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Review of the technical and environmental capabilities of Geothermal Systems through Life Cycle Assessment (LCA)

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In an era of increased environmental awareness, many countries turn to renewable energy sources for large applications (e.g. electricity generation power plants) and small (e.g. building heating and cooling). In this context it makes sense that there is an increasing interest for technologies that depend on renewable energy such as geothermal energy, with the utilization of advanced tools such as Life Cycle Analysis (LCA). In this study, an effort is made to review previous studies that use LCA in various applications of geothermal energy, as well as the capabilities it has to offer.

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1. Introduction

We live in an era where the impacts of climate change are being intensely experienced all over the world. Only recently, in many countries like Greece or Spain, extended periods of heat were followed by periods of large temperature drops. In other countries like Britain, France or Italy, floods have caused millions of Euros of damage in buildings, infrastructure and human lives.

The scientific community all over the world has made efforts to understand the phenomena of climate change and propose ways to mitigate its effects. One way to decrease the effects of climate change is by turning to renewable energy sources to produce electricity, heating and for other domestic and industrial activities.

Modern tools such as Life Cycle Analysis (LCA) help to depict the entire life cycle of a system from its construction to its dismantling, showing not only financial indicators but also environmental ones, which help in the final decision making procedures.

One of the renewable energy sources available to exploit in both domestic and industrial scales is geothermal energy, the exploitation of earth's heat. A lot of work has been done in this area by many different scientific groups all over the world, trying to see the potential of geothermal energy from as many angles as possible.

In this thesis we are trying to make an overview of the work that has been made, so that the reader can catch all the potential benefits and applications of geothermal energy. We will start with the various methods and tools that are used to analyze a possible application, then describe the various geothermal power generation technologies and finally describe the possible applications of geothermal energy.

2. Methods

On this part we will make a quick reference on the methods that are being used to study, analyze and describe a particular system or application. The main tool used in all the examined studies is LCA, often combined with other methods for improving its results.

2.1. Life Cycle Analysis (LCA)

Life cycle assessment (LCA) is an established way of measuring total environmental effects of products and services. LCA takes all the phases of a product life cycle into account, starting from the acquisition of raw materials to the end-of-life phase (e.g., disposal of product or demolition of a building). The International Standard ISO 14040 defines the phases of an LCA as follows [1]:

1. Goal and scope definition: defines the goal, characteristics and borders of an LCA.
2. Inventory analysis: defines the characteristics of data collection and calculation procedures.
3. Impact assessment: evaluates the potential significance of the results of LCA.

4. Interpretation of results: the findings of the inventory analysis and the impact assessment are combined together [1].

The most established methods in LCAs are process LCA and IO-LCA (input-output LCA). The process LCA is a traditional way of analyzing product life cycle emissions. The principle of the process LCA is to calculate GHGs of each process of the product life cycle individually in order to form a chain of the processes that covers the whole life cycle. Each process analysis is conducted using process-specific primary (i.e., material and energy flows in the manufacturing process) and secondary data (i.e., amount of GHG emissions per manufacturing process), which lead into very accurate results of the modeling. However, there is nearly an indefinite amount of single processes in a product life cycle, and including all of them in the modeling is practically impossible. This problematic characteristic of process LCA modeling is known as a truncation problem. A process LCA practitioner has to define a border that separates the processes included in the modeling from those that are left out of it. Thus, it is probable that significant processes are also left out of the modeling along with the insignificant ones. Process LCAs are also very laborious and require a large amount of data since secondary data has to be acquired separately for each process. Furthermore, process LCA software is usually expensive [1].

Another widely used LCA method, IO LCA, was invented in the 1970s by Nobel Prize winner Wassily Leonthief. IO-LCA converts monetary costs into environmental effects, often according to national input-output matrices. There are a few different IO-LCA models for different economies, but also more and more prevalent are the so-called multi-region IO models. The truncation problem is not an issue in IO-LCAs since every sector of a national economy is included in a model and the number of included sectorial transactions is indefinite. Additionally, data requirements are significantly different between IO-LCAs and process LCAs. IO-LCAs require monetary transaction data, whereas process LCAs requires detailed data on the material and energy flows of all processes in a production process chain. All required secondary data in the IO-LCAs lie within the IO-LCA matrices, while process LCAs require case-specific secondary data [1].

IO-LCA suffers from the aggregation problem, since even in the most disaggregated models several industries as well as all the products of a specific industry are aggregated into each IO sector. The industry sectors in IO-LCAs thus represent the averages of several sectors of an economy, making the method not applicable in modeling specific products or comparing similar products within one industry. Additionally, IO-LCA models in general appear as a “black box” to the LCA practitioner. Thus, examining characteristics of a specific process within an IO-LCA model is usually impossible. Partly related to the same issue, two other well recognized problems of IO-LCAs are homogeneity and proportionality assumptions. Of these, the homogeneity assumption means that sector outputs are assumed to be proportional to price, regardless of the variation of products inside a sector. The proportionality assumption means that the inputs to a sector are assumed to be linearly proportional to its output [1].

The hybrid LCA method combines the process LCA and IO-LCA into a single model. The method combines the advantages of the two traditional LCAs and avoids known problems. Using hybrid LCA avoids the truncation problem of the process LCA and relieves the issue of the aggregation problem inherent in IO-LCA modeling. One of the most popular applications of hybrid LCA is tiered hybrid LCA, which consists of process LCA for the emissions of production processes, whereas the indirect emissions are modeled with IO-LCA. As a result, the model is accurate since process data is used for the most important processes (avoiding the aggregation problem) and IO-LCA covers the supply chains (avoiding the truncation problem) [1].

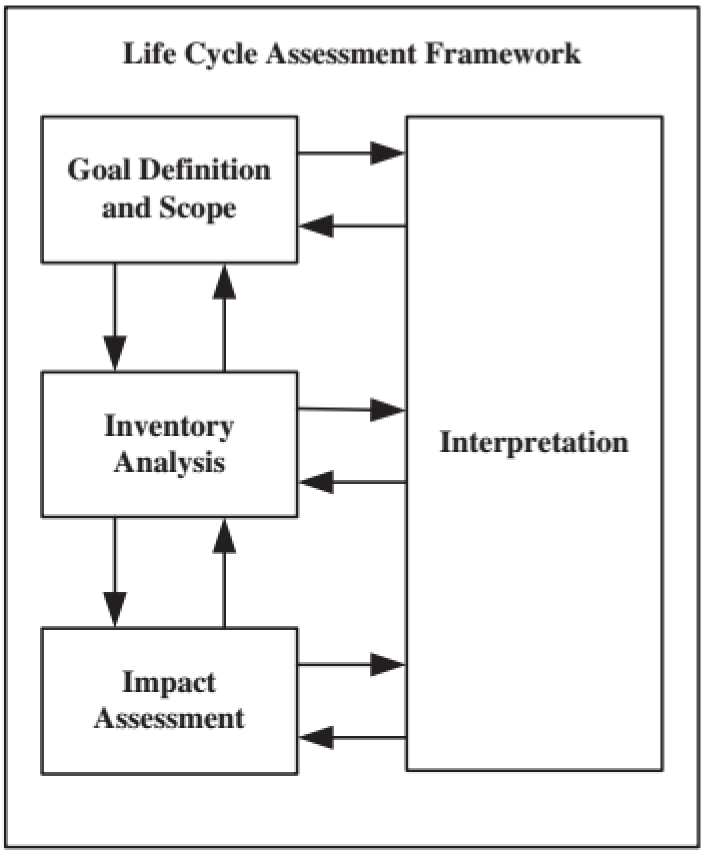

Fig 1: Methodology stages of the life cycle analysis [2].

2.2. Life Cycle Costing (LCC)

LCC is a valuable financial approach for evaluating and comparing different designs in terms of initial cost increases against operational cost benefits with a long-term perspective. The key incentive for applying a LCC analysis is to increase the possibility of cost reductions for the operational phase, even if an additional increase in the initial investment is necessary. By applying a LCC perspective in the early design phase, decision makers are able to obtain a deeper understanding of costs during the life cycle for different design strategies. Buildings for example are a long-term investment associated with environmental impacts over a long duration. Fundamental environmental responsibility aims for a long-term view and with that an understanding that initial design decisions have a significant impact over a building's life span [1].

LCC is defined as "a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs" (Standardized Method of Life Cycle Costing for Construction Procurement ISO15686, 2008). It is important to notice that traditional LCC is purely economical and does not take into account environmental aspects. Earlier development has focused on developing LCC methodology for the construction industry and placing LCC in an environmental context [1].

Essential decisions and activities to undertake an LCC analysis are:

1. Defining alternative strategies to be evaluated: specifying their functional and technical requirements.
2. Identifying relevant economic criteria: discount rate, analysis period, escalation rates, component replacement frequency and maintenance frequency.
3. Obtaining and grouping of significant costs: in what phases different costs occur and what cost category.
4. Performing a risk assessment: a systematic sensitivity approach to reduce the overall uncertainty [1].

The LCC methodology can (and must) be criticized. A LCC analysis is based on the estimation and valuation of uncertain future events and outcomes. Hence, subjective factors are involved in the process and will affect the results [1].

Even though LCC is not recognized as theoretically accurate, the LCC methodology presents many benefits. For example, the analysis provides an indication of what strategic options and aspects to seriously consider, the results of the LCC analysis are presented with a common unit (currency), an LCC analysis processes and simplifies a huge amount of information and provides a valuable life cycle perspective to the different alternative options [1].

From a user and consumer perspective, it is valuable to link environmental issues with financial outcomes in a strategic decision making context. However, it is important to note that the LCC methodology is developed only for financial analysis, whilst LCA assessment focuses on the environmental impact [1].

2.3. Exergy Analysis – Exergoenvironmental Analysis

The exergy analysis is a method based on the Second law of thermodynamics and the concept of irreversible production of entropy. The founders of exergy were Carnot in 1824 and Clausius in 1865 who laid down the fundamental of the exergy method. The energy-related engineering systems are designed and their performance is evaluated primarily by using the energy balance deduced from the First law of thermodynamics. Traditionally it is the first law of thermodynamics analysis has been applied by engineers and scientists to calculate the energy losses and quantify the loss of efficiency in any process. In recent years the exergy concept has gained considerable interest in the thermodynamic analysis of thermal processes and plant systems since it has been seen that the First law analysis is insufficient from an energy performance point of view. The aim of the exergy analysis is to identify the magnitudes and the locations of exergy losses, in order to pinpoint to the improvements of an existing system, or to develop new processes or systems. This analysis allows one to quantify the loss of efficiency in a process that is due to the loss in energy quality. It will specify where the process can be improved and therefore, it will signify what areas should be given consideration [2].

To calculate the exergy of a system, the various forms of energy that the system has, (kinetics, dynamics, energy flow, enthalpy, etc.) must be first identified and then calculate the exergy for all the energy forms and add it. The change in exergy of a system during a process is equal to the difference between the total transfer of exergy through the boundaries of the system and the exergy destroyed within the boundaries of the system because of the irreversibility (or entropy production) [2].

Exergy analysis provides a powerful tool for assessing the quality of a resource as well as the location, magnitude, and causes of thermodynamic inefficiencies. Exergoenvironmental analysis is a suitable combination of exergy analysis and LCA, thus gaining the benefits of both [3].

Exergoenvironmental analysis consists of three steps. The first step is an exergy analysis of the energy conversion system. In the second step, a LCA of each relevant system component and all relevant input streams to the overall system is carried out. In the last step, the environmental impact obtained from the LCA is assigned to the exergy streams in the system. Thus exergoenvironmental variables are calculated, and an exergoenvironmental evaluation is carried out. The final product or service exergoenvironmental value can be used to compare with the other alternatives that fulfill the same function [3].

2.4. Global Sensitivity Analysis (GSA)

Life cycle assessment (LCA) is widely considered as the most relevant methodology to assess the environmental performances of products and processes over their life cycle and is currently applied to different industrial sectors. Due to the inherent variability of the input parameters, the large number of assumptions and sometimes the incomplete knowledge of modeled process, the importance of assessing uncertainties through sensitivity analysis (SA) has been stressed since the early development of the LCA methodology. The ISO standard for LCA (ISO 14040, 2006; ISO 14044, 2006) also indicates SA as a fundamental part of the analysis, without however recommending a particular calculation technique [4].

In the LCA context, global sensitivity analysis (GSA) has been recently identified by several authors as a relevant practice to address several issues [4]:

1. to study the combined influence of the different input parameters
2. to assess the robustness of the results
3. to enhance the understanding of the structure of the model
4. to ensure transparency, reliability and credibility of LCA practices
5. to contribute to the decision-making process [4].

GSA allows establishing a ranking among the input parameters and identifying the most influential on the variability of the output of the model. The identification of such key parameters is fundamental when aiming at the simplification of the uncertainty quantification: in fact, based on the GSA results, the efforts to minimize the uncertainty can be focused only on few key input variables while the others can be fixed to average values without influencing the results [4].

Identifying the most influent variables also allows developing simplified parameterized LCA models. In general, GSA techniques support the execution of LCAs and facilitate its interpretation, promoting an enhanced decision making process [4].

To perform GSA in a LCA, a comprehensive multi-step protocol for the integration of sensitivity and uncertainty analysis in the impact assessment phase of LCAs is proposed [4]:

1. Step 1: Identification of the LCA model
2. Step 2: Description of the inputs of the model
3. Step 3A: Baseline global sensitivity analysis
4. Step 3B: Analysis of the influence of the inputs' description
5. Step 4: Overall evaluation
6. Step 5: Identification of key input parameters of the LCA model [4].

Possible applications of the GSA in the LCA context could be the elaboration of simplified calculation models, where the life cycle impacts are expressed as a function of few key parameters identified through the GSA, or eco-designed scenarios established using the lower values of the most influential drivers, or recalculation of the uncertainty propagation considering only the key parameters [4].

2.5. Emergy Analysis (EMA)

The EMA method is an environmental assessment procedure aimed at evaluating the performance of a system on the global scale of biosphere, also taking into account free environmental inputs (e.g., solar radiation, wind, rain, and geothermal flows) as well as indirect environmental support embodied in human labor and services. While LCA includes in the assessment of CED (Cumulative Energy Demand) only the renewable energy flows that are captured through technological devices (e.g., photovoltaic modules), EMA also accounts for the broader ecosystem services that indirectly support the human society and economy, but are not generally included in economic and biophysical accounts [5].

According to this method, inputs are accounted for in terms of their solar emergy, defined as the total amount of solar available energy (exergy) directly or indirectly required to make a given product or support a given flow and measured as seJ (solar equivalent joules). The emergy required to generate one unit of each product or service is referred to as its UEV (Unit Emergy Value) or emergy intensity (seJ J^{-1}, seJ g^{-1}, seJ $€^{-1}$ etc.). UEVs are used to convert matter and energy input flows into emergy units [5].

The main steps followed to perform the EMA of a power plant are:

1. Identification of the boundaries (spatial and temporal) of the study area.
2. Modeling of the investigated system through an emergy system diagram according to Odum's diagramming language.
3. Calculation of matter, energy and money flows supporting the system.
4. Conversion of the above flows into emergy units by using suitable UEVs.
5. Assessment of the total emergy used by the system.
6. Calculation and interpretation of emergy-based indicators of environmental performance and sustainability [5].

The technique has gained wide recognition in the past decade but still faces methodological difficulties which prevent it from being accepted by a broader stakeholder community. Benedetto Rugani and Enrico Benetto in their review “Improvements to Emergy Evaluations by Using Life Cycle Assessment” aim to elucidate the fundamental requirements to possibly improve the Emergy evaluation by using LCA. Despite its capability to compare the amount of resources embodied in production systems, emergy suffers from its vague accounting procedures, its lack of accuracy, reproducibility and completeness. An improvement of Emergy evaluations can be achieved via [6]:

1. Technical implementation of Emergy algebra in the Life Cycle Inventory (LCI)
2. Selection of consistent Unit Emergy Values (UEVs) as characterization factors for Life Cycle Impact Assessment (LCIA)
3. Expansion of the LCI system boundaries to include supporting systems usually considered by Emergy but excluded in LCA (e.g., ecosystem services and human labor) [6].

Whereas Emergy rules must be adapted to life-cycle structures, LCA should enlarge its inventory to give Emergy a broader computational framework. The matrix inversion principle used for

LCAs is also proposed as an alternative to consistently account for a large number of resource UEVs [6].

3. Geothermal Technologies

Most of the power generation technologies currently available in the geothermal industry have been designed for exploiting the conventional convective geothermal systems (also referred as hydrothermal systems). The selection process of the most suitable geothermal power generation technology essentially depends on the properties of the geothermal resource (fluid and reservoir) that require to be exploited (i.e., geological, chemical, physical and thermodynamic properties) [7].

Geothermal resources suitable for power generation can be categorized in three major groups:

1. Vapor dominated systems with temperatures >240^{o}C
2. Liquid (or hot water) dominated systems with temperatures up to 350^{o}C
3. Petro-thermal or solidified hot dry rock resources with temperatures up to 650^{o}C [7].

Groups (1) and (2) are related to the convective hydrothermal systems which are commercially exploited in the world, whereas group (3) is referred to the exploitation project of the hot dry rock (HDR) or enhanced geothermal systems (EGS) [7].

The energy conversion technology used for exploiting the geothermal systems depends on the reservoir properties (e.g., geological, geophysical, geochemical, physicochemical, thermodynamic, among others). Three types of mature technologies have been commercially and successfully used for the exploitation of geothermal resources: dry steam, flash (single, double and triple) and binary cycle power plants. A brief overview of these technologies is given as follows [7]:

3.1 Dry Steam

There are privileged places, such as The Geysers in California and Larderello in Italy, where the earth's gradient temperature leads to reservoirs with high temperature (>240 ^{o}C). The vapor extracted from these reservoirs is transported to a steam turbine that converts thermal energy into mechanical energy, which is then sent to a generator from where electricity is produced and distributed into the grid (Fig 2A) [39]. This conversion technology is known as dry steam, and due to its plant set up it is the cheapest geothermal generation process [7].

Furthermore, based on the steam's chemical composition, which is generally characterized by water steam (>90% wt. of steam) and non-condensable gases (NCG) (<10% wt. of steam), the plant set up can also have a gas extraction system. This system can include vacuum pumps or stream-jet ejectors, which are designed to remove NCG that among other gases include CO2, H2S, NH3 and some trace gases (e.g., He, H2, Ar, N2, CH4, and CO). The presence of the NCG in the steam stream has represented a challenge in the market of electricity production by geothermal means, since due to their potential corrosive effects different modifications are sometimes required to avoid a reduction in the turbine's efficiency. This is because of two factors that decrease the power production rate, which might lead to a reduction in the plant's profit [7].

3.2. Single and multi-stage (double and triple) flash

If the geothermal fluid in the reservoir is a liquid-vapor mixture, then a separation process commonly known as flash is used for the power generation. Based on the thermodynamic mixture's characteristics, the separation process can include one, two or three stages, namely single-, double-, and triple-flash systems, respectively [7].

When the mixture temperature is over 210^{o}C, a single-flash set up is generally used (see dotted lines in Fig 2B). In this case, the geothermal fluid is extracted from the production well and sent to a cyclonic separator (Webre type) where the liquid and vapor phases of the mixture are efficiently separated due to a difference in densities [7].

The primary vapor passes from the separator to an expansion steam turbine and finally to a generator to complete the process. The remaining liquid phase mixture (also known as brine) obtained from the separator is sent to a reinjection well, which in turns receives cooling water from a condensation process that is designed to treat steam coming from the expansion turbine [7].

In order to increase the efficiency of this process a second separation stage (known as double-flash) is added (see solid lines in Fig 2B). This process is used to separate low-pressure steam coming from the brine leaving the single flash cycle. The secondary low-pressure steam is led to either a low-pressure turbine or a suitable stage of the main turbine (with dual-pressure and dual-admission specifications). Although this is a general description of the process, it should be noted that based on the chemical composition of the geothermal fluid, an integration of a NCG abatement equipment could be also required if the amount of the NCG is high. The double-flash power plants are recommended to increase both the efficiency of the process generally by 35% and the power generation by 20% in relation to the single-flash set up [7].

In this context, a third separation stage could be integrated in the plant set up, which is known as triple-flash power plants (see Fig 2C). This process is designed to utilize energy available in the brine coming from the double flash cycle, as well as to decrease the non-condensable gas (NCG) content of the geothermal fluid. This technology is currently used in some of geothermal fields of U.S., New Zealand and Turkey [7].

The use of single and double flash conversion technology contributes to 63% of the world's geothermal power installed capacity, and an additional 2% is provided by triple flash power plants [7].

3.3. Binary cycle

In liquid-dominated reservoirs with temperatures lower than 200^{o}C, a binary cycle system is used for power generation, which represents 12% of the worldwide installed capacity. In this system, the geofluid cannot be used directly as in other power generation technologies previously described. This is due to the low temperature of the geofluid, which leads to a poor vapor production. However, the thermal energy available in the geofluid can be used to vaporize a working fluid (which has a lower boiling point, e.g., n-isobutane, n-isopentane and pentane), by using either a thermodynamic organic Rankine cycle (ORC) or Kalina cycle to produce electricity. The heat transfer process occurs in a heat exchanger from where an organic vapor is produced and sent to a turbo generation system for producing electricity (see Fig 2D). Remaining steam coming from the turbine is sent to a condenser whose brine is conducted to the heat exchanger, thus closing the thermodynamic cycle [7].

3.4. Engineered or enhanced geothermal systems (EGS)

The power generation process theoretically proposed for the exploitation of enhanced geothermal systems (EGS) is generally the same as the one described for binary cycle plants. These systems are aimed to exploit widely available deep underground reservoirs (namely hot dry rock, hot wet rock and hot fractured rock resources), where insufficient water exists and/or the rock-formation permeability is low [7].

In order to exploit such geothermal systems, an enhanced process in the rock permeability is required either by opening preexisting fractures in the rock or by forming new ones to create an artificial reservoir. The thermal energy is generally exploited by injecting water, or another appropriate fluid (e.g., CO_2) into the hot fractured rock (or artificial reservoir) to stimulate an intense heat exchange, and to extract most of the energy available in the rock. Sometimes, there is circulation of the fluid already present in the rock formation, which acts as a geothermal fluid loop. The hot fluid is extracted from production wells and pumped to a power plant installed on the surface to generate electricity. In spite of the potential use of the EGS, the implementation of these systems in the commercial market is not widespread. This is explained because the learning curve of this technology is at an early stage. Nowadays, there are technological advances with the installation of some pilot projects in Australia, U.S., Italy, France, Germany, Switzerland, Japan, and El Salvador, which have demonstrated the feasibility of exploiting these systems at depths between 3 km and 10 km [7].

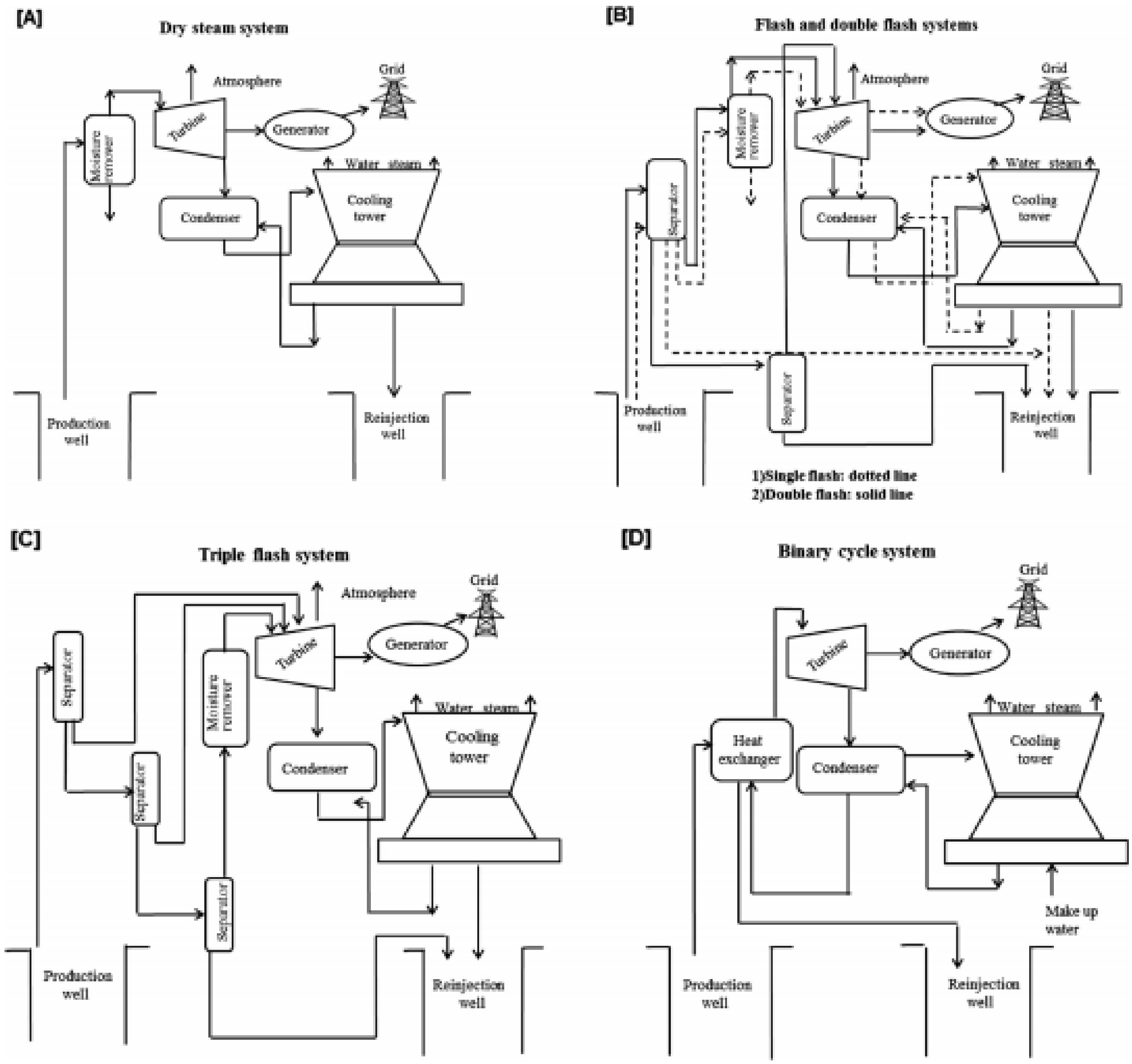

Fig 2: Simplified schematic diagrams showing the typical technologies used for geothermal power generation [A: Dry steam]; [B: Single and double flash systems]; [C: Triple-flash], and [D: Binary cycle] [7].

4. Applications

In this part we will present some of the various applications of geothermal energy as well as its efficiency in the way they were examined in each case. Applications found in literature can be summarized in the categories below:

4.1. Combination of Geothermy and Biomass
4.2. District Heating
4.3. Domestic Heating
4.4. Electricity Generation

4.5. Environmental Studies on Pre-existing Power Plants
4.6. Greenhouse Heating
4.7. Improvement of existing technologies of geothermal systems
4.8. Water Consumption

Some categories have been studied more than others, electricity generation for example. But this is reasonable if someone considers the importance and size of each category. Continuing we will examine each category separately and present each study that was made, its methods and results.

4.1. Combination of Geothermy and Biomass

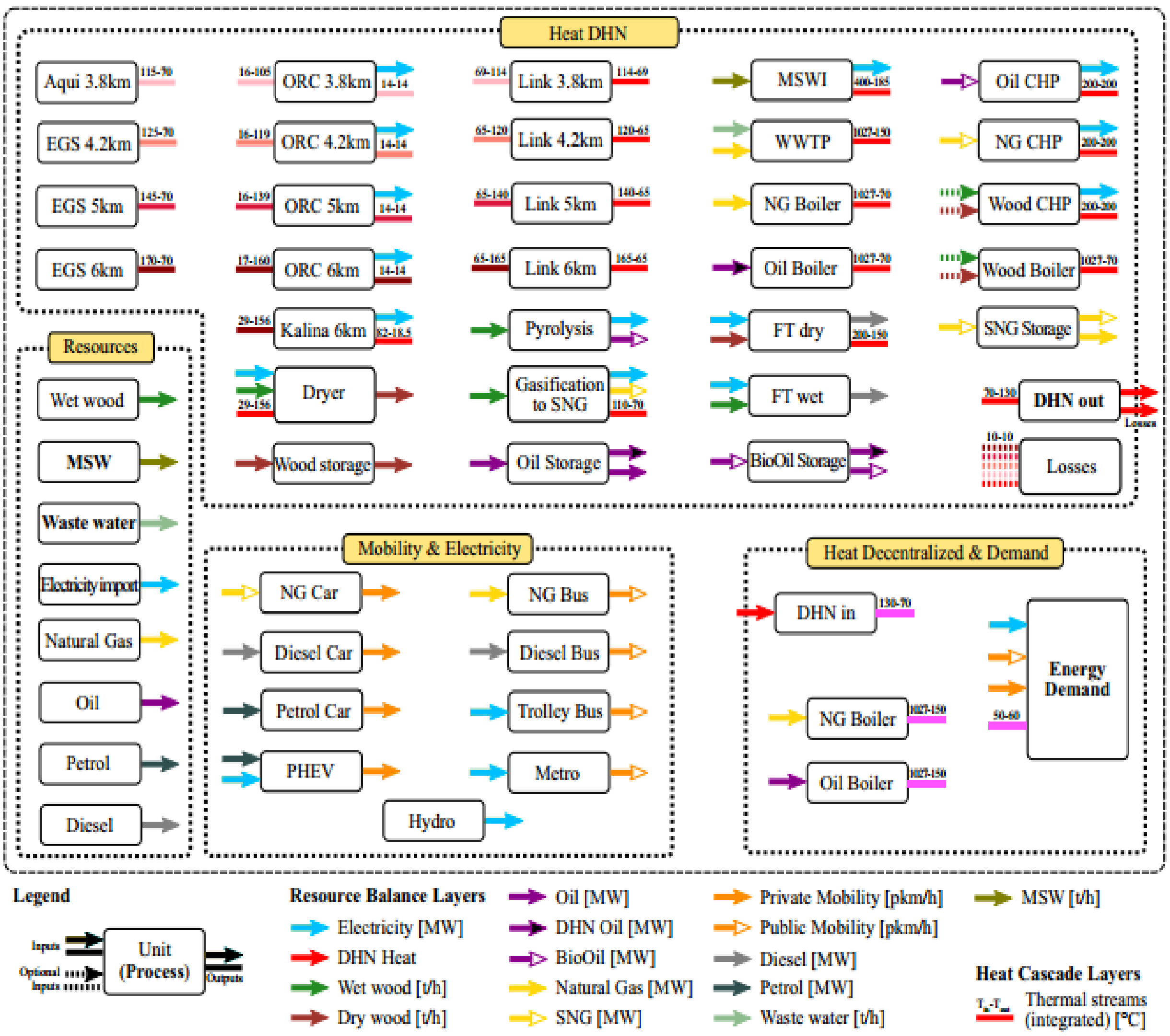

Figure 3: The Urban energy system model used by the authors [8].

Stefano Moret, Emanuela Peduzzi, Léda Gerber and François Maréchal [8] in their paper "Integration of deep geothermal energy and woody biomass conversion pathways in urban systems" based on the projected increasing trend of energy consumption and energy-related greenhouse gas emissions of urban systems, investigate the potential benefits of the combination of deep geothermal energy and woody biomass for the production of heat, electricity and biofuels, thus constituting a renewable alternative to fossil fuels for all end-uses in cities: heating, cooling, electricity and mobility. Their case study is a city modeled in its entirety as a multi-period optimization problem with the total annual cost as an objective, assessing the environmental impacts as well with a Life Cycle Assessment approach. With a scenario - based approach, all pathways are first individually evaluated for each of the two technological options. Then, all possible combinations between geothermal and biomass options are systematically compared, taking into account the possibility of hybrid systems. Results show that integrating these two resources generates configurations featuring both lower costs and environmental impacts. In particular, synergies are found in innovative hybrid systems using excess geothermal heat to increase the efficiency of biomass conversion processes.

4.2. District Heating

In this section the different studies examine the possible ways to heat not one but a very large number of households using geothermal energy. Halit Arat and Oguz Arslan [9] in their paper "Exergoeconomic analysis of district heating system boosted by the geothermal heat pump" examine the problem of heating a large residential area in Turkey, more specifically a town center with a population of 25.000. They used Energy and Exergy analysis combined with Life Cycle Costing (LCC) and coupled with Net Present Value (NPV) analysis to compare different methods and ways to address the problem. According to the taken ranges of the designing parameters such as temperature and pressure of twelve (12) different working fluids, they performed a number of 4686 designs, from which they found the optimum.

On the other hand Ali Keçebas [10] in his paper "Exergoenvironmental analysis for a geothermal district heating system: An application", investigates Afyon GDHS (geothermal district heating system) at the component level in terms of environmental impact by using exergo-environmental analysis. The Afyon GDHS has a total heating capacity of 102 MW_t and was designed for 10 thousand residencies. The results revealed that of the total environmental impact of the Afyon GDHS, nearly 0.0004% is related to the component, 12% is related to exergy losses and 18% is related to the exergy destruction of the system components. Because of the low impact related to the components, the author proposed that priority should be given to the improvement of the heat exchangers and the reduction of their thermodynamic inefficiencies.

On a more theoretical perspective, Miro Ristimäki*, Antti Säynäjoki, Jukka Heinonen and Seppo Junnila [1] in their study "Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design", focus on the life cycle design of a district energy system for a new residential development in Finland. By combining LCC and LCA, a LCM (life cycle management) perspective is portrayed to support decision-making on a long-term basis. The energy design options they compare are: (1) district heating (reference design), (2) district heating with building integrated photovoltaic panels, (3) ground source heat pump, and (4) ground source heat pump with building-integrated photovoltaic panels. In their results they show that the design option with the highest initial investment (4) is in fact the most viable from a life cycle perspective and that this further strengthens the connection between cost savings and carbon emissions reduction in a life cycle context. Furthermore, the aim of their study is not to evaluate which technical energy design solution is more sustainable in the long run, but to portray that economic and environmental benefits support each other in urban residential development, and additionally that a methodological life cycle assessment framework should be used in decision-making processes.

We can see that geothermal energy is a very viable option for applications such as district heating, despite of their initial investment costs. None the less, there is room for improvement in the current technologies used in these applications [10].

4.3. Domestic Heating

In this part different aspects of domestic heating are viewed. As domestic heating we refer to the heating of one building regardless of its size (e.g. from a small house to a large office building).

Although geothermal energy is a renewable source it is not free of GHG emissions. The GHG emissions of geothermal energy can be attributed for their larger part to their construction phases. Many articles have been published comparing different technologies in terms of environmental impacts and economic criteria, in order to find out which is best suited. Aysegul Abusoglu and Murad S. Sedeeq [3] in their article "Comparative exergoenvironmental analysis and assessment of various residential heating systems" explore the potential energetic, exergetic and environmental performance of three heating systems commonly used in the residential building sector in Turkey: a conventional coal boiler, a condensing natural gas boiler and a ground source heat pump, by using a combination of exergy analysis and life cycle assessment (LCA). From a thermodynamic perspective the ground source heat pump is an efficient heating system for the given application in terms of the coefficient of performance and exergy efficiency. However, the LCA results demonstrate that the system-related environmental impact associated with ground source heat pump is the highest among the compared systems. The main reasons for this are the copper and refrigerant R-134a from the construction stage, borehole drilling and polyethylene pipes from the installation stage and refrigerant top-up from the maintenance stage. The authors conclude that the most economic and environmentally friendly energy production for heating applications can be satisfied by using condensing natural gas boilers in the buildings in Turkey under the present circumstances.

Geothermal energy based heating systems require connection and utilization of the existing power grid in order to operate. This is a cause for concern, as in most countries (e.g. Greece, U.S.A) the main resource used for electricity production is coal. That means that the geothermal system will not only have GHG emissions in its construction phase but also in its operating phase. Anna Nitkiewicz and Robert Sekret [11] in their study "Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler" compare the life cycle impacts of three heating plant systems which differ in their source of energy and the type of system. More specifically, they compare an electric water-water heat pump, an absorption water-water heat pump and a natural gas fired boiler. The method used for life cycle assessment is eco-indicator '99. The data describing the preceding life cycle phases: extraction of raw materials and fuels, production of heating devices and their transportation is borrowed from Ecoinvent 2.0 life cycle inventory database. They analyzed the results on three levels of indicators: single score indicator, damage category indicators and impact category indicator. The indicators were calculated for characterization, normalization and weighting phases as well. SimaPro 7.3.2 is the software used to model the system's life cycle. Their study shows that heating plants using a low temperature geothermal source have lower eco-indicator than a gas boiler unit. The comparison between the two heat pumps showed that the absorption heat pump has a lower environmental impact than the electrical heat pump. However, in spite of the high level eco-indicator, the gas boiler has the lowest damage to human health. That is because the environmental impact of the electrical heat pump strictly depends on its efficiency (COP) and electricity generating profile. The higher the COP is, the lower the electricity consumption and the emissions are from its production. In Polish conditions, where the fraction of electricity generated from coal reaches almost 90%, the damage to human health is significant.

Dominik Saner, Ronnie Juraske, Markus Kubert, Philipp Blum, Stefanie Hellweg and Peter Bayer [12] in their study "Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems" examine shallow geothermal systems such as open and closed geothermal heat pump (GHP) systems which are considered to be an efficient and renewable energy technology for cooling and heating of buildings and other facilities. The objective of their study is not only to discuss the net energy consumption and greenhouse gas (GHG) emissions or savings by GHP operation, but also to fully examine environmental burdens and benefits related to applications of such shallow geothermal systems by employing a state-of the-art life cycle assessment (LCA). The applied life cycle impact assessment methodology (ReCiPe 2008) shows the relative contributions of resources depletion (34%), human health (43%) and ecosystem quality (23%) of such GSHP systems to the overall environmental damage. Climate change, as one impact category among 18 others, contributes 55.4% to the total environmental impacts. The life cycle impact assessment also demonstrates that the supplied electricity for the operation of the heat pump is the primary contributor to the environmental impact of GSHP systems, followed by the heat pump refrigerant, production of the heat pump, transport, heat carrier liquid, borehole and borehole heat exchanger (BHE). GHG emissions related to the use of such GSHP systems were carefully reviewed; an average of 63 t CO_2 equivalent emissions was calculated for a life cycle of 20 years using the Continental European electricity mix with 0.599 kg CO_2eq/kWh. However, resulting CO_2eq savings for Europe are between 31% and 88% in comparison to conventional heating systems such as oil fired boilers and gas furnaces.

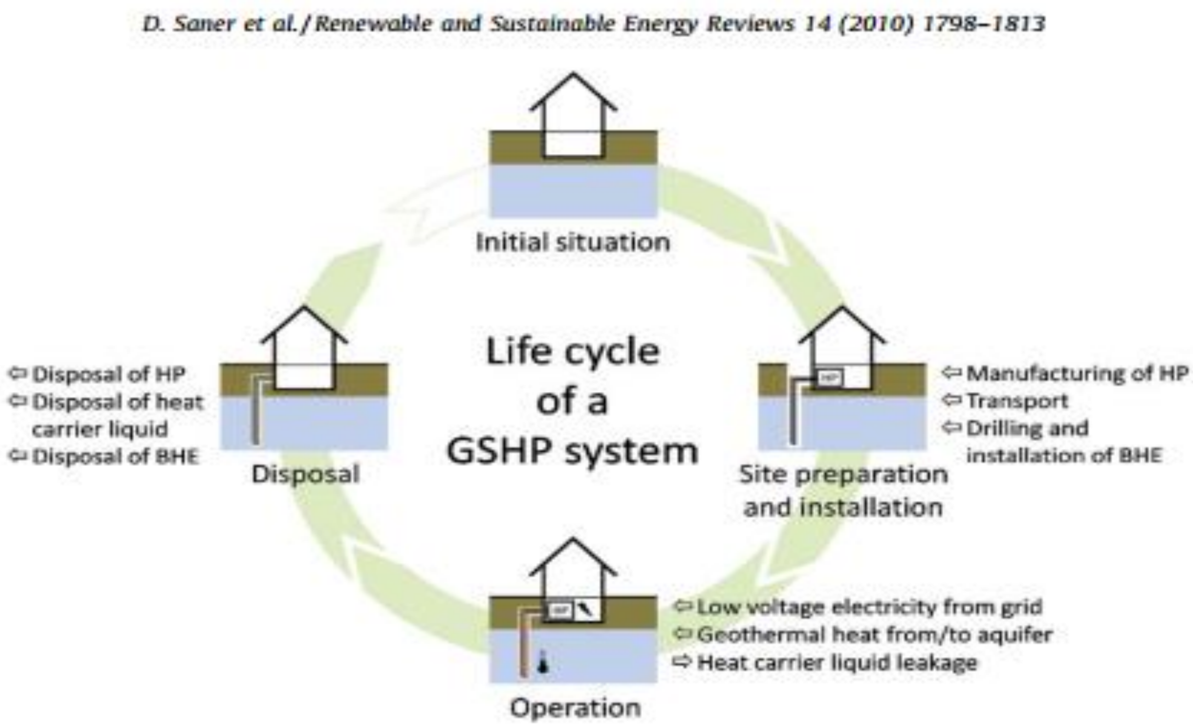

Fig 4: Different life stages of a ground source heat pump (GSHP) system and the main flows of unit processes contributing to the life cycle [12].

Andrew Simons and Steven K. Firth [13] in their article "Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building using water-based sensible heat storage" based on the grounds that providing 100% of a building's heating and hot water using a solar thermal system in a European climate has been shown to be both practically feasible and functionally successful for a new apartment building in Switzerland, conducted a life cycle assessment of a solar thermal system and compared the results with an air-source heat-pump, ground-source heat pump, natural gas furnace, oil furnace and a wood-pellet furnace. Using a range of lifetime scenarios it was found that the solar thermal system displays potentially significant advantages over all other systems in terms of reductions for purchased primary energy (from 84 to 93%) and reductions in GHG emissions (from 59 to 97%). However, due to the heavy industrial processes and the particular metals used in manufacturing, the solar thermal system was shown to have a higher demand for resources which, in relation to the natural gas system, can be by a factor of almost 38. Potential impacts on ecosystem quality were marginally worse than for the heat-pump and fossil fuel systems due to resource use impacts whilst potential human health impacts were similar to the heat pump systems but better than the fossil and biomass fuelled systems.

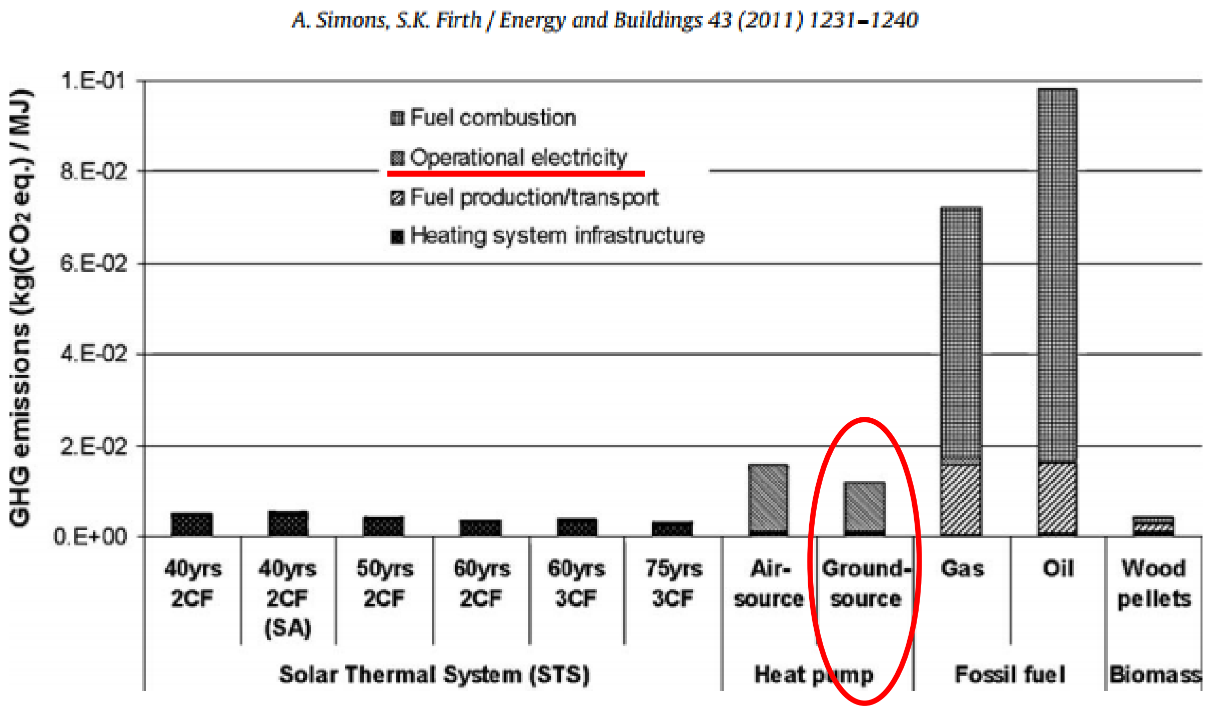

Fig 5: Life-cycle greenhouse gas (GHG) emissions of each heating system [13].

From the above figure we can see clearly enough that most GHG emissions related to the Ground Source Heat Pump are from electricity needed for the operation of the system. We can also see that the ground source heat pump's infrastructure impacts are lower than that of the solar systems' and greater than those of the conventional systems. This brings us back to the electricity mix problem: cleaner electricity mix means cleaner operation phase of ground source heat pump systems.

Christopher J. Koroneos and Evanthia A. Nanaki [14] in their study "Environmental impact assessment of a ground source heat pump system in Greece" examine the technical and environmental performance of a ground source heat pump system (GSHP) using Life Cycle Assessment (LCA). Their LCA study quantifies the environmental impacts of the installation of a ground heat exchanger based system of the Town Hall of Pylaia in Thessaloniki, Greece. They examine the manufacturing, transportation as well as the operation stages of the GSHP system and record energy consumption as well as air emissions to the environment. The system boundary includes the production of raw materials such as copper, plastic, steel, aluminum, rubber, the transportation of heat pumps and pipes, drilling, as well as the operation of the

GSHP system, and finally the assembly process. The environmental impacts categories considered in their study are these of greenhouse effect, ozone depletion, acidification, eutrophication, carcinogenesis, winter smog and heavy metals. Analysis of the system indicates that 73% and 14.54% of the assessment are attributed to the categories of acidification and greenhouse effect respectively. The main reason for the acidification is sulphur dioxide (SO_2), which comes out of the use of lignite (coal) in the Hellenic electric power production. On these grounds it is safe to assume that if the renewable energy fraction is increased in the electricity power mix of Greece and of other countries generally, then the environmental benefits of the geothermal systems would definitely improve.

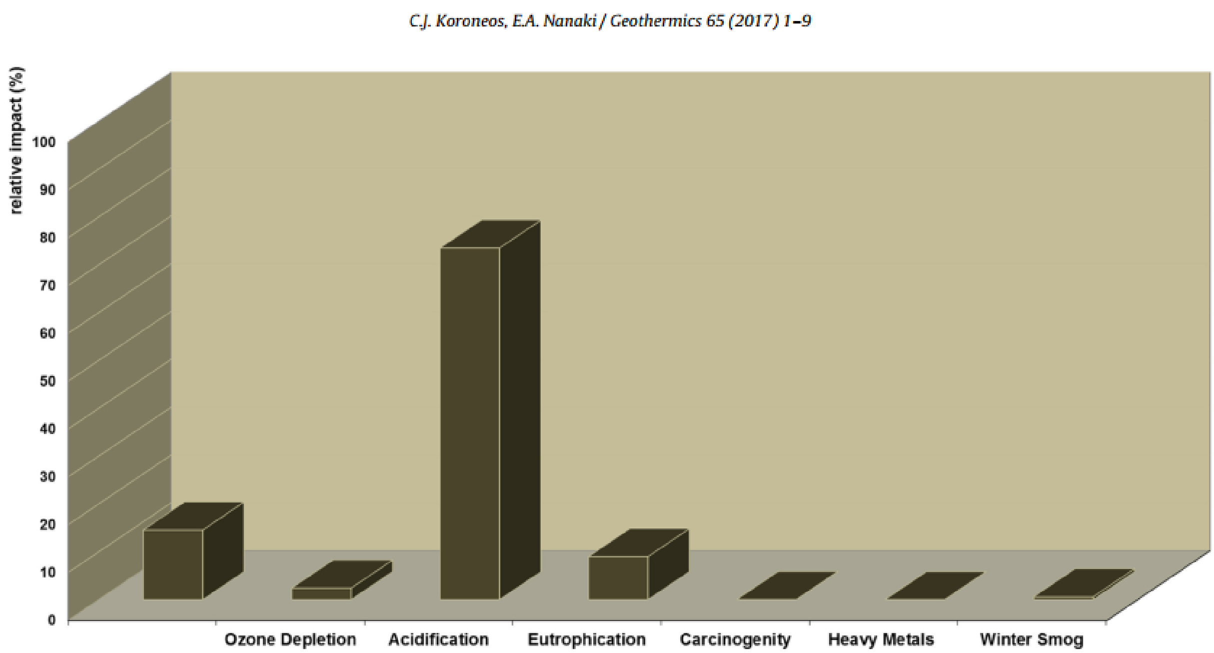

Fig 6: Environmental Impact Assessment of each category during GSHP's system life span [14].

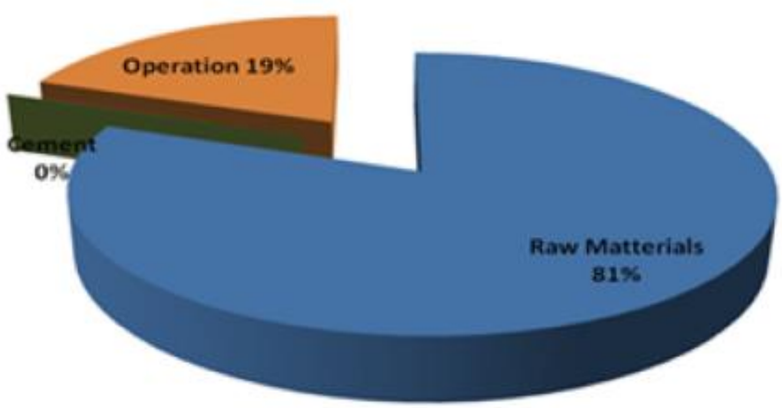

Fig 7: SO2 emissions from all stages during the GSHP system life span [14].

Another way to mitigate the effects of the existing power grid on the environmental efficiency of geothermal systems as explained above is by combining them with other renewable energy sources like Photovoltaic Panels or Solar heating systems. Michaelis Karagiorgas, Dimitrios Mendrinos and Constantine Karytsas [15] in their study “Solar and geothermal heating and cooling of the European Centre for Public Law building in Greece” examine the European Centre for Public Law in Legraina near Athens in Greece, which is heated and cooled by a combined solar and geothermal system. Its main components are a saline groundwater supplying well, water storage tank for 6 hours autonomy, inverter for regulating geothermal flow, heat exchanger, two electrical water source heat pumps placed in cascade, fan coils, air handling units, as well as solar air collectors for air preheating in winter. In addition, hot water is supplied to the building hostel by solar water heaters. Measurements during a winter’s day and calculations performed, proved that solar energy can effectively contribute to the energy balance of the building, increasing the overall share of renewable energy use.

To further strengthen the argument of technology combination, Ayman Mohamed, Mohamed Hamdy, Ala Hasan, Kai Sirén [16] in their study “The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions” investigate the economic viability of small-scale, multi-generation systems (combined heat and power (CHP), combined cooling, heating, and power (CCHP)), along with conventional heating and cooling systems combining sixteen heating/cooling energy generation systems (H/C-EGSs). The Energy Performance of Buildings Directive (EBPD) comparative framework methodology was followed. The local cost-optimal solution for an office building, in Helsinki, Finland is determined for each H/C-EGS as well as the global cost-optimum. The suggested energy efficiency measures get 144 building combinations, and alongside the H/C-EGSs, altogether 2304 cases. The results show that the global cost-optimum belongs to the ground source heat pump with free ground cooling. The investigated biomass-based CHPs are economically viable only with high overall efficiency and low power-to-heat ratio due to both low investment and operational costs. The biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs due to the significant increase entailed of both investment and operational costs. The fossil fuel-based CHPs with high operational costs are the worst solutions economically and environmentally. Extending the cost optimal solutions by a photovoltaic panels system yields the net zero-energy office building with minimum life-cycle costs as well.

In addition to the above, Xin Zheng, Hong-Qi Li, Ming Yu, Gang Li and Qi-Ming Shang [17] in their research paper “Benefit analysis of air conditioning systems using multiple energy sources in public buildings” explore the potential of reducing the energy consumption of large public buildings in Beijing by comparing three different air-conditioning systems. Those are an air source heat pump system, a ground source heat pump coupled with an air source heat pump system and a solar assisted ground source heat pump coupled with an air source heat pump system. They made a cost-benefit analysis for each type of air conditioning system and then computed the building load using the DeST simulation software and used economic indicators to evaluate the systems economics in terms of the initial investment, life cycle cost (LCC), operating cost, payback period, energy conservation rate and cooling and heating cost in hourly moments. The building they study has a total floor area of 3500m^2, faces south and has five floors where the first floor was 4.5 m high and the other floors were 4 m high. Their results show that the a solar assisted ground source heat pump coupled with an air source heat pump system had better economic results than the other two, especially the air source heat pump system and although the initial investment is higher, it has a payback period of less than 3 years compared to the air source heat pump system.

Another interesting technology combination proposal was made by Emanuele Bonamente and Andrea Aquino [18] in their paper "Life-Cycle Assessment of an Innovative Ground-Source Heat Pump System with Upstream Thermal Storage", where they present an innovative space-conditioning system, which is composed by a ground-source heat pump system (GSHP) and includes upstream thermal storage (TS). A prototype of the examined system is currently in use in an industrial building for space heating and cooling. As a result of the TS designed to decouple the geothermal side from the heat-pump side, the system is able to provide the required thermal energy to the building with a reduced-size geothermal installation (i.e., shorter/fewer boreholes (BHs)). The performance of the examined system was monitored for over two years in both heating and cooling modes. The authors perform an LCA of the system on the basis of specific data for implementation and operation phases. The results are given in terms of the comprehensive ReCiPe midpoint and endpoint indicator suite and are compared with literature studies of other conventional technologies for space conditioning.

In the spirit of economic efficiency as well as environmental efficiency, a number of studies have been conducted. Beijia Huang and Volker Mauerhofer [19], in their article "Life cycle sustainability assessment of ground source heat pump in Shanghai, China" state that apart from the energy saving measures adopted by governments worldwide because of the Greenhouse effect, environmental and social impacts should also be considered as well, as to make sure that the application of these measures can also meet sustainable development requirements. They propose a sustainability evaluation method based on Life Cycle Theory innovatively designed in their study. They describe it in detail and test it by means of a case study on Ground Source Heat Pumps (GSHP), which is a renewable technology that is widely applied in the building sector in China. Their results show that the energy consumption of the investigated GSHP cases have energy saving rate as around 40.2% by comparing with the traditional air condition system. The main environmental impacts of GSHP are found to be global warming, acidification and eutrophication in the production process, and soil temperature change in the operation process. The prevention cost of the environmental impacts is around 15.84 RMB/m^2 in the production process, and 5 RMB/m^2 in the operation process. The payback time of their cases is around 4 years, and it will rise to 4.29 years if the environmental prevention cost is included.

Also, Yuan Chang, Yurong Gu, Lixiao Zhang, Chuyi Wu and Liang Liang [20] in their article "Energy and environmental implications of using geothermal heat pumps in buildings: An example from north China" examine the environmental effects of the application of a geothermal heat pump in a university building. A process-based hybrid life cycle inventory (LCI) modeling approach was used to enable a comprehensive system boundary for footprint accounting and to provide specific insights for the design and operation of the examined technology. The life-cycle energy of the GHP system was 192 TJ, and the life-cycle SO2, NO_x, and greenhouse gas (GHG) emissions were estimated at 35 metric tons (MT), 45 MT, and 19130 MT CO_2e. The annual operational energy use of the GHP was 6.2 and 4.1 kWh per square meter floor area for building heating and cooling respectively. This was an energy use reduction of 84% and 83% compared to municipal heating and air conditioner cooling. The energy and GHG payback times of the GHP systems were 0.5 and 0.3 years respectively, and the facility is estimated to be economically cost-effective in 7.4 years.

For the proposed new office building on the Winnebago Reservation in northeastern Nebraska Andrew Chiasson [21] in his report "Life-cycle cost study of a geothermal heat pump system BIA Office BLDG, WINNEBAGO, NE" conducted a life-cycle cost analysis for various heating, ventilating, and air conditioning (HVAC) systems. Three HVAC systems were considered: (1) rooftop units with gas heat and direct expansion (DX) cooling (air-cooled condensers), (2) air-source heat pumps, and (3) geothermal heat pumps (GHPs). The heating and cooling loads were estimated by using building energy simulation software. The peak cooling load was estimated at 264,000 Btu/hr (22 tons), and the peak heating load was estimated at about 178,000 Btu/hr. The annual energy demand of the building is 246 kBtu for heating and 479 kBtu for cooling. To compare alternatives, the net present value (NPV) of 30-year life-cycle cost was computed for each alternative. The GHP system was found to have the lowest net present value of life-cycle cost, approximately 18% lower than the conventional alternatives, which have very similar life-cycle costs to each other. The GHP system was more expensive to install, but has considerably lower operating and maintenance costs than conventional alternatives. A greenhouse gas analysis was also conducted, and has shown that use of a GHP system can reduce annual greenhouse gas emissions by 15 tons of CO_2 equivalent over the use of rooftop units with gas heat and by 33 tons of CO_2 equivalent over the use of air source heat pumps.

Another critical factor that determines the economic feasibility of geothermal heat pump systems is the seasonal coefficient of performance (SCOP), as explained by Lars Junghans [22] in his study "Evaluation of the economic and environmental feasibility of heat pump systems in residential buildings, with varying qualities of the building envelope". The author examines the economic and environmental feasibility of air-to-air and geothermal heat pump systems and also demonstrates the significance of the insulation level of the envelope on the economic and environmental feasibility of heat pump systems. His objective is to quantify the extent to which the local climate and the building insulation level could influence the economic and environmental feasibility of a geothermal water-to-air heat pump system and an external air-to-air heat pump system. The results of the study show that slightly increased insulation levels have a huge influence on the SCOP and therefore on the economic and environmental feasibility of Heat Pump systems. The author explains that SCOP levels for Heat Pump systems should be presented, depending on both the climate and the insulation level of the building, when they are used for feasibility studies.

4.4. Electricity Generation

One of the most important aspects of geothermal energy is its capability of producing electrical energy. Electricity is one of the cornerstones of modern society, as it is utilized in almost everything we do, from lighting to the use of computers and the internet and it is going to be used even more, as it slowly gains ground in areas where other forms of energy dominate, such as transportation and heating.

Coal power plants form the majority of electricity generation, which in turn makes electricity generation one of the biggest factors contributing to the Greenhouse Effect. This fact turns humanity's attention to most environmentally friendly and resource independent energy generation technologies. Geothermal energy is a possible candidate as it is a renewable form of energy and does not require the consumption of fossil fuels. In this part of the paper we explore the potential of geothermal energy to produce clean electrical energy.

Annette Evans and Assoc. Prof. Vladimir Strezov [23] in their paper "A sustainability assessment of electricity generation", assess the sustainability of electricity generation by the application of eight key indicators. They compare price, greenhouse gas emissions, efficiency, land use, water use, availability, limitations and social impacts on a per kilowatt hour basis of eight different methods of electricity production: photovoltaic, wind, hydro, geothermal, biomass, natural gas, coal and nuclear power.

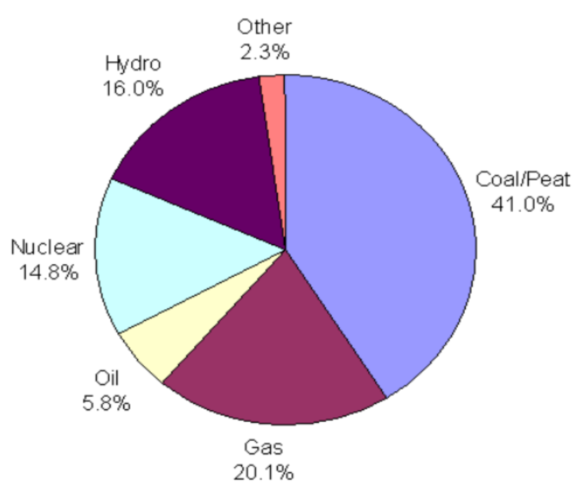

Fig 8: World electricity production by fuel 2006 [23].

Their conclusion shows that coal and nuclear power have the lowest average price, while hydro and geothermal have the lowest possible price. Solar (Photovoltaic) had both the highest average and overall highest cost, but at its lowest limit it was cheaper than coal or gas. Hydropower shows the highest and photovoltaic the lowest electrical efficiency. Greenhouse gas emissions were low in all non-fossil fuels, with wind, hydro and nuclear showing the lowest values. Coal had the highest emissions by a significant margin. Water use was the lowest in photovoltaic and wind power and highest for dedicated biomass energy crops. Hydro power has a very high water requirement, but most of this is not consumed, but returned to the stream. Nuclear, photovoltaic and wind power have the smallest land use, with biomass the largest. With respect to social impacts, wind and photovoltaic are the most sustainable, while all thermal technologies the least sustainable.

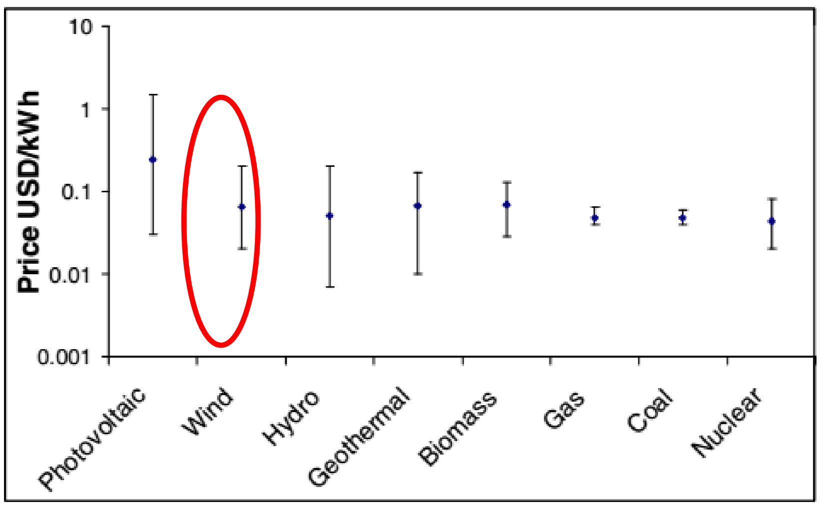

Fig 9: Prices of electricity generation [23].

In another article with the name “Assessment of sustainability indicators for renewable energy technologies” [24], Annette Evans, Vladimir Strezov and Tim J. Evans assess non-combustion based renewable electricity generation technologies (photovoltaic, wind, hydro and geothermal) against a range of sustainability indicators: price of generated electricity, greenhouse gas emissions during full life cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts. Renewable energy technologies were then ranked against each indicator assuming that indicators have equal importance for sustainable development. It was found that wind power is the most sustainable, followed by hydropower, photovoltaic and then geothermal. Wind power was identified with the lowest relative greenhouse gas emissions, the least water consumption demands and with the most favorable social impacts comparing to other technologies, but requires larger land and has high relative capital costs.

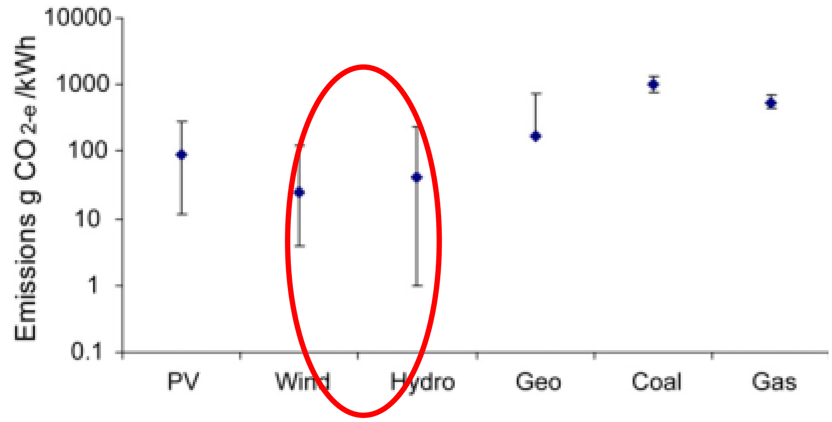

Fig. 10: Carbon dioxide equivalent emissions during electricity generation [24].

If each indicator is separately examined, then:

1. As far as the price of electricity generation is concerned, geothermal energy and wind energy have the same average cost with geothermal energy exhibiting a lower range in price variations [24].
2. The authors find that the average emissions from geothermal power plants are fair at 170 g/kWh, however the range includes all possible values for gas emissions and may even be as high as a low-emitting coal fired power station. Nonetheless, geothermal emissions are most significantly impacted by technology choices. Waste gases are over 90% CO_2 by weight, so if directly released, emissions will be high. Most modern plants, however, either capture the CO_2 and produce dry ice, or reinject it back into the well [24].
3. Geothermal power is geographically limited to appropriate sites where the resource is present, however there are many such sites worldwide, spread over 24 countries with an operating potential of 57 TWh/year. Geothermal energy is attractive for its ability to provide base load power 24 hours a day. Extraction rates for power production will always be higher than refresh rates, but reinjection helps restore the balance and significantly prolongs the lifetime of geothermal sites. The site of reinjection must be carefully selected to ensure short-circuiting does not occur. Reinjection also increases the frequency, but not severity of seismic activity [24].
4. Geothermal power has the lowest efficiency, far less than other technologies [24].
5. Geothermal power plants have relatively small surface footprints, with major elements located underground. Due to the risk of land subsidence above the field, the whole geothermal field is used in the footprint calculation. A typical geothermal footprint is in the range 18–74 km^2/TWh [24].
6. Geothermal power consumes large amounts of water required for cooling. Water consumption can be controlled by the total reinjection of polluted and foul smelling wastewater, non-evaporative cooling, general pressure management and closed-loop

recirculating cycles. Geothermal plants produce more wastewater than thermal power plants at up to 300 kg/kWh [24].

7. Geothermal adversely affects communities where wastes are not properly managed as geothermal process waters are offensive smelling from hydrogen sulfide and contaminated with ammonia, mercury, radon, arsenic and boron. Geothermal fluids can be processed in a completely closed-loop system and then reinjected, mitigating these problems [24].

We can easily deduce from the above that geothermal energy may not be as environmentally friendly as one would think, but it has certain advantages when compared to others, such as relatively small land use, the ability to provide base load power on a 24-hour basis and its independence from weather conditions.

To better understand the environmental impacts of geothermal power generation Elvira Buonocore, Laura Vanoli, Alberto Carotenuto and Sergio Ulgiati [5] in their article "Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy" performed a LCA (Life Cycle Assessment) and an EMA (Emergy Assessment) of a 20 MW dry steam geothermal power plant located in the Tuscany Region (Italy). The plant is able to produce electricity by utilizing locally available renewable resources together with a moderate support by non-renewable resources. This makes the geothermal source eligible to produce renewable electricity. However, the direct utilization of the geothermal fluid generates the release into the atmosphere of carbon dioxide, hydrogen sulfide, mercury, arsenic and other chemicals that highly contribute to climate change, acidification potential, eutrophication potential, human toxicity and photochemical oxidation. Their study aims to understand to what extent the geothermal power plant is environmentally sound, in spite of claims by local populations, and if there are steps and/or components that require further attention. The application of the Emergy Synthesis method provides a complementary perspective to LCA, by highlighting the direct and indirect contribution in terms of natural capital and ecosystem services to the power plant construction and operation. The environmental impacts of the geothermal power plant are also compared to those of renewable and fossil-based power plants. The release of CO_2eq calculated for the investigated geothermal plant (248 g/kWh) is lower than fossil fuel based power plants but still higher than renewable technologies like solar photovoltaic and hydropower plant. Moreover, the SO_2eq release associated to the geothermal power plant (3.37 g/kWh) is comparable with fossil fuel based power plants. Results suggest the need for further investigation of other geothermal options (e.g. binary systems) in order to reduce the environmental impacts while taking the maximum advantage of the geothermal resource.

In the spirit of comparing different renewable energy options, Francesco Asdrubali, Giorgio Baldinelli, Francesco D'Alessandro and Flavio Scrucca [25] in their paper "Life cycle assessment of electricity production from renewable energies: Review and results harmonization" review approximately 50 papers, related to more than 100 different case studies regarding solar energy (Concentrated Solar Power, Photovoltaic), wind power, hydropower, and geothermal power, in order to make a harmonization of the results. The detailed data collection and the results normalization and harmonization their team made allowed a more reliable comparison of the various renewable technologies. The results of their paper show that Wind power had the lowest CO_2eq emissions and the lowest embodied energy, while geothermal power and PV power, instead, came out as the renewable technologies with the highest overall environmental impact values and the widest ranges of variability. Within the other technologies considered, CSP was positioned at a medium level of environmental impact, resulting better than PV, geothermal, and hydropower plants in almost all the impact categories considered. Nonetheless, extending the comparison of the harmonized results to conventional power systems (e.g. hard coal or natural gas power station) the analysis of all impact categories demonstrates that renewable energy technologies show significant environmental advantages.

It is clearer now that geothermal energy is not as environmentally beneficial as other renewable energy options, but it has a great variability and it is still cleaner than fossil fuel based energy options.

It is important though that in order to fully understand the impacts associated with electricity generation from geothermal power plants, a comparison with both renewable and conventional power generating technologies must be made. J.L. Sullivan, C.E. Clark, J. Han and M. Wang [26] in their article "Life-Cycle analysis results of geothermal systems in comparison to other systems" conducted a life-cycle energy and greenhouse gas emissions analysis for geothermal power-generating technologies, including enhanced geothermal, hydrothermal flash, and hydrothermal binary technologies with Argonne National Laboratory's expanded Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.

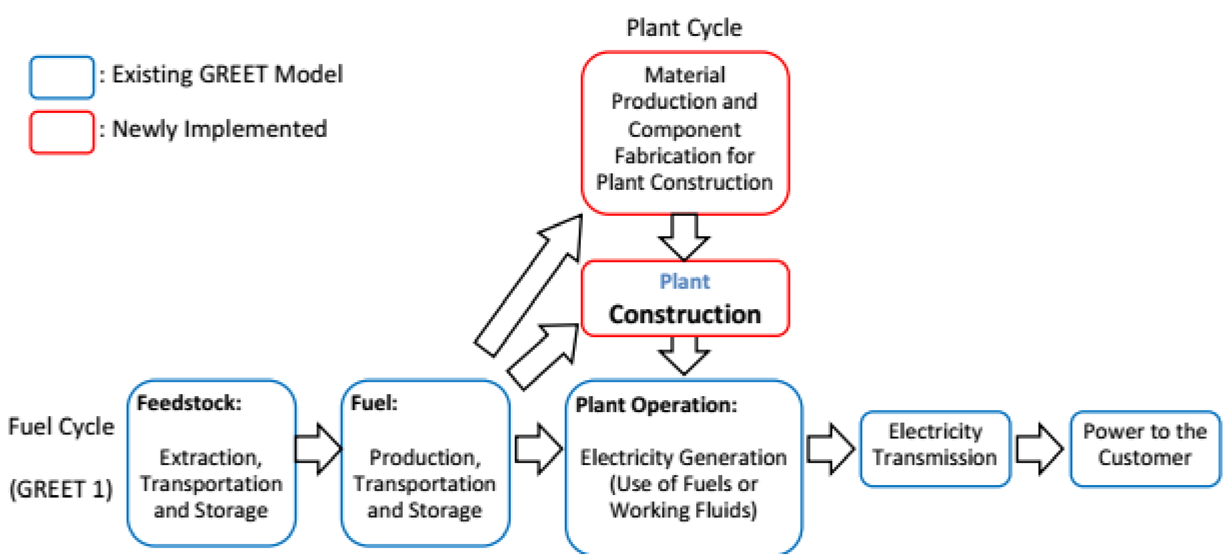

Fig 11: Flowchart of Life-Cycle Analysis [26].

They also conducted a similar analysis for other power-generating systems, including coal, natural gas combined cycle, nuclear, hydroelectric, wind, photovoltaic, and biomass. What's important is the fact that they expanded the GREET model to include power plant construction for these latter systems with literature data. In this way, the GREET model has been expanded to include plant construction, as well as the usual fuel production and consumption stages of power plant life cycles. For the plant construction phase, on a per-megawatt (MW) output basis, conventional power plants in general are found to require less steel and concrete than renewable power systems. With the exception of the concrete requirements for gravity dam hydroelectric, enhanced geothermal and hydrothermal binary used more of these materials per MW than other renewable power-generation systems. Energy and greenhouse gas (GHG) ratios for the infrastructure and other lifecycle stages have also been developed in this study per kilowatt-hour (kWh) of electricity output by taking into account both plant capacity and plant lifetime [26].

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Geothermal Technology	EGS	EGS	Hydrothermal	Hydrothermal
Net Power Output (MW)	20	50	10	50
Producer to Injector Ratio	2	2	3 or 2	3 or 2
Number of Turbines	Single	Multiple	Single	Multiple
Generator Type	Binary	Binary	Binary	Flash
Cooling	Air	Air	Air	Evaporative
Temperature (°C)	150–225	150–225	150–185	175–300
Thermal Drawdown (%/year [yr])	0.3	0.3	0.4–0.5	0.4–0.5
Well Replacement	1	1	1	1
Exploration Well	1	1 or 2	1	1
Well Depth (kilometer [km])	4–6	4–6	<2	1.5 < 3
Pumping	Injection and production	Injection and production	Injection and production	Injection only
Pumps, Injection	Surface	Surface	Surface	Surface
Pumps, Production	Submersible 10,000 feet (ft)	Submersible 10,000 ft	Lineshaft or submersible	None
Distance between Wells (m)	600–1,000	600–1,000	800–1,600	800–1,600
Location of Plant to Wells	Central	Central	Central	Central
Geographic Location	Southwestern United States	Southwestern United States	Southwestern United States	Southwestern United States
Plant Lifetime (yr)	30	30	30	30

Table 1: Parameter Values for the four investigated Geothermal Power Plant Scenarios [26].

Generally, energy burdens per energy output associated with plant infrastructure are higher for renewable systems than conventional ones. GHG emissions per kWh of electricity output for plant construction follow a similar trend. Although some of the renewable systems have GHG emissions during plant operation, they are much smaller than those emitted by fossil fuel thermoelectric systems. Binary geothermal systems have virtually insignificant GHG emissions compared to fossil systems. Taking into account plant construction and operation, the GREET model shows that fossil thermal plants have fossil energy use and GHG emissions per kWh of electricity output about one order of magnitude higher than renewable power systems, including geothermal power [26].

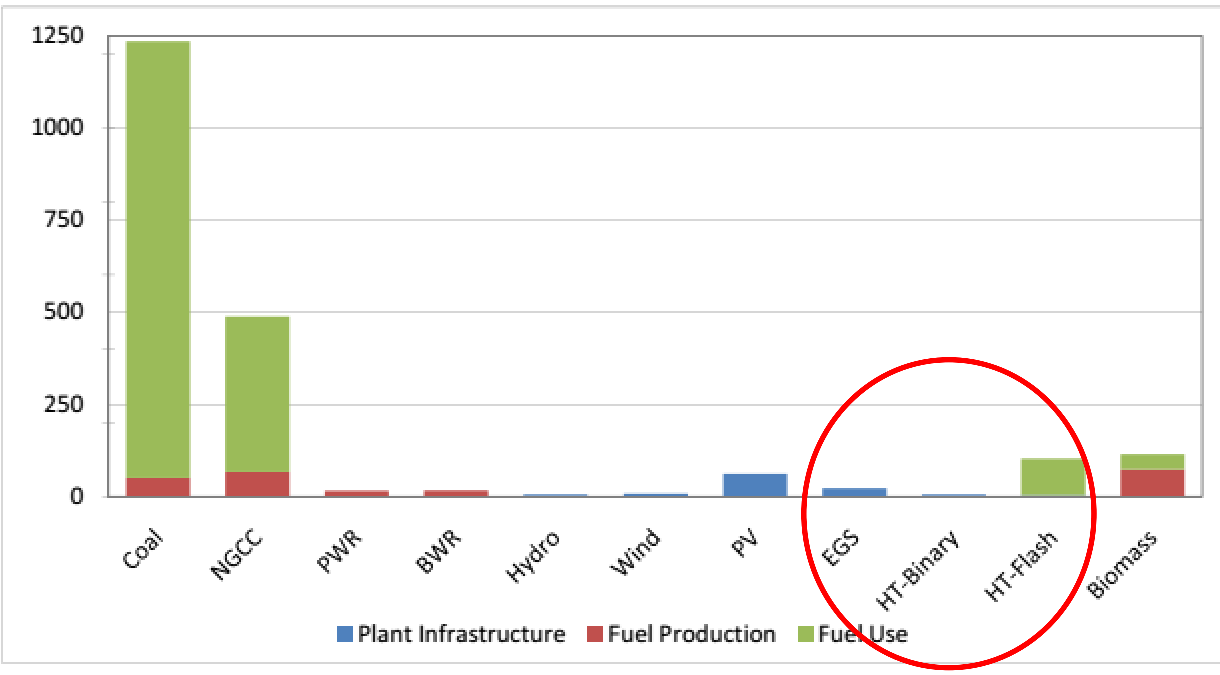

Fig 12: GHG Emissions (gCO2e/kWh) by Life Cycle Stage for Various Power-Generating Technologies as Determined in GREET 2.7 [26].

The same authors in a later article [27] "Life-Cycle analysis results of geothermal systems in comparison to other systems: Part II" include some new technologies in their previous study. The additional technologies included concentrated solar power, integrated gasification combined cycle, and a fossil/renewable (termed hybrid) geothermal technology, more specifically, co-produced gas and electric power plants from geo-pressured gas and electric (GPGE) sites. For the latter, two cases were considered: gas and electricity export and electricity-only export. Also modeled were cement, steel and diesel fuel requirements for drilling geothermal wells as a function of well depth. The impact of the construction activities in the building of plants was also estimated. The results of this study are consistent with previously reported trends found in Part I of this series. Among all the technologies considered, fossil combustion-based power plants have the lowest material demand for their construction and composition. On the other hand, conventional fossil-based power technologies have the highest greenhouse gas (GHG) emissions, followed by the hybrid and then two of the renewable power systems, namely hydrothermal flash power and biomass-based combustion power.

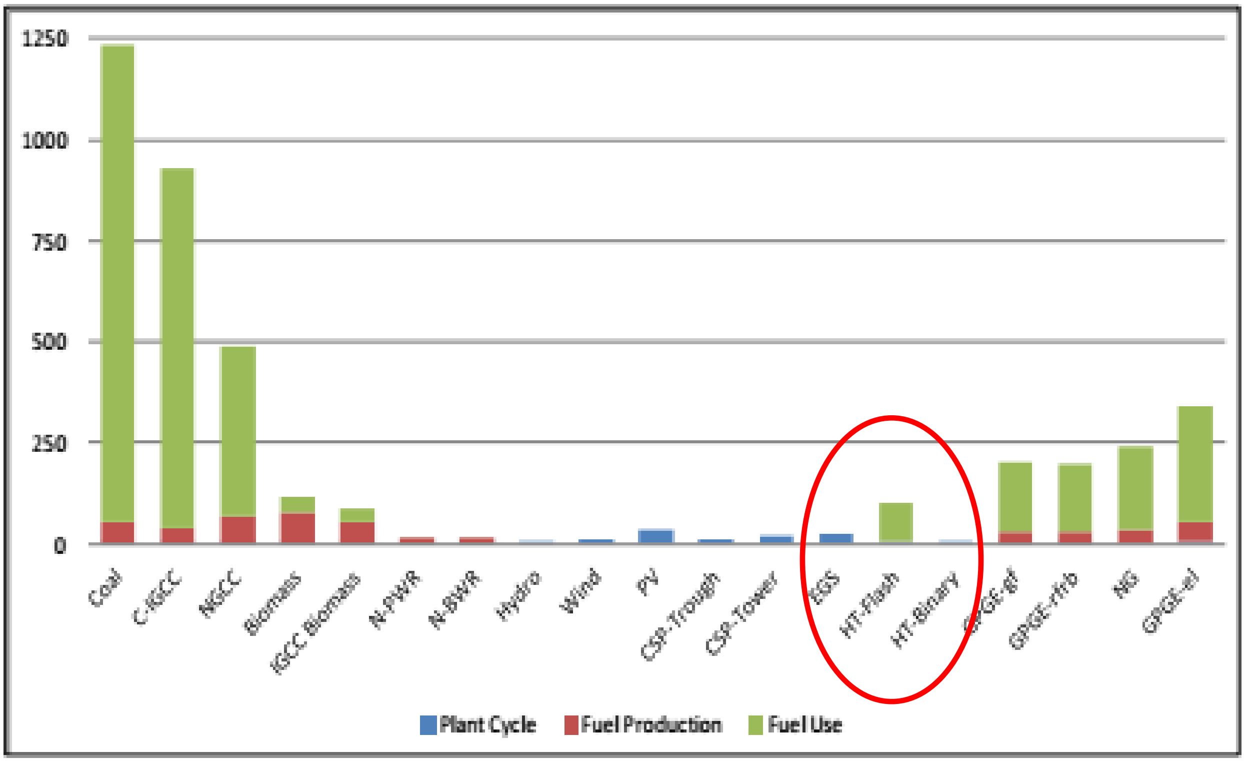

Fig 13: Greenhouse gas emissions (g/kWh) by life-cycle stage for various power-production technologies relative to total energy output; entries are based on average MPRs given above and GREET 1.8 data [27].

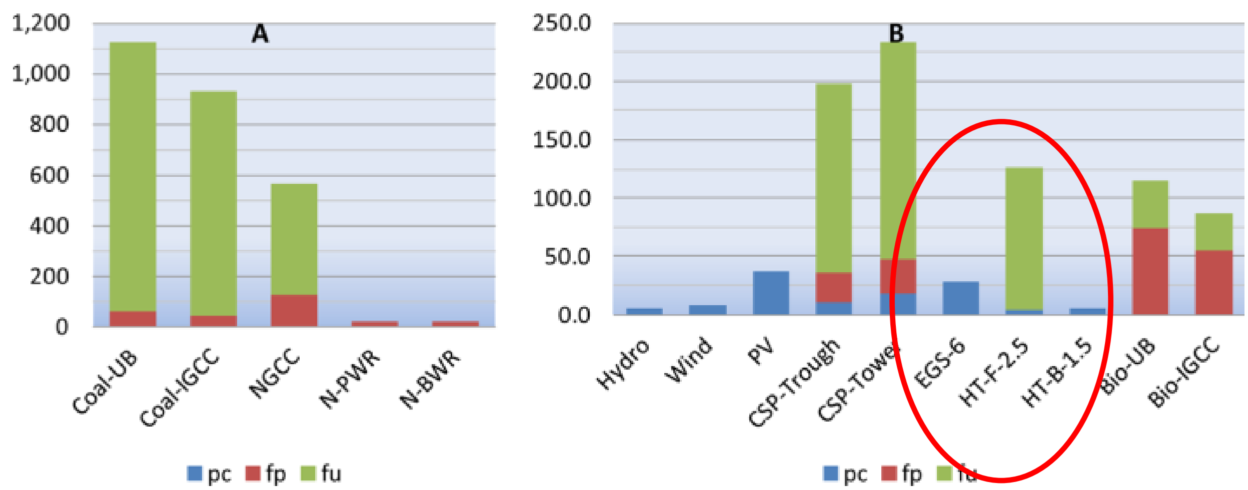

Fig 14: GHG total (g/kWh) by life cycle stage for a number of fossil and renewable electricity production technologies; panel A for coal, natural gas and nuclear and panel B for renewable; life cycle stages include plant cycle fuel production and fuel use; post-script numbers for EGS, HT-F, and HT-B denotes well depths in km [28].

J. L. Sullivan and M. Q. Wang [28] in their article "Life cycle greenhouse gas emissions from geothermal electricity production" present an LCA study for greenhouse gas (GHG) emissions and fossil energy use associated with geothermal electricity production with a special focus on operational GHG emissions from hydrothermal flash and dry steam plants. Their analysis includes results for both the plant and fuel cycle components of the total life cycle. A special emphasis was placed on elucidating greenhouse gas emissions incurred during geothermal power plant operation. Those emissions are only significant for flash and dry steam geothermal (HT-F) power plants; they are zero for binary plants. GHG emissions from HT-F plants can range from almost zero to over 400 g/kWh. The resulting life cycle fossil energy and greenhouse gas emissions values are compared among a range of fossil, nuclear, and renewable power technologies.

We can see from Fig 14 that GHG emissions of geothermal power plants are comparable to other renewable energy options and are much lower than those of fossil fuel based options, except nuclear power plants. This shows that geothermal energy has the potential to bring better environmental results if certain requirements are met. Among those are increased material requirements in the construction phases of the power plants as shown below in Fig 15.

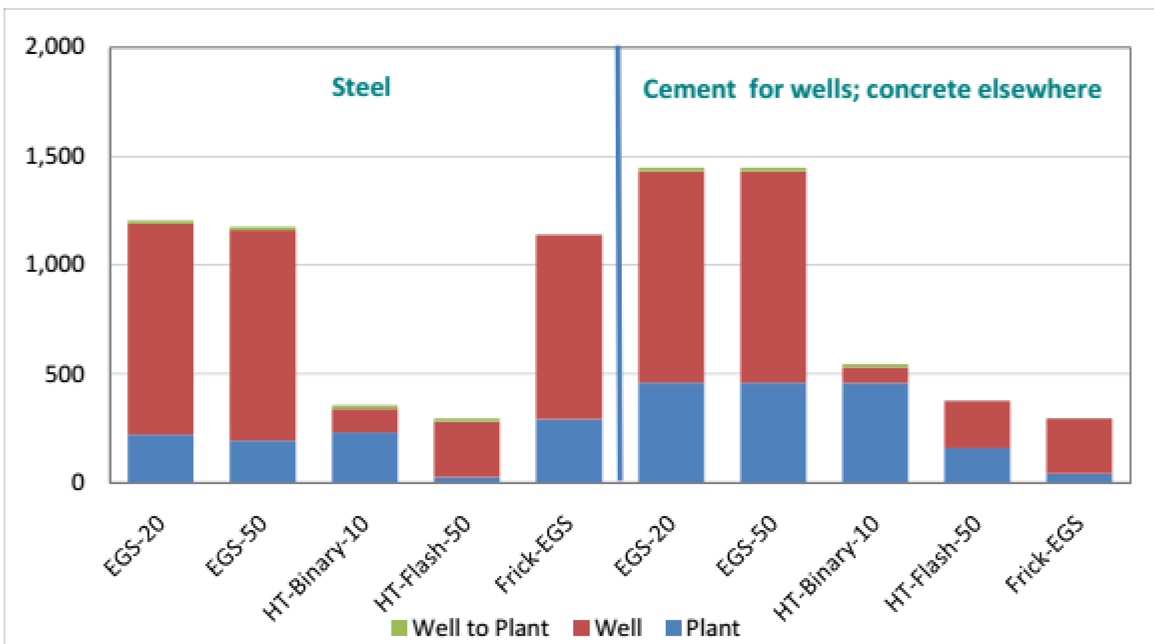

Fig 15: Mass-to-power ratio(s) (tons/MW) for Geothermal Power Plants [26].

Corrie Clark, John Sullivan, Chris Harto, Jeongwoo Han and Michael Wang [29] in their article "Life Cycle Environmental Impacts of Geothermal Systems" present potential impacts and factors associated with construction, drilling and production activities of enhanced geothermal systems (EGS), hydrothermal binary, hydrothermal flash and geo-pressured geothermal systems. Five power plant scenarios were evaluated: a 20-MW EGS plant, a 50-MW EGS plant, a

10-MW binary plant, a 50-MW flash plant and a 3.6-MW geo-pressured plant that coproduces natural gas. Finally, the impacts associated with these power plant scenarios are compared with those from other electricity generating technologies.

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Geothermal Technology	EGS	EGS	hydrothermal	hydrothermal	geopressured
Net Power Output, MW	20	50	10	50	
Producer-to-Injector Ratio	2:1	2:1	3:1 and 2:1	3:1 and 2:1	2:1
Number of Turbines	single	multiple	single	multiple	single
Generator Type	binary	binary	binary	flash	binary
Cooling	air	air	air	evaporative	air
Temperature, °C	150–225	150–225	150–185	175–300	130–150
Thermal Drawdown, % per year	0.3	0.3	0.4–0.5	0.4–0.5	0
Well Replacement	1	1	1	1	0
Exploration Wells	1	1 or 2	1	1	0
Well Depth, km	4–6	4–6	<2	1.5, <3	4–6 (producers) 2–3 (injectors)
Flow Rate per Well, kg/s	30–90	30–90	60–120	40–100	35–55
Gas/Brine Ratio, scf/stb	not applicable	not applicable	not applicable	not applicable	25–35
Pumps for Production	submersible 10,000 ft	submersible 10,000 ft	lineshaft or submersible	none	none
Distance between Wells, m	600–1,000	600–1,000	800–1,600	800–1,600	1,000
Location of Plant in Relation to Wells	central	central	central	central	central
Plant Lifetime, years	30	30	30	30	30

Table 2: Parameters evaluated for the various geothermal technology scenarios [29].

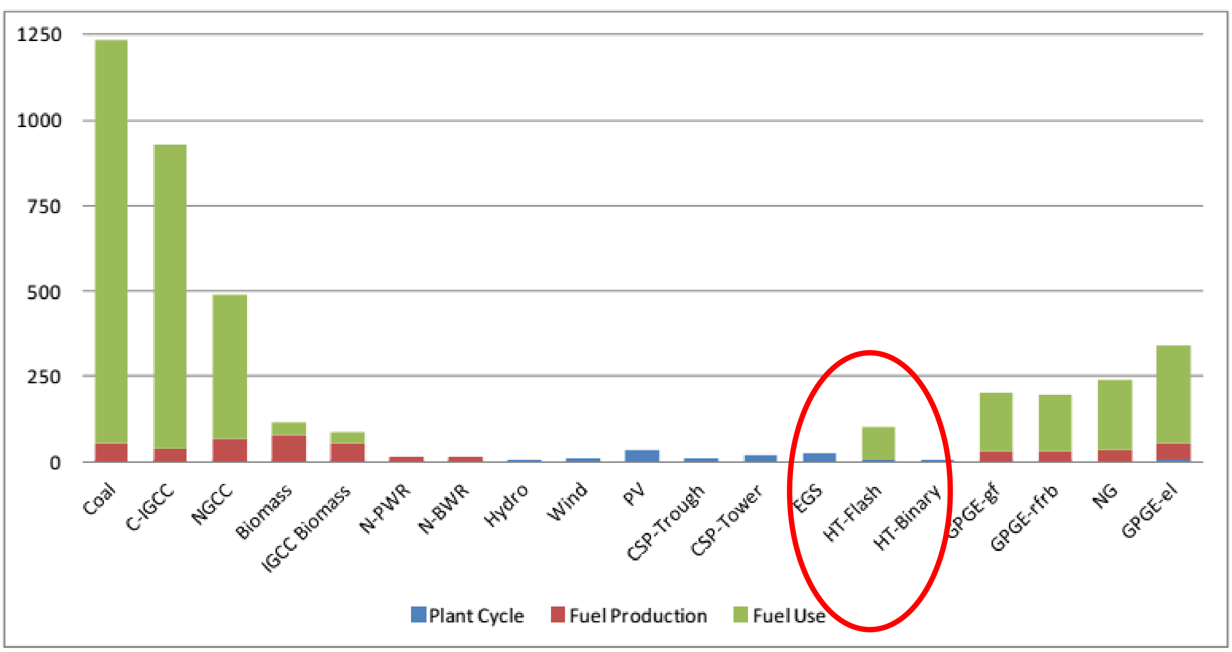

Fig 16: Greenhouse gas emissions (g/kWh) by lifecycle stage for various power production technologies relative to total energy output; entries based on average MPRs given above and GREET 1.8 data [29].

These results agree with their previous study and show that geothermal energy is capable of low carbon emissions, which are primarily attributed to the construction phase, like most renewable energy technologies.

Geothermal installed capacity is currently about 10.7 GW_e worldwide, mostly shared among a few countries, such as the US (29%), the Philippines (17.8%), Indonesia (11%), Mexico (9%) and Italy (7.8%).Clearly, producing electricity using these systems is highly dependent on the availability of geothermal hot water or steam: this represents a limiting factor. Most of these power plants are located in sites characterized by high-enthalpy reservoirs, but this favorable condition is quite rare. On the other hand, outside these particular sites, large geological areas show the presence of low-temperature resources, which represent huge and still unexplored geothermal potential. Consequently, in the recent past, research has been carried out to develop appropriate means to capture this energy and convert it into electrical power, developing the so-called "enhanced geothermal systems" (EGS). Their principle is to enhance and/or create a geothermal resource through hydraulic stimulation at great depth (more than 2.5 km) in considerably hot crystalline rocks (around 150-200oC) [30]. As a result, it is very important to understand the opportunities that this new technology offers and how we can use it in our advantage.

Martino Lacirignola and Isabelle Blanc [30] in their article "Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment" present an analysis of the environmental performances of Enhanced Geothermal Systems (EGS) located in central Europe based on life cycle assessment (LCA) of ten significant design options. Each of those is identified with a set of several technical parameters including the risk of induced seismicity. Results show that EGS impacts are comparable to those of other renewable energy technologies and significantly lower than those of conventional power plants. Furthermore, their capacity to produce base load power at a competitive price, make them a very advantageous option for a future energy scenario. A comparison of the ten scenarios enables us to formulate recommendations on the environmental suitability of their design. Moreover, it emerges from this study that the risk of induced seismicity is a key discriminating factor, as it increases proportionally to the environmental benefit. The model based on five impact categories presented in this paper provides a useful tool for obtaining an overview of the environmental constraints of EGS installations and can be replicated to evaluate possible analogous installations exploring other design options. One of the results that bears particular significance and is also noted in many studies is the fact that in geothermal installations drilling is the process with the highest environmental impact, essentially because of its use of fossil fuel. Alternative power supply solutions in this phase, such as connecting to the national grid, could produce relevant improvements in environmental performance.

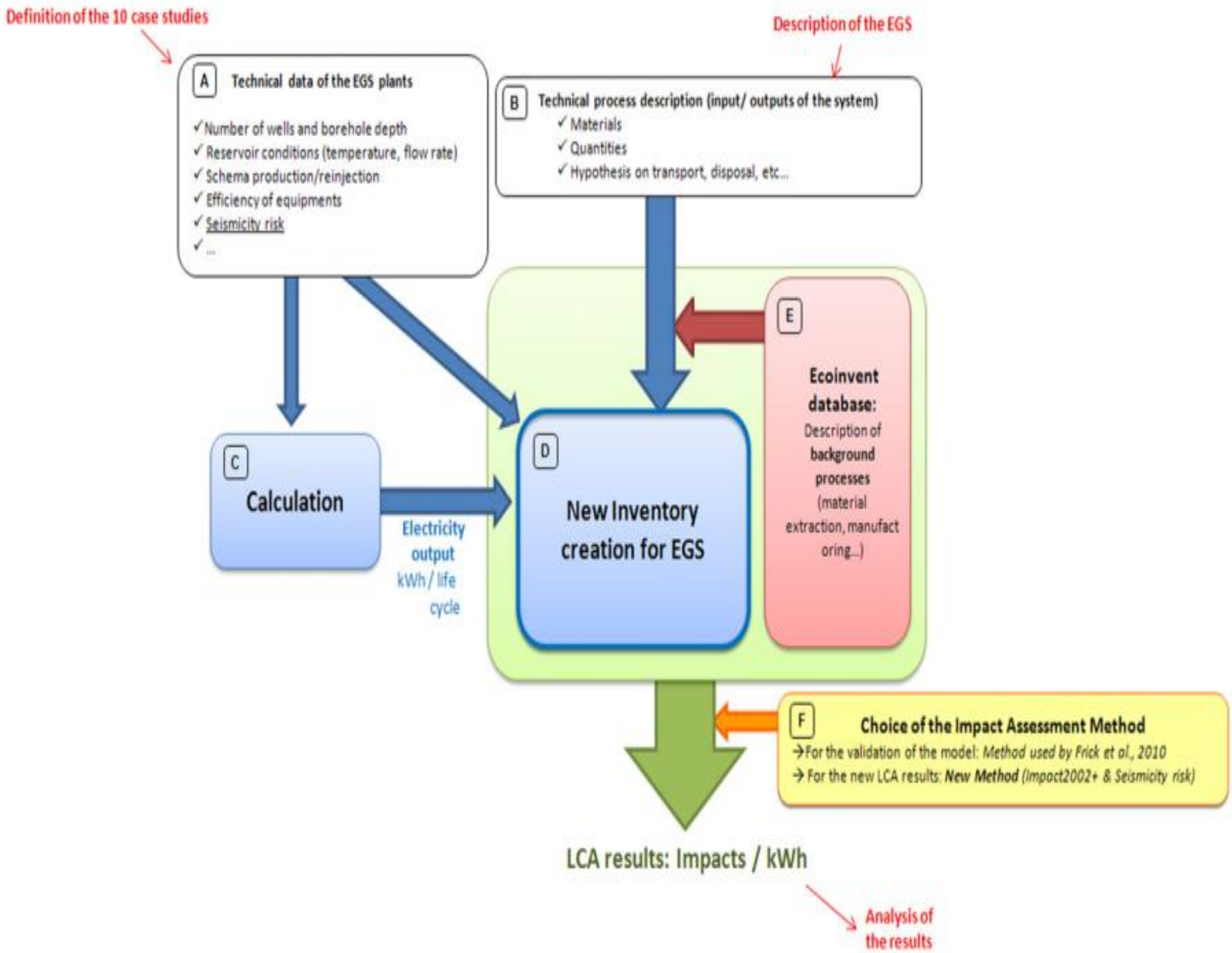

Fig 17: Methodology applied in this study [30].

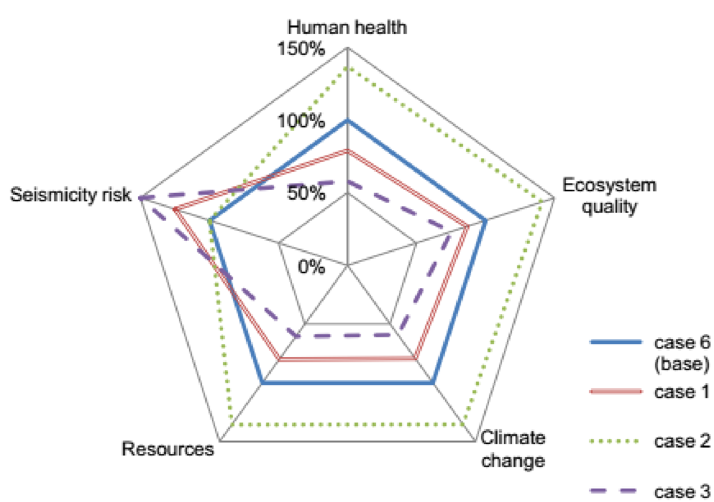

Fig 18: LCA results of case 1, 2 and 3 compared to those of the base case (6) [30].

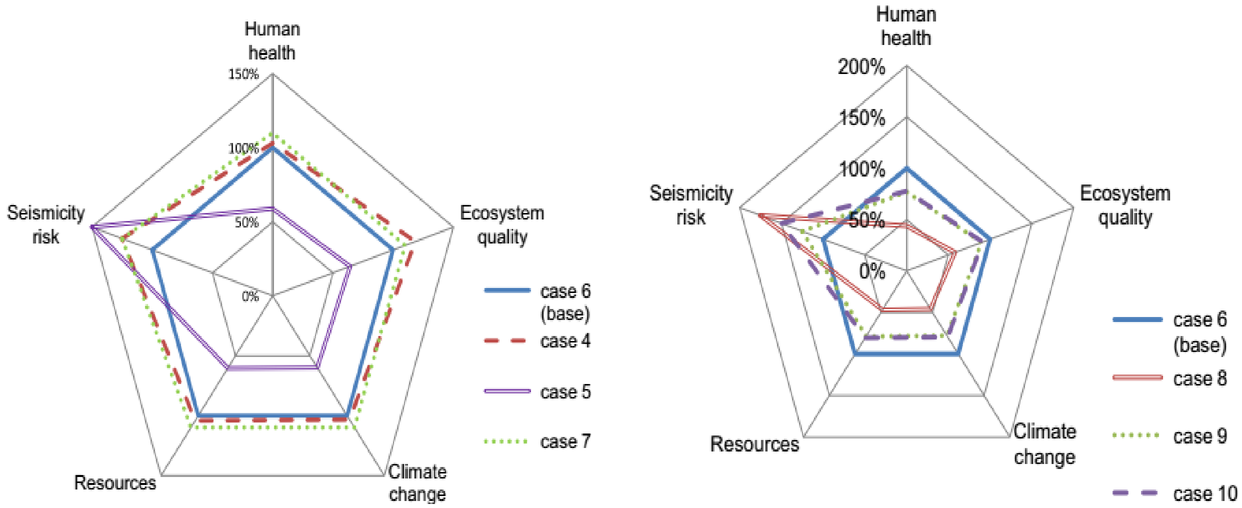

Fig 19: LCA results of case 4, 5 and 7 compared to those of the base case (6) and LCA results of case 8, 9 and 10 compared to those of the base case (6) [30].

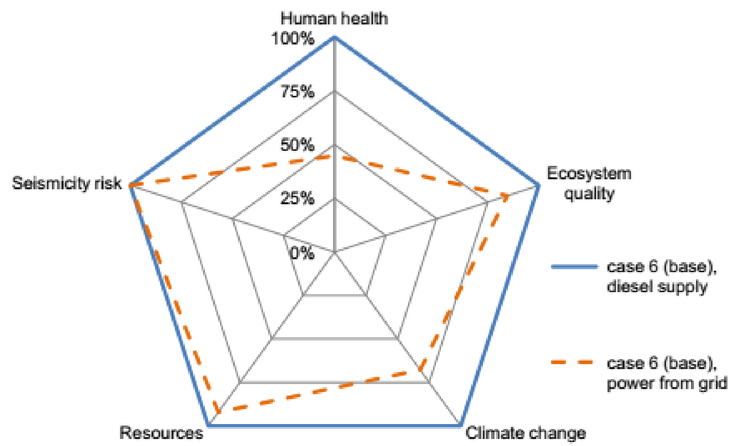

Fig 20: LCA results of case 6 comparing two options for the supply of energy to drive the drilling rig: use of diesel in stand-alone generation machines or connect to the national electricity grid [30].

Léda Gerber and François Maréchal [31] in their article "Environomic optimal configurations of geothermal energy conversion systems: Application to the future construction of Enhanced Geothermal Systems in Switzerland", study Enhanced Geothermal Systems (EGS) for the cogeneration of electricity and district heating by the following criteria: the economic profitability, the thermodynamic efficiency in the usage of the resource, and the generated life-cycle environmental impacts, which are as well a key point for the public acceptance of geothermal energy. Process design and process integration techniques are used in combination with Life Cycle Assessment (LCA) and multiobjective optimization techniques, using a multi-period strategy to account for the seasonal variations in the district heating demand. Different conversion cycles are considered: single and double-flash systems, organic Rankine cycles (ORC), and Kalina cycles. The optimal configuration is determined at each construction depth for the EGS from 3000 down to 10,000 m and at each district heating network installed capacity from 0 to 60 MW_{th}. An important conclusion from their study is that all the optimal economic configurations have a beneficial environmental balance, both in terms of avoided CO_2-eq emissions and life-cycle avoided impacts. However, the variations among the optimal configurations are important, depending on the EGS construction depth, on the district heating design size and on the technology choice. Results show that in the shallowest range of depths (3500-6000 m), the optimal configurations for all considered performance indicators are EGS between 5500 and 6000m with a Kalina cycle for cogeneration, and a district heating network with an installed capacity between 20 and 35 MW_{th}. In the deepest range (7500-9500 m), when compared with the single electricity production, the cogeneration of district heating is less favorable from an economic and exergetic perspective (11% and 17% of relative penalty, respectively, for a district heating network with an installed capacity of 60 MW_{th}) but more favorable in terms of environmental performance (37% of relative improvement for avoided CO_2 emissions).

Stephanie Frick, Martin Kaltschmitt and Gerd Schröder [32] in their article "Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs" are trying to answer the question if geothermal binary power plants are also environmentally promising from a cradle-to-grave point of view, as they have gained increasing interest in the recent years due to political efforts to reduce greenhouse gas emissions and the consumption of finite energy resources. In order to do this they perform a comprehensive Life Cycle Analysis (LCA) on geothermal power production from EGS (enhanced geothermal systems) low-temperature reservoirs. The results of their analysis show that the environmental impacts are very much influenced by the geological conditions that can be obtained at a specific site. At sites with average and above average geological conditions, geothermal binary power generation can significantly contribute to more sustainable power supply. At sites with less favorable conditions, only certain plant designs can make up for the energy and material input to lock up the geothermal reservoir by the provided energy. The main reasons for which the geothermal binary power plants can have large impacts on the environment are the large amount of material and energy inputs they require, especially during construction of the subsurface plant part and the large influence of the auxiliary power required for delivering the geothermal fluid from the reservoir on the net power output. The main aspects of environmentally sound plants are enhancement of the reservoir productivity, reliable design of the deep wells and an efficient utilization of the geothermal fluid for net power and district heat production. The authors state that if the aspects addressed in their paper are taken into consideration, geothermal heat and power generation from low-temperature resources can make a large contribution to a more sustainable energy system today and in the future.

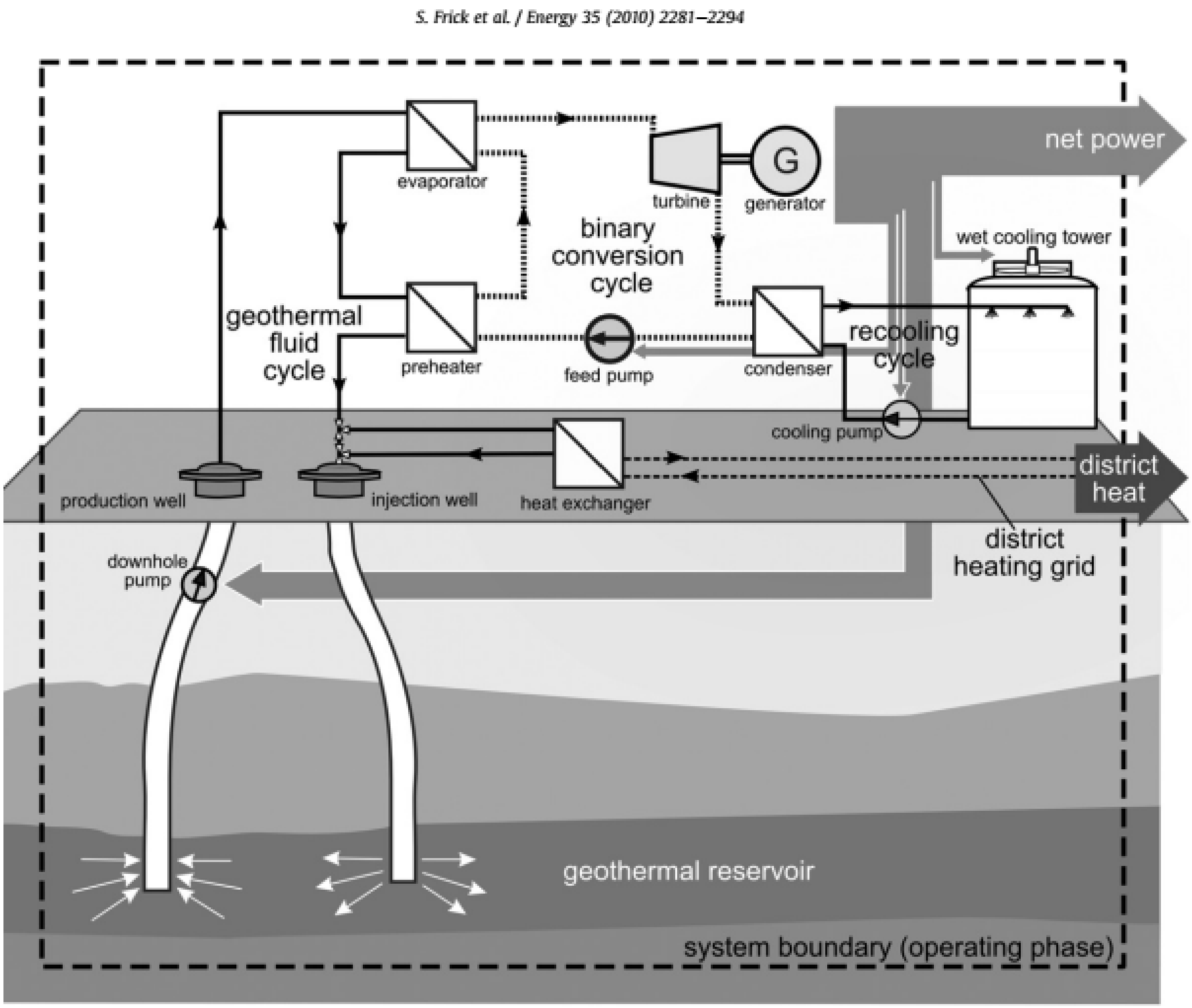

Fig 21: Plant design and system boundaries of the analyzed geothermal binary power plants exploiting a low-temperature reservoir for the supply of net power and, optionally, district heat [32].

The above articles show a different perspective of geothermal energy, as they all conclude to the fact that EGS power plants are economically and environmentally beneficial at the same time not only compared to thermal based power plants, but also to renewable energy power plants.

The following articles recognize two very important factors of GHG related emissions on geothermal power plants, the refrigerant that is used in the cooling stages and the diesel fuel that is used in the construction phases, especially drilling.

Jorge Isaac Martínez-Corona, Thomas Gibon, Edgar G. Hertwich and Roberto Parra-Saldívar [33] in their article "Hybrid life cycle assessment of a geothermal plant: From physical to monetary inventory accounting" try to assess the environmental impacts of electricity generation, as it is deemed fundamental for designing a low-carbon future for future societies. They present a comparison of environmental assessment methods for geothermal plants, based on physical and/or monetary data. Their team aimed to conduct a hybrid LCA for the Wairakei Geothermal Project by using two inventories: mass requirements and monetary capital. The assessment was based on the ISO 14040 series standard. Results show that some hybrid (mass-monetary) inventories yield results that vary significantly between impact categories. However, for the particular geothermal system investigated, direct emissions of geothermal fluids dominate the few impact categories to which they contribute.

Florian Heberle, Christopher Schifflechner and Dieter Brüggemann [34] in their article "Life cycle assessment of Organic Rankine Cycles for geothermal power generation considering low-GWP working fluids" execute a life cycle assessment (LCA) for geothermal power generation by binary power plants, which are based on representative geothermal conditions in Germany. Potential power plant concepts (subcritical one-stage and two-stage Organic Rankine Cycle (ORC) power systems as well as supercritical cycles) are evaluated by the use of LCA in regard to working fluid losses and the associated environmental impact. Due to the restrictive regulations by the European Union for the use of fluorinated refrigerants, a special focus is laid on the evaluation of so-called low-GWP working fluids in ORC systems. In particular, the substitution of R245fa and R134a by working fluids like R1233zd and R1234yf or natural hydrocarbons is examined by a second law analysis. In addition, the environmental impact of the considered power plant concepts is calculated. The results show that the investigated low-GWP fluids lead to equivalent second law efficiency and significant lower environmental impact in comparison to common fluorinated working fluids. In case of a low-temperature heat source, the second law efficiency decreases by 2% and the global warming impact of the ORC is reduced by 78% by using R1233zd as a working fluid instead of R245fa. For the supercritical cycle with R1234yf an efficiency increase of 37% and also a significant decrease of the CO_2eq are obtained. For geothermal conditions with higher temperatures of the geothermal fluid and a limitation of the reinjection temperature, like in the Upper Rhine Rift Valley, the considered optimization approaches lead to an efficiency increase of up to 7%. In this context, the concept of a two-stage ORC is favorable. Compared to a subcritical one-stage system with R245fa as a working fluid, the two-stage ORC with R1233zd leads to 2% higher exergetic efficiency and a reduction of the global warming impact from 78 gCO_2/kWh_e to 13 gCO_2/kWh_e.

C. Tomasini-Montenegro, E. Santoyo-Castelazo, H. Gujba, R.J. Romero and E. Santoyo [7] in their paper "Life cycle assessment of geothermal power generation technologies: An updated review" provide an updated review of life cycle environmental studies for geothermal power generation. Their results have been compiled by energy conversion technology: dry steam, binary cycle, single flash, and double flash, including the generation pilot projects of enhanced geothermal systems. Their analysis shows that regardless of the type of technology diesel consumption, which is required for the construction stages (well drilling and completion: drilling fluid and cement pumping, and casing due to steel production; and well and fluid transport piping), is the main factor responsible for related impact on global warming. In addition to global warming, information about eutrophication, acidification, resource consumption and land use is presented, which includes from 1 to 18 life cycle indicators, identifying the LCA hot spots for each impact category, subject to data availability. Also, it is possible to conclude that the life cycle environmental impacts vary in relation to two factors: local geological characteristics and other methodological choices inherent to the LCA methodology, including the definition of the functional unit, the system boundaries, the life span, the impact assessment method and the allocation procedure. A deeper analysis of the life cycle environmental impacts to promote an environmental sustainable management of geothermal power generation is proposed, which still represents a challenge for this industrial sector.

Thomas Gibon, Anders Arvesen and Edgar G. Hertwich [35] in their article "Life cycle assessment demonstrates environmental co-benefits and tradeoffs of low-carbon electricity supply options" are trying to make a comparative assessment of different electricity generation technologies addressing a wide range of environmental impacts and using a consistent set of methods. They do that by assessing a consistent set of life cycle inventories of a wide range of electricity generation technologies using the Recipe midpoint methods. The life-cycle inventory modeling addresses the production and deployment of the technologies in nine different regions. The analysis shows that even though low-carbon power requires a larger amount of metals than conventional fossil power, renewable and nuclear power leads to a reduction of a wide range of environmental impacts, while CO_2 capture and storage leads to increased non-GHG impacts. The manufacturing of low-carbon technologies is important compared to their operation, indicating that it is important to choose the most desirable technologies from the outset. The geothermal plant assessed in this study has a high load factor and a very long assumed lifetime. As a consequence, emissions from the production phase are relatively low. However, direct emissions are at least one order of magnitude higher than indirect emissions regarding greenhouse gas emissions, toxicity, particulate matter emissions, photochemical ozone formation, and acidification. This is due to the high geogenic emissions: 83 g CO_2/kWh, 0.1587 g SO_2/kWh, 0.75 g CH_4/kWh, 0.06 g NH_3/kWh and 4 gHg/MWh. These assumptions can be considered conservative (especially for human toxicity and freshwater eco-toxicity, for which the characterization factor of mercury is one of the highest across all substances), as most of the environmental impacts are caused by direct site-specific emissions from the geothermal fluid during the plant operation.

Mario Martín-Gamboa, Diego Iribarren and Javier Dufour [36] in their article "On the environmental suitability of high- and low-enthalpy geothermal systems" address the life cycle assessment of power generation in a binary-cycle power plant using high-enthalpy geothermal resources and heat generation in a closed-loop geothermal heat pump system using low-enthalpy resources. The LCA of power generation in binary-cycle power plants using high-enthalpy geothermal resources showed that geothermal electricity is an appropriate candidate to replace fossil-derived electricity. Although the environmental profile and the life-cycle energy balance of geothermal power systems are highly favorable, even better performances could be achieved by optimizing the material needs of site operation activities such as drilling and casing, and by using ecological friendly working fluids. The LCA of heat generation in closed-loop GHP systems using low-enthalpy geothermal resources showed that the high electricity demand of heat generation and use is the factor that determines the environmental performance of geothermal heat systems. Even though geothermal heat accounts for a more favorable global warming performance and a lower non-renewable energy demand than fossil heat, the availability of more environmentally friendly electrical grids is a critical issue to minimize the impact of geothermal heat. The authors believe that in general GE systems have the potential to supply energy products with low environmental impact and that they are expected to play a significant role in the future energy system. However, further efforts need to be made in order to guarantee the environmental sustainability of Geothermal Energy.

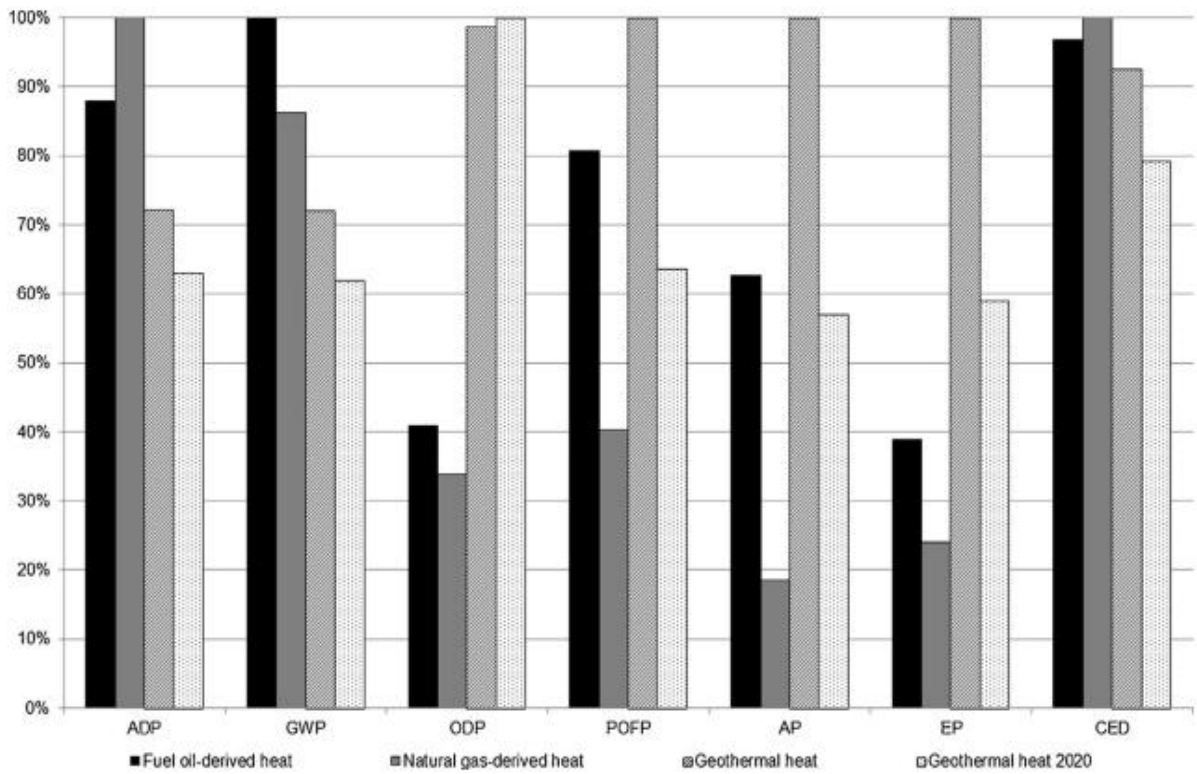

Fig 22: Comparison of the environmental impacts of geothermal heat (current and projection for 2020) and fossil-derived thermal energy. Abbreviations: ADP (abiotic depletion potential), GWP (global warming potential), ODP (ozone layer depletion potential), POFP (photochemical oxidant formation potential), AP (acidification potential), EP (eutrophication potential) and CED (cumulative energy demand) [36].

Following the opinion expressed in the above article, that a more environmentally friendly electrical grids is a critical issue to minimize the impact of geothermal heat comes the article by Joe Marriott, H. Scott Matthews and Chris T. Hendrickson [37] “Impact of Power Generation Mix on Life Cycle Assessment and Carbon Footprint Greenhouse Gas Results", who explore the potential impacts that the energy mix has on the results of an LCA case study. They have shown that regional variations in the local generation mix can significantly affect greenhouse gas emission estimates relative to using a national generation mix assumption. They also found out that greenhouse gases for certain sectors and scenarios can change by more than 100%. Finally the authors advise practitioners to exercise caution or at least account for the uncertainty associated with mix choice.

In the spirit of improving the results of the various studies come the following articles which explore new methods for conducting a LCA.

Martin Pehn in his article [38] "Dynamic life cycle assessment (LCA) of renewable energy technologies" investigates the potential of a dynamic approach on LCA on the grounds that background system impacts such as supply of materials or final energy for the production of the energy system have the potential to improve over time. Therefore he proves that for all renewable energy chains, the inputs of finite energy resources and emissions of greenhouse gases are extremely low compared with the conventional system. With regard to the other environmental impacts the findings do not reveal any clear verdict for or against renewable energies.

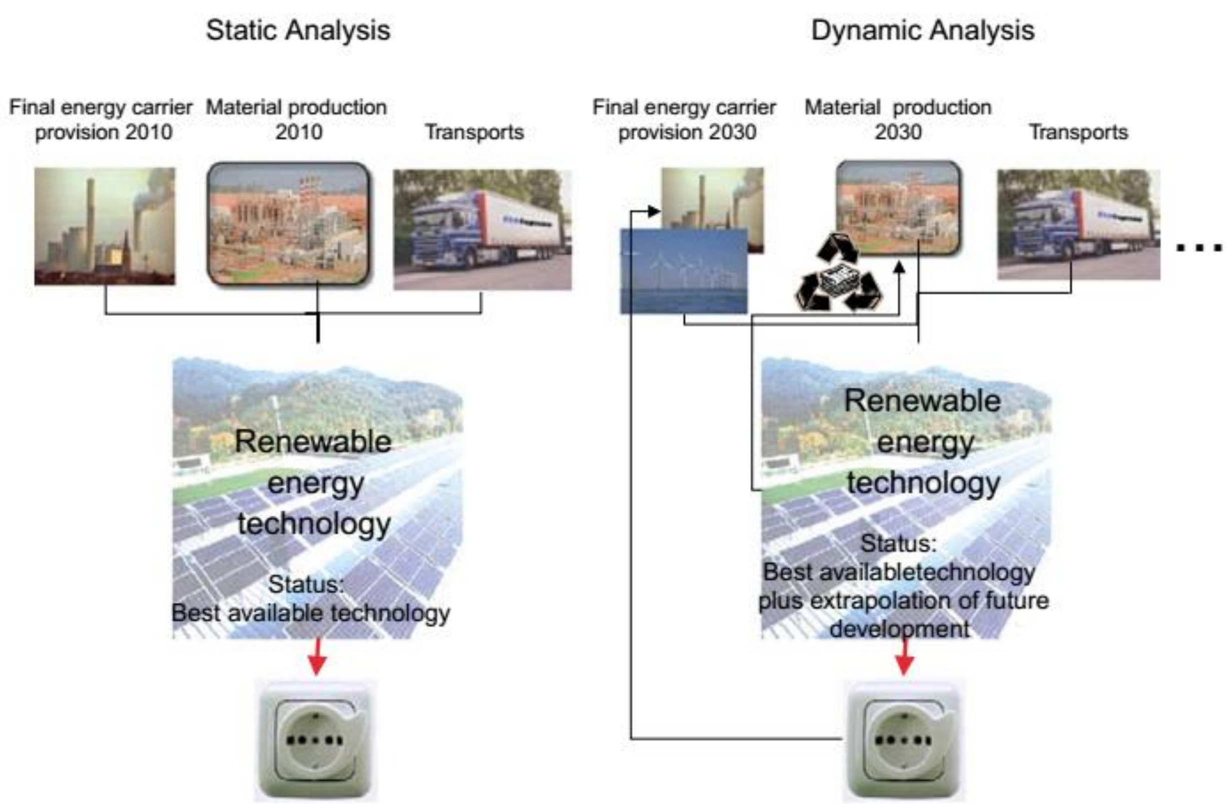

Fig 23: Dynamic LCAs: principle [38].

Nana Yaw Amponsah, Mads Troldborg, Bethany Kington, Inge Aalders and Rupert Lloyd Hough [39] in their article “Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations”, review 79 studies which involved the life cycle assessment (LCA) of renewable electricity and heat generation based on onshore and offshore winds, hydropower, marine technologies (wave power and tidal energy), geothermal, photovoltaic (PV), solar thermal, biomass, waste and heat pumps. Their study demonstrates the variability of existing LCA studies (results) in tracking GHG emissions for electricity and heat generation from Renewable Energy Technologies (RETs). Their review has shown that the lowest GHG emissions were associated with offshore wind technologies (mean life cycle GHG emissions could be 5.3–13 gCO_2eq/kWh). Results compared with GHG estimates by fossil fuel heat and electricity indicated that life cycle GHG emissions are comparatively higher in conventional sources as compared to renewable sources with the exception of nuclear-based power electricity generation. However, energy from waste (waste to energy) and dedicated biomass technologies (DBTs) were found to potentially have high GHG emissions based on the feedstock, selected boundary and the inputs required for their production (97.2–1000 gCO_2eq/kWh; 14.4–650.0 gCO_2eq/kWh respectively). The review further demonstrates the variability of existing LCA GHG emission estimates for electricity and heat generation from renewable energy technologies. While some of these differences may reflect actual differences in GHG emissions, others may largely be due to assumptions and other modeling choices. This offers areas for improvement and opportunities for standardization. The results of their review can provide suitable baseline estimates for future projects in developing renewable energy technologies for electricity and heat production.

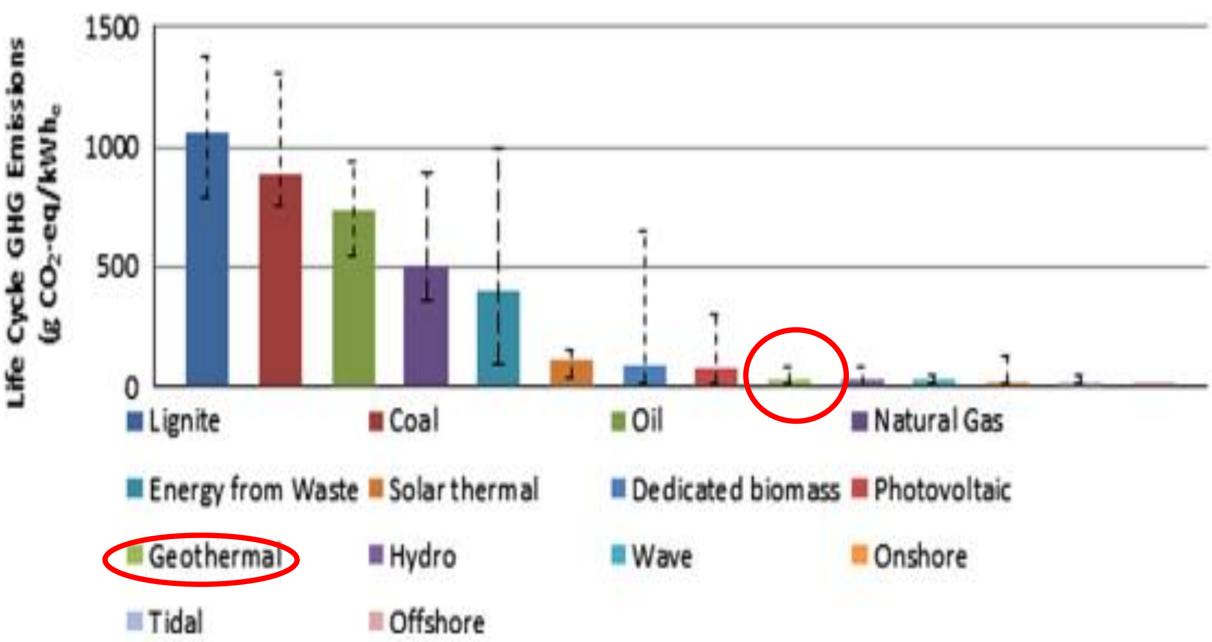

Fig 24: Life cycle GHG emission estimates of electricity generation methods [39].

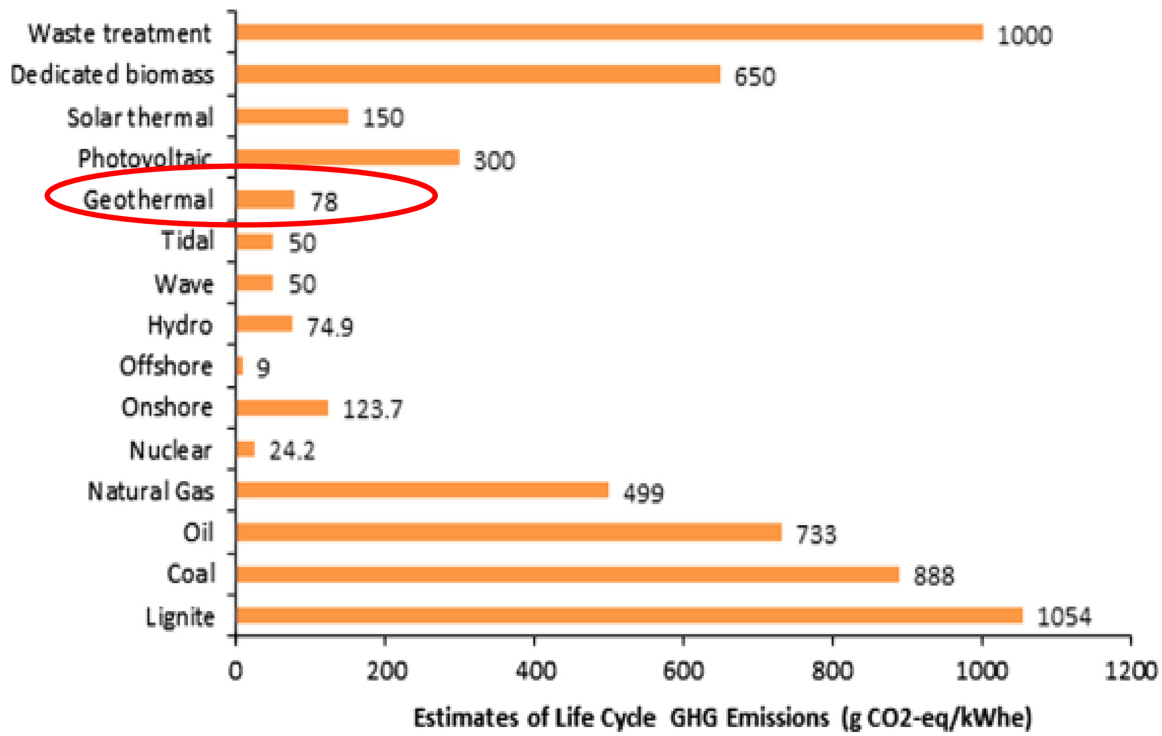

Fig 25: Maximum GHG emission levels of electricity generation methods [39].

Peter Bayer, Ladislaus Rybach, Philipp Blum and Ralf Brauchler [40] in their paper "Review on life cycle environmental effects of geothermal power generation" present a comprehensive overview of potential environmental effects during the life cycle of geothermal power plants using available information from diverse literature sources. The authors state that Life cycle assessment (LCA) studies on geothermal electricity production are scarce and typically country or site-specific. Also life cycle fugitive emissions, the threat from geological hazards, and water and land use effects are highly variable and may even change with time. Based on their survey, ranges are provided for emissions and resource uses of current worldwide geothermal power generation. They also define an approximate universal case that represents an expected average. The collected data is suitable to feed life cycle inventories, but is still incomplete. Potential emissions of critical toxic substances such as mercury, boron and arsenic and their local and regional environmental consequences are particularly inadequately addressed on the global scale.

Martino Lacirignola, Bechara Hage Meany, Pierryves Padey and Isabelle Blanc [41] in their article "A simplified model for the estimation of life-cycle greenhouse gas emissions of enhanced geothermal systems" develop a new type of LCA-based approach, called simplified model, based on the analysis of environmental performance variability of energy pathways. Such methodology has been applied to produce a reduced parameterized model, designed to estimate life-cycle greenhouse gas (GHG) emissions of EGS power plants applicable to a large sample of configurations. The results of their study are two parameterized models to assess EGS greenhouses gases (GHG). A parameterized reference model is developed to describe a large sample of possible EGS power plants located in central Europe. Two or three wells plants equipped with a binary system producing only electricity are accounted for. Applying global sensitivity analysis (GSA) to this reference model allowed for the identification of three key variables, responsible for most of the variability on GHG results: installed power capacity, drilling depth, and number of wells. A reduced parameterized model for the estimate of the GHG performances as the only function of these three key variables was then established. A comparison with the results of published EGS LCAs confirms the representativeness of their new simplified model. The simplified model, issued from the reference parameterized model, enables a rapid and simple estimate of the environmental performances of an EGS power plant, avoiding the extensive application of the LCA methodology. It provides an easy-to-use tool for the stakeholders of the EGS sector and for decision makers. It aims at contributing to the debate about the performances of this new emerging technology and its related environmental impacts.

4.5. Environmental Studies on Pre-existing Power Plants

In this part of the paper, follow two articles concerning studies on pre-existing power plants. Mirko Bravi and Riccardo Basosi [42] in their article "Environmental impact of electricity from selected geothermal power plants in Italy" study the electricity production phases of four geothermal electricity plants in Mount Amiata area, in Tuscany region, Italy. With geothermal power making up for 1,8% of the total electricity production in Italy and the global trend towards renewable energy sources, the authors are making an effort to understand the environmental characteristics of geothermal power generation and to find solutions to minimize its impacts. The power plants are analyzed by means of a careful airborne emissions assessment carried out over the entire LCA. The impact categories considered are global warming (GWP), acidification (ACP) and human toxicology (HTP), while the functional unit used is 1 MWh of electric energy produced. Their Analysis shows that electricity from the geothermal plants in Mount Amiata area cannot be considered "carbon free" as claimed so far. Although Human Toxicity Potential did not provide worrisome values, greenhouse gas emissions are in some cases generally higher than those from natural gas plants and in some sampling not very far from the values of coal plants. Furthermore, the Acidification Potential of electricity produced from geothermal plants considered here is 2.2 times higher than that for coal plants. In one case this difference increases by a factor of 4.4 and is about 28 times higher than the ACP of natural gas plant. Although binary cycle technology is not, at the moment, the best solution from the point of view of efficiency and cost, the idea of considering the minimization of impacts (through the complete reinjection of incondensable fluids into the reservoir) is necessarily a promising avenue based on environmental considerations for geothermal power plants in the future.

On the other hand, O. Hanbury and V.R. Vasquez [43] in their article "Life cycle analysis of geothermal energy for power and transportation: A stochastic approach" explore the potential environmental benefits of using a renewable power source, in this case geothermal power, for transportation. To achieve this they use a plant in northern Nevada (Blue Mountain) as a case study, which has a capacity of approximately 484 MW of geothermal power. As an extension of this case study, they analyze the life cycle of transportation vehicles making use of geothermal energy. Geothermal power has large variations between plants owing to differences in the hydrothermal reservoir chemistry and thermodynamic conditions, so the authors use a stochastic approach to determine the amount of variation that is likely to be seen using this energy source. The results show geothermal power to have a low environmental impact relative to other methods of energy production for use in transportation.

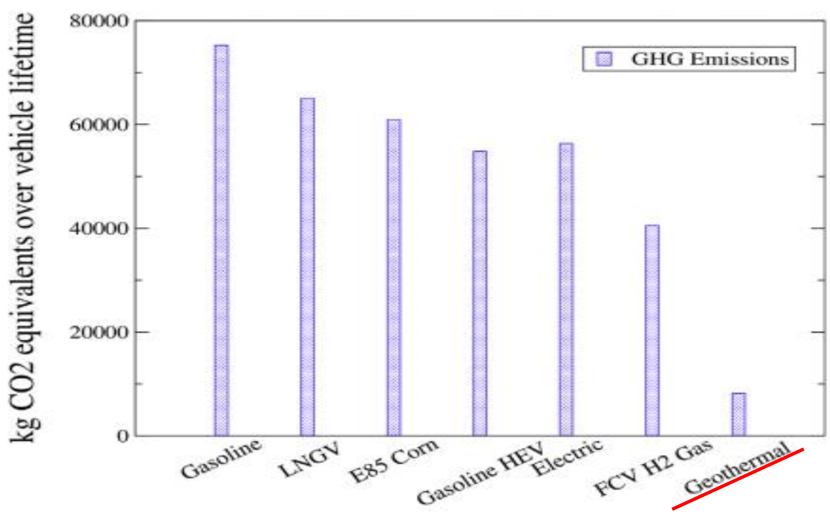

Fig 26: Comparison of greenhouse gas emissions for different vehicle types. LNGV stands for liquified natural gas, E85 is an 85% mixture of ethanol and gasoline, HEV is a hybrid electric vehicle and FCV H2 is a fuel cell vehicle that runs on hydrogen gas. Electric vehicle in this is case is the same vehicle as in the geothermal column, but it uses a standard mix of electricity common in the US (coal, natural gas, nuclear, etc.) [43].

4.6. Greenhouse Heating

Giovanni Russo, Alexandros S. Anifantis, Giuseppe Verdiani and Giacomo Scarascia Mugnozza [44], in their research paper "Environmental analysis of geothermal heat pump and LPG greenhouse heating systems" demonstrate via environmental analysis the efficiency of a Photovoltaic Geothermal Heat Pump integrated system (PV-GHP) as a greenhouse heating system, compared to a conventional hot air generator using liquefied petroleum gas (LPG-HG). Their tests were carried out in twin experimental greenhouses in the Mediterranean area (Valenzano-Italy). The objective of their paper is an environmental analysis, by means of life cycle assessment (LCA), of two different heating systems for a greenhouse: a pilot plant photovoltaic-geothermal heat pump integrated system (PV-GHP) and a conventional hot air generator supplied by liquefied petroleum gas (LPG-HG). Those two technologies currently encouraged by Italian policies for the reduction of greenhouse gases emissions were evaluated to establish which of the two was more environmentally friendly. Experimental tests and the subsequent comparison of microclimatic conditions and environmental performance were realized. A technological scenario (GHP) was also examined by assuming that electricity was not provided by solar panels but by the Italian national grid. The microclimatic conditions in the two greenhouses, the thermal energy produced and the electricity consumption were analyzed. Furthermore, in order to evaluate the long-term environmental impact, an environmental analysis was conducted using life cycle assessment (LCA) methodology, carried out according to standard UNI EN ISO 14040. The interpretation of the results using method CML2001 (Centre of Environmental Science, Leiden, Netherlands) showed that neither system is more advantageous from an environmental point of view and that the GHP scenario has the higher environmental burdens. Limiting the analysis to the emissions responsible for the greenhouse effect, the plant with the geothermal heat pump and photovoltaic panels reduces carbon emissions by 50%. In order to assess the sustainability of the geothermal heat pump plant, the estimated payback-time for energy and for carbon emissions were 1 year and 2.25 years, respectively.

4.7. Improvement of existing technologies of geothermal systems

Articles have been published that investigate the effects of specific changes to the existing geothermal technology in order to improve it. Aurelian Buzaianu, Petra Motoiu, Ioana Csaki, Gabriela Popescu, Kolbrun Ragnarstottir, Sæmundur Guðlaugsson, Daniel Guðmundsson and Adalsteinn Arnbjornsson [45] in their paper "Experiments on life cycle extensions of geothermal turbines by multi composite technology" approach a new solution for protecting the steel turbine components of geothermal power plant turbines against aggressive corrosion by coating with multi-composite layers. Their objective is the design and synthesis of new complex powder mixtures NiCr/NiCoCr with different addition of ZrO_2 stabilized with Y_2O_3 that can be used to obtain protective layers with improved wear, thermal shock and abrasion resistance. The plasma jet method the team used provides the tested layer deposits with high wear and corrosion resistance as well as for the layer deposits that are resistant when applied on high precision pieces. The method itself is very flexible from the technological point of view and it is used to test various deposit materials multiple composites layers.

W. Grassi, P. Conti, E. Schito and D. Testi [46] in their paper "On sustainable and efficient design of ground-source heat pump systems" aim at stressing some fundamental features of the GSHP design and based their study on a broad research they are performing at the University of Pisa. In particular, they focus the discussion on an environmentally sustainable approach, based on performance optimization during the entire operational life. The proposed methodology aims at investigating design and management strategies to find the optimal level of exploitation of the ground source and refer to other technical means to cover the remaining energy requirements and modulate the power peaks. The method is holistic, considering the system as a whole, rather than focusing only on some components, usually considered as the most important ones. Each subsystem is modeled and coupled to the others in a full set of equations, which is used within an optimization routine to reproduce the operative performances of the overall GSHP system. As a matter of fact, the recommended methodology is a 4-in-1 activity, including sizing of components, lifecycle performance evaluation, optimization process, and feasibility analysis. Their paper reviews also some previous works concerning possible applications of the proposed methodology. In the end they describe undergoing research activities and objectives of future works.

4.8. Water Consumption

In a water-constrained world, it is critical to understand how water is used throughout the entire life cycle of electricity generation. In this context, J. Meldrum, S. Nettles-Anderson, G. Heath and J. Macknick [47] in their article "Life cycle water use for electricity generation: a review and harmonization of literature estimates" provide consolidated estimates of water withdrawal and water consumption for the full life cycle of selected electricity generating technologies, which includes component manufacturing, fuel acquisition, processing, and transport, and power plant operation and decommissioning. Despite limitations to available data, they find that: water used for cooling of thermoelectric power plants dominates the life cycle water use in most cases, the coal, natural gas, and nuclear fuel cycles require substantial water per megawatt-hour in most cases and a substantial proportion of life cycle water use per megawatt-hour is required for the manufacturing and construction of concentrating solar, geothermal, photovoltaic, and wind power facilities.

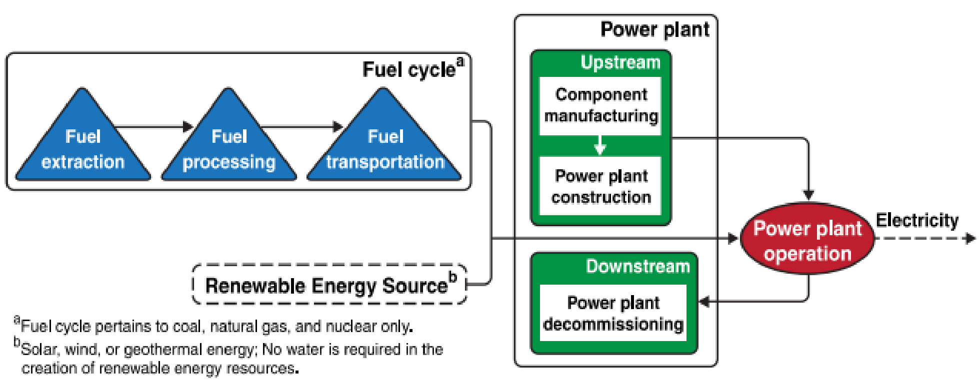

Fig 27: A schematic of the significant life cycle stages for each electricity generation technology demonstrates the additional role of fuel cycle water use in contributing to the life cycle water use for coal, natural gas, and nuclear generation technologies. The power plant life cycle stage consists of an upstream component manufacturing and plant construction phase and a downstream phase when the power plant is decommissioned [47].

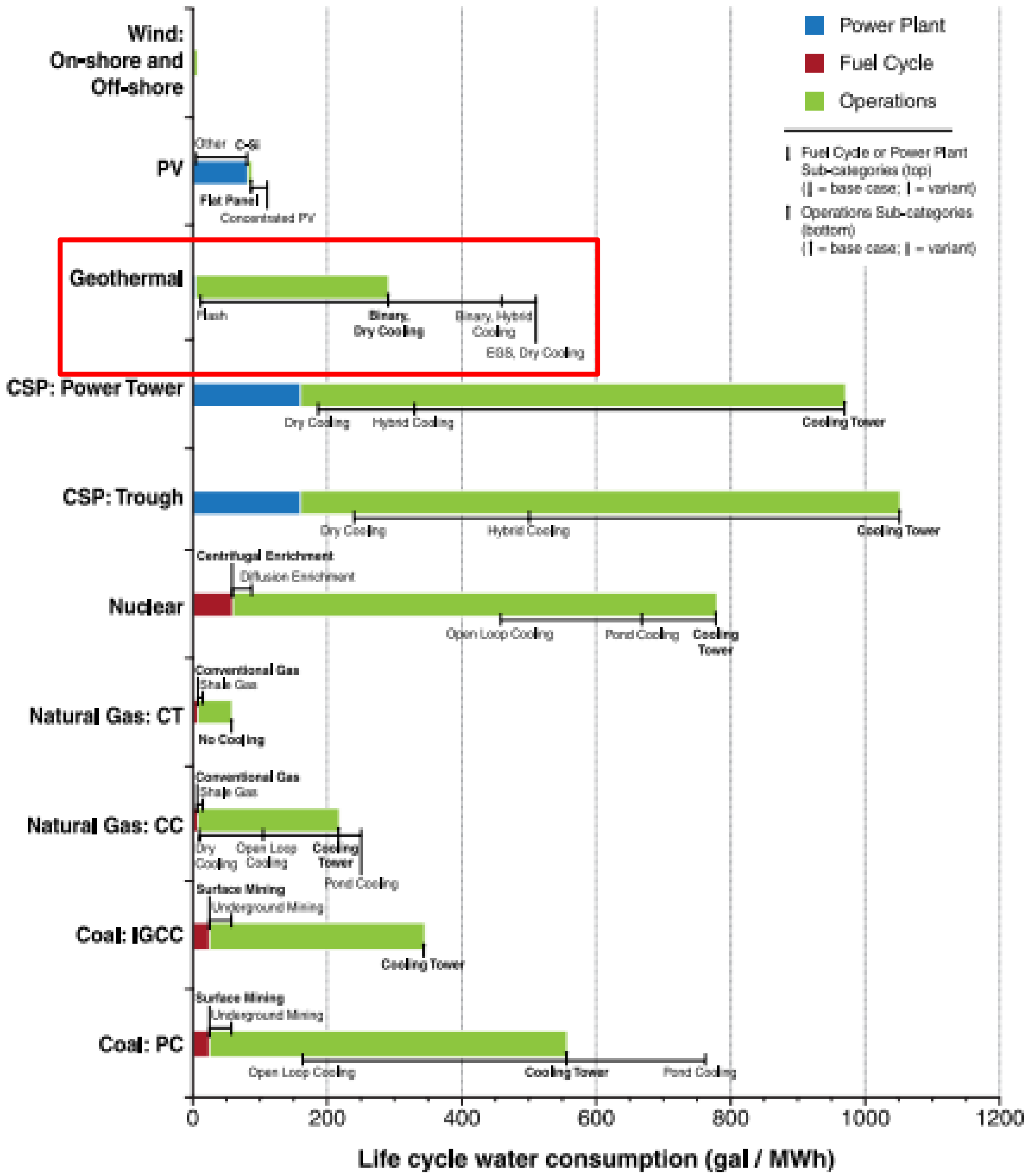

Fig 28: Estimated life cycle water consumption factors for selected electricity generation technologies, based on median harmonized estimates, demonstrate significant variability with respect to technology choices. Base case estimates for each life cycle stage, presented in bold font, are held constant for estimating life cycle water consumption factors for other life cycle stages. Estimates for production pathway variants in fuel cycle or power plant (labeled on top of the bars) or operations (bottom) are labeled at points connected to the base case estimate with horizontal lines. Note: PV D photovoltaics; C-Si D crystalline silicone; EGS D enhanced geothermal system; CSP D concentrating solar power; CT D combustion turbine; CC D combined cycle; IGCC D integrated gasification combined cycle; and PC D pulverized coal, sub-critical [47].

5. Conclusions

5.1. References Tables

A table of all the examined articles follows, which presents them in a manner according to their category or application, the used methodology, the examined impacts and the software that was used:

CATEGORY / APPLICATION								
COMBINATION OF TECHNOLOGIES	DISTRICT HEATING	DOMESTIC HEATING	ELECTRICITY GENERATION	PRE-EXISTING PLANTS	GREENHOUSE HEATING	TECHNOLOGICAL IMPROVEMENTS	WATER CONSUMPTION	REFERENCE
	X							1
		X						2
		X						3
						X		4
			X					5
								6
			X					7
X								8
	X							9
	X			X				10
		X						11
		X						12
		X						13
		X						14
X		X						15
X		X						16
		X						17
		X						18
		X						19
		X						20
		X						21
		X						22
			X					23
			X					24
			X					25
			X					26
			X					27
			X					28
			X					29
			X					30
			X					31
			X					32
			X					33
			X					34
			X					35
		X	X					36
			X					37
			X					38
			X					39
			X					40
			X					41
				X				42
				X				43
					X			44
						X[a]		45
						X[b]		46
							X	47

Table 3: Category or Application listing of examined articles. (X[a]): vane surface coating, (X[b]): technological design.

ADDITIONAL INFO			METHOD									
COMPARING DIFFERENT TECHNOLOGIES	PROPOSING METHOD IMPROVEMENTS	GEOTHERMAL TECHNOLOGY	SUSTAINABILITY ASSESMENT	LCA	LCC	EMA	EXERGY	ENERGY	GSA	LITERATURE REVIEW	REFERENCE
X				X	X						1
		SOLAR		X			X				2
X				X			X				3
	X	EGS		X					X		4
X		DRY STEAM		X		X					5
	X			X		X					6
		ALL								X	7
		EGS		X							8
					X		X	X			9
				X			X				10
X				X							11
X		GSHP									12
X		GSHP		X							13
		GSHP		X							14
								X			15
					X						16
X					X						17
		GSHP		X							18
		GSHP	X	X							19
		GSHP		X							20
		GSHP			X			X			21
X	X	GHP								X	22
X			X							X	23
			X							X	24
X										X	25
X		ALL		X				X			26
X		ALL		X				X			27
		FLASH/ DRY STEAM		X							28
X		ALL		X							29
		EGS		X							30
		EGS		X							31
		BINARY - EGS		X							32
	X			X						X	33
				X							34
											35
X		BINARY / GSHP		X							36
	X^d										37
	X			X							38
X										X	39
	X									X	40
	X^c	EGS		X						X	41
				X							42
		BINARY		X							43
X				X							44
											45
		GSHP								X	46
X										X	47

Table 4: Additional Information and Method Used Listing of examined articles. (X^c): simplified model, (X^d): power generation mix.

ENVIRONMENTAL INDICATORS							
GHG - CLIMATE CHANGE	HUMAN HEALTH	ECOSYSTEM QUALITY	SEISMICITY RISK	RESOURCE DEPLETION	RESOURCE AVAILABILITY	WATER USE / CONSUMPTION / POLLUTION	REFERENCE
X							1
X	X	X					2
X	X	X		X			3
							4
X	X	X					5
							6
X	X	X	X	X		X	7
X	X						8
							9
	X	X		X			10
X	X	X		X			11
X	X	X		X			12
X	X	X		X			13
X	X	X					14
							15
X							16
							17
X	X	X		X		P	18
X	X	X					19
X	X	X					20
X							21
X							22
X						U	23
X					X	U	24
X	X	X				U	25
X							26
X							27
X							28
X						C	29
X	X	X	X	X			30
X							31
X	X	X		X			32
X	X	X		X		P	33
X	X	X		X			34
X	X	X		X		P	35
X	X	X					36
							37
X		X		X			38
X							39
X	X	X	X	X		P	40
X							41
X	X	X					42
X	X	X		X			43
X	X	X		X			44
							45
	X						46
						U	47

Table 5: Environmental Indicators Used listing of examined articles. On Water Use/ Consumption/ Pollution Column: (U): Use, (P): Pollution, (C): Consumption.

OTHER INDICATORS					REFERENCE
ECONOMIC	LAND USE	EFFICIENCY OF ENERGY CONVERSION	SOCIAL	TECNOLOGICAL LIMITATIONS	
X					1
					2
					3
					4
					5
					6
	X				7
					8
X					9
					10
	X				11
					12
					13
					14
		X			15
X					16
X					17
	X				18
X			X		19
					20
X					21
					22
X	X	X	X	X	23
X	X	X	X		24
X	X				25
					26
					27
					28
					29
					30
X		X			31
					32
					33
					34
	X				35
					36
					37
					38
					39
	X				40
					41
					42
					43
		X			44
					45
					46
					47

Table 6: Other Indicators Used listing of examined articles.

SOFTWARE	DATABASE	REFERENCE
ENVIMAT		1
SimaPro /Gabi		2
SimaPro v.7.1	Ecoinvent	3
Parameterized Reference model by Lacirignola et al. (2014)	Ecoinvent v2.2	4
CML 2001/ CED		5
		6
		7
IPCC 2013 - GWP 100a / impact 2002+ / ecoscarcity 2013	Ecoinvent	8
		9
SimaPro v.7.2	Eco-indicator 99	10
SimaPro v.7.3.2	Ecoinvent	11
ReCiPe 2008	Ecoinvent	12
SimaPro	UNIQUE	13
SimaPro v.7.1.8	Eco- Indicator 95	14
		15
IDA-ICE / MATLAB		16
		17
SimaPro v.8.2.3	Ecoinvent v.3.2	18
GABI v.6	GABI v.6	19
		20
RetScreen		21
		22
		23
		24
		25
GREET	GREET	26
GREET	GREET	27
	GREET1	28
GREET 1.8		29
IMPACT 2002+		30
Ecoindicator99-		31
-	Ecoinvent	32
THEMIS	Ecoinvent 2.2 / EXIOBASE	33
	ECOINVENT/ PROBAS	34
ReCiPe v.1.08	ecoinvent v.2.2	35
SimaPro v.7		36
		37
Umberto	Umberto	38
		39
		40
Parameterized Reference model by Lacirignola et al. (2014)	Ecoinvent v2.2	41
SimaPro	ARPAT	42
TRACI		43
GABI6	Ecoinvent	44
		45
		46
		47

Table 7: Software and Databases Used listing of examined articles.

5.2. Discussion

After studying the above articles we have safely reached to certain conclusions about geothermal energy and its applications.

The advantages of geothermal energy are:

1. It is a renewable energy.
2. Geothermal power plants can work 24 hours a day, seven days a week without stopping.
3. Geothermal power plants are not affected by the weather or other natural phenomena.
4. Newer technological improvements increase the number of potential geothermal sites that can be exploited.
5. Certain technologies of geothermal power generation have almost zero GHG emissions during their operational phases (e.g. EGS).
6. It has a broad spectrum of possible applications, from very small like water and space heating (e.g. GSHP), to very large like electricity generation.
7. Electricity generation from geothermal power plants is concentrated in its form, not widespread like photovoltaic or wind power and as a result it is more easily combined with the currently existing electricity transfer grid.
8. High grade geothermal resources are available in over 80 countries around the world, with a potential generating capacity of 11,000 ± 1,300 TWh/ year. The feasible, currently economical potential is estimated at 8,100TWh/ year, with a total theoretical potential of around 400,00TWh/year. This is much larger than the current production level of 2,600TWh/ year [23].

The disadvantages of geothermal energy are:

1. Its high construction costs.
2. Its high material requirements.
3. Some electrical power generation geothermal technologies have GHG emissions during their operation phase (e.g. HT-Flash).
4. Ground source Heat Pumps are inevitably connected to the national power grid which can cause GHG emissions during their operation phase.
5. There is the risk of increased seismicity among other environmental impacts.
6. Environmental impacts associated with geothermal power generation include surface disturbances, physical effects, such as land subsidence caused by fluid withdrawal, noise, thermal pollution and the release of offensive chemicals. Nonetheless, there are large variations from site to site that are technologically dependent [23].

To sum up, geothermal energy is a renewable form of energy that is not based in the consumption of fossil fuels, but it requires the use of fossil fuels for its installation and in some cases its operation phases (e.g. borehole drilling, electrical pumps connected to the national power grid). It also produces GHG emissions from gases that naturally escape from the geothermal reservoir during the power plants' operation phase.

Geothermal power provides advantages both for the environment and for dependability in electricity generation. Although large amounts of steel and concrete are required per MW power capacity, enhanced geothermal systems are one of the lower GHG emitters of the renewable systems studied per unit of lifetime kWh output [26]. Also, geothermal power shows the lowest possible prices of electricity generation, together with hydro power [23].

Another of its most important aspects is its capability of space heating, using low enthalpy reservoirs that exist practically everywhere.

A lot of work has been made these recent years by many scientists around the world, who are trying to comprehend the environmental impacts of this form of energy. The results are promising, even when compared with other forms of renewable energy. Geothermy can play a vital role in the zero GHG emissions societies of the future if certain steps are accomplished:

1. The improvement of the electricity generation mix.
2. Innovations in borehole drilling and transportation, which will cause for mitigated environmental impacts in the construction phase of the technologies.
3. Improvements in the design of various components.
4. Reinjection of harmful emissions of existing geothermal power plants, which do not only cause a mitigation of environmental impacts, but also increase the life expectancy of the geothermal source.

Just as any other case of renewable energy, Geothermy is not the panacea for the future. It is nonetheless a very viable alternative that can be combined with the other renewable energy options and produce good and solid results for mitigating the effects of the existing electricity generation grid on the planets environment.

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