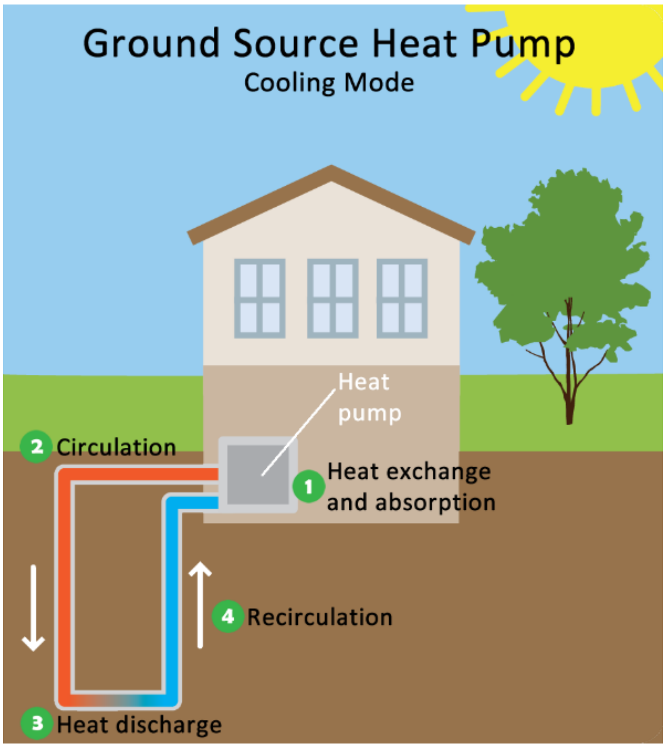

Figure 2 Illustration of a GSHP system for space cooling purposes, removes heat from the building and delivers it to the ground [3]

The other field of geothermal application is electricity generation. In order to generate electricity from geothermal energy, wells are drilled to reach the reservoirs to access the underground steam and hot water that will then be used to drive the turbines which are connected to electricity generators. The three types of geothermal power plants are the dry steam, flash steam and binary plants.

Dry steam technology is used when the geothermal fluid is in vapor state. So, once they reach the surface the steam that is extracted from the underground wells is used directly to drive the turbine [2], [4]. At first, the turbines get in motion, producing the kinetic energy that drives the generator which produces electricity. Then the steam gets condensed, cooled and sent back to the ground through the injection wells while a portion of the fluid is released in the atmosphere. These plants use fluids with temperature higher than 250°C and their average capacity is around 45MW.

In flash steam plants the fluid reaches the surface in both vapor and liquid state. The liquid gets separated from the steam and is used for running the turbine, while the liquid is reinjected together with the steam that will be condensed after completing the cooling process. The fluid is reinjected almost at 60-90%. The temperature of the geothermal fluids is above 180°C and the plants size has average values between 30 to 90 MW.

Binary cycle technologies were initially used to produce electricity from fluids with lower temperatures (around 110°C). In this case, the geothermal fluid contacts a working fluid with low boiling point and high vapor pressure at low temperatures compared to steam. It is then vaporized and used to run the turbine and at the last step it gets condensed and cooled. After that the cycle restarts. The reinjection of the geothermal fluid is successful 100% since it is a closed loop technology that ensures its minimum interaction with the environment. Nevertheless, the efficiency of this practice is lower than other technologies. [2]

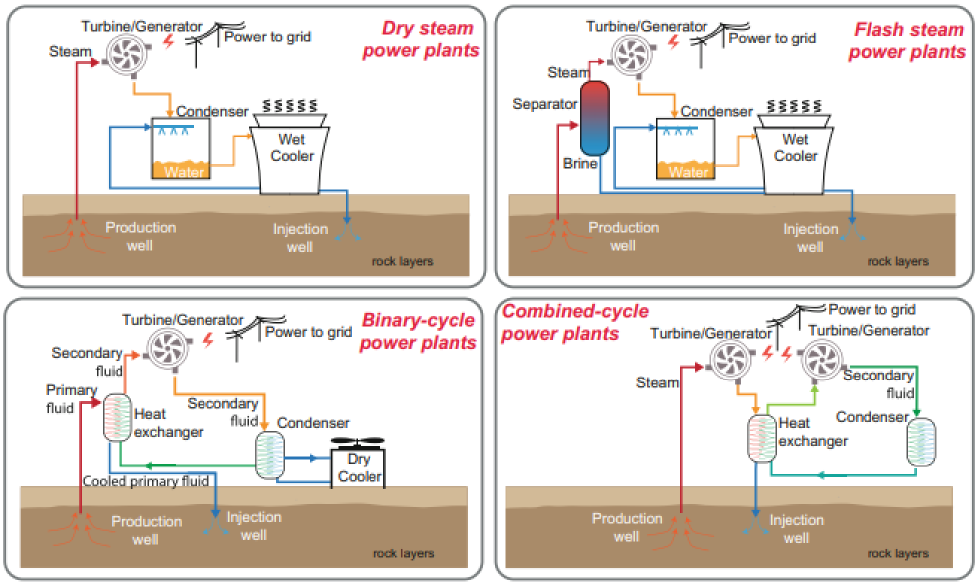

Figure 3 Flow diagram for dry steam (top left), single flash (top right), binary-cycle (bottom left) and combined-cycle (bottom right) geothermal power plant. [2]

Until now, only in a few areas with particularly favourable site conditions, economic exploitation of geothermal fields is possible. The largest geothermal plant in the world is Geysers Geothermal Complex in the US with a capacity of 900 MW, whereas the entire country's installed capacity is 3.639 GW making the US leading producer of geothermal energy across the world [5]. Many more countries, like Indonesia and Philippines with an already high installed capacity (28.000 and 1.900 MW respectively), aim to increase their geothermal power production in the next few years. However, even if global geothermal power potential is approximately at 75 GW, only 15% of the known geothermal fields are being exploited, producing a total of 14 GW in 2021. This constitutes only to 0,005% of the total global power production from renewable sources, which is in total 2.799 GW [6], [7].

Therefore, it is clear that despite its large potential, geothermal energy has a large growth margin. It is estimated that by 2050, 140 GW of geothermal power could be installed, composing 8,3% of the world's power generation, serving 17% of the population and eliminating over 1.000 million tons of CO_2 annually [8]. However, there are many barriers that do not allow the rapid growth of geothermal energy in the sector of power production. The aim of this thesis is to investigate these obstacles from a sustainability point of view focusing on the environmental, economic and social aspects.

Chapter 2

2. Environmental Aspect

To meet the challenges of climate change, it is necessary to replace fossil fuels at a massive scale with renewable energy sources (RES) thus, geothermal energy's immense potential must be taken into consideration. Unlike most other RES, it is available continuously, no matter the climate or the season and therefore it is capable of delivering base-load energy [9].

From an environmental perspective geothermal energy is considered as a renewable source of energy for the following reasons. To begin with, geothermal resources are usually classified as renewable since they maintain a continuous energy current. Such a classification is insufficient as the stored energy can sometimes be renewed quite slowly, assuming geothermal energy is not necessarily a renewable energy source on a human time scale. Therefore, the degree of renewability determines whether a reservoir can be sustainable or not. Furthermore, when the production rate of a geothermal system is lower or equal to its maximum energy production rate it is considered sustainable towards the energy production. However, this definition doesn't consider further environmental issues or any economic or social aspects to determine whether geothermal system is sustainable in every aspect [9], [10].

To conclude if a geothermal project is sustainable and under what conditions, further examination on an environmental, social and economic perspective must always be made.

2.1: Life Cycle Assessment

Life Cycle Assessment (LCA) is an integrated methodology that is used to assess the potential environmental consequences of a product, process or activity throughout all the stages of their life cycle. The life cycle of a product involves every process from raw material extraction, manufacturing and processing to disposal. This is also referred to as cradle-to-grave analysis, cradle representing the raw material extraction phase of the product and grave representing its end-of-life phase [11], [12].

The regulatory procedures for conducting an LCA are defined by the 14000 series of environmental management standards of the International Organization for Standardization (ISO), more specifically by the ISO 14040 that considers the "principles and framework" of the Standard and the ISO 14044 that determines the "requirements and guidelines" for carrying out the study [13].

The main phases of a Life Cycle Assessment are Goal & Scope Definition, Inventory Analysis (LCI), Impact Assessment (LCIA) and Interpretation of Results.

Goal & Scope Definition: This phase ensures the consistency of the LCA performance. The set of a goal, including the objective, the audience and whether the results will be used for a critical review or not, which determines the scope, the functional unit, the required level of detail and quality of the Data and the system boundaries, are defined.

Inventory Analysis (LCI): In this phase an energy or material inputs and environmental discharges inventory is formed. It is the process of identifying and quantifying those inputs and outputs at every stage of the life cycle. The allocation of the data to the goal and scope requirements is a necessary step to achieve consistency and accuracy to the procedure.

Impact Assessment (LCIA): This phase is related to sustainability assessment. The potential environmental impacts are selected, the inventory results are assigned to the chosen impacts based on their known environmental effects and the LCI results are quantified within every impact category by using characterization factors which actually determine the level of contribution of the results to each impact category.

Interpretation of Results: In the final step, identifying the significant issues, evaluating how complete, consistent and sensitive the study was and interpreting and combining the results of the LCI and LCIA leads to the formation of conclusions and recommendations on the study [12], [14], [15].

2.1.1: Limitations

However, there are several limitations that can lead to questionable results as to their validity and quality. First of all, LCA studies use assumptions and potential scenarios in order to simplify a real-world situation. Also, the fact that the selection of the methodological aspects, such as the system boundaries, the functional unit and the scope of the study, is not predefined by the guidelines and the framework, can lead to variation in approaches or results of different studies and therefore makes it challenging to perform a comparison among them[16], [17]. In addition, in order to perform an LCA it is necessary to use a large amount of data, and despite there are many LCI databases, the form of a complete database is not possible due to the huge variation of the components that affect its formation [18].

The improvement of LCA's harmonization would help overcome those limitations and this could be achieved by developing more firm guidelines that would define the exact scope of a study and all the means to perform it along with setting up databases based on every aspect of a potential study [17].

2.1.2: Sensitivity Analysis

Sensitivity analysis assesses the contributions of the inputs to the model's overall uncertainty outcomes. Due to the variable nature of the input parameters, the plethora of assumptions, and sometimes the insufficient knowledge of a modelled process, it is necessary to assess uncertainties through sensitivity analysis [19]. However, not many studies perform a systematic sensitivity analysis to address the effect that input uncertainties have on the output. That could be explained by the fact that the ISO standard 14044 indicates sensitivity analysis as a vital part of the LCA framework, without however suggesting a specific calculation methodology [20].

However, there are two approaches of sensitivity analysis. The first one, from the area of local sensitivity analysis, basically determines the effect of a (small) change in, one at a time, input parameters. The other, from the area of global sensitivity analysis, determines how much each input parameter contributes to the output variance [20].

2.1.3: Uncertainty analysis

Another way to make data and results more transparent is uncertainty analysis as it assesses the extent of uncertainties that are produced in the LCA model's output and are a result of uncertainties that already existed in input values.

Each one of the LCA phases, alongside their associated databases and models, has considerable related uncertainties. Eliminating the presence of uncertainty in many aspects of a study, can be essential for improving its reliability and usefulness. An uncertainty can either be a database uncertainty that derives from measurement variabilities, insufficient data, and deficient model assumptions or a model uncertainty where wrong functional form of data regression, unknown interactions among parameters and lack of knowledge about how the system functions may occur by errors related to model's design decisions. There is also the statistical/measurement error, caused by several reasons like: distributions of properties from a limited set of sample data create statistical variability or the sample data may have measurement errors, or the standards used to collect and quantify the data may not be known. Monte Carlo simulation, for example, is one of the several statistical methods that locates uncertainties [11].

2.1.4: Datasets and Software

Life-cycle-oriented methods, that preceded current LCA, were formed in the 60s. These early methods were mostly material and energy accounting, focusing on inventorying energy and resource use, gas emissions and solid waste throughout the life cycle of production systems. As the complexity of inventories was increasing the interest on physical flows was extended to translating these results into potential environmental impacts. Later, in the early 90s, the evolution of impact assessment methods led to the development of many different databases concerning various industrial sectors, managed by different institutions and organizations. The inconsistency of data standards and quality among different databases made their use case-specific and practically ''single-used''. This situation started improving in 2003 when the first ecoinvent database was introduced, including all industrial sectors and using consistent data quality and standards [21]. This consistency adjusted to every activity making the performance of LCA studies easier whereas it increased the credibility and acceptance of the results.

Ever since, the Swiss Centre for Life Cycle Inventories (Ecoinvent Centre) is aiming to promote the use and good practice of inventory analysis through supplying LCI data to support environmental and socio-economic impact assessment of decisions. The provision of the most relevant, transparent, consistent, reliable and accessible LCI data for every user around the world is their main purpose. Currently, Ecoinvent contains LCI data on every economic activity, while the dataset of each activity describes the activity at a level of unit process. The stringent validation and review system maintains the quality of data. The LCI and LCIA results of Ecoinvent datasets can be used for comparative assessments in order to identify which goods or services are environmentally preferable but should only be used after being adjusted to the specific assessment. Moreover, they could be useful as background datasets for studies in material flow accounting and general equilibrium modelling [11], [22].

As the method's use was spreading, more and more complex product systems needed to be modelled, while the amount of LCI data and impact assessment methods was being multiplied. Thus, in order to simplify and facilitate the process, dedicated LCA software products were created. The first version of two of the most widely used software, SimaPro and GaBi, was released in the early 90s and until today alongside other software like Umberto and OpenLCA have been improved and updated. All statistical methods, technical calculations, assessment and quantification of the environmental impacts, LCA calculations that rely on Life Cycle Inventory data, economic and energy impacts evaluation associated with the systems, control of entire supply networks, insight into databases and unit processes, are included with minimum uncertainty and conducted through a software [21], [23], [24].

2.2: LCA and geothermal energy

2.2.1: Environmental Impacts

LCA examines the potential environmental impacts that might occur. It is worth mentioning that geothermal energy is always more environmentally friendly than other conventional fossil sources and as mentioned before, it is a very important source on the global decarbonization effort.

Atmospheric emissions: Starting with atmospheric emissions, in deep pressurized hot water sources, large amounts of dissolved gases like CO_2, H_2S, NH_3 and CH_4 are contained. Their release happens while the fluid gets depressurized and cooled, whereas products from oxidation, such as SO_2 and NO_x, are generated. The solution consists of metal salts, like salts of mercury, boron, arsenic and other metals, that may either be a part of geothermal brine ponds that must be disposed or be released to the atmosphere from cooling towers as fine-grained particulate matter. Further, methane harms the ozone layer and causes high short-term (decades) greenhouse gas (GHG) impact, while mercury and arsenic entering the food chain is known to risking human health.

Along the life cycle of a geothermal power plant, common atmospheric emissions stem from exhaust related with transportation and application of diesel engines during the construction of the roads, the wells and the power plant. However, the exhaust emissions are relatively low compared to the fugitive emissions. The constant release of steam during the operation of the plant is of highest importance for the atmospheric emissions, commonly for flash- or dry-steam plants. However, the environmental impacts of the flash-steam plants are reduced in relation to the dry-steam's, mostly because the latter do not produce mineral-laden brine. Also, binary plants which return the fluids directly to depth on a closed-loop system, do not produce emissions.

However, a key advantage of geothermal energy is the low impacts of air pollution. Compared to fossil fuels, the CO2 emissions of a geothermal plant is up to 10 times lower than gas-driven plants and up to 20 times lower than oil and coal powered ones. Compared to other RES, geothermal energy seems to have less emissions than solar and biomass. Lastly, the emissions of SO_2, particulates matter and NOx with acidification potential and eutrophication potential are way lower than of fossil fuels [25], [26].

Table 1 This table compares the emissions of some power plants with the emissions of geothermal plants. [25]

Emission	CO_2 [kg/MWh]	SO_2 [kg/MWh]	NOx [kg/MWh]	Particulates Matter [kg/MWh]
Lignite	940–1250			
Coal fired	994	4.71	1.955	1.012
Oil fired	758	5.44	1.814	
Gas fired	550	0.0998	1.343	0.0635
Biomass	40–100			
Solar				
Monocrystalline silicona	60–200			
PV Polycrystalline SOG-Si	99	0.000228	0.00034	0.000119
Nuclear	15–30			
Fission power generation	22.25			
Wind				
Onshore 1.5 MW	10.2	0.0000395	0.0000311	0.0000422
Offshore 2.5 MW	8.9	0.0000354	0.0000209	0.0000109
Hydroelectric				
Hydropower 3.1 MW_{el}	10	0.000017	0.000036	0.000026
Geothermal				
EGS	16.9–49.8			
Binary plant	42–62	0.00035–0.00051		
Single-ORC	80.49	0.00025		
Flash-ORC	13	0.00004		
Single flash	12	0.00006		
Double flash	3.88	0.0000304		
Hydrothermal Geysers-dry (steam field)	40.3	0.000098	0.00058	Negligible
Hydrothermal flash-steam (liquid dominated)	27.2	0.1588	0	0
Hydrothermal closed-loop binary	0	0	0	Negligible

PV, Photovoltaic; SOG-Si, Solar-grade silicon; EGS, Enhanced Geothermal System; ORC, Organic Rankine Cycle.

Land usage: This category involves the use of land, meaning any alterations to the landscape and to other natural features. Although geothermal energy exploits the underground resources, the use of the land surface is necessary across various life cycle phases of the power plant, either temporarily during its construction, or permanently during its operation.

Usually, geothermal resources are located in remote, rural and underpopulated areas. Thus, the installation of a geothermal plant demands infrastructure, such as accessible roads and extended power transmission lines, that ''disturbs'' the natural format of the area. Forests, agricultural areas and national parks can be damaged or downgraded economically, culturally and environmentally. Also, surface installations that cause visual intrusion can destroy locations of high scenic quality [26].

On the other hand, much less space is required for geothermal installations than for any other power plant. A solar installation demands 20 times more space than a geothermal, a photovoltaic (PV) solar plant up to 50 times and fossil plants require 30 to 35 times more space. Generally, the geothermal land footprint is low, and its visual impacts are even lower [25].

Geological hazards: Producing geothermal energy is directly associated with the exploitation of the circulating geofluids and steam which are constantly being extracted, meaning that the shallow and deep underground is disturbed. Various geological impacts depict potential dangers, often exclusively for geothermal activities. For example, the extraction and reinjection of fluid through the geothermal wells causes subsurface pressure, which is then transferred to the ground, causing seismicity. Changes in the area’s water and heat flow can also stimulate landslides. Ground deformations, like subsidence, can also occur when fluid subtraction causes the decline of the reservoir’s pressure.

In conclusion, the required conditions for geothermal energy manipulation, where site-specific characteristics, sensitive environments and geologically unique locations need to be accessed and harnessed, rises the risk of geological hazards. These hazards menace both geothermal installations and local natural environmental conditions [25], [26].

Noise: During the life cycle of a geothermal plant, noise may be produced by many different sources. Constructing and drilling activities, operation and dismantling of a geothermal facility, are prospective sources of noise. As is understandable, the greatest noise is when the wells are drilled, reaching up to 120 dB, while during the testing of wells the noise levels are from 70 to 110 dB. During the operation of the plant, cooling towers are the main source of noise while during the construction or decommissioning of the facilities, noise is caused by several different machinery, like bulldozers, vehicles, graders etc. When facility is located near a populated area, noise can be a serious problem, causing people to object to the project. In order to mitigate the noise, silencers for drilling rigs and cooling towers are used, while suitable soundproofing materials are applied to generators and turbines [25], [26].

Table 2 This table shows the noise produced during different operations of a geothermal facility set up, as well as the limits of human tolerance to noise [25]

Noise source	Level (dB-A)
Threshold of hearing	0
Threshold of pain	120
Geothermal	
Geothermal air drilling rig at 8 m (25 kg/s steam entry, no muffler).	114
Geothermal air drilling rig at 8 m (25 kg/s steam entry, with muffler).	84
Geothermal steam well (with open vertical discharge at 900 m).	71–83
Geothermal air drilling rig at 75 m (25 kg/s steam entry, with muffler).	65
Discharging wells after drilling (to remove drilling debris).	Up to 120
Well testing (if silencers used).	70–110
Well bleeding.	85
Mud drilling.	80
Heavy machinery (earth moving during construction).	Up to 90
Diesel engines (if suitable muffling is used).	45–55
Water cooling towers at 3 m.	82–83
Geothermal turbine building at 8 m.	73

Water use: During geothermal power production, water is consumed primarily for cooling needs, and secondly for powering the facilities as it is extracted from the geothermal reservoir in high temperatures. Understandably, in smaller quantities water is also used during the development of the facility, as well as during its operation for cleaning and sanitary use. However, geothermal plants consume less amounts of water than coal, nuclear and natural gas power plants as shown in Figure 4.

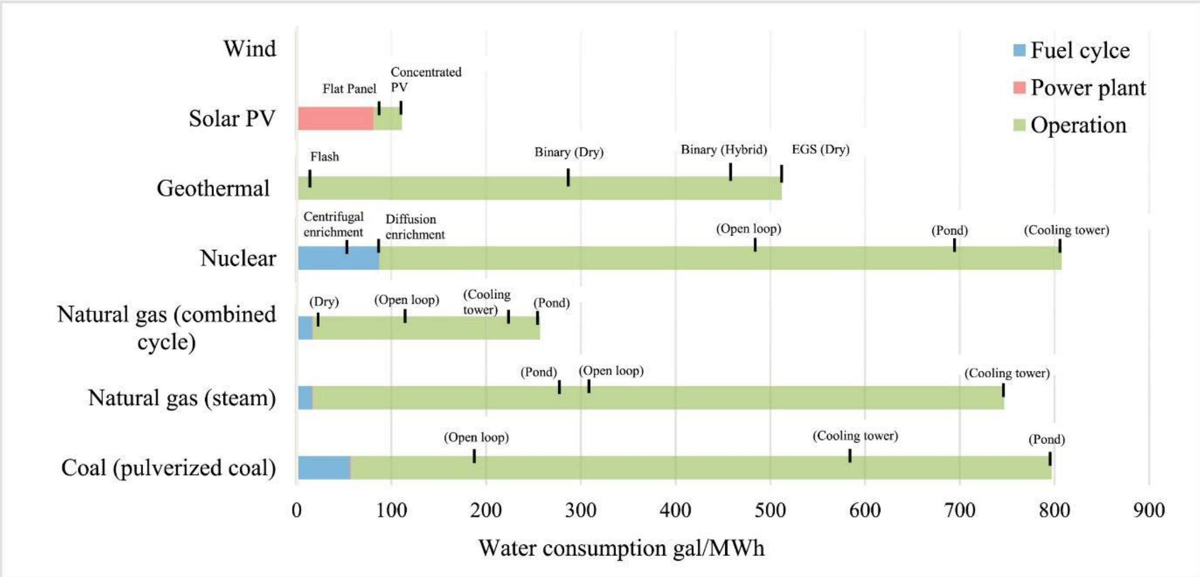

Figure 4 Water consumption of various plants [25]

The energy sector requires more water than any other sector, mainly due to the cooling requirements. To mitigate the impact of huge water consumption, geothermal water instead of fresh water can be used for cooling of a geothermal plant, or alternative cooling methods like air, dry or hybrid cooling systems that require less water consumption, can be used.

Furthermore, when geothermal power plants use closed loop systems (ex. binary-cycle power plants) that reinject the water back to the reservoir, the water is airtightly restrained within the system and therefore any water contamination or further consumption need is avoided. In other types of plants, (ex. flash power plants) steam is released to the atmosphere and consequently the entire amount of water cannot be reinjected back to the reservoir. Therefore, in order to prevent the reservoir from running dry, water must be brought from an external source. A beneficial solution to avoid further waste of water is to reinject non-potable water, including water that has been disposed after other uses [27].

Waste and pollution: Geothermal fluid consists of compounds of different elements, usually harmful. In a closed loop, all the fluid is successfully returned to the ground, but due to technical or economic issues this is often not possible and so decontamination is necessary before any discharge to surface water bodies. Furthermore, gases are released during plant’s operation that can cause soil and water contamination via rainfall.

Solid waste may occur by the drilling processes or by the discard of different materials and packaging. However, geothermal plants produce relatively low solid waste and therefore it is not considered a top environmental concern.

To mitigate waste production, correct installation of equipment and its maintenance, full reinjection of the fluid and separation and storage of solid waste are recommended[25], [26].

Biodiversity, flora and fauna: Outstanding ecological effects can stem from developing and exploiting geothermal resources in protected areas. Ecological resources that include wildlife, aquatic biota, vegetation and their habitats, are usually threatened by the power plant activities throughout its life cycle. Drilling of wells, operating of wells and cooling towers construction and transportation disturb nature undeniably. Furthermore, the quality of soil is affected, and water is polluted, causing damage to the ecosystems.

Protecting the environment is substantial therefore it is necessary to develop facilities that will prevent as much damage as possible [25].

Waste heat: This category is related to the conversion technology of the power plant. All systems that convert heat to power emit waste heat, the amount of which depends on how the conversion is done. Generally, geothermal plants release larger quantities of waste heat, compared to other types of power plants, due to their lower conversion efficiency. The waste heat is released around the plant into the air, ponds or natural water bodies.

More specifically, the level of temperature of the produced geothermal fluid affects the conversion efficiency. The considerably lower efficiency of binary plants leads to relatively larger amounts of waste heat, whereas the direct and flash steam plants produce less.

However, waste heat can be used for direct heating purposes like feeding district heating systems (DHS), fish farming, greenhouse heating etc. That can lead to boosting of the economy of geothermal development and avoiding waste hit emission to the surrounding, leading to significant environmental benefits [25].

2.2.2: Constraints

For geothermal energy, as for every new technology or product, an LCA is performed aiming to determine which phase of the process cause which environmental impact. The main constraint on conducting an LCA for any geothermal plant, regardless of its technology, is how each possible location's traits vary. The local and case specific impacts do not allow general and valid conclusions to be drawn from single studies. Despite other LCA studies on more industrial based renewable energy technologies, for potential remote geothermal areas the abnormality of geological conditions and case-specific characteristics of the affected local environment makes it almost impossible to come up with a general and valid assessment of environmental impacts. Moreover, the effect of geothermal power plants on local and regional water quality, the potentially threatened environments and the local flora and fauna is unique and demands separate attention. Consequently, LCA studies on geothermal power production are rare [26].

In 2020, a review aiming to compare the number of LCA studies conducted worldwide for various categories of geothermal systems and the number of installed geothermal plants in Europe, revealed that for heating systems, most of the studies were concentrated on geothermal energy extracted via borehole heat exchanger, either for individual or district networks heating and cooling. Furthermore, it concluded that there is a lack of LCA studies for geothermal systems of lower enthalpy extracting groundwater using heat pumps for both individual and district network heating and cooling, as well as for systems that extract groundwater at a temperature that is enough to fulfil heating demand without a heat pump, despite being highly deployed. On the other hand, most studies in the literature focus on electricity production plants and only one concerns high enthalpy industrial heat, which is consistent with the small amount of such installations [28].

In order to enrich life cycle inventories and establish consistency about the technical information, it is necessary that technical information given be standardized to be available for future LCA studies. The main goal will be identification of the connection between various power plant parameters and the life cycle environmental impacts [29].

2.2.3: Life Cycle Assessment of various case studies

Hellisheiði Plant: LCA was performed on Hellisheiði plant, a double-flash heat and power plant located in Iceland. The plant’s installed capacity is 303.3 MW of electricity and 133 MW of hot water (Technical details of the study on Table 5 below). The purpose of the study had two folds. Firstly, to identify environmental hot spots throughout the life cycle of the plant and secondly to show the potential of geothermal energy in the process of decarbonizing the power generation industry.

The results showed (Figure 5) that most environmental impacts, except climate change and ecotoxicity, stem from the construction phase of the power plant along with the consumption of diesel during the drilling of the wells and the use of steel at the casing of the wells. Another considerable environmental hot spot in the ecotoxicity category occurred at the end-of-life dealing of copper and the disposal of drilling waste, with the latter also having a substantial impact in the categories of eutrophication (freshwater) and toxicity. During plant operation the predominant category was climate change due to the increased atmospheric emissions of CO_2. This happens because during the condensation of the geo-fluid, prior to its re-injection, the non-condensable gases that it carries, get released.

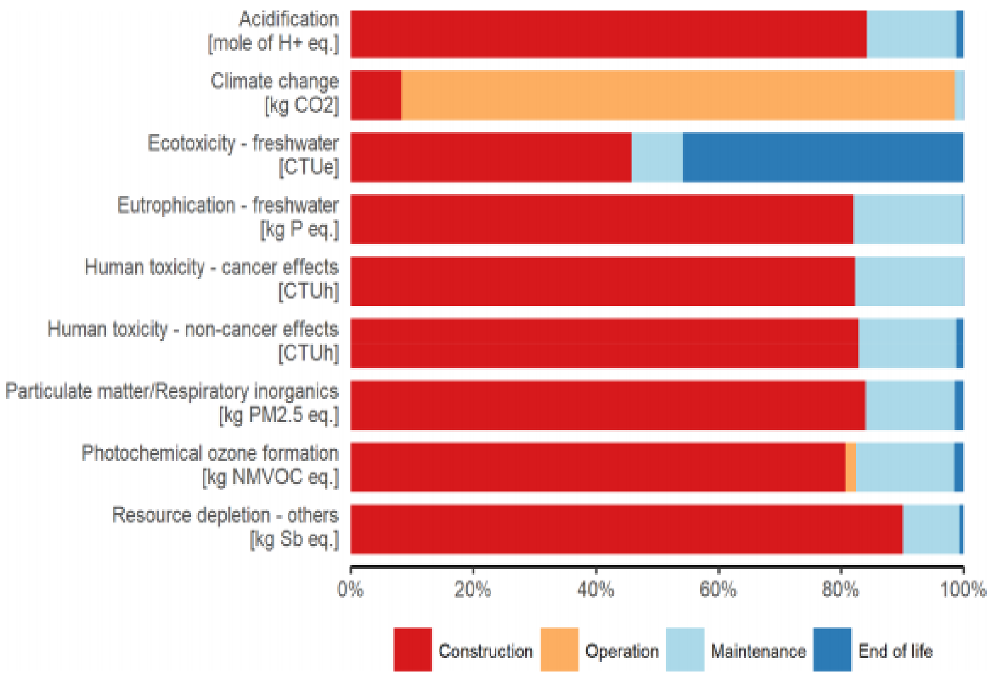

Figure 5 Hot spot analysis of the geothermal system [30]

However, by comparing Hellisheiði's emissions with other geothermal plants (Figure 6) and energy sources, its environmental performance proved to be higher than other double flash plants and close to binary cycle geothermal plants, solar photovoltaic and onshore wind. This is a resultant of the low concentrations of CO_2 dissolved in the geo-fluid which is the trait every Icelandic reservoir has.

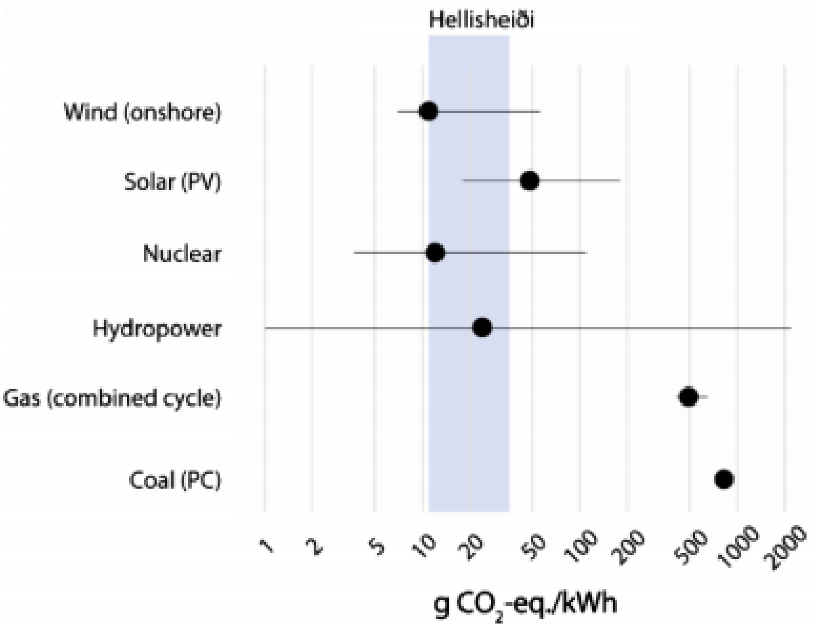

Figure 6 Comparison of climate change impacts (g CO2-eq./kWh) between Hellisheiði and other energy sources. The blue area identifies the minimum and maximum carbon intensity of Hellisheiði according to different configurations. The dots represent the median values of carbon intensity of other energy sources and the lines the minimum and maximum ranges [30].

Concerning the potential that geothermal energy might have in decarbonizing the power generation industry and achieving the goals of Paris Agreement, the results demonstrated that combining geothermal energy with other alternative and renewable sources can make an essential difference [30].

Hellisheiði Plant-Upgraded: A further study was performed to the previous geothermal plant, considering two different scenarios. The first scenario was based on the initial (the above) power plant case (2012 inventory) which consisted of 64 operation wells, whereas a new maintenance well would be drilled approximately every two years, to maintain the production of electrical/thermal energy constant. In this scenario it is considered that each well is drilled by using diesel generators. The second scenario was formed in 2016 and was an upgrade of the first which included carbon sequestration and acid gas removal (CarbFix and SulFix Project), as well as drilling of the maintenance wells with electrical drill rigs. Therefore, in 1st scenario diesel consumption was taken into account for evaluating all maintenance wells, while in 2nd scenario a progressive substitution of the diesel to the electrical drilling was considered (Technical details of the study on Table 5 below).

The outcomes revealed that the categories that were causing the most impact are acidification, human toxicity, and ecotoxicity, while climate change is also considered critical. The stage that mostly contributed to the impacts is the construction of wells, pipelines, and mechanical equipment. Lastly, the maintenance of the power plant had a minor environmental impact whereas the end-of-life contribution was insignificant.

The comparison of the above scenarios, presented in Figure 7, indicated that the reduction of hydrogen sulphide and carbon dioxide to air in 2nd scenario affected essentially the categories of acidification, climate change, particulate matter, and photochemical ozone formation while a further improving the exhausting vapor handling system in CarbFix and SulFix projects could reduce drastically the impacts for the same categories.

Electric drilling of wells also represented a minor improvement since a mere 14 wells are drilled using electricity throughout the lifetime of the power plant (30 years), whilst 66 wells have already been drilled with diesel fuel consumption (64 operation wells and 2 maintenance wells at the beginning of the plant). Future geothermal plants can achieve significant improvements in environmental performance once they use electric drilling platforms for the drilling of production and re-injection wells from the beginning of their operation [31].

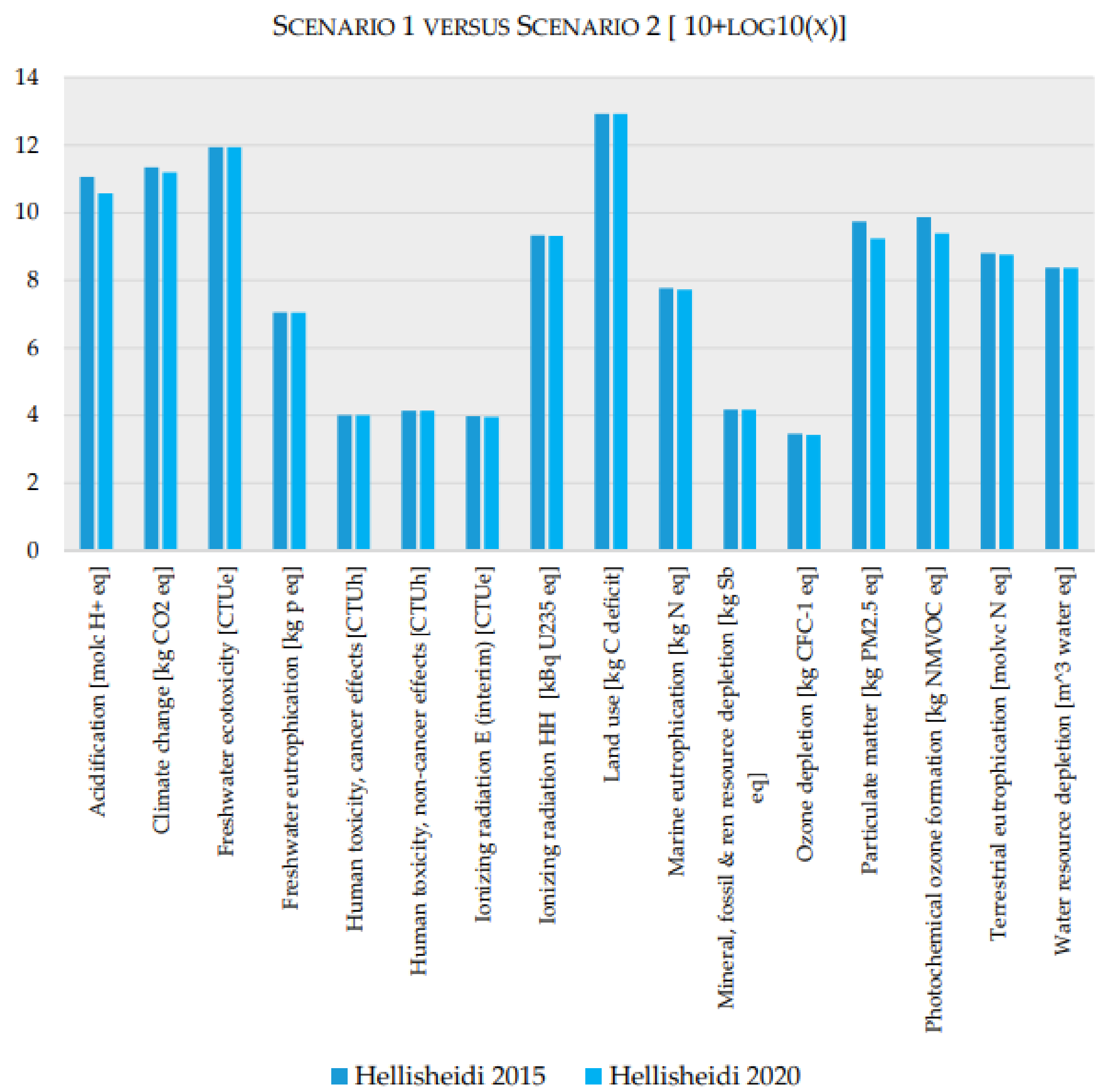

Figure 7 Results on environmental impacts between the two scenarios [31]

"Cornia 2", Tuscany Italian region: This study examined a geothermal power plant called "Cornia 2", in the municipality of Castelnuovo di Val di Cecina in the Province of Pisa, Italy. It is a dry steam power plant, with 20MW of installed capacity that uses steam channelled from eight production wells. The study also considers the construction and delivery of the major components of the power plant as well as the dismantling of the plant and the waste disposal (cradle to grave).

The main goal of this LCA study was to associate the environmental impacts with the phase of the plant's life cycle. Moreover, a comparison in LCA performance between the geothermal system with other power plants, powered by other sources, was performed (Technical details of the study on Table 5 below).

LCA results (Figure 8) indicated that the impact categories that were most affected are eutrophication, acidification and climate change. The interpretation of the normalized impacts of each phase to impact categories confirms that the operation of the plant is responsible for the highest impacts in all categories, succeeded by the construction phase, while decommissioning and disposal are playing a minor role.

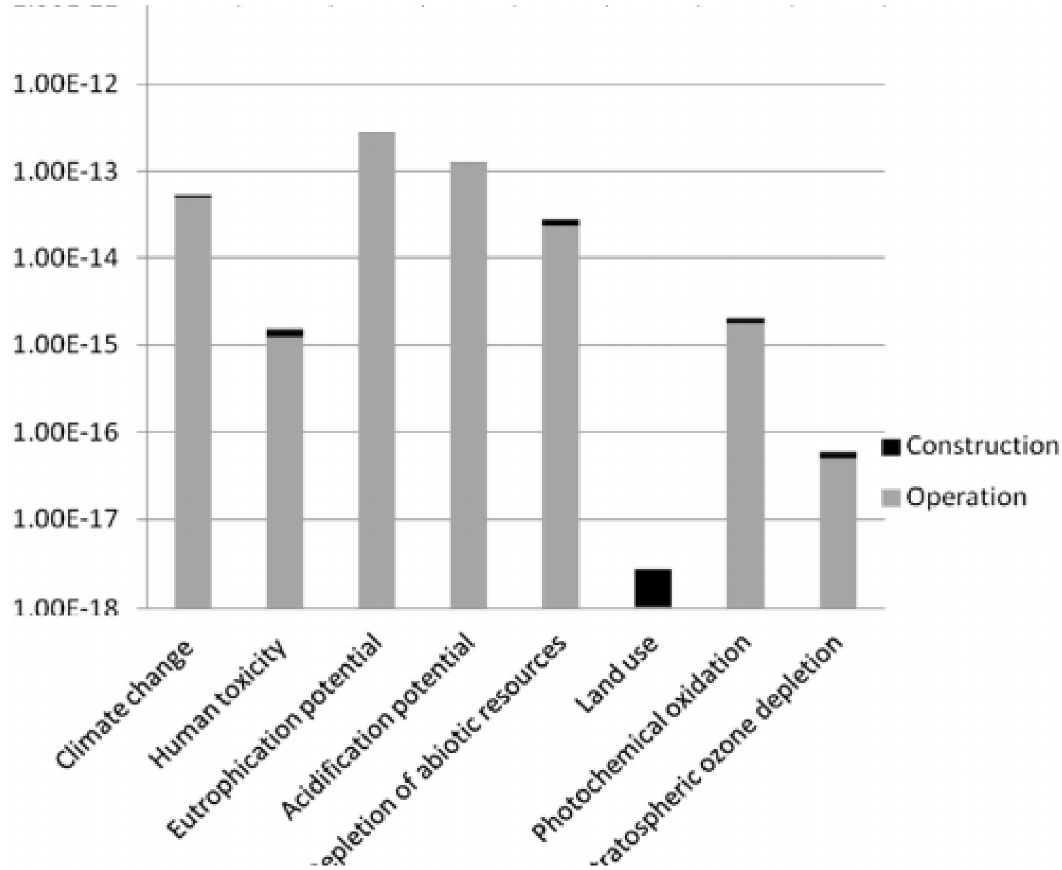

Figure 8 *Normalized impacts of the different phases (dismantling and disposal are not included since they have negligible effects)* [32].

The comparison resulted that the plant's efficiency is 14%, which corresponds to the average geothermal dry-steam technology. But this low level of efficiency leads to a much higher environmental impact, in every impact category, compared to other RES. On the other hand, generating 1 kWh of geothermal electricity emits about 248 g CO_2, which is way lower than electricity that comes from fossil resources [32].

Pancevo City, Republic of Serbia: A residential neighbourhood and associated district heating system built in the early 1980s, intended to supply with heat and sanitary hot water (SHW) its residents. The distribution network system is composed by three pipes. One pipe is used to carry heat for space heating, the other pipe distributes SHW, and the third is a simple return pipe. The network serves multi-story residential buildings with a mean number of 1.66 users per apartment.

Two systems were evaluated through Life Cycle Analysis: the existing hot water condensing boiler (HWCB) system and the proposed sequential groundwater heat pump system (GWHP) used for SHW preparation in district heating system (DHS) (Technical details of the study on Table 5 below).

The LCA of the two systems, for a period of 30 years, indicated (Figure 9) that the GWHP system would cause worst environmental effects. More specifically, the existing system had 82% lower climate change impacts than those of the proposed geothermal system. It also turned out having lower impacts across all impact indicators except terrestrial ecotoxicity, natural land transformation and fossil depletion. The adverse environmental consequences were mainly attributed to the current electricity supply grid mix in Serbia which is mostly coal-based but by supplying electricity from renewable sources and restricting the refrigerant leakage the potential environmental benefits would be significant [33].

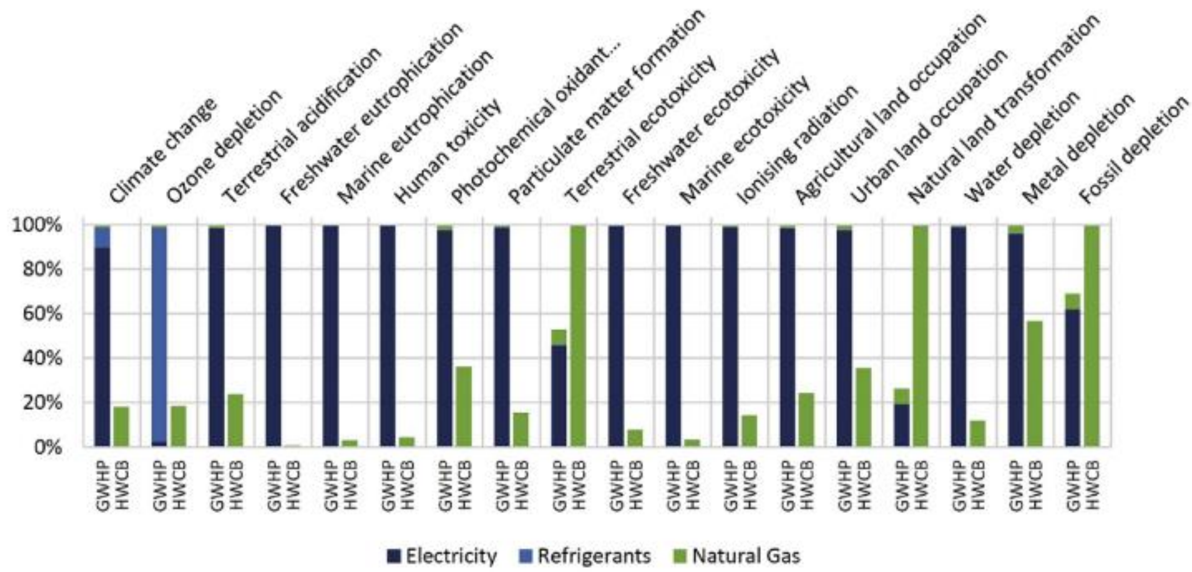

Figure 9 Impact indicators for the GWHP system and the HWCB system, normalized to the higher contributor in each impact category [33].

UIC Case Study: In this study, a sustainability assessment is performed on a geothermal heating and cooling system. The system consists of three buildings at the University of Illinois at Chicago. Further, a comparison is made between geothermal and conventional heating and cooling systems.

Conventional (Heating, Ventilation, and Air Conditioning) HVAC systems typically convert direct electric or fossil fuel energy to heat. Using geothermal energy as an alternative source could reduce the energy consumption in half (Technical details of the study on Table 5 below).

The gross result revealed that the geothermal system has less environmental impact and generates also negligible greenhouse gas emissions. Thus, it is more sustainable if compared to a conventional system due to the fact that there is no need for burning or combusting fossil fuels for heat production [34].

Renewable systems for heating and cooling, Bologna, Italy: A comparative LCA was conducted for a geothermal and a solar thermal energy system for heating and cooling (RES-HC) purposes. Both systems are installed in Bologna and the components are produced in Milan. The two systems exhibit different lifespans, 80 years for the geothermal system and 20 years for the solar thermal system. Thus, in order to have a common service life, a period of 80 years was considered as their lifetime. Consequently, the solar thermal system and the heat pump in the geothermal plant will be substituted 4 times during the whole life cycle, since the lifetime of the last is 20 years (Technical details of the study on Table 5 below).

In all considered categories the geothermal system indicates a better environmental performance than the solar thermal system. If the geothermal system is examined separately, the most impactful component, especially for GHG emissions, is the heat pump. That is because the electric consumptions during its performance, as well as the installation (and so the production) and the dismantling of four heat pumps that will be used along the lifetime of the system, are taken into consideration. Another phase with a very important effect in all impact categories is the drilling of the vertical pipes' installation [35].

Experimental greenhouses in the Mediterranean area (Valenzano-Italy): This study refers to two different heating systems for a greenhouse. The first is a pilot plant photovoltaic-geothermal heat pump integrated system (PV-GHP) and the other is a conventional hot air generator driven by liquefied petroleum gas (LPG-HG). A technological scenario for a geothermal heat pump (GHP) that uses electricity provided by the Italian national grid instead of the solar panels, was also examined (Technical details of the study on Table 5 below).

LCA results indicated that the initial energy requirement for PV-GHP plant is approximately halved in the case of LPG-HG plant and about one-fifth for the GHP scenario. This is due to the use of geothermal and solar renewable energy. Furthermore, the GHP scenario has the highest environmental burdens compared to the other two plants. The overall comparison among the two systems didn't give a clear result on which would always be the preference in incentive policies. It is obvious that PV-GHP system is more beneficial than LPG-HG plant regarding reduction of CO_2 emissions and use of fossil resources [36].

Banchory, Scotland: An LCA of GHG emissions was performed related to a potential 2.5 MWth capacity deep geothermal heat system in Banchory, Scotland. The project would be extracting heat from the Hill of Fare granite via one injection and one production borehole. The related emissions of development and operation phase of the geothermal project from site preparation to just before decommissioning are studied. The decommission activities are not included since they largely depend on how the site is re-purposed which is decided towards the end of the project life. The project lifetime was estimated to be 30 years (Technical details of the study on Table 5 below).

LCA outcomes showed that most of the emissions associate with the preoperational stage, and thus are susceptible to site-specific features, like the depth of the boreholes, the length of the pipeline, the amount of consumed water during the drilling, and material-specific features or type of soils of the certain area that is disturbed when laying pipelines and constructing access roads. Throughout the operation, the intensity of the carbon of the produced heat depends on the pump rate and the carbon intensity of the electricity grid (used to power the pump).

The study was performed on a potential project that would solely provide heat. Thus, in order to identify which factors from its construction and operation, like the characteristics of the location, the drilling conditions etc, contribute the most to carbon emissions, there is a range of possible results, presented in the table below (Table 3), depending on the selection of these factors [37].

Table 3 Calculated GHG emissions for every step of the life cycle assessment of the project [37]

Activity	Carbon emissions t(CO_{2e})			Direct/indirect emission	Source
	Calculated GHG emissions, expressed	Calculated GHG emissions, expressed	Calculated GHG emissions, expressed		
1. Construction (pre-operation)					
a) Site preparation					
Access roads	60–126				
Pipeline (buried)	280–589				
Well pad	60–126				
Total (land use change)	400–841			Direct	Bond et al. (2014)
Pipeline	63			Indirect	Fröling et al. (2004)
Drill rig transport	15			Direct	NYSDEC (2011)
b) Borehole construction					
Drill rig operation	1243	994	2486	Direct	Bradley (1987)
Drilling fluids/water	10	7.5	20	Indirect	DEFRA (2018)
Well casing	1296	863	1944	Indirect	Yu et al. (2015), WorldSteel (2016)
Borehole cement	360	324	720	Indirect	Salas et al. (2016)
System surface elements (e.g. pump, heat exchanger etc.)	Not calculated			Indirect	
2. Operation (30 year lifetime operating at 60% load)					
Pump rate (min – 14 kW)	419			Indirect	
Pump rate (max – 56 kW)	1678			Indirect	
Total					
Decommissioning	Not calculated				
Total					
Direct CO_2 emissions	1658–2099	1414–1832	2906–3324	Direct	
Indirect CO_2 emissions	2148–3407	1677–2936	3166–4425	Indirect	
Overall	3806–5506	3086–4768	6067–7767		

Possible systems in the State of Geneva: An LCA was performed in geothermal power plants in the State of Geneva. Since the implementation of a geothermal heating and cooling system can happen in several ways, the environmental impacts may vary. Therefore, to analyse the impacts that might occur from different types of systems, six configurations (Table 4) were defined by combining four categories of well depths (very shallow, shallow, medium depth, and medium-large depth) with corresponding temperatures of geothermal resources and different setups of a connected decentralized heat pump or district heating and cooling networks. The capacity of the geothermal resource was calculated using the production and injection temperatures and the flow rate [38].

Table 4 The six configurations of geothermal heating and cooling systems and the main parameters' reference values [38]

Depths of geothermal wells	Types of heating and cooling network (A): Connected decentralized heat pumps	District heating and cooling with heat pump	District heating and cooling without heat pump	Reference values of geothermal parameters and cooling technology (B): Production temperature	Injection temperature during heating	Flow rate	Well diameter	Cooling technology	Injection temperature during cooling
10°C < t < 14°C 10 l/s – 50 l/s Very shallow 10 m – 100 m	Configuration 1	Configuration 2		12°C	9°C	25 l/s	1 m [4]	*Free cooling*	*15°C* [6]
20°C < t < 55°C 20 l/s – 80 l/s Shallow 350 m – 1600 m	Configuration 3	Configuration 4		45°C	*15°C* [1]	50 l/s	20 inch [5]	*Reversed heat pump*	*56°C* [7]
60°C < t < 75°C 20 l/s – 80 l/s Medium depth 1800 m – 2300 m		Configuration 5		67°C	40°C [2]	50 l/s	20 inch [5]	*Reversed heat pump*	*78°C* [7]
78°C < t < 120°C 20 l/s – 80 l/s Medium-large depth 2300 m – 4000 m			Configuration 6	105°C	*55°C* [3]	50 l/s	20 inch [5]	*Absorption chiller*	*95°C* [8]

In this LCA study (Technical details of the study on Table 5 below), activities related to drilling, construction of H&C network, operation and maintenance and decommission were included. The results showed that, for heating, connected decentralized heat pumps are less harmful than district heating, while combining them with 'shallow' wells can mitigate the impacts even more. For cooling, free cooling has lower impacts than the other cooling technologies, except for the mineral resource scarcity and the land use impacts.

Examining the impacts per process indicated that primary factors of environmental impacts in every case are metal products, electricity transmission and distribution lines. Concerning metal products, well casings, network pipes and heating equipment cause the biggest issue. These parts particularly, deteriorate the situation for mineral resource scarcity, water consumption, global warming, fossil fuel scarcity, land use, particulate matter, and terrestrial acidification. The diesel used for the well drilling processes adds to the particulate matter emissions, fossil resource scarcity and global warming issues. The required cement and concrete conduce to global warming, fossil resource scarcity, and water consumption. Lastly, the impacts of transportation activities can only be detected as a land use matter and are attributed to the construction of the roads.

The contribution of electricity consumption is easier to be noticed in systems that use heat pumps, in that electricity consumed by the downhole pump, network pipes and absorption chiller is negligible. In the case of gross energy demands the electricity consumption seems to be reduced as the temperatures of geothermal production increases, whereas for cooling the reverse is observed. Finally, free cooling configurations cause the least harm as the amount of electricity they consume is negligible and they require no additional equipment [38].

Table 5. Summarized technical details on the case studies

Location	Technology and Installation	Software and Database	Functional Unit	System Boundaries	End of life	Lifetime	Impact Assessment	Ref.
Hellisheiði, Iceland	Double-flash heat and power plant, 64 wells plus 2 every year	Ecoinvent 3.4	electricity and hot water production per second	cradle to grave	Closure of wells, dismantling of plant and heating station	30 years	ILCD (International Life Cycle Data System)	[30]
Hellisheiði, Iceland	Double-flash heat and power plant, 64 wells plus 2 every year, SulFix and CarbFix Project and electric Drilling of the new wells	Ecoinvent 3.6 OpenLCA 1.10.2	1 MWh of exergy (electricity and heat allocated to exergy)	cradle to grave	Not included	30 years	ILCD 2011, Recipe 2016, and CML-IA ILCD 2011 midpoint	[31]
''Cornia 2'', Tuscany, Italy	Dry steam power plant	Ecoinvent	kWh of electricity yearly produced	cradle to grave	dismantling and disposal of waste	20 years	CED	[32]
Pancevo City, Republic of Serbia	District heating system for heating and SHW	Ecoinvent 3	Amount of SHW that evidently supplied the 1274 apartments in a year	operation phase	Not included	30 years	ReCiPe midpoint	[33]
Potential plant in Bologna city, assuming that production of components happens in Milano	RES-HC	SimaPro 6.0 software	400lt of produced HW (a family of 6 house's needs)	Cradle to Grave	Dismantling	80 years	CML baseline 2000	[35]
Valenzano, Italy	PV-GHP integrated system and LPG conventional hot air generator and GHP that uses electricity by the national grid	GABI 6 software and Ecoinvent database	kW or thermal MJ	Cradle to grave	Disposal	20 years	CML2001 (CML, 2006)	[36]
Banchory, Scotland	Deep geothermal heat system	Not included	CO_{2eq}	Cradle-to-gate	Not included	30 years	Not included	[37]
Geneva, Switzerland	Geothermal H&C systems, configurations that combine categories of different well depths with different setups of a connected decentralized heat pump or district H&C networks	projects in Switzerland and France, equipment's technical datasheets, WEEE-LCI	MWh of heating and cooling	cradle to grave	Cement bridges while abandoning wells, transportation of equipment to the recycling station and handling of heat pumps and refrigerant at the end-of-life phase	30 years	Cumulative Energy Demand (CED), Recipe midpoint	[38]

2.2.4: General Conclusions

Information regarding the environmental indicators, which compose the life cycle environmental impacts, is yet insufficient. The majority of LCA studies focus on examining and evaluating the global warming impact, properly adjusted to the type of technology that is being analysed, while comparing it to other conventional energy systems. Conducting a review on case studies concerning all kinds of technologies, areas and sources can draw some generic conclusions. Commonly to all types of technology, the consumption of diesel required for the construction phases was found to be the factor that is most responsible for the impacts related to global warming. Additionally, an aftermath of diesel requirements is also the energy consumption throughout the life cycle of the power plants.

Generally, life cycle environmental impacts are highly dependent on local, geologically related, characteristics, as well as other technical options concerning LCA methodology. The first directly affects the performance and maintenance of the power plants on both material and energy requirements and the second defines the goal and scope, the functional unit, the system boundaries and the life span, as well as the impact assessment method and allocation procedure.

It is also critical to emphasize the effect that geothermal power generation has in the reduction of GHG emissions, as well as to the energy demand throughout the life cycle of the considered conversion technologies [29].

Generally, global warming potential is the impact factor that has been examined the most. Also, geothermal systems of lower enthalpy whether using a heat pump or not, have less environmental impacts than of a small-scale oil boiler. On the contrary, it is unclear whether systems of geothermal energy extracted via borehole heat exchanger perform better. However, the number of studies is too low for any definite conclusions, while if LCA is merely performed on heat pumps the system's overall environmental sustainability can be misinterpreted [28].

Chapter 3

3. Social Aspects

The global transition to a sustainable future, with the reduction of GHG emissions being the main concern, is under social and political pressure. The commitments to this transition can be addressed by the development of renewable energy sources and the increase of energy efficiency. Projects concerning renewable energy, like geothermal, demand the coordination of different interconnected infrastructures, such as social, political and economic systems, to develop progressively. However, public support has often been compromised or least prioritized in renewable energy development projects. Therefore, over the past decade, approaches and social scientific conceptual frameworks have been developed, aiming to a further comprehension of how geothermal energy is related with societies. Studying public opinion and understanding of energy issues can help policymakers and stakeholders come to an agreement with the public [39].

Therefore, social acceptance is achieved by meeting the requirements of the society. The concept of social acceptance is defined as the level of positive attitude towards a proposed plan, measure or technology that leads to the support of its realization and to the prevention of any opposition against it [40]. Higher level of social acceptance by local communities can accelerate or obstruct the process, something necessary for the evolution of a renewable energy source like geothermal energy. The successful implementation of energy policies is also highly affected by the public's compliance.

However, the social acceptability of geothermal energy is at lower levels than that of other renewable energies. Certain factors that lead to this fact are the insufficient public awareness of the technology, the unfavourable information found across media, the potential environmental risks and the distrust in the integrity of the decision-makers and other stakeholders. However, the development of geothermal energy can contribute in ameliorating the local life quality by providing local energy sources, employment, boosting local economy and limiting government energy dependence

The main principles that form social acceptability include public understanding, energy consumption, employment, environment, health and safety, development of local infrastructure, culture and education [25].

3.1 Public understanding

First, socio-economic issues stem from misinformation between public and geothermal energy companies that undertake the project. That is mostly because the companies withhold information from the public for the sake of competition or marketing. Therefore, unwillingness to involve citizens in the process raises suspicions against companies' motives, creates a perception of danger and enhances public's objection. For these reasons, geothermal energy companies have to meliorate in the citizen's perspective through involving them in the process, using appropriate strategies and actions [2]. For example, during a survey on public engagement in renewable energy systems in central Italy, it was observed that even though the citizens were highly supportive over other renewable technologies (like solar and wind) due to their various positive effects on the quality of their lives, they were highly suspicious over geothermal technology. This concern was mostly caused by a general distrust towards the decision makers. Besides, the perception of citizens on common good and the sustainable development of the community, stands in contrast to the corporate and private interests of power actors and stakeholders. In order to allay this dissent, it is crucial to consider engaging citizens in the development process of geothermal energy sector. Fostering socially sustainable approaches to future guidelines and policies will reinforce knowledge, awareness and collaboration between all societal actors and could ease the transition to low carbon societies [41].

On the other hand, sustainable development of a project can be compromised by the adverse and deficient public understanding over the project [25] or by the excessive information on the subject, which confuses and discourages people, regardless if those in charge carry it out properly [2]. For example, when shallow geothermal energy (SGE) systems were introduced, besides their valuable potential, installation flexibility and high performance, they were not able to be established. This was attributed to the fact that on their earliest market stage, companies decided to promote SGEs with a tailor-made approach. That is, customer's control over technical features like the system sizing, the most suitable choice of machine according to the underground explorations etc., considering that citizens would prefer being in charge. Instead, the complexity of technical information led citizens to feel unable to control the installations. Later, to prevent such misconception, technology providers started promoting SGEs as a standardized technology that does not require particular abilities and expertise to be used, aiming to less perceived complexity, involvement of citizens in the process and promotion of SGEs' development [2].

3.2 Energy consumption and household preferences

Reliable and affordable energy is required for a functional and developing everyday life. Each sector, from medicine to agriculture, is supported by an established energy system. Consequently, lack or difficulty in access to energy supplies blocks social and economic development [42]. Therefore, promoting the affordability and stability that a new technology like geothermal energy offers, is crucial towards its embrace. Geothermal energy, despite the high installation cost, provides low current expenses, compared to other energy sources, which do not fluctuate like fossil fuels.

European Social Survey (ESS) conducted a fieldwork in August 2016 till December 2017, using a full dataset of 44,387 respondents from 23 countries. One of the examined areas was ''climate change and energy security concerns''. The responses indicated that people are mostly worried about the affordability of energy. Such a concern was particularly widespread in Spain (70%) and Portugal (68%), followed by Belgium (51%), Israel (49%), Russia (47%) and Lithuania (45%). On the contrary, countries like Sweden, Iceland, Switzerland, and Norway, scored less than 15% [43] in the same topic.

3.3 Energy poverty

According to the international Network for Sustainable Energy (INFORSE)-Europe, there is an increasing number of households that struggle paying their energy bills due to the shift of energy prices and financial crisis. Being unable to cover the costs of necessary energy consumption (for heating, cooking, lighting etc.) is defined as energy poverty and can also be described as the expense of more than 10% of household's revenue on energy bills [44].

Thus, when an energy technology like renewables is introduced to the public, it is important to consider and support households that are in danger of Energy Poverty. The attention of the European Union (EU) on the matter is increasing and therefore, various related policies are proposed and adopted. In order to relief and decrease energy poverty in EU various policies and measures like Clean Energy for All Package (CEP), The Recovery Plan for Europe and the European Green Deal were adopted by regional and local organizations. It is considered a fundamental requirement towards a fair transition to sustainability to decrease this phenomenon. In January 2020 Green Deal Communication announced, "Just Transition Mechanism" and "Just Transition Fund" and stated that people, areas and sectors most affected by energy transition is the main concern of the Mechanism. The aim is to transform the local economy and labour market in the areas that mostly depend on fossil fuels or carbon-intensive processes. Training people and transforming jobs into innovative economic fields and energy-efficient housing is among the promoting tools, resulting to the investment of funds in measures against energy poverty and mitigation of vulnerability, inadequate housing, and mass unemployment.

Stakeholders of European national and regional authorities also take several initiatives and actions to deal with the matter. For example, in Germany, in May 2019, the Green party ratified the termination of power cuts in poverty-stricken households and the implementation of support for consumers under energy-poverty. In Estonia, the Estonian Union of Co-operative Housing Associations (EKYL) aims to raise awareness on energy poverty, while In Tallinn, the ''Sõpruse 202 programme'' authorised an innovative financing scheme to decrease energy consumption without raising the rents. Also, an Energy Poverty Observatory was developed by the Centre for Renewable Sources and Energy Saving (CRES) in 2014 in Greece, that aimed to familiarize the public and policy makers with the issue. The National Energy and Climate Plans (NECP) of Greece indicated that around 23% of the population claims to not being able to heat their homes. To take action, in 2018, a legislative framework on energy communities was set, which included a support scheme for mitigating energy poverty.

In conclusion, great effort is made by the majority of the Member States and the authorities, with each one of them making their own progress, adjusting the measures to their needs and demands, maintaining the same goal [45].

3.4 Economic development- employment

Generating electricity by renewable resources, like geothermal, can benefit the economy primarily by reducing imported energy dependency. Hawaii, for instance, uses geothermal sources for water and heat for centuries and currently exploits it for recreational and agricultural needs. Power generation has also been giving a stable energy supply, with predictable long term electricity rates and fewer transnational energy expanses that instead can be used for other purposes that ensures the island's prosperity and boost of its economy. Tourism has also been benefited by the power generation [46].

Furthermore, employment is a vital matter for any government or community as it bears financial welfare of people and society. It includes, besides the recruitment, the provision of new opportunities for paid employment, poverty decrease and growth of the manufacturing sector in which high-quality jobs as well as economic and social stability are established. Geothermal development generates occupational opportunities both during the exploration and construction phase, that normally last for a few years, and during the exploitation phase that creates full-time, permanent careers. Occupational opportunities in construction and maintenance of the plants are considered direct, while occupations that secure the necessary materials and services for their construction and operation are considered indirect jobs [25].

Currently more than 11.4 million people are working in the renewable energy field worldwide, of which around 100 thousand are working in geothermal energy [47].

3.5 Health and safety

The development of geothermal energy can have both positive and negative impacts on society's health. Mostly for the developing countries, where a great deal of people does not have access to electricity and water, the mortality rates drop, the health care gets upgraded and the nutritional status is improved.

On the other hand, concerns about health and safety stem from the use of geothermal energy. Environmental issues like GHG emissions, water and soil contamination, dissolved minerals contained in high-temperature heat mines and noise pollution are considered very important and potentially harmful by the local communities that might live or have been living near a geothermal plant.

In a review on social aspects' studies in Greece, it is reported because locals have experienced a negative situation with the pilot power plant in Milos Island, that started operating in the 80s and caused tremendous ecological impact to the local environment, extensive air pollution and soil contamination, public's view on further exploitation of geothermal energy is from quite cautious to negative until today. The exploitation of deep geothermal sources is not only considered polluting by the local communities of the affected areas Milos, Nisyros and Kimolos islands, but by the majority of Greeks, and that is the main reason why such resources for power generation in Greece, besides its large potential, are under-utilized.

Raising awareness about environmental impacts of geothermal power plants and acquainting ways to prevent them can improve public acceptance concerning their installation [48].

3.6 Development of local infrastructure

The development of a community is strongly connected to basic substructure like electrical supply, communication systems, roads, water supply, and sewage. Using geothermal energy directly, from the production of electricity to direct heating and cooling, can utterly upgrade the life quality of local communities.

Furthermore, to conduct a geothermal installation, especially when the area is isolated, unexploited and inaccessible, upgrading the substructure of the area is necessary for accessing it, providing long-term advantages and reinforcing productivity and improvement of quality of life [25].

Considering the geothermal development in Indonesia, Kamojang is one of the few places that achieved a successful development of geothermal power generation while gaining the highest benefits and local economic growth. More than 470,000 families are constantly supplied with electricity, produced by clean energy. As mentioned before, through such power production, local governments are flexible to use available funds for the prosperity of their community. In the development of Kamojang power generation, massive infrastructure improvements have been made as well as Corporate Social Responsibility (CSR) programs that Pertamina Geothermal Energy (PGE) has continuously implemented. Both institutes have created facilities that can be used by the locals and contributed to local economy growth. Tourist processes have also been upgraded by creating facilities as attraction for different forms of tourism, while industrial processes, like roasting coffee beans and cultivating crops, have been made easier and therefore prospered [46].

3.7 Culture and Religion

Another important concern for many communities is the threat that a geothermal installation poses to their cultural or religious heritage. A research in Mount Ungaran, Indonesia, indicated that a rural community, that is highly influenced by informal leaders, religion, women and local officials, is likely to reject a geothermal project due to fear of environmental damage as well as cultural damage by corroding the temple area. [49] Furthermore, considering an area of interest as a sacred place is a point of disagreement for the local communities of Mt. Lawu, Indonesia. According to the locals, it is a place that should not be disturbed as it is considered the earths' hub, the hermitage and the former saint's place of reaching moksha (freedom, liberation). There are also plenty of cultural sites like temples and religious ritual sites that are feared to be damaged during geothermal exploration and exploitation [50]. Lastly, for many communities like the Mapuche (Araucania region, Chile), there is a spiritual relationship to volcanoes. They see them as sources of spiritual energy that should not be disturbed by humans, an alive entity that they cannot imagine drilling, thus a negative perception towards any further exploitation is created [51].

One way to promote geothermal energy to such communities is to educate them over the technology and the positive impacts it can offer, whereas involving the local authorities or leaders in the process can also serve as a starting point towards public acceptance.

Chapter 4

4. Economic Aspects

4.1 Cost analysis of geothermal projects

As mentioned in previous chapters, generating heat and power from geothermal sources can happen at any time and with high efficiency and thus, in this global cry for more sustainable energy alternatives, geothermal energy is an accessible source ready to be exploited.

Economics and sustainable operation of geothermal energy are usually considered as two separate issues. Connecting them is highly important since this practice could provide us with more accurate and generalized evaluation of this resource, regarding its economic viability and maximization of the profits and an optimal lifetime for a sustainable use [9].

In previous chapters we have explained how a resource is defined as sustainable, though as an investment, there are other things to consider. Generally, geothermal energy demands high investment costs and it also takes approximately 6 years from the exploration to commercial operation phase, resulting in longer payback times than most other RES technologies.

4.1.1 Cost of GSHP systems for heating and cooling

When examining the cost of a GSHP system, plant installation and operating costs are more complicated than for other sources of energy. The overall cost is determined by the characteristics of the resource (heat availability, fluid discharge rate, drilling extent), the efficiency, the load time, the cost from installing and operating the plant, the available incentives, the tariffs, and the current pricing of other available energy sources. Moreover, the cost changes according to the application (district or building heating, greenhouse etc.). This case-specific costing does not offer a standard investment cost thus, because of limited measuring standards and the lack of a thorough dataset, there is a large margin of uncertainty when performing a cost analysis for the total cost and the cost of the produced heat [2].

4.1.2 Cost of geothermal power plants

For electricity production, the situation is even more complicated. In general, the investment cost is divided into surface and subsurface costs. The first one refers to the surface equipment, that is, the entire plant's system and the necessary area infrastructure, and the second mainly deals with the drilling operations which are affected by the resource type, depth, capacity, flow rate, and temperature of the reservoir. Lower temperature of a deep source or low well productivity may significantly increase the cost of drilling. Exploration costs are a relatively minor issue when dealing with medium-small plants (5-10 MW), especially when the fields are already known, whilst are considerable when the development is done on unknown or undeveloped [52], [53]. Operating expenses and management capital, however, are lower than conventional systems, since the energy source is free, and it is possible to adjust the production with the energy demand.

Geothermal systems are usually capital intensive, whereas the main cost is formed by the initial investments in production and injection wells, and down-hole pumps. Therefore, risk analysis is a key topic, as unlike electricity from fossil fuels, geothermal requires large upfront investments. Consequently, the risk of investors is higher since funding must occur before the system become operational, and therefore the rate of return of their investment increases. Adding to that, there is a chance that the resource under exploration will not be as expected after drilling the first wells (i.e., after almost spending one third of the total cost), which clearly raises the overall risk, the uncertainty of the plant construction and complicates the decision of the investment of the upfront total [1]. To mitigate the risk, techno-economic analysis is suggested to allow developers, investors, and policy makers to attain a thorough overview of the financial pre-feasibility of these kind of highly risky investment decisions [54].

Regarding, geothermal projects analysis it is possible to focus either on specific phases of the development or on the overall project. Many studies have separately estimated the cost of drilling, the cost of operation and maintenance the cost of electricity generation etc. and others have studied the feasibility of developing a geothermal power plant. However, a very important tool, that helps estimating the initial and annual cost, the saving and energy production, while focusing on the development before the construction, is pre-feasibility study. [54] It is basically a preliminary study aiming to determine, evaluate, and select the most profitable business scenario before proceeding to a feasibility analysis. That is a high beneficial strategy because when a project is advanced to the feasibility study stage, companies have often committed considerable capital resources and professional reputation and after assuming that the project is feasible. On the contrary, in pre-feasibility study, it is assumed that there is more than one possible scenario, from which the best one, both technically and financially, is selected. Then, only if the selected scenario turns out to be feasible, it is recommended to proceed to feasibility analysis, aiming to a deeper investigation of the particular project [55].

4.1.3 Case studies in cost analysis of geothermal installations

Case study in Chachimbiro, Ecuador

On the global effort to a cleaner future, Ecuador has committed to increase its share of renewable energy. Geothermal power generation was studied technically, financially, and environmentally using RETScreen-International, a Clean Energy Project Analysis Software for performing pre-feasibility and feasibility studies. Three scenarios for the development of a geothermal power plant in Chachimbiro were examined, considering different variables, including lifetime. For scenario 1 and 2, incentives of 132.1 USD/MWh of electricity and 3 million USD grants were considered, whereas for scenario 3 the export price of electricity was set to 49.3 USD/MWh. Scenario 3 was also divided into scenario 3A and 3B, where the first considered a 3 million USD grant, while the second considered an income of 8.9 USD/MWH for selling heat in direct applications. Financial and economic analysis indicated that the initial development cost of the 22 MW binary power plant would be 110 million USD, approximately 5,000 USD/kW, a rational amount according to previous literature. According to the cost model, presented on the table below (Table 6), the largest amount was allocated to the construction of the power plant, followed by the engineering and well field development, both accounting for the 80% of the total investment. Operation and maintenance costs were also analyzed.

Table 6 Total initial and annual costs obtained by using the RETScreen model [54]

Initial costs (credits)			Relative cost
Feasibility	4,500,000	USD	3.9%
Development	750,000	USD	0.7%
Engineering, and well field development	35,000,000	USD	30.6%
Power system	57,375,011	USD	50.2%
Balance of system & miscellaneous	16,635,302	USD	14.6%
Construction Contingencies	12	%	
	11,715,001	USD	
Interest during construction (6%) –	18	Months	
Period	4,920,301	USD	
Subtotal	**114,260,313**	**USD**	**100%**
Annual costs – Operation and Maintenance			
Parts & labour	344,988	USD	
Well field and reservoir management, community benefits and overhaul	1,613,129	USD	
Annual Contingencies	6.5	%	
Subtotal	**2,085,618**	**USD**	

Financial viability for the examined scenarios is presented on the table below (Table 7). In scenarios 1 and 3 the dept payment was calculated at 5.36 million USD/year, whereas for the 2nd scenario at 7,06 million USD/ year. The financial feasibility of each scenario was decided mostly by the Net Present Value (NPV), which was positive for all scenarios but scenario 3A, indicating that for this scenario the project was not feasible. The simple and equity paybacks are also a very important aspect and were estimated to be 4.9 and 3.2 years for the 1st scenario, 4.9 and 3.7 years for the 2nd, making them a very attractive choice for investors. In the case of scenario 3A the NPV was negative meaning that the project is financially unattractive, including a payback time of around 16 years in a 25-year project. After 20 million USD government grants and the income from sales for direct applications scenario 3B was considered financially attractive with a respectively reduced simple and equity payback time of 9.3 and 5.6 years. The latter clearly highlights that direct applications, public incentives and clean funding mechanisms are essential for the success of geothermal energy projects. In addition, the study showed that developing such a power plant in this area would lead to savings of 24.3 million USD in oil consumption annually. Additionally, geothermal is a great option for reducing the country's dependency on external energy supply by approximately 40 million USD annually [54].

Table 7 Financial viability for the three scenarios using RETScreen modelling [54]

Financial indicator	Scenario I	Scenario II	Scenario III (25 years)		Units
	(25 years)	(15 years)	Case A	Case B	
Incentives and grants	3,000,000	3,000,000	3,000,000	20,000,000	USD
Pre-tax IRR - equity	45.7	41.7	8.0	23.8	%
Pre-tax IRR - assets	19.3	15.6	0.8	6.4	%
After-tax IRR - equity	32.6	27.8	4.5	18.3	%
After-tax IRR - assets	13.3	8.2	− 2.4	2.9	%
Simple payback	4.9	4.9	15.6	9.3	Years
Equity payback	3.2	3.7	16.0	5.6	Years
Net Present Value (NPV)	62,776,769	35,959,376	− 24,831,772	7,870,200	USD
Annual life cycle savings	9,133,920	5,854,509	− 3,612,983	1,145,102	USD/year
Benefit-Cost (B-C) ratio	2.37	1.79	0.46	1.17	
Debt service coverage	4.34	3.30	1.37	1.94	
Energy production cost	72.20	91.68	72.20	41.87	USD/MWh
GHG reduction cost	56	36	22	7	USD/tCO_2
Annual costs and debt payments					
O&M costs	2,085,618	2,085,618	2,085,618	2,085,618	USD/year
Debt payments	5,362,296	7,058,735	5,362,926	5,362,926	USD/year
Total annual costs	7,448,543	9,144,352	7,448,543	7,448,543	USD/year
Total annual savings and income	24,699,421	24,699,421	9,217,876	12,221,955	USD/year

Case study in Izmir, Turkey

Turkey has achieved an outstanding development in the field of geothermal power production and direct use of H&C, accounting for approximately 227 geothermal fields and 2000 hot water resources, while reaching over 400MW of electricity production. In this case, an economic analysis on a geothermal energy driven ammonia-water absorption refrigeration system for building cooling, in the city of Izmir, is performed, and the economics of this system is evaluated. As mentioned before, for cooling systems the total cost is based on the cost of the components, the O&M costs, and the cost of geothermal water cooling.

Table 8 Total capital investment for the water ammonia absorption cooling system [56]

I. Fixed capital investment (FCI)	3713 kW
A. Direct cost (DC)	
1.Onsite cost (ONSC) − Purchased equipment cost (PEC)	
• Generator	300,000
• Rectifier	200,000
• Condenser	300,000
• Flash valve 1	20,000
• Evaporator	20,000
• Absorber	300,000
• Pump	20,000
• Regenerator	300,000
• Flash valve 2	20,000
• Purchased equipment cost of cooling system (PEC)	1,480,000
Total Onsite cost	1,480,000
2. Offsite cost (OFSC)	
• Civil, structural and architectural work (20% of ONSC)	296,000
• Service facilities (hot source and cold sink connection) (20% of ONSC)	296,000
• Contingencies (10% of ONSC)	148,000
Total Direct cost (DC)	**2,220,000**
B. Indirect cost (IDC)	
• Engineering and supervision (15% of DC)	333,000
• Construction cost including contractor's profit (15% DC)	333,000
• Contingencies (20% of DC)	444,000
Fixed capital investment, total (FCI)	**3,330,000**
II. Other outlays	
A. Start up cost (6% of FCI)	199,800
B. Working capital (5% of FCI)	166,500
C. Cost of licensing, research and development	20,000
Total capital investment (TCI)	**3,716,300 $**

The life cycle cost analysis indicated (Table 8) that the geothermal cooling provides an annual benefit of 166,610 $/year throughout the system’s lifetime, whereas the cooling cost per unit is calculated to be around 0.01295 $/kWh. According to the results of the analysis the annual revenue is calculated to be 653,818 $/year, while the simple and discount payback period is 5.684 and 8.816 years, which can decrease with the increase of geothermal water temperature. Therefore, with a lifetime of 20-30 years, this project is considered financially feasible for further investigation. Using geothermal energy for cooling activities not only maximizes the potential profit but also contributes to eliminating the emission of pollutants associated with the combustion of fossil fuels used for electricity generation. Results of this study can be help in developing sustainable buildings, along with further research in energy and exergy costs of various energy sources and temperatures [56].

Case study in Iran

Regarding renewable energy, Iran has a remarkable variety of renewable sources. Applications associated with RES has grown over the past few years, but the country still depends highly on fossil fuels. In the field of geothermal energy, by the end of 2010 only two power production projects had been implemented, despite the 8.8% of Iran's geothermal energy potential.

In this study, considering the diversity among Iran's regions, both climatically and geographically, the most appropriate region to install a GSHP system is examined. Two main factors that could impact a geothermal project is temperature and humidity. To evaluate the influence of these variables on the economic analysis of GSHPs, Iran was divided into 9 different regions according to their temperature (lower than 16 °C are the cool regions, 16 °C-22 °C the mild, and higher than 22 °C the hot regions) and their average annual relative humidity (dry regions with less than 40%, moderate with 40-60% and humid with more than 60%). The economic assessment and feasibility study to identify the most appropriate area, was performed using RETScreen software. Also, two different scenarios were tested regarding natural gas price raise, the main Iranian space heating resource.

First scenario considers the current natural gas price trend to reach the international market price after 7 years. In the second, this increase happens more rapidly, after 4 years. This aims to a faster clean energy development since people would be more eager to use new alternatives due to the rising cost of gas and therefore to compensate for the initial costs, as natural gas subsidy could be given for RES development.

According to the renewable energy legislation, 50% of the initial cost is offered as subsidies by the government and 30% is considered a 10-year bank loan with 10% dept ratio. The feasibility of the project is evaluated considering all financial parameters within a 25-year lifetime by calculating the NPV and payback time. The results for both scenarios for each area are presented in Table 9.

Table 9 Results of feasibility analysis [57]

City	1st scenario		2nd scenario		GHG reduction tons
	NPV (25 years)	Payback time	NPV (25 years)	Payback time	
Qaen	17892	7.3	19883	5.0	143
Kerman	6923	13.1	8374	10.5	105
Jask	−6154	Not in lifetime	−5562	Not in lifetime	53
Mashhad	19645	6.9	21774	4.6	151
Aq qaleh	11636	11.4	13310	9.5	124
Boushehr	−8525	Not in lifetime	−8285	Not in lifetime	32
Khal khal	38267	3.1	41673	2.2	237
Babolsar	4275	17.2	5541	15.0	96
Mirab	−17402	Not in lifetime	−17323	Not in lifetime	25

According to the results, it is obvious that for the first scenario Khalkhal has optimum conditions for installing GHSPs, having a positive NPV and a very small payback time of 3.1 years. In the second scenario, where support from the government is provided, more regions (Khalkhal, Mashhad, and Qaen) are introduced as cost-effective for GSHP utilization, with reduced payback times (2.2 years for Khalkhal) and higher NPVs.

The temperature also plays an important part for the economics since cities with average temperature below 16 °C (Khalkhal, Mashhad, Ghaen) have shown better results, thus the use of GSHP technology in such conditions is suggested. On the other hand, using GSHP at temperatures above 22 °C should be avoided due to the fact that as Iran has hot and dry climate, the use of such technology would consume a lot of electricity which cannot be economically viable. The well-radiated location of Iran makes solar technology its greatest option.

Lastly, GHG reduction is a primary goal for the use of renewable energy and the results show that the installation of GSHPs in an area with high gas consumption results in significant GHG decrease [57].

Case study in Chile

The Chilean case is an interesting one, since before 2017, there was no geothermal power production despite the large availability of resources on the Andean orogeny and despite the fact that geothermal exploration activities had started in 1908. What is peculiar is that when different areas were studied for potential power plants and proved to be economically and technically feasible, none of them was implemented. Thus, Andes was considered the largest unexploited geothermal region worldwide.

Generally, geothermal energy can help Chile develop a more secure and sustainable electricity mix, with less fossil fuel dependence and less imported energy. This conducted study's target is to form a general review of the barriers that lead to that almost nonexistent progress that geothermal energy field has in this part of the Andes. In particular, it is mainly attributed to the lack of public policies and financial incentives or the existence of insufficient ones. To be more specific, the cost analysis indicated that because geothermal resources of Chile are in remote and high-altitude areas, in addition to the fact that there are few permanent drilling rigs in the country, the rig mobilization costs increase instantly and the exploration and drilling costs are higher than the international average. Furthermore, the particularity of these areas raises the cost factor of the transmission investments, since the project can be still at 75 km distance, or more, from the nearest transmission lines. This could be assisted by government policies to reduce capital costs by sharing the investment costs, either for the cost of the connection to the transmission lines, for the drilling equipment or for any other part of the exploration phase.

Apart from the capital costs, geothermal generation's economics is affected by a discount rate. For countries with existing geothermal experience the discount rate is relatively low due to the lower development risk, whereas in Chile, companies must invest in a market which is not familiar with geothermal projects, resulting in higher risks and considerably higher discount rates. Policies could improve this situation by providing drilling insurance, shared investments, subsidies etc.

In this study, by performing a levelized cost of geothermal energy (LCoE) for differently supported scenarios, it becomes obvious that government policies can significantly impact geothermal economics. The base case investment cost is at 4,500 $/kW$_e$ for the environmental assessment of a 70 MW and 50 MW in two Chilean areas, with a 12% discount rate and Non-Conventional Renewable Energy (NCRE) credits of 10 $/MWh, no other incentives considered. The other scenarios consider a range of discount rate from 9% to 15% for risk variation and policy sensitivity, while the NCRE credits range from 0 to 25$/MWh. The results revealed that the LCoE was 94.97 $/MWh for the base case, while with NCRE credits it drops at 84.91 $/MWh, an almost competitive price considering that the average contract price of the main electricity grid (ASCP) is at 82.6 $/MWh. The diagram below (Figure 10) depicts the LCoE for these scenarios, while the ASCP is shown for comparison [58].

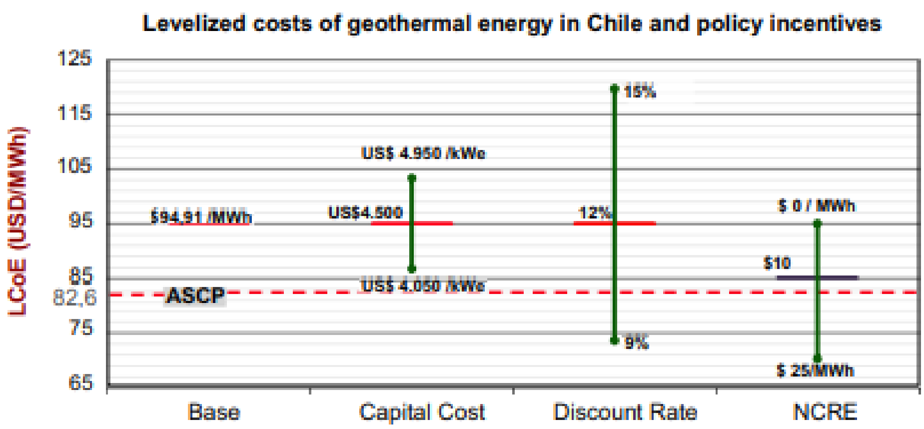

Figure 10 *LCoE in Chile for different scenarios. Even without government incentives, geothermal energy has "near competitive" cost, especially when considering the NCRE-credits.* [58]

Case study in Cerro Pabellón, Chile

In 2017, Cerro Pabellon geothermal power plant started its operation, the first power plant in South America and the only power plant in Chile until 2021. It is about a high enthalpy binary cycle plant that uses the most updated geothermal technologies to withstand the extreme conditions of its location. Moreover, it is the power plant with the highest altitude in the world, 4,5 km above sea level, on a desert, where during the day the sun is burning and during the night strong winds and snow drop the temperature to -30 ^{o}C. It has a total capacity of 48 MW and another 33 MW extension is in the making. When it would be fully operational, it would be able to produce an average of 340 GWh/year. The construction of this facility required a 320 million USD under the supervision of Geotermica del Norte S.A. (GDN).
The decision to build a facility in such a place was based on the following. First, Chile is on top of the largest volcanic chain of Earth, with a geothermal potential of more than 3,600 MW that had never been commercially exploited before. Second, GND is a joint venture between Chilean state-owned Empresa Nacional del Petróleo (ENAP), a state-owned hydrocarbon company that holds 15.37% of the project, along with Enel Green Power, which holds the remaining 84.63%. The latter made it possible as it is a subsidiary of the Italian energy company ENEL, one of the strongest companies in this field, with the ability and the expertise to pursue this project after many years of building and operating geothermal power plants in Italy and in U.S. Furthermore, this project was meant to supply power to Chilean Northern Interconnected System, which was almost entirely dependent on fossil fuels, and could benefit the area both financially and environmentally. Lastly, it would offer jobs and permanent electric power to the surrounding communities [59]–[61].

4.2 Optimization of geothermal systems

As mentioned before, only a small share of the geothermal potential is used globally. To obtain a full or at least a high deployment of this potential, technologies that will reduce the costs and increase the performance must be improved or developed by focusing on optimizing the heat extraction technologies and minimizing the risk of drilling a non-commercially viable geothermal resource.

One way to achieve that is the combination of different technologies. For example, the efficiency of a power plant can be improved when dry or flash steam technology is combined with a binary cycle, using the wasted steam that exits the turbine to produce electricity. However, combining a typical geothermal plant with another heat source, preferably a renewable one, to increase the temperature of geothermal fluids it can result in producing more power. The sequential operation of geothermal heat by integrating different technologies that use progressively lower temperatures, known as cascade applications, can also improve energy efficiency and benefit the local community. Typical examples are the combination of power or district heating plants with greenhouses or fish farming projects, or with hydrotherapy and therapy centers.

For example, when solar energy is used to superheat the steam in a power cycle or preheating the geothermal brine, the power generation is greater. As Anderson & Rezaie [62] stated in their research, by superheating the working fluid of a single or double flash plant, the power rates increased by 0.23 kWe/kWth and 0.29 kWe/kWth, respectively, while by preheating the brine the increase was 0.16 kWe/kWh for the single flash and 0.17 kWe/kWth for the double flash. These result in lower costs as the LCoE for the two systems was 64 $/MWh and 56$/MWh, respectively (LCoE for geothermal-only power plants varies from 60 to 205 $/MWh) [62], [63]. Another study of an Australian hybrid geothermal and solar power plant also indicated that when geothermal and solar are combined (48% solar-52% geothermal), the LCoE could be decreased from 225 $/MWh (only from geothermal) to 165 $/MWh. In general, the size of the solar field area defines the LCoE and the lower the temperature of the geothermal fluid is, the greater the amount of solar energy required to make up for the lack of available energy [62], [64].

Another significant innovation that is under development, is the Enhanced (or engineered) geothermal systems (EGS) (Figure 11). A natural geothermal system is defined by its heat, fluid, and permeability at depth. An EGS is an artificial reservoir created when the permeability or fluid saturation of the existing hot rock is insufficient resulting in not enough water flowing through them to produce hot water. To expand or re-open natural fractures among the production and injection wells, hydraulic and chemical stimulation is used, preventing them from shutting once the pressure of injection is reduced. This would increase the global share of geothermal energy significantly [65], [66].

The International Energy Agency's Net Zero by 2050 report estimates that to prevent the worst impacts of climate change, by 2050, 126 gigawatts (GW) of additional geothermal capacity will be required. This capacity is more than 8 times higher than the world has today. Most geothermal projects use conventional hydrothermal reservoirs. However, only 2% of the earth's geothermal resources are available. That's where EGS technology is needed, as it is able to cover 40 times more energy, enough to achieve net-zero GHG emissions globally. It is an amazing tool that can turn in exploitable projects, unprofitable geothermal fields or facilities that had a different purpose (like wells pumping fossil fuels).

However, current drilling technologies are not suitable for performing such penetration, therefore the drilling process is time consuming and expensive. Furthermore, the temperatures are often not as high, hence the technology to generate electricity is more complex and expensive. The stimulation process can also cause small earthquakes which is also considerable. These issues don't allow EGS to grow and must be overcome. So far, there are only 18 operating and planes EGS sites globally [67], [68].

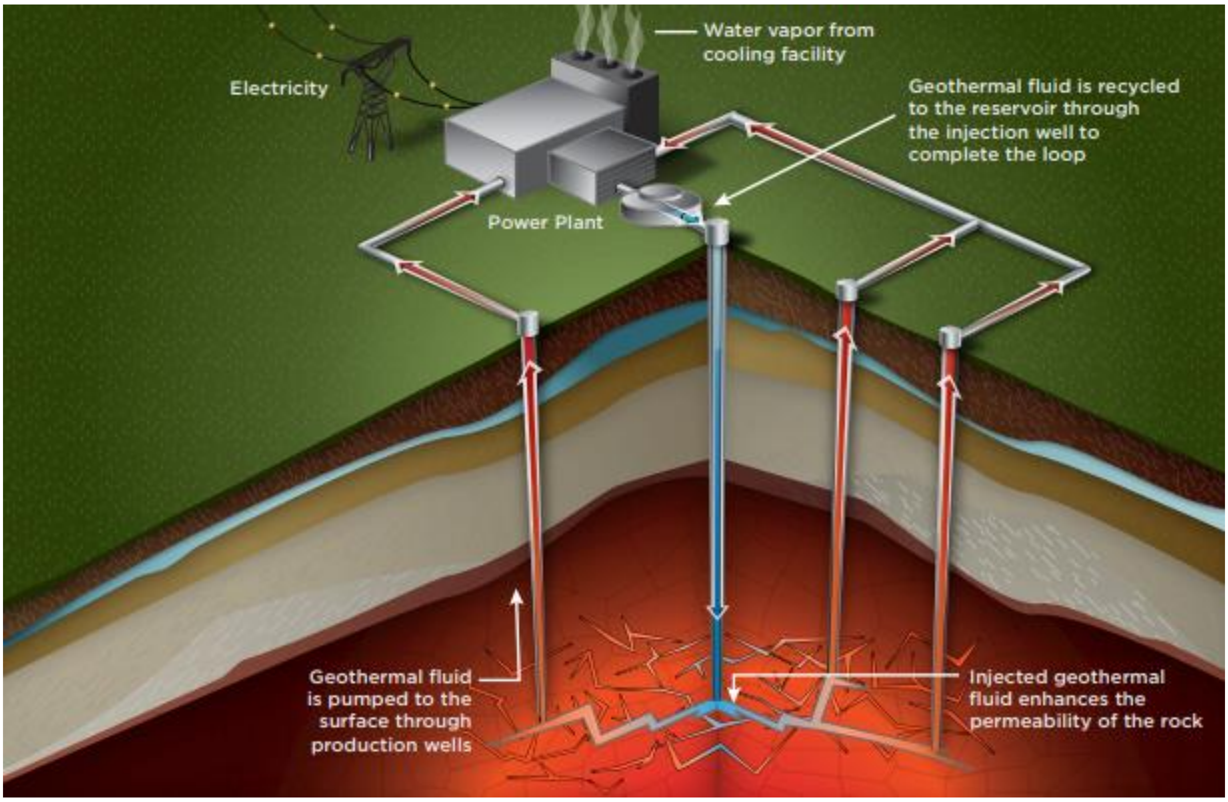

Figure 11 ***Fluid injection turns hot rock to a geothermal resource*** [66]

The first EGS power plant took more than 20 years of studies to be built. It is located in Soultz-sous-Forets in France and began to operate in 2009. Despite being in an area with no active volcano within its natural low-permeability reservoir this is a proof that geothermal power production can thrive with the help of EGS. It worked as a pilot project mostly because this area is one of the oldest known oilfields, with several thousand boreholes already drilled and a well-known geology and temperature distribution in depth. Currently, the LCoE from an EGS plant is not yet low, but it can compete with other renewable energy options [69].

Another very promising case of geothermal energy production field, is Chingshui, Taiwan. Due to former studies of the resource and the available boreholes and production wells that were drilled in the past by the Chinese Petroleum Corporation and the Industrial Technology Research Institute, this region's geology and the characteristics of the reservoir are well-known. Thus, it is an excellent choice for geothermal exploitation. The demonstration of the potential geothermal project, including the review of land area data and analysis of the systems' installed capacity, estimated that with a lifespan of 30 years and 3 MWs of installed capacity it can produce 18.2 GWh of net power annually, the wholesale geothermal power would be 0.16 $/kWh and the net profit would be around 0.196 million USD annually with an investment return rate at 7.3%. Hence, Taiwan could provide a solid foundation for establishing geothermal resource as an economically viable technology in the future [70].

China on the other hand has about 860 million megaton of coal equivalent in hot dry rock (HDR) resources, meaning $2x10^5$ of its total energy consumption in 2015. Thus, exploiting these resources could dramatically transform the fossil-dominated energy structure to a more clean renewable and low-carbon one. Due to low fluid permeability of HDR reservoirs, EGS development is necessary for exploiting this unreachable heat [71].

4.3 General Conclusions

Although geothermal resources are abundant worldwide, only a small fraction can be economically exploited. High initial costs, long payback times, the risk of drilling a lower quality and size resource due to difficulty of resource assessment, are just some of the financial barriers contributing to that. One way to overcome these barriers is to increase the efficiency with the lowest possible cost, by improving the properties of the working fluid and the operational parameters of the power plants. Also, using alternative plant configurations such as binary flash systems, internal heat exchangers, combining geothermal technology and solar heat or biomass can help improve performance and increase the system’s efficiency. To reduce the initial investment cost and minimize the risk, government policies of TAX reduction, providing subsidies, financial incentives must be established. Geothermal energy is a powerful tool that could really change the global energy mix and have a great effect on the environmental crisis we are facing, thus it is important to find the way to adopt it.

Chapter 5

5. Legislative framework

5.1 Geothermal Energy regulations and policies in EU

It is well known that geothermal energy development faces several challenges, with policy and regulation gaps being one of them. Inconsistencies in legislation and objectives indicate a lack of an overall long-term strategy which results in the lack of stability and trust, as well as to the adoption of counterproductive measures that suspend its deployment. However, the complexity of the regulatory framework for geothermal development cause delays in project implementations. This is due to the fact that, in many EU countries, geothermal energy is regulated by national Mining or Water Acts and the responsibilities are scattered around various ministries and institutes. Other legal matters, like resource ownership, licensing, environmental protection, and water extraction, also need to be settled. To ameliorate the situation, EU's executive branches develop frameworks and support mechanisms for geothermal energy, considering that government support can mitigate the risk of a geothermal project and speed up the processes [72].

Furthermore, a main focus for the Commission is the allocation of funds and how the capital cost of a renewable energy project will be reduced, since it defines its total cost, as well as its competitiveness on the market. Geothermal energy Research, Development and Innovation (RD&I) projects rely on government support to compete against natural gas and other renewables.

EGS projects have received the largest share of RD&I funding of any other geothermal topic, yet there are few operating plants around the world. Other research areas that have received the most attention (in financial terms) relate to drilling and district heating systems. In general, despite that numerous support mechanisms are running, geothermal heat and electricity deployment remain at low levels for the majority of the Member States [72], [73].

The implementation of such support policy instruments have already resulted, for many Member States in an acceleration of geothermal development. Over the past decade, the overall geothermal market in Europe has been growing at a 10% annual rate and the geothermal district heating market's annual growth rate is around 3%. To support geothermal electricity and heat development, feed-in tariffs, feed-in premiums, subsidies, loans, tenders, quota systems, net-metering, and tax regulation have been made available [72].

Geothermal energy in the EU is promoted by the EU's Climate and Energy objectives. The regulatory and policy framework is quite complex (Figure 12) and may discourage potential project investments. That is because the particularity of a geothermal project's requirements, related to drilling, extraction of fluid, potential gas emissions etc., put it within the scope of many different European environmental legislations [72].

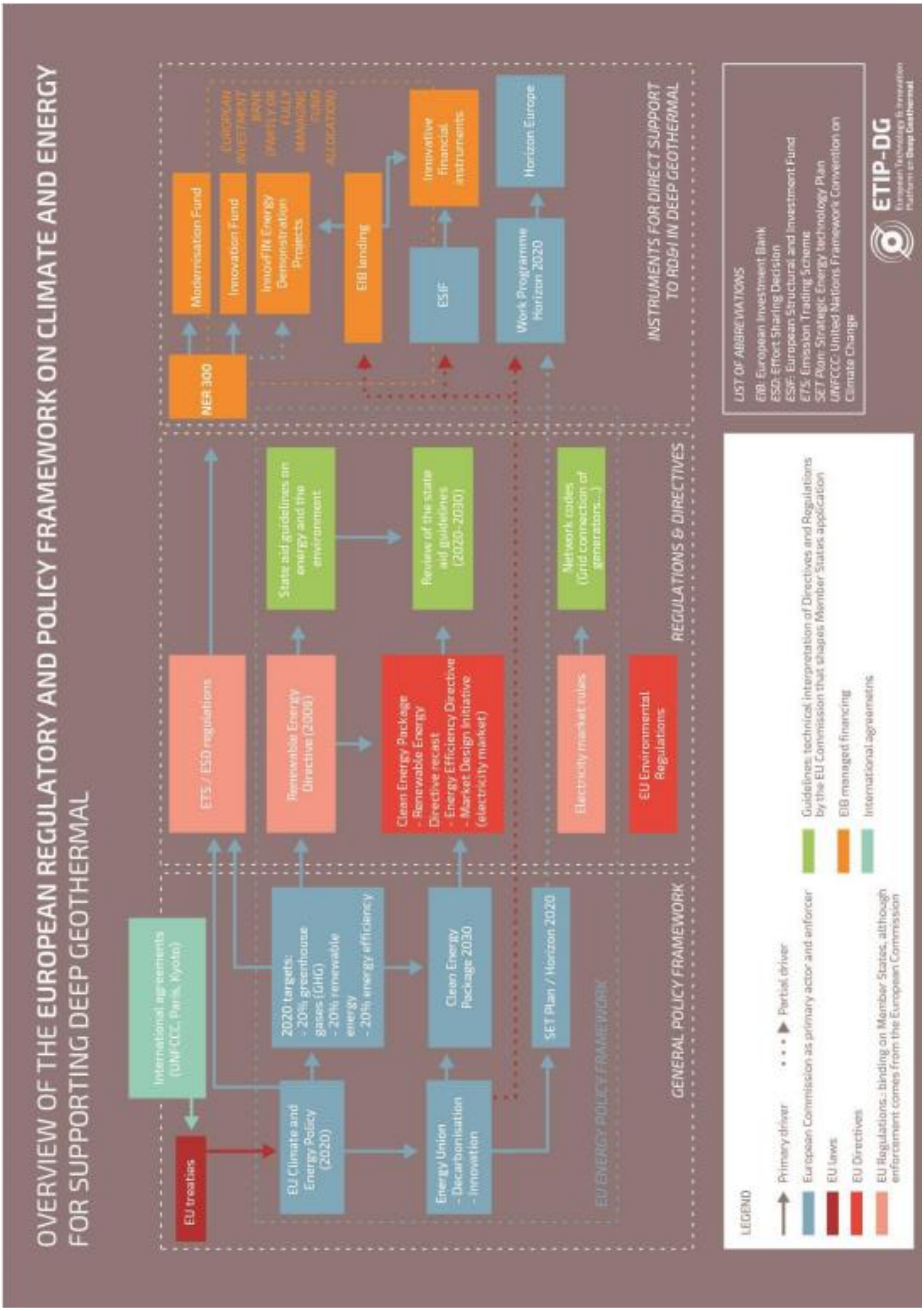

Figure 12 Regulatory and policy framework on climate change [72]

The two axes that structure the European Climate and Energy Framework [72] are:

- The climate and energy targets on renewable energy, energy efficiency and GHG emission reduction, including the corresponding legislations (Renewable Energy Directive (RED) 2018/2001 and Energy Efficiency Directive (EED) 2018/2002)
- The Emission Trading Scheme (ETS) which is a market-based approach to controlling emissions by providing economic incentives for their reduction.

5.2 Geothermal Energy Deployment in Greece

As the global research for sustainable energy solutions is ongoing, geothermal energy exploration can be the key for those countries who has access to it, and Greece is one of them. Rich in geothermal resources due to intense tectonic and volcanic activity, Greece has high enthalpy fields in the Aegean volcanic arc's islands, especially Milos and Nisyros and extensive geothermal fields gathered in northern Greece, mainly in Central and Eastern Macedonia and Thrace, but also in islands of the Eastern Aegean, Chios and Lesvos. This plethora of fields could satisfy a great part of those areas' energy demand. However, because of the incident in the 80's (3.5 Health and safety), geothermal power sector in Greece has been fairly limited, with only a few investments in the geothermal heating sector, mostly in agricultural business. On the contrary, the use of GSHPs on shallow resources and geothermal exploitation for direct uses (thermal spas, greenhouses, aquaculture etc.) grow steadily, constituting most of the domestic geothermal market [74].

Over the last few years though, keeping up with the commitments on renewable energy share, interest in this field in Greece has been sparked and a number of projects in the North part of the country are being developed. One such project is in Alexandroupoli, which exploits a near area's low enthalpy field for district heating use that is intended for municipal buildings and social housing and a longer-term aim to use the district heating networks to residential buildings and industrial consumers. The installed geothermal capacity in Greece has been increased by 17% since 2016, mainly because of these projects in Northern Greece, as well as because of the spread of GSHPs installations. However, it is still the renewable source that has the smallest share in Greece's energy mix [74], [75].

5.2.1 Objectives

In line with its commitments and while considering the Commission's recommendations, Greek government formed its National Energy and Climate Plan (NECP) for battling climate and energy issues, that sets out a roadmap to attaining its energy and climate targets by 2030. Concerning RES, Greek government's target for the share of renewables in the gross final energy consumption by 2030 is at least 35% (in the initial draft it was 31% which was raised after the NECP's revision). Current RES share for Greece is around 18%. Regarding RES in power generation in particular, the aim is to exceed 65% of domestic power generation and 60% of the gross final electricity consumption, by 2030. Their share in H&C sector must go beyond 40% and in transportation beyond 14%, aligned with the EU calculation methodology [76].

Like most Member States, the greatest challenge Greece is facing in the promotion of RES in the power sector is the complex, time consuming and instable existing frameworks along with the licensing of RES power plants. For heating and cooling sector, the lack of an implementation monitoring mechanism and the incomplete existing regulatory framework interfere with the promotion of using RES in buildings that consume almost no energy from fossils, while it is urgent to educate and train the stakeholders in order to achieve adaptation to any technical requirements. In case of geothermal energy, despite the significant potential of some Greek areas, the insufficient knowledge and the technical constraints in implementing and developing the relevant district heating networks raise the greatest obstacles against its spread. Regarding their exploitation for electricity production, there have been no developments, as mentioned before, either due to technical issues or deficient licensing processes or due to objections from local communities, keeping constantly functional and flexible power generation plants off the electricity system.

5.2.2 Regulatory Framework

Geothermal exploration and exploitation were first regulated in Greece by Law 1475/1984, while geothermal energy was categorized in mineral resources under the provisions of the Greek Mining Code. After further developments, Law 317/2003 followed along with regulatory texts that covered mostly the primary sector applications (agriculture, aquaculture etc.). Efforts for producing electricity failed and deserted in 1986 (after Milos' incident). Meanwhile, as EU policies began to promote the use of RES to fight climate change and geothermal technologies evolved, this Law was insufficiently supporting the dynamics of geothermal energy. Therefore, Law 3175/2003 was developed covering the implementation gaps, mostly concerning the high-temperature fields. This law identified that as a source, geothermal energy is reliable and has limited negative environmental impact. Although the new law maintained Mining Code's provision for exploration and exploitation, it provided revolutionary advances along with comprehensive definitions of geothermal potential, fields and products. The categorizing of geothermal fields was made in relation to their temperature (''high'' for T>90°C, ''low'' for 25°C<T<90°C) and also, according to their characteristics as "proven" and "probable" the criteria of which were determined under the provisions of the Ministerial Decision D9B/F166/1508/GDNR374/10/27.01.2004 (GG vol A no 208). Key point of the law was that for the low-temperature fields, regional governments were responsible for them managing, and for high-temperature or unexplored areas, responsibilities laid on the Ministry of Development and later on the Ministry of Environment and Energy. The rights for exploration and exploitation were subjected to a transparent bidding procedure.

As of 2010, the adoption of green policies by the EU, the establishment of RES as the energy problem's solution and the transformation in the Greek administration and industry, led to an increasing interest in exploring geothermal potential and to the need for an updated legal framework. Thus, Law 4602/2019 was produced, which stated that geothermal energy exploration, exploitation and management rights belong to the Greek State, and can be solely exercised or leased by it.

This law, not deviating much from the previous framework, redefined terms and concepts as well as set a new framework to determine roles, responsibilities and obligations for a proper geothermal use in Greece while providing stability for inviting new investments. The main axes include:

- Any earth gas, surface and underground hot water, and geological heat over 30°C is defined as geothermal energy, 5°C more than the previous law. By that, the utilization of several agricultural irrigation wells got released.
- Classification of the fields change to ''of local interest'' (for 30°C<T<90°C) and ''of national interest'' (for T>90°C). Areas with indications of existing field of temperature up to 90°C are defined as "Areas of Geothermal Interest".
- The ministry of Environment and Energy is responsible for the rights of geothermal fields of national interest and unexplored areas, whereas the Decentralized Administrations manage the rights of the local interest fields and the areas of geothermal interest.
- Also, the exploitation right is differentiated from the management right, whereas the management right includes the entire geothermal field.
- The duration of the lease of the exploration right of unexplored areas, fields of local interest and areas of geothermal interest is set up to five years with a possible extension of four years. The lease period for the management and exploitation right of both national and local interest fields can reach thirty years, which a possible twenty-year expansion.
- If during exploring geothermal potential is detected, exploitation can co-exist.
- When an interested party applies for claiming the rights, the authority responsible for the case calls public to express interest. If there is no response, the initial application is examined and the concerning right gets leased. If other parties express interest, the right lease enters a bidding process.
- The use of geothermal potential for H&C needs of schools, health centres, and hospitals, does not require a lease payment or a guarantee of the contract terms.
- A five-year development plan by the decentralized administrations is required as a guarantee of rational use and protection of the natural resource within the areas of their responsibility.
- The utilization of all available geothermal data and monitoring of the relevant activities is anticipated to be established by the Ministry of Environment and Energy and Hellenic Survey of Geology and Mineral Exploration.

Another major step toward the promotion of geothermal exploration and production is the elaboration of a new Regulation on Geothermal Works. Rewritten between 2019-2020 and came into force on May 2021 after getting the approval of the Ministerial Decision YPEN/DAP/42138/552/29.04.2021, it incorporates innovative regulations related to the country's geothermal potential, while ensuring the health and safety of workers and the environmental protection. Concerning the incentives, decisions that create or provide access to financial tools is quite complex. The Law 4602/2019 has little to do with the geothermal power production process, distribution and required authorizations. Thus, any financial incentives and tools related, need the collaboration of the Regulatory Authority for Energy (RAE) and the Ministry of Finance [77]–[80].

5.3 General Conclusions

To overcome the barriers, provide security for the investors and make RES technologies competitive under the current market conditions, more policy instruments are required. Support schemes for geothermal (and other RES) should provide compensation in case of market failures and create a secure environment for the investments, allowing the technology to grow while it is researched. Support schemes may also help increase awareness and enhance consumer's confidence of using the technology, especially for GSHPs.

Furthermore, for geothermal power production, it is important that policy support mechanisms for mitigating the initial risks should not only focus on those who support the operational phase of the project. Also, since the initial risk is high, private investors demand higher returns resulting in increased LCoE and tariff. This increase can be balanced by public measures that reduce the risk of resource exploration, political imbalance and currency variance, providing access to longer-term and lower-cost dept than of any other available on the commercial market. Governments can also achieve the same amount of electricity generation while providing only 15-35% of the financial resources when engaging the private sector, compared to developing and operating projects themselves. By setting ambitious deployment targets, governments will signify that there is potential for geothermal energy, attracting international private developers, investors and energy providers. Lastly, public agencies and private developers, by sharing the data of already explored geothermal resources, will significantly reduce exploration risks, and by providing accurate survey data they can prevent costly and long legal disputes on ownership while attracting investors into new markets [72].

It is obvious that Greece intends to benefit from its geothermal fields and promote this new RES sector. Modern technology and stable regulatory frameworks can benefit investments in the field and become a tool for the country's transition to clean energy. Nonetheless, the geothermal energy sector of Greece has huge prospect and could provide investors and local or national economy with great opportunities. Yet, geothermal fields, mostly of national interest, are highly underdeveloped, and there is a long way for Greece to reach its desirable utility levels [77].

Chapter 6

6. Conclusions

Geothermal energy has significant untapped potential. In this global transformation to decarbonization, using geothermal energy offers cost-effective renewable solutions with many advantages. Under the right conditions, it can economically compete with fossil sources like coal and natural gas, meaning that countries could depend less on imported fuels and increase their energy security. Unlike other renewable sources, it is constantly available since it is unaffected from climate and seasonal conditions and therefore it is capable of delivering base-load energy.

Despite its large potential, geothermal deployment faces many challenges like environmental concerns, social acceptance, financial constraints, and insufficient legislation that have contributed to its obstruction.

Environmentally, it is a source with limited impacts and if combined with other RES these impacts can lessen even less. First of all, atmospheric emissions are lower than fossil sources and from most RES due to the fact that during the operational phase of a geothermal plant the energy needs are negligible. Moreover, the amount of water consumed is less than that of coal, nuclear and natural gas power plants. Regarding land use, much less space is required for geothermal installations than for any other power plant. However, as geothermal power plants are usually located in remote areas infrastructure is needed to access the location damaging the natural area format and downgrading forests, national parks and agricultural areas. Furthermore, the process of extracting and reinjecting geofluids can disturb the underground causing seismicity and ground deformations. Lastly, noise from construction and drilling activities is also another disturbing impact.

To examine whether a geothermal plant is environmentally sustainable, Life Cycle Assessment method is applied. Through LCAs, the potential environmental impacts of geothermal installations are analysed and corresponds to the different lifecycle stages of the plant. Most LCA studies examine global warming in order to highlight the importance of geothermal power generation in reducing GHGs from the atmosphere. What most LCAs indicate is that geothermal plants whether for power production, H&C or direct applications are always environmentally friendlier than other conventional fossil sources and depending on the case, than other RES. On the other hand, in majority construction processes cause the greater damage since they require electricity. However, life cycle impacts vary depending on geological site characteristics and technical parameters concerning LCA methodology and due to the fact that the number of performed studies is inadequate, no definite conclusions can be drawn.

Social acceptance is another crucial element for achieving climate targets. Public opposition could delay or obstruct the implementation of geothermal projects, whereas achieving acceptance through building confidence and sharing knowledge on the subject could contribute to the success of the project.

The main obstacles though in the development of geothermal sector are of financial nature. High initial investment cost, long payback times, risk of drilling in vain are just a few parameters that must be considered when investing on a geothermal project. By increasing the efficiency of a plant, optimizing the working fluid and combining geothermal technology with other technologies might help overcoming these barriers. Moreover, regarding risk mitigation and cost reduction, government policies for providing subsidies and financial incentives should be established.

Lastly, geothermal energy development faces challenges with policy and regulation gaps. Inconsistencies in legislation and objectives result in lack of stability and trust, as well as in suspension of its deployment. Delays in project implementations also occur because of complex frameworks that require the engagement of many different ministries and institutes.

However, with increasing its ambitious towards RES' energy share, EU's efforts to promote geothermal energy are guided by the European Climate and Energy Framework. The two axes that form its structure are the climate and energy targets on renewable energy, energy efficiency and GHG emission reduction and the Emission Trading Scheme (ETS) which is a market-based approach to controlling emissions by providing economic incentives for their reduction.

Greece, rich in geothermal fields, also intends to take advantage of its potential and use geothermal energy to promote its progress in RES sector. Committed to raise its share of RES, Greece's interest in exploring geothermal potential has increased. Law 4602/2019 regulates geothermal exploration, exploitation and management rights. Under this framework, innovating concepts and consistent guidance lead the way to a sustainable and reasonable use of geothermal energy while providing stability for inviting new investments.

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