energies

Review

Evaluating the Technical and Environmental Capabilities of Geothermal Systems through Life Cycle Assessment

Maria Milousi [1], Athanasios Pappas [2], Andreas P. Vouros [3,4], Giouli Mihalakakou [3], Manolis Souliotis [1,*] and Spiros Papaefthimiou [2,*]

[1] Department of Chemical Engineering, University of Western Macedonia, 50100 Kozani, Greece
[2] School of Production Engineering & Management, Technical University of Crete, 73100 Chania, Greece
[3] Department of Mechanical Engineering & Aeronautics, University of Patras, 26504 Patras, Greece
[4] Department of Mechanical Engineering, University of Peloponnese, 26334 Patras, Greece
* Correspondence: msouliotis@uowm.gr (M.S.); spiros@pem.tuc.gr (S.P.)

Abstract: In these days of heightened environmental consciousness, many countries are shifting their focus towards renewable energy sources for both large-scale uses (such as power plants that generate electricity) and smaller-scale applications (e.g., building heating and cooling). In this light, it is not surprising that there is a growing interest in technologies that are reliant on non-conventional sources of power, such as geothermal energy. This study is making an effort to provide a comprehensive understanding of the possible advantages and multiple uses of geothermal energy systems, in the context of their technical and environmental evaluation through Life Cycle Assessment. A brief description of the analyzing methods and the tools used to study a particular system or application is presented. The geothermal technologies and the applications of specific systems are discussed in detail, providing their environmental advantages and their technical barriers as well. District and domestic heating systems cover a significant fraction of the geothermal energy potential. The majority of the discussed studies cover the electricity production as the most important application of geothermal energy. The overall conclusion of the current work is that geothermal energy is an extremely viable alternative that, combined with other renewable energy systems, may mitigate the negative effects of the existing energy mix worldwide.

Keywords: geothermal energy systems; life cycle assessment (LCA); thermal energy analysis; environmental and economy profile; environmental impacts of geothermal systems; district heating systems; domestic heating systems; electricity production

Citation: Milousi, M.; Pappas, A.; Vouros, A.P.; Mihalakakou, G.; Souliotis, M.; Papaefthimiou, S. Evaluating the Technical and Environmental Capabilities of Geothermal Systems through Life Cycle Assessment. *Energies* **2022**, *15*, 5673. https://doi.org/10.3390/en15155673

Academic Editor: Renato Somma

Received: 22 June 2022
Accepted: 3 August 2022
Published: 4 August 2022

1. Introduction

We are currently living in a time when the effects of climate change are being keenly felt all over the world. This is a global phenomenon. Not very long ago, in many places such as Greece or Spain, protracted periods of heat (warming) were followed by times of substantial temperature reductions. This pattern of weather is relatively new. In other countries, such as the United Kingdom, France, and Italy, floods have been responsible for millions of euros worth of damage to structures, as well as the loss of human life. The scientific community in every region of the world has collaborated in an effort to better comprehend the phenomenon of climate change and to recommend actions that might be taken to lessen its impacts. Utilizing renewable energy systems for the generation of electricity, as well as for a variety of other purposes such as heating and cooling in the residential or industrial sectors, is an indubitable strategy ensuring the mitigation of the negative consequences of climate change. In addition, geothermal energy, which involves drawing heat from the ground, is a renewable energy source that is appropriate for the above goal. During the last years, a significant amount of research has been put into this field by a wide variety of scientific organizations all over the world. Their ultimate aim is to examine the viability of geothermal energy from as many perspectives as possible.

Taking into account a holistic method, LCA on the one hand allows to display the whole life cycle of a system from the extraction of raw materials, its creation to the production phase and finally to its disposal. On the other hand, it reveals through multiple environmental impact categories, the hot spots that account for the different stages of the cycle defining the environmental identity of the system and consequently driving policy makers on taking final decisions. The aim of the present review is to provide a comprehensive understanding of the possible advantages and multiple uses of geothermal energy systems in the context of their technical and environmental evaluation through Life Cycle Assessment. At first, the authors will discuss the various techniques and existing tools that are used in order to conduct an analysis of a possible geothermal power plant. Continuing, a display of several technologies used to generate power using geothermal resources will take place, and last but not least, the potential applications of geothermal energy will be shown. The contents of the current work are presented through a flowchart in Figure 1.

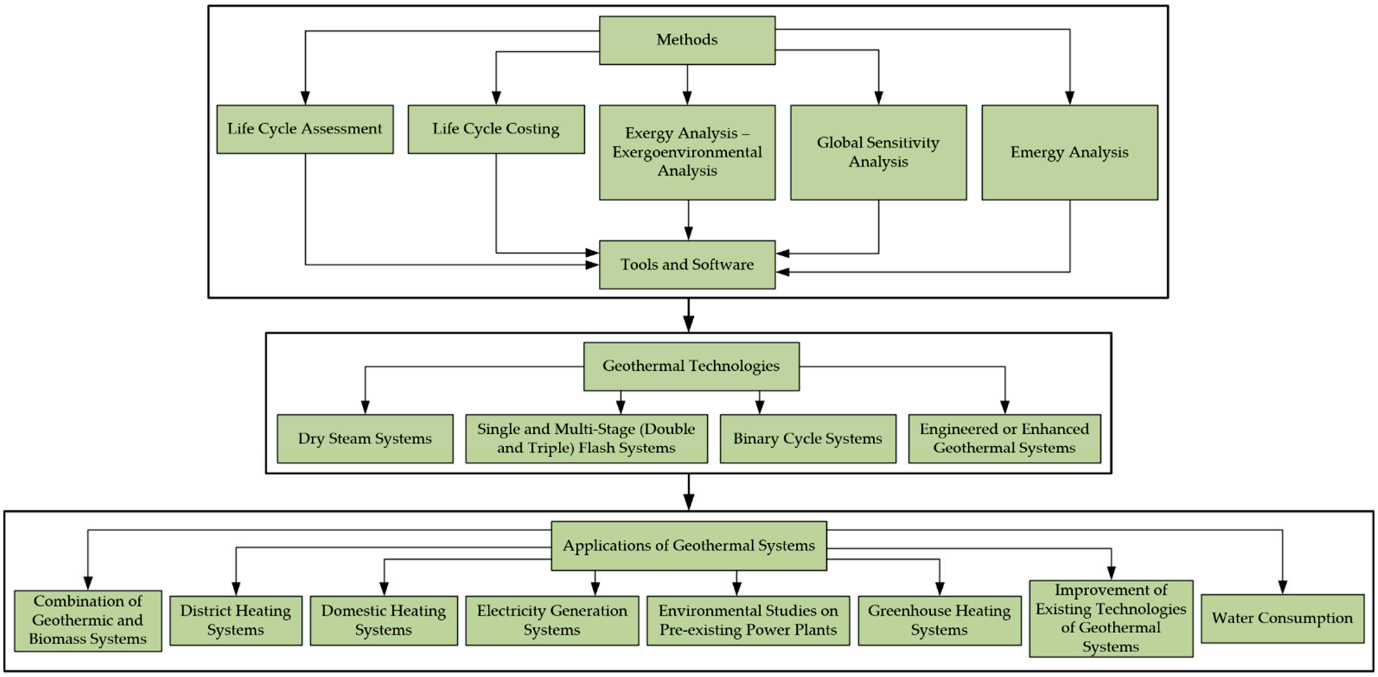

Figure 1. Flowchart indicating the contents of the present review.

2. Methods

A brief description of the analyzing methods used to study a particular system or application is presented. The main tool used in all the examined studies is LCA, often combined with other methods for improving its results.

2.1. Life Cycle Assessment (LCA)

An established method for measuring the total environmental impact of products and services from the acquisition of raw materials to their end-of-life phase (e.g., disposal of product or demolition of a building) is LCA. LCA consists of four distinct stages: goal and scope, life cycle inventory, life cycle impact assessment and the interpretation of the results. The principle of LCA process is the Greenhouse Gas (GHG) emissions of each process individually, in order to form a chain, covering the whole life cycle, even where there is a number of single processes that makes modeling practically impossible, known as the truncation problem. In an Input–Output Life Cycle Assessment (IO-LCA), the truncation problem is not a concern because every sector of a national economy is included in a model and the number of involved sectorial transactions is infinite. In addition, data requirements for IO-LCAs and process LCAs differ greatly. IO-LCAs necessitate data on monetary transactions, whereas process LCAs necessitate information on the material and energy flows of all processes in a production process chain. Even in the most disaggregated models, numerous industries, as well as all the products of a particular industry, are aggregated into each IO sector, causing the IO-LCA to suffer from the aggregation problem. The industrial sectors in IO-LCAs therefore represent the averages of multiple economic sectors, rendering the approach inapplicable for modeling specific items or comparing similar products within the same industry. Other well-known issues with IO-LCAs include the homogeneity and proportionality assumptions. The first one refers to the linear relationship between sector outputs and prices, irrespective of the variety of products within a sector.

The hybrid LCA technique merges the LCA and IO-LCA processes into a single model, combining the benefits of the two classic LCAs while eliminating the truncation issue and alleviating the aggregation issue inherent to IO-LCA modeling. One of the most common uses of hybrid LCA is a tiered hybrid LCA, which consists of an LCA for the emissions of production processes and an IO-LCA model for indirect emissions. By eliminating the truncation problem, the model is more accurate in solving the aggregation problem for the most significant processes when IO-LCA covers the supply chains [1].

2.2. Life Cycle Costing (LCC)

LCC is a beneficial financial method for analyzing and comparing different designs, with a long-term perspective in terms of initial cost increases vs. operational cost benefits. The primary motivation for conducting an LCC analysis is to improve the probability of operational phase cost reductions, even if this requires an increase in the initial expenditure. By adopting an LCC technique, a more comprehensive understanding of the costs incurred over the life cycle of various design solutions is produced. Buildings, for instance, are a long-term investment with long-lasting environmental effects. Keeping this in mind, initial design decisions have a substantial impact on the lifetime of a building. LCC is defined as “a strategy that enables comparative cost assessments over a particular time period, incorporating all important economic aspects, both in terms of initial expenses and future operations costs” [2]. Traditional LCC is primarily commercial and disregards environmental considerations. Earlier research focused on creating LCC methodology for the building sector and embedding it within an environmental framework. Essential decisions and activities to undertake an LCC analysis include: (a) definition and evaluation of alternative strategies, (b) identification of relevant economic criteria, (c) grouping of significant costs, (d) risk assessment performance.

LCC methodology can be criticized; it is based on the estimation and valuation of uncertain future events and outcomes on subjective decided factors. Although LCC is not recognized as a theoretically accurate method, it is beneficial in providing a valuable life cycle outlook on various alternatives indicating strategies and aspects that should be considered where LCC results are presented in a single unit currency. From a user and a consumer perspective, it is valuable to link environmental issues to financial outcomes in a strategic decision-making context. However, LCC methodology is developed only for financial analysis, whilst LCA focuses on environmental impacts [1].

2.3. Exergy Analysis—Exergoenvironmental Analysis

The exergy analysis is a method based on the application of the second law of thermodynamics, depicting the entropy production. The energy system performance is evaluated primarily by the energy balance deduced from the first law of thermodynamics, indicating the energy losses affecting the efficiency of any process, but is insufficient to quantify the energy degradation and quality. The goal of exergy analysis is to discover the magnitudes and locations of energy losses so that changes can be made to an existing system or so that new processes or systems can be developed. Exergy is calculated for all the energy forms identified in a system (kinetic, dynamic, energy flow, enthalpy, etc.). During a process, the change in exergy is equal to the difference between the exergy transferred over the system’s boundaries and the exergy destroyed within the system (or entropy production) [3].

Thermodynamic inefficiencies can be located and measured, and the reasons for them can be determined via exergy analysis. Exergoenvironmental analysis is a suitable combination of exergy analysis and LCA, thus gaining the benefits of both methods. Three stages are involved in exergoenvironmental analysis. The exergy study of the energy conversion system is the initial phase in the process. The second phase entails doing a life cycle assessment (LCA) on each relevant system component and all relevant system input streams. After that, the LCA's environmental impact is attributed to the system's exergy streams [4].

2.4. Global Sensitivity Analysis (GSA)

Due to the inherent diversity of the input parameters among the majority of assumptions and occasionally the partial understanding of the modeled process, the significance of analyzing uncertainties has been emphasized due to Sensitivity Analysis (SA) [5]. In the LCA context, researchers have recently identified GSA as a relevant practice to address several issues such as: (a) studying the combined influence of the different input parameters, (b) assessing the robustness of the results, (c) enhancing the understanding of the structure of the model, (d) ensuring transparency, reliability and credibility of LCA practices, (e) contributing to the decision-making process. Moreover, GSA gives rise to a ranking of input parameters by identifying the key parameters affecting the model output. The identification of these essential characteristics is critical to reducing the complexity of the uncertainty quantification. As a result, attempts to reduce uncertainty can be narrowed down to only a few essential input variables, while the average value of the rest can remain unchanged. Simplifying parameterized LCA models by recognizing the most important variables is also a benefit. Finally, GSAs support the implementation of LCAs and their interpretation, allowing for better decision making [5].

In order to perform GSA in an LCA, a comprehensive multi-step protocol for the integration of sensitivity and uncertainty analysis during the Life Cycle Impact Assessment (LCIA) phase is proposed including: (a) identification of the LCA model (step 1), (b) description of the inputs of the model (step 2), (c) baseline GSA (step 3a), (d) analysis of the influence of the input descriptions (step 3b), (e) overall evaluation (step 4), (f) verification of key input parameters of the LCA model (step 5). Simplified calculation models that express life cycle impacts as a function of only a few key parameters identified through the GSA could be developed; or, eco-designed scenarios could be established using the lower values of the most influential drivers. Moreover, uncertainty propagation could be recalculated considering only the key parameters [5].

2.5. Emergy Analysis (EMA)

It is possible to use the Emergy Analysis (EMA) approach to measure a system's performance at a global level of the biosphere, taking into consideration not only direct environmental inputs (such as solar radiation) but also indirect environmental support (such as wind, rain and geothermal flux). Solar emergy is defined as the total quantity of solar accessible energy (exergy) required to produce a specific product or to support a particular flow. Unit Emergy Value (UEV) or emergy intensity (seJ/J, seJ/g, seJ/€ etc.,) is the emergy required to generate one unit of each product or service that is used to convert matter to energy input flows. There are several main steps that must be taken before an energy plant's EMA can be completed: first, the boundary (spatial and temporal), then the model of the investigated system, then the calculation of matter, energy and cash flows supporting the system, then the conversion into emergy units using suitable UEVs and, finally, the assessment of the total emergy used by the system [6].

Although this technique has gained wide recognition, it is still facing methodological difficulties, especially in accounting procedures, accuracy, reproducibility and completeness. To improve the emergy evaluation, Rugani and Benetto use LCA to clarify the fundamental requirements. It is claimed that emergy evaluations can be improved by (a) technical implementation of algebra in the Life Cycle Inventory (LCI), (b) selection of consistent

UEVs as parameters for LCIA and (c) expansion of the LCI system boundaries to include supporting systems that are usually considered by emergy but not included in the LCA system (e.g., ecosystem services, human labor). LCA should expand its inventory to provide emergy a broader computational framework, whereas emergy rules must be tailored to life cycle structures. Matrix inversion is another way to consistently account for a large number of resource UEVs, according to the LCA method [7].

2.6. Tools and Software of LCA

Life Cycle Assessment tools have been around since the 1990s. With sustainability, climate change and the circular economy being more publicly debated topics, the market for LCA tools itself has also developed. Today, there are many different LCA tools available, and they all serve different purposes. Some still share the academic background of LCA, yet others have been developed to help businesses measure their environmental footprint. Some are focused on specific industries, while others can be used in many different industries. The goals of an LCA can be very different. As a consultant, business owner, sustainability manager, researcher or student, your goals may vary a lot. There are many niche solutions in the LCA world that serve niche markets. For this overview, the above paragraphs focus on the solutions that are most used commercially.

Life Cycle Assessment calculations rely on LCI data. Whilst many tools offer their own databases, most databases are commercially available for a fee. This means that the data must be taken into consideration when calculating the price of an LCA tool. Below, the most commonly used tools/software of LCA are presented:

- *Ecochain* is an environmental intelligence platform. It is focused on company-wide footprints. That means that it is designed to provide high-level steering information to the company and to provide dashboards of the environmental performance. At the same time, Ecochain enables you to create footprints and Environmental Product Declarations (EPDs) for your entire portfolio, all at once. Ecochain is used in a number of different industries, from construction to packaging, food, agriculture and chemicals.
- *openLCA* is the cheapest solution because it is free. openLCA is an open-source LCA solution, which means that it is attractive for anyone starting off in the LCA world without a big budget. However, openLCA also has extensive deep-dive functionality, which makes it useful for users with a more technical background. Taking into account that any LCA tool relies on the databases you want to use, openLCA provides access to many different databases, and many of them are not free.
- *Mobius* is a new solution for product environmental footprints. Mobius is built with product design in mind. That means that the user can model the product and compare different product scenarios in Mobius.
- *SimaPro* has been established for more than 30 years and is probably the most well-known LCA tool in the market. SimaPro is used primarily in the academic field and by experienced LCA consultants. SimaPro is a complex application with many optional add-ons that make it very versatile, and it enables its users to dive deep into the LCA calculations of a product.
- *GaBi*, like SimaPro, has been established since the mid-90s. It is also a very established LCA tool, being used in many industries, especially in its home market, Germany. Just like SimaPro, GaBi is a rather technical solution with many potential add-ons for product development.
- *OneClickLCA* is the only application that is specifically designed for one industry, the construction sector. Because OneClickLCA focuses on one specific industry, it offers many functionalities specifically needed for the construction sector.

3. Geothermal Technologies

In the geothermal business, the vast majority of currently available power generation methods have been developed, taking advantage of typical convective geothermal systems (also referred to as hydrothermal systems). The features of the geothermal resource (fluid and reservoir) to be exploited have a significant impact on the selection process for the best geothermal power generation technology (i.e., geological, chemical, physical and thermodynamic properties). In particular, there are three types of geothermal fields:

1. Vapor dominated systems with temperatures greater than 240 °C;
2. Liquid (or hot water) dominated systems with temperatures up to 350 °C;
3. Petro-thermal or solidified hot dry rock resources with temperatures up to 650 °C.

Convective hydrothermal systems (groups (1) and (2)) are commercially exploited around the world, while group (3) refers to the exploitation of the Hot Dry Rock (HDR) or Enhanced Geothermal Systems (EGS). The geothermal systems can be exploited using a variety of technologies, depending on the reservoir's characteristics (e.g., geological, geophysical, geochemical, physicochemical, thermodynamic among others). This has been accomplished through the commercial and successful application of three types of mature technologies: dry steam, flash (single, double and triple) and binary cycle power plants (Figure 2). A quick rundown of several emerging technologies follows [8].

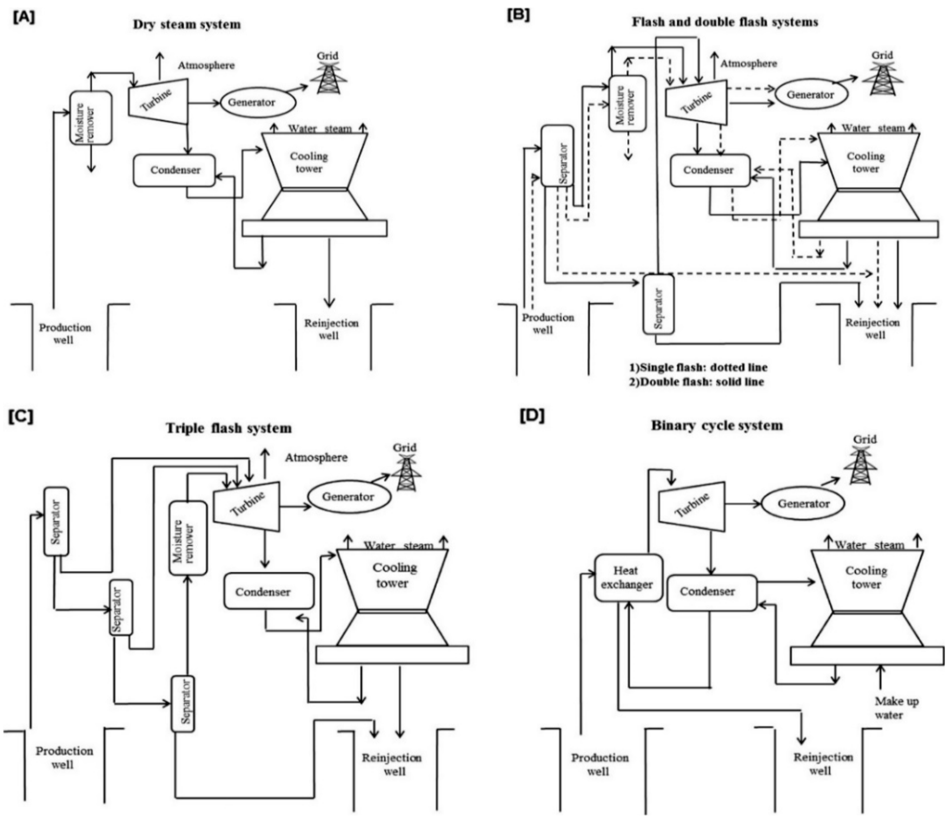

Figure 2. Simplified flow diagram for dry steam systems (**A**), single and double flash systems (**B**), triple flash system (**C**) and binary-cycle (**D**) geothermal power plant [8].

3.1. Dry Steam Systems

The earth's gradient temperature leads to reservoirs of high temperatures (>240 °C) in certain privileged locations, such as the geysers in California and Larderello in Italy. The steam turbine is used in alternating the reservoir vapor into mechanical energy, then sending it to a generator, where it is converted into electricity and transmitted to the grid (Figure 2A). Because of its simple plant design, dry steam is the cheapest method of generating geothermal energy. In addition, a gas extraction system can be included in the plant setup if the chemical composition of the steam is water steam (>90% wt. of steam) and Non-Condensable Gases (NCG) (10% wt. of steam). Many other gases can be removed with this technique, such as H_2S, CO_2, H_2S-nitrogen trioxide, NH_3 and other trace gases (e.g., He, H_2, Ar, N_2, CH_4 and CO). Due to the potential corrosive effects of the NCG in the steam stream, additional changes are occasionally necessary to avoid a decrease in the turbine's efficiency in geothermal power generation. As a result of these two causes, the power plant's output is expected to fall, which could result in lower profits [8].

3.2. Single and Multi-Stage (Double and Triple) Flash Systems

When the geothermal fluid in the reservoir is a mixture of liquid and vapor, the power generating process is known as flash. Single-, double- and triple-flash systems can be used in the separation process, depending on the thermodynamic mixture's characteristics. A single-flash setup is commonly utilized when the mixture temperature exceeds 210 °C (dotted lines in Figure 2B). By applying a cyclonic separator (Webre type), the geothermal fluid is recovered from the production well and delivered to separate the liquid and vapor phases of the combination. An expansion steam turbine and a generator complete the process of removing the primary vapor from the separator. Condensed cooling water from the expansion turbine's steam condenser flows into an injection well, where the leftover liquid phase mixture (known as brine) can be reined in [8].

Adding a second separation stage (known as double-flash) to this technique improves its efficiency (solid lines in Figure 2B). A single-flash cycle of low-pressure steam is separated using this method. A low-pressure turbine or an appropriate stage of the main turbine are the two possible destinations for the secondary low-pressure steam (with dual-pressure and dual-admission specifications). In case the amount of NCG in the geothermal fluid is very high, an integration of an NCG abatement device may be necessary, despite the fact that this is merely an overview of the process in general. Both process efficiency and power generation can be increased by 35 and 20%, respectively, by using double-flash power plants [8].

Triple-flash power plants are possible in this context, where a third separation step can be incorporated into the plant setup (Figure 2C). Brine from the double-flash cycle, as well as NCG from the geothermal fluid, is used in this procedure to extract the maximum amount of energy possible from the brine. Some geothermal fields in the United States, New Zealand and Turkey currently make use of this technology [8]. Concluding, 63% of the world's installed geothermal power capacity comes from single- and double-flash conversion technology, while 2% comes from triple-flash power plants.

3.3. Binary Cycle Systems

Referring to temperatures lower than 200 °C, a binary-cycle power production system is applied, which accounts for 12% of the world's capacity. The geo fluid cannot be utilized directly in this system as it can in the other power generation technologies that have been discussed so far. This is due to the inadequate vapor generation caused by the geo fluid's low temperature. A thermodynamic Organic Rankine Cycle (ORC) or a Kalina cycle can be used to evaporate working fluids with lower boiling points such as isobutane, n-isopropyl and pentane, which can then be used to generate electricity. In a heat exchanger, an organic vapor is generated and transferred to a turbo generator system for generating power (Figure 2D). Flowing steam from the turbine is condensed in a condenser and the brine is returned to the heat exchanger [8].

3.4. Engineered or Enhanced Geothermal Systems (EGS)

As with binary cycle plants, it is theoretically possible to generate electricity by utilizing EGS. Deep subsurface reservoirs with low permeability and/or insufficient water supply can be exploited using these technologies (specifically, hot dry rock, hot wet rock and hot fractured rock resources) [8].

An artificial reservoir must be created by either opening existing fractures in the rock or developing new ones in order to take advantage of such geothermal systems' greater rock permeability. For the most part, heat energy is extracted from heated fractured rock (or artificial reservoirs) by injecting water (or another appropriate fluid such as CO_2) into the rock to drive a vigorous heat exchange and extract as much of the rock's available energy as possible. Geothermal fluid loops are sometimes created by circulating fluid that is already present in the rock formations. Hot fluid from the well is retrieved and pumped to a power plant on the surface to create electricity. Despite the potential of the EGS, it is not widely used in the commercial market. This can be explained by the fact that this technology is still in its infancy. Several pilot projects in Australia, the United States, Italy, France, Germany, Switzerland, Japan and El Salvador have proved the viability of using these systems at depths ranging from 3 to 10 km, thanks to recent technological developments [8].

4. Applications of Geothermal Systems

4.1. Combination of Geothermic and Biomass Systems

The potential benefits of the combination of deep geothermal energy and woody biomass for the heat production, electricity and biofuels were investigated, as energy consumption and energy-related GHG emissions of urban systems are increased. According to the LCA approach employed in the case study, the overall yearly cost of running the city was a primary target, while also measuring the environmental effect. Initially, all pathways were evaluated individually for each of the two technological options. When all conceivable combinations between geothermal and biomass solutions were studied, hybrid systems with fewer costs and environmental consequences were found. Furthermore, new hybrid systems that utilize excess geothermal heat to improve biomass conversion processes were discovered [9].

Another application of the combination of geothermal and biomass scheme was accomplished in Italy. This case study conducted a life cycle analysis of a commercially available 150 kW co generative ORC system attached with a biomass boiler to assess its environmental impacts. While the used software was SimaPro, the data were gathered from the five years' activity of the plant. The ORC module was a commercially available Combined Heat and Power (CHP) unit, adopting as working means a mix of hydrocarbons. In addition, the plant was driven by woodchip with values: 40%, 24%, 20%, 14% and 2% of birch, spruce, pine, beech and oak wood, respectively. Lastly, the obtained findings showed that the biomass production and the leaks of the organic liquid impacted by 71% and 19% of the total environmental impact, respectively [10].

4.2. District Heating Systems

In this section, different studies examine all possible ways to heat a very large number of households using geothermal energy. The problem of heating a large residential area, more specifically a town center with a population of 25,000 habitants, has been examined. An energy and exergy analysis combined with LCC coupled with Net Present Value (NPV) analysis were applied by comparing different methods and ways to address the problem. According to the designing parameters of temperature and the pressure of twelve alternative working fluids, 4686 designs were performed, obtaining the optimum scenario [11].

An exergoenvironmental analysis of the Afyon Geothermal District Heating System (GDHS) has been conducted, examining its environmental impact. An estimated 10,000 residencies may be heated by the Afyon GDHS' total heating capability of 102 MW. Exergy losses of 12%, exergy destruction of 18% and approximately 0.0004% of the environmental effect were found to be attributable to system components, according to the study results. Priority should be directed to improving heat exchangers and reducing their thermodynamic inefficiencies, according to the findings [12].

On a more theoretical perspective, an effort focusing on the life cycle design of a district energy system for a new residential development in Finland has been accomplished. By combining LCC and LCA, a Life Cycle Management (LCM) perspective is portrayed to support decision making on a long-term basis. Several energy design options were compared: (a) district heating (reference design), (b) district heating with building integrated PhotoVoltaic (PV) panels, (c) Ground Source Heat Pump (GSHP) and (d) GSHP with building-integrated photovoltaic panels. The authors identified that the design option with the highest initial investment was (d), being the most viable from a life cycle perspective by further strengthening the connection between cost savings and carbon emissions reduction in a life cycle context. Furthermore, their study was aiming to portray the mutual support between economic and environmental benefits in urban residential development, rather than evaluating the sustainability of a technical energy design solution in the long run. They concluded that geothermal energy is a rather viable option for applications such as district heating, even though the initial investment costs and improvements should be considered [1].

Under investigation was the scenario where a plant was running in CHP mode for 3000 h/yr, corresponding to a heat generation of 33,750 MWh in its lifetime. Particularly, the ORC was assumed to work with a regenerative sub-critical cycle, where the valuable heat was provided as hot water at around 80 °C [10].

On the other hand, Douziech et al., [13] conducted a comparative LCA on the production of 1 kWhth among the Rittershoffen geothermal heat plant in France and the produced heat from natural gas in Europe. Their article showed that, in climate change and resource-use fossil categories, the Rittershoffen plant impacted less than the average heat production. Moreover, LCA results highlighted that in the operation and maintenance phases, the hot spot was the electricity production for numerous impact categories.

4.3. Domestic Heating Systems

In this part, different aspects of domestic heating are investigated. Domestic heating is referred to a building, regardless of its use and size. Although geothermal energy is a renewable source, it is not free of GHG emissions, where this factor can be vastly attributed to the construction phase of the plant.

A major aspect is the comparison of different technologies in terms of environmental impacts and economic criteria, targeting the most appropriate. When combined with LCA, the prospective energy, exergetic and environmental performance of three regularly used residential building heating systems was investigated in Turkey. In more detail, a conventional coal boiler, a condensing natural gas boiler and a Ground Source Heat Pump (GSHP) were compared. From a thermodynamic perspective, the GSHP was an efficient heating system for the given application in terms of the coefficient of performance and exergy efficiency. No matter how it is compared with other systems, LCA results showed that the greatest impacts came from GSHP's environmental effect: (a) borehole drilling, polyethylene pipes and copper pipelines, all of which are used during installation, and (b) the refrigerant top-up in the maintenance stage. According to the study, condensing gas boilers were the most cost-effective and ecologically friendly option for heating applications in Turkish buildings at that time [4].

Geothermal energy-based heating systems require indispensable connection and utilization of the existing power grid. This is of main concern, since in many countries (e.g., Greece, USA) the leading resource used for electricity production is coal. That means that a geothermal system will not only have GHG emissions in its construction phase but also in its operational phase. An interesting study comparing the life cycle implications of three heating plant systems that differ in their energy source and system type has been implemented. An electric heat pump, an absorption water–water heat pump and a natural gas-fired boiler were studied in further depth using Eco-indicator ′99 as the LCA approach. The Ecoinvent 2.0 LCI database was applied to gather data on the extraction of raw materials and fuels, the fabrication of heating equipment and their transportation. Single score, damage category and effect category indicators were studied by the researchers. All calculations for characterization, normalization and weighting phases were simulated by SimaPro 7.3.2 throughout the complete system's life cycle. In that investigation, it was obvious that heating plants employing a low temperature geothermal source had a lower eco-indicator than a gas boiler unit did; because of this, the comparison between absorption and electrical heat pumps revealed that the former had a lesser environmental effect. Accordingly, despite a high eco-indicator, it was revealed that the gas boiler was the least harmful to human health as Coefficient of Performance (COP) and power generation profiles dictated the environmental effect of the electrical heat pump. The greater the COP, the lower the power used and the emissions. Human health suffered significantly in Poland, where about 90% of the country's power is generated from coal [14].

Research into shallow geothermal systems, such as open and closed Geothermal Heat Pump (GHP) systems, had resulted in an efficient and renewable energy technology for cooling and heating buildings and other structures. By utilizing a cutting-edge LCA, the researchers were able to comprehensively assess the environmental costs and advantages of using shallow geothermal systems, including net energy consumption and GHG reductions due to GHP operation. Figure 3 shows the relative contributions of such GSHP systems to environmental degradation in terms of resource depletion (34%), human health (43%) and ecosystem quality (23%), as shown by the LCIA technique (ReCiPe 2008). Out of the overall number of environmental damages, 55.4% may be attributed to climate change. Additionally, LCIA found that the heat pump refrigerant, heat pump manufacturing, transport, heat carrier liquid and the borehole and Borehole Heat Exchanger (BHE) were all major contributors to the environmental burden of GSHP systems. When utilizing the continental European power mix of 0.599 kgCO_2eq/kWh, an average life cycle of 20 years was determined to have an average of 63 tCO_2eq. However, the CO2eq reductions for Europe range from 31% to 88 % when compared with traditional heating systems such as oil-fired boilers and gas furnaces [15].

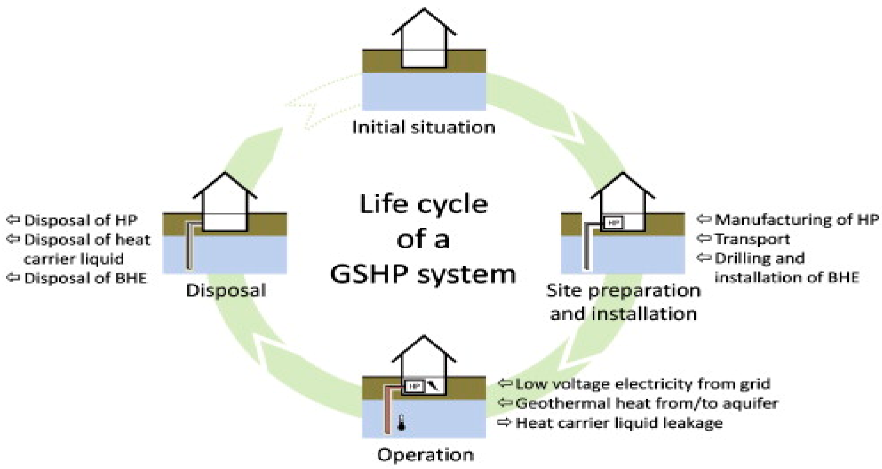

Figure 3. Life cycle stages of a GSHP system and the main flows of unit processes contributing to the whole life cycle [15].

A new apartment building in Switzerland performed a comparative LCA between a solar thermal system, an Air-Source Heat Pump (ASHP), a natural gas furnace, an oil furnace and a wood-pellet stove. The solar thermal system showed potential benefits over all other systems in terms of reductions in bought primary energy (from 84% to 93%) and reductions in GHG emissions, according to a variety of life cycle scenarios (from 59% to 97%). Due to intensive industrial operations and the specific metals used in production, the solar thermal system was found to have a larger demand for resources, which in proportion to the natural gas system, may be almost 38. Although the heat pump systems had similar potential human health implications, they were more advantageous than the fossil and biomass driven systems in this regard. In Figure 4, it is evident that most GHG emissions, related to GSHP, were from electricity required for the system operation. Additionally, the GSHP's infrastructure impacts were lower compared with the solar systems' and greater than those of the conventional ones. This verifies the electricity mix problem: a cleaner electricity mix means a cleaner operation phase of GSHP systems [16].

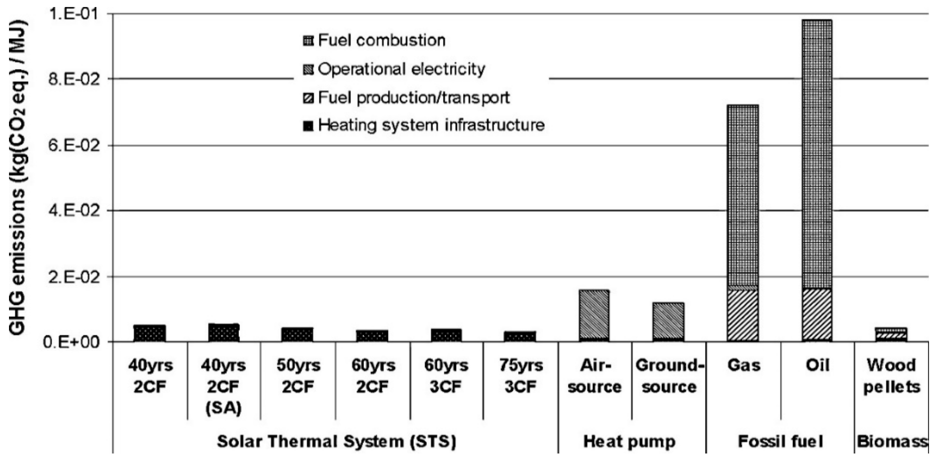

Figure 4. Life cycle GHG emissions of each heating system [16].

The technical and environmental performance of a GSHP using LCA was investigated for the Pylaia Town Hall in Thessaloniki, Greece. A ground heat exchanger installation was assessed for its impact on the environment using an LCA study. The researchers focused on the GSHP system throughout its life cycle, from manufacturing and transportation to installation and operation, and recorded energy consumption and air emissions. The manufacturing of raw materials including copper, plastic, steel, aluminum and rubber was part of the system's border. Heat pumps and pipes were transported as well as the GSHP system was operated, and ultimately the assembly was completed. Moreover, the environmental impact categories considered were those of greenhouse effect, ozone depletion, acidification, eutrophication, carcinogenesis, winter smog and heavy metals. The system analysis indicated that 73% and 14.54% of the emissions were attributed to acidification and greenhouse effect, respectively, while SO_2 was produced by the use of lignite (coal) in the Hellenic electric power production, resulting as the main cause for the acidification (Figure 5).

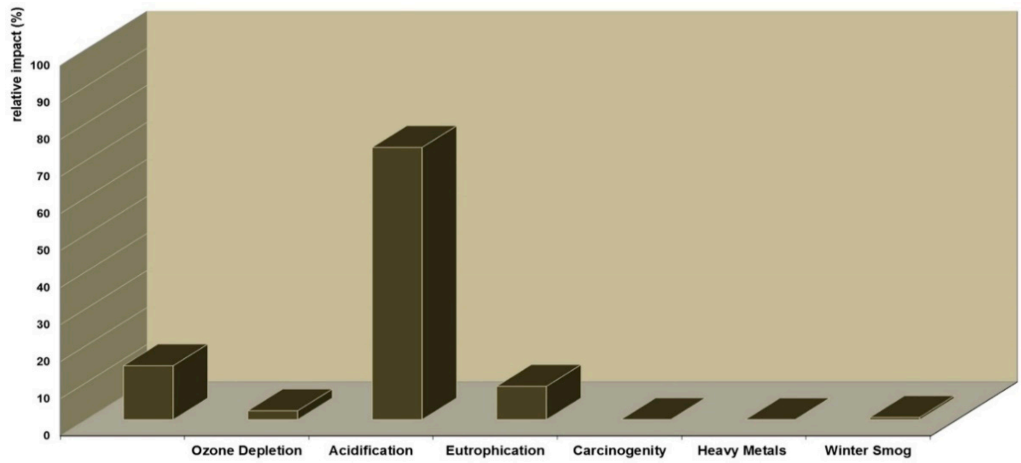

Figure 5. Environmental impact assessment of each category during GSHP's system lifespan [17].

In this view, the authors assumed that when increasing the renewable energy fraction in the electricity power mix of Greece, the environmental impacts of the geothermal systems would definitely improve [17].

The mitigation of the effects of the existing power grid on the environmental efficiency of geothermal systems can be achieved by combining them with other renewable energy sources such as PV panels or solar heating systems. The European Centre for Public Law in Legraina, Greece used a hybrid solar and geothermal heating and cooling system, according to the results of research. A saline groundwater well, a water storage tank for 6 hours' autonomy, an inverter that regulated geothermal flow, a heat exchanger, two electrical water source heat pumps set in cascade, fan coils, air handling units and solar air collectors for air preheating in winter were considered. Moreover, the building hostel's hot water supply was achieved by solar water heaters. Solar energy's ability to contribute to the building's energy balance was demonstrated during winter measurements, boosting the overall proportion of renewable energy consumption [18].

By examining small-scale multi-generation systems, CHP, Combined Cooling, Heating, and Power (CCHP) as well as traditional systems with sixteen Heating/Cooling Energy Generation Systems (H/C-EGSs), the case of technological combination was further strengthened. A comparison approach for evaluating the energy performance of buildings under the European Building Performance Directive (EBPD) was utilized. Local and global cost optimums for an office building in Helsinki, Finland were calculated for each of the H/C-EGS. A total of 144 building combinations and 2304 examples of H/C-EGSs were included in the proposed energy-saving measures. According to the findings, the GSHP with free ground cooling was the most cost-effective option available globally. Only with great overall efficiency and a low power-to-heat ratio might biomass-based CHPs be economically viable due to low investment and operational costs. There were no economic or environmental advantages to biomass-based CCHPs over biomass-based CHPs due to the considerable rise in both investment and operational expenses. Using coal-fired CHPs, which had significant operating costs, was the most inefficient and ecologically damaging option. The net zero energy office building was created by extending the cost-optimal solutions with a PV solar panel system [19].

An alternative way for the reduction of the energy consumption of large public buildings in Beijing by comparing three different air-conditioning systems has been examined. ASHP coupled with GSHP and GSHPs with solar assistance were all considered. Using DeST modeling software, the building load was calculated and economic indicators such as initial investment, LCC, operating cost, payback period, energy saving rate and cooling and heating costs per hour were evaluated. Results implied that a solar-assisted GSHP 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 was higher, it had a payback period of less than 3 years compared with the air-source heat pump system [20].

On the other hand, Bartolini et al., [21] presented a techno-economic and environmental analysis of four different weight concentration fluids: propylene glycol at 25% and 33%, calcium chloride at 20% and pure water. The outcomes revealed that the use of pure water as a heat carrier fluid was appropriate for cooling buildings (i.e., in Seville, Lisbon and well-insulated buildings in Bologna), but, for heating-dominated buildings, this choice led to a remarkable increase in the length of needed BHE. However, OpenLCA software calculated the carbon footprint of the BHE during the installation phase, showing an amount 25.61 kgCO_2eq/m of BHE. Regarding the carbon footprint of other fluids: 4.67 and 1.02 kgCO_2eq/kg emitted for the propylene glycol and the calcium chloride, respectively, while the water's carbon footprint was negligible.

In the spirit of economic and environmental efficiency, Huang and Mauerhofer stated that, apart from the energy saving measures adopted by governments worldwide due to the greenhouse effect, environmental and social impacts should also be considered, ensuring that these measures can also meet sustainable development requirements. An advanced sustainability evaluation method is based on the life cycle theory designed in that study. Case studies were used to evaluate this concept, since GSHP is a renewable technology widely used in China's building sector. The energy usage of the GSHP cases studied was found to be 40.2% lower than that of a conventional air conditioning system. Global warming, acidification and eutrophication in the manufacturing process and soil temperature change in the operation phase were shown to be the primary environmental consequences of GSHP [22]. Aiming at the public buildings sector, the environmental impacts of a GHP application in a university building were studied. A process-based hybrid LCI modeling technique was utilized to provide a full system boundary for footprint accounting, offering unique insights into the design and functioning of the researched technology [23].

However, Heating, Ventilation and Air Conditioning (HVAC) systems were examined in the Winnebago Reservation in northeastern Nebraska as part of an LCC investigation. Rooftop gas heat and direct expansion (DX) cooling units (air-cooled condensers) were one option, as were air-source heat pumps and geothermal heat pumps (GHPs). Building energy modeling software was implemented to evaluate the heating and cooling demands. An estimated 264,000 Btu/h of cooling capacity and 178,000 Btu/h of heating capacity were calculated. Heat demand for the building was 246 kBtu and cooling demand for the building was 479 kBtu, both all year long. The NPV of 30 years of an LCC was calculated for each option in order to compare them. There were no significant differences in LCCs between the GHP and the traditional systems in terms of their NPV, which was determined to be around 18% lower. Installing the GHP system was a little more expensive, but the running and maintenance expenses were far cheaper than with traditional systems. GHG emissions may be reduced by 15 tCO_2eq and 33 tCO_2eq per year by using a GHP system instead of a rooftop gas heat unit or an air-source heat pump, according to their GHG study [24].

GHPS economic viability was further affected by the Seasonal Coefficient of Performance (SCOP), as described by Junghans. Air-to-air GHPSs were studied on their economic and environmental viability, and the author established the importance of the envelope's insulation level in determining whether heat pump systems were economically and environmentally viable. A geothermal water-to-air heat pump and an exterior air-to-air heat pump were evaluated for their economic and environmental viability in the context of their local climate and building insulation. Increased insulation levels were shown to have a significant impact on the SCOP, which in turn affects the heat pump system's economic and environmental viability. SCOP values for heat pump systems were shown to be climatic and building insulation dependent [25].

4.4. Electricity Generation Systems

Electricity production is one of the most important applications of geothermal energy. Coal power plants that form the majority of electricity generation contribute mainly to the GHG effect worldwide. In this view, attention is paid to more environmentally friendly and resource-independent energy generation technologies. Geothermal energy is a promising candidate as a renewable form of energy. In this part of the paper, the potential of clean electricity production applying geothermal energy is investigated.

Eight important variables have been used to evaluate the long-term viability of power generating. Price, GHG, efficiency, land usage, water consumption and social implications on a per kWh basis were examined for eight alternative ways of energy generation: solar, wind, hydro, geothermal, biomass, natural gas and nuclear power. Coal and nuclear power had the lowest average prices, whereas hydro and geothermal power had the lowest feasible prices, according to the authors. The average and total costs of PVs were the highest of all. The most efficient sources of energy were hydropower and PV, with hydropower coming out on top. Coal, as predicted, emitted the most GHGs of any fossil fuel. Biomass energy crops had the largest water needs, even if in hydropower the vast majority of water was not used but rather recycled back into the stream. Instead of biomass, nuclear, solar and wind power used the least amount of land. In reference to social impacts, wind and PV were the most sustainable, while on the contrary all thermal technologies were the least sustainable [26].

Several sustainability indicators have been used to evaluate renewable electricity generation technologies (PV, wind, hydro and geothermal), including the cost of generated electricity, GHG emissions over the course of the technology's entire life cycle, the availability of renewable energy sources, the efficiency of energy conversion, land requirements, water consumption and social implications. Wind power was shown to be the most sustainable energy source overall, followed by hydropower, solar power and finally geothermal energy. On the one hand, wind power contributed the lowest GHG emissions, having the most favorable social impacts compared with other technologies, but on the other hand required bigger land and capital costs. Indicators were examined separately, leading to remarkable statements:

As far as the price of electricity generation is concerned, geothermal energy and wind energy had the same average cost with geothermal energy exhibiting a lower range in price variations.

- Geothermal power plants' average emissions were found to be reasonable at 170 g/kWh by the authors' calculations, although the range covered all potential values for gas emissions and could be as high as a low-emitting coal-fueled power station. However, technological decisions had the greatest effect on geothermal emissions. Emissions would increase if the waste gases, which included more than 90% CO_2 by weight, were discharged directly into the atmosphere. However, most contemporary plants either reinject the CO_2 or trap it to make dry ice.
- Although the use of geothermal energy is constrained to areas where the necessary geothermal resource is already in place, there are many such areas in the globe (24 countries, with a total operational potential of 57 TWh/year). The attraction of geothermal energy is that it can be used around-the-clock to supply reliable "base load" electricity. Even though the extraction rates of the power generation will always be higher than refresh rates, the latter may be made up for reinjection, which greatly increases the lifespan of geothermal installations. If someone wants to avoid a short circuit, then they need to be selective about where they perform the reinjection. Seismic activity was improved by reinjection, but only in terms of its frequency; its intensity remained the same.
- Geothermal power had the lowest efficiency, far less than other technologies.
- The surface area occupied by geothermal power plants was little, since the bulk of the infrastructure was buried beneath the earth. The entire geothermal field was factored into the footprint analysis to account for the possibility of ground subsidence above the field. The average footprint of geothermal energy was between 18 km^2/TWh and 74 km^2/TWh.
- Geothermal energy plants use a lot of water for cooling purposes. Non-evaporative cooling, pressure management, closed-loop recirculating cycles as well as the complete reinjection of filthy and offensive-smelling wastewater are all methods that might be used to reduce water usage. When compared with thermal power plants, geothermal facilities' wastewater output was higher, at up to 300 kg/kWh.
- Geothermal adversely affects communities when wastes were not properly managed as geothermal process waters are offensive smelling from hydrogen sulfide and are contaminated with ammonia, mercury, radon, arsenic and boron. These issues may be reduced if geothermal fluids were treated in a closed-loop system before being re-injected.

From the above results mentioned it is easily concluded that geothermal energy may not be as environmentally friendly as one would think, but it has certain advantages as compared with others, such as relatively small land use, the ability to provide base load power on a 24-h basis and its independence from weather conditions [27].

The combined LCA and EMA analysis of a 20 MW dry steam geothermal power plant in the Tuscany region, Italy highlighted the environmental implications of geothermal power generation. The plant relied mostly on renewable resources found in the area, with some support from nonrenewable resources. However, carbon dioxide, hydrogen sulfide, mercury, arsenic and other pollutants were produced during direct consumption of the geothermal fluid, greatly contributing to climate change, acidification potential, eutrophication potential, human toxicity and photochemical oxidation. Despite the thoughts of some locals, the study found that geothermal power plants are generally safe for the environment. However, there are some parts and processes that might use some modifications [6].

By stressing the direct and indirect contribution in terms of natural capital and ecosystem services to the power plant construction and operation, Emergy Synthesis offers a supplementary perspective to LCA. The geothermal power plant's environmental effects were also compared with those of other types of power plants, such as those that use renewable energy and fossil fuels. The geothermal plant had a release of 248 gCO_2eq/kWh, which was lower than fossil-fuel-based power plants, but still higher than renewable technologies as solar PV and hydropower facilities. Furthermore, the amount of SO_2eq emitted (3.37 g/kWh) was similar to that of power plants that used fossil fuels. According to the findings, further research into other geothermal solutions (such as binary systems) is required in order to minimize negative environmental effects without sacrificing productivity gains [6].

In the spirit of comparing different renewable energy options, more than a hundred distinct case studies, including solar (concentrated solar power, PV), wind, hydro and geothermal energy, were evaluated by Asdrubali et al., [28]. A more accurate comparison of the available renewable technologies was possible, supported by the extensive data collecting, normalization and harmonization. Wind power was shown to have the least CO_2eq emissions and the least embodied energy, whereas geothermal and PV power had the greatest overall environmental effect values and the largest ranges of variability. Concentrating Solar Power (CSP) was rated as having a moderate environmental effect, ranking higher than PV, geothermal and hydropower facilities in nearly all impact categories. However, when the harmonized results were compared with those from traditional power systems (such as hard coal or a natural gas power station), the examination of all effect categories showed that renewable energy technologies provided considerable environmental advantages. However, it was evident that geothermal energy was not as environmentally beneficial as other renewable energy options, but it had a great variability and results cleaner than fossil-fuel-based energy options.

On the other hand, Stoppato and Benato [10] showed that in the studied 150 kW ORC system attached with a biomass boiler, the corresponding electricity production was 11,160 MWh during the entire life of the plant. For GWP, a noticeably lower amount of 85.2 gCO_2eq/kWh was emitted compared with approximately 500 gCO_2eq/kWh coming from the production of fossil fuels for the Italian fossil mix. Similarly, the CED method resulted that the unit used approximately 7.3 kWh and 0.24 kWh of biomass and fossil fuels, respectively, for each kWh of electricity, mostly due to the requirement of diesel for biomass transportation, chipping and harvesting.

In order to highlight the impacts associated with electricity generation, a comparison between renewable and conventional power generating technologies from an LCA perspective was conducted. To this end, the GREET model was used to conduct a life cycle energy and GHG emissions study for several geothermal power producing systems (Table 1), taking into account Argonne National Laboratory's expanded GHGs, regulated emissions and energy consumption in transportation. The researchers extended the GREET model to include power plant building for coal, natural gas combined cycle, nuclear, hydropower, wind, solar and biomass, and performed an identical study for these systems. It was found that steel and concrete were used less in traditional power plants than in renewable energy systems (see Figure 6). Enhanced geothermal and hydrothermal binaries needed more of these resources per MW than other renewable power generating technologies, with the exception of the concrete requirements for gravity dam hydropower. When considering both plant capacity and lifetime, energy and GHG ratios per kWh of power generation have been determined. In general, the infrastructure costs for renewable energy plants were greater per unit of energy produced than those for conventional plants. Construction plants followed a pattern with similar increases in GHG emissions per kWh of energy generation. Although certain renewable systems might produce GHG emissions during plant operation, these emissions were far lower than those produced by fossil fuel thermoelectric systems. The GHG emissions from binary geothermal systems were negligible in comparison to those from fossil fuels. The GREET model found that fossil thermal plants used nearly an order of magnitude more fossil energy and produced about twice as many GHG emissions per kWh of electricity as renewable power sources, including geothermal power [29].

Table 1. Parameter values for the four investigated geothermal power plant scenarios [29].

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 (%/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 (km)	4–6	4–6	Less than 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 ft	Submersible 10,000 ft	Lineshaft/Submersible	None
Distance between Wells (m)	600–1000	600–1000	800–1600	800–1600
Location of Plant to Wells	Central	Central	Central	Central
Geographic Location	Southwestern US	Southwestern US	Southwestern US	Southwestern US
Plant Lifetime (yr)	30	30	30	30

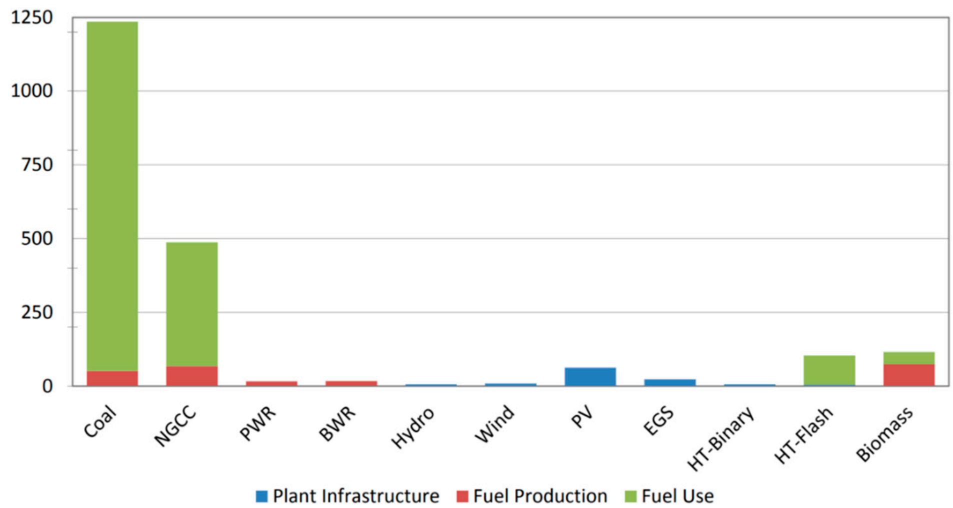

Figure 6. GHG emissions (gCO_2eq/kWh) by life cycle stage for various power-generating technologies as determined in GREET 2.7 [29].

Concentrated solar power, integrated gasification combined cycle and fossil/renewable (termed hybrid) geothermal technology, in the form of co-produced gas and electric power plants from Geo Pressured Gas and Electric (GPGE) sites, were all introduced by the previous authors in a later article. In the latter example, they examined two scenarios: gas and electricity export and solely electricity export. Additionally analyzed as a function of well depth were the cement, steel and diesel fuel needs for drilling geothermal wells. The impact of construction activities on new plant construction was also calculated. The research findings were consistent with those of the prior study. Construction and components of fossil combustion-based power plants needed the fewest raw materials. Hydrothermal flash power and biomass-based combustion power were found to have the lowest GHG emissions, whereas traditional fossil-based power systems had the highest [30].

An LCA study on GHG emissions and fossil-energy use associated with geothermal electricity production was accomplished [31]. Hydrothermal flash and dry steam facilities operating GHG emissions were the subject of this study. Focusing on understanding GHG emissions caused by geothermal power plant operations, the analysis included findings for both the plant and the fuel cycle components of the overall life cycle. Only flash and dry-steam geothermal power facilities produced significantly high levels of such pollutants (zero values for binary plants). It was possible that the latter plants' GHG emissions would be anywhere from nearly null to more than 400 g/kWh. Values for fossil energy consumption and GHG emissions during the whole life cycle were calculated and then compared across a variety of fossil, nuclear and renewable power sources. GHG emissions of geothermal power plants were comparable with other renewable energy options and much lower than those of fossil-fuel-based options, except nuclear power plants. It can be obtained that geothermal energy had the potential to bring better environmental results if certain requirements are met.

EGS, hydrothermal binary systems, hydrothermal flash systems and geo-pressured geothermal systems were all compared in a separate research, with their possible implications and influencing variables highlighted. 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 co-produces natural gas were all considered and analyzed. Finally, the impacts associated with these power plant scenarios were compared with those from other electricity generating technologies. The results displayed that geothermal energy was capable of low carbon emissions, which were primarily attributed to the construction phase, similar to most renewable energy technologies [32].

Producing power from geothermal sources is constrained by the need for a constant supply of hot water or steam. High-enthalpy reservoir locations, where power plants can operate efficiently, are rather uncommon. Low-temperature resources, present over extensive geological regions, constitute a massive as-yet-untapped geothermal potential. Therefore, in the recent past, efforts have been made to investigate and develop suitable techniques for capturing this energy and transforming it into electrical power, resulting in the EGS. The basic idea was to use hydraulic stimulation at great depth (more than 2.5 km) in very hot crystalline rocks (about 150–200 °C) to improve and/or generate a geothermal resource. In this view, it was very important to understand the opportunities that this new technology offered and to explore possible ways that it could be advantageous [33].

An analysis on the environmental performances from an LCA perspective of the above-mentioned systems (i.e., EGS) of ten significant design options located in central Europe has been presented [33]. Each of these configurations was assigned a unique set of technical criteria, one of which was the potential for induced seismicity. Compared with conventional power plants, the results suggested that the consequences of EGS were on a par with those of other renewable energy sources. In addition, they could provide affordable base load electricity, making them an attractive choice for the energy systems of the future. Recommendations on the 10 scenarios' environmental appropriateness were produced by comparing them. Additionally, the risk of induced seismicity was shown to be a crucial differentiating factor, with its importance growing in direct proportion to the environmental gain. The five-impact-category model was helpful for getting an overview of the environmental restrictions of EGS installations, and it might be used again to assess similar installations using alternative design approaches. One of the most important findings, corroborated by several studies, was that drilling had the greatest environmental impact of any step in the production of geothermal energy. Connecting to the national grid or some alternative energy source during this stage might significantly enhance their environmental performance [33].

An intriguing study has been given on the topic of EGSs used for both power generating and district heating. The examined topics were the public's adoption of geothermal energy, along with its parameters of economic viability, the thermodynamic efficiency in resource utilization and its life cycle environmental impacts. Utilizing a multi-period approach, it accounted for seasonal changes in district heating demand through the use of an LCA and multi-objective optimization approaches, in addition to process design and process integration. Single- and double-flash systems, as well as ORCs and Kalina cycles, were among the several conversion methodologies studied. The optimal configuration for the EGS was calculated for a range of depths, from 3000 to 10,000 m, and for a range of district heating network installed capacities, from 0 to 60 MWth. All optimal economic configurations were shown to have a beneficial environmental balance, measured in terms of avoided CO_2eq emissions and avoided impacts across the life cycle. However, there were substantial differences in the best possible configurations, which depended on factors such as the EGS construction depth, the size of the district heating design and the technology selected. EGS with depths between 5500 and 6000 m with a Kalina cycle for cogeneration and a district heating network with an installed capacity between 20 and 35 MWth were found to be the optimal configurations for all studied performance metrics in the shallowest depth range (3500–6000 m). When comparing the economic and exergetic benefits of cogeneration of district heating with those of single electricity production at the deepest depths (7500–9500 m), cogeneration of district heating was found to be less advantageous from both perspectives (11% and 17% relative penalty, respectively, for a district heating network with an installed capacity of 60 MWth). Nevertheless, it was more advantageous in terms of environmental performance (37% of relative improvement for avoided CO_2 emissions) [34].

The question raised is the application ability of the geothermal binary power plants from a cradle-to-grave point of view, as they have gained increasing interest in reducing GHG and consume less finite energy resources. To this end, a complete LCA of geothermal power generation from EGS low-temperature reservoirs has been carried out, with results showing that the environmental consequences are considerably impacted by the geological parameters at a given location (Figure 7). Binary geothermal power generation could greatly contribute to a more sustainable power supply at places with ordinary and above average geological characteristics. However, only a selected few plant layouts were capable of compensating for the energy and materials needed to seal the geothermal reservoir at less-than-ideal locations. However, geothermal binary power plants could have significant environmental impacts due to the extensive resources needed for their construction, particularly the underground portion of the plant. Consideration must also be given to the substantial impact that the auxiliary power needed to transport the geothermal fluid from the reservoir had on the net power production.

Enhancing reservoir productivity, designing deep wells reliably and making effective use of geothermal fluid for net power and district heat generation were essential components of ecologically friendly plants. The authors argued that low-temperature geothermal resources may be used to generate heat and electricity in the near and far future, resulting in a more sustainable energy system [35].

In the discussion above, a different perspective of geothermal energy is raised, since EGS power plants are economically and environmentally beneficial compared both with thermal based power plants and with renewable energy power plants. In the following paragraphs, two very important factors of GHG-related emissions on geothermal power plants, the refrigerant used in the cooling stages and the diesel fuel consumed during the construction, especially drilling, are highlighted.

An effort has been conducted to assess the environmental impacts of electricity generation, as it is deemed fundamental for designing a low-carbon future. Methods for evaluating geothermal plants' impact on the environment, based on physical and/or monetary data, were compared. As part of that research, a hybrid LCA was carried out for the Wairakei Geothermal Project, which involved taking stock of both material needs and financial resources. The ISO 14040 series standard was utilized for the evaluation [36]. Some hybrid (mass-monetary) inventories were found to produce considerably different findings across effect categories. However, for specific geothermal systems studied, direct emissions of geothermal fluids dominated the few impact categories to which they contributed [37].

Based on typical geothermal conditions in Germany, an LCA was performed on binary power plants that generate electricity using geothermal energy. Working fluid losses and environmental effects were included in an LCA of several power plant ideas (subcritical one-stage and two-stage ORC power systems and supercritical cycles). Since fluorinated refrigerants are prohibited by EU law, research into alternative working fluids with a low GWP for ORC systems is a priority. In particular, a second law analysis was performed on the concept of replacing R245fa and R134a with other working fluids such as R1233zd and R1234yf or natural hydrocarbons. Additionally, the ecological footprint of each potential power plant design was determined. The collected findings showed that the low GWP fluids tested guided to an equivalence of the second law efficiency and vastly reduced environmental effects compared with typical fluorinated working fluids. Using R1233zd as the working fluid instead of R245fa lowered the ORC's global warming impact by 78% and caused a 2% loss in second law efficiency when dealing with a low-temperature heat source. The efficiency of the supercritical cycle operating with R1234yf raised by 37%, while the produced amount of CO_2eq remarkably decreased. The studied optimization options boost efficiency by as much as 7% in geothermal circumstances with higher temperatures of the geothermal fluid and a limitation of the reinjection temperature, such as in the Upper Rhine Rift Valley. The idea of a two-stage ORC seemed promising in this setting. The two-stage ORC with R1233zd resulted in 2% greater exergetic efficiency and a reduction in global warming impact (CO_2 emissions) from 78 to 13 g/kWhe when compared with a subcritical one-stage system using R245fa as the working fluid [38].

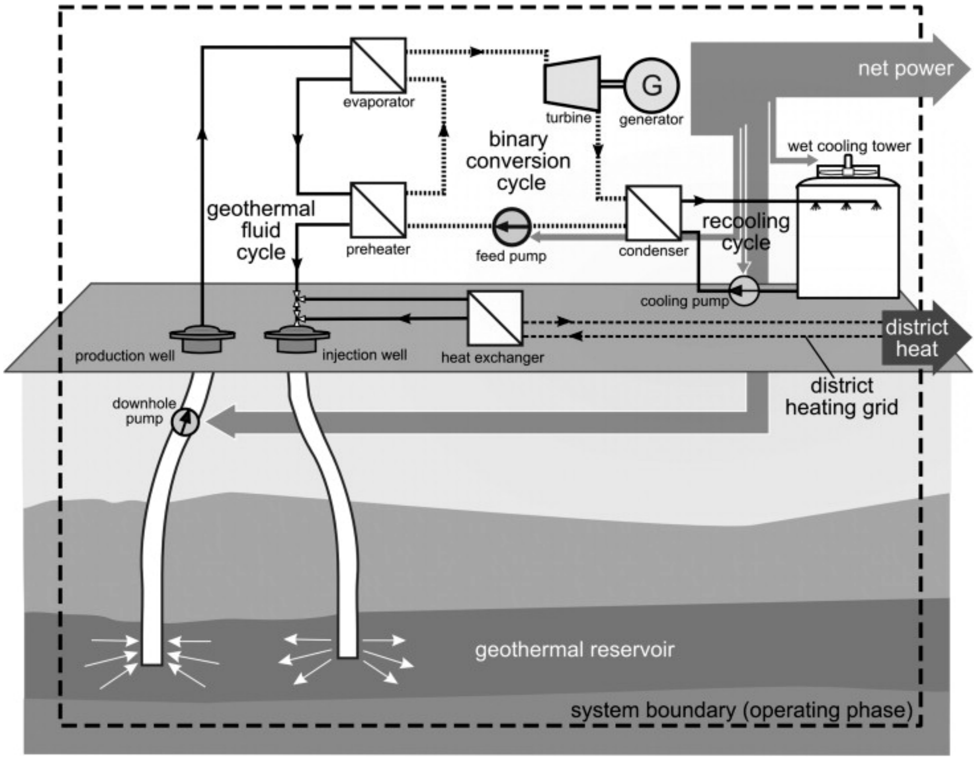

Figure 7. Plant design and system boundaries of the analyzed geothermal binary power plants exploiting a low-temperature reservoir for the supply of net power and, optionally, district heat [35].

Geothermal power generation has been the subject of an updated evaluation of life cycle environmental studies. The findings have been organized according to the following technologies for energy conversion: dry steam, binary cycle, single flash and double flash. The development of pilot projects for improved geothermal systems is also mentioned. The research concluded that the primary factor responsible for the associated impact on global warming was the consumption of diesel fuel, which was required for the construction stages (well drilling and completion, drilling fluid and cement pumping, casing due to steel production and well and fluid transport piping). Additionally, data availability dependent LCA hot areas for each effect category were identified, together with their accompanying information on global warming, eutrophication, acidification, resource consumption and land use. Similarly, a conclusion could be drawn that the life cycle environmental impacts varied depending on two factors: local geological characteristics and other methodological choices inherent to LCA methodology, such as the definition of the functional unit, the system boundaries, the lifespan, the impact assessment method and the allocation procedure [8].

The environmental implications of various energy producing systems have been evaluated and compared. The ReCiPe midpoint technique was applied to a standardized collection of LCIs representing a broad variety of methods for generating power. The LCI analysis took into account the manufacturing and rollout of the technologies over nine geographical areas. Based on the data collected, it was determined that even low carbon power required more metals than traditional fossil power, that renewable and nuclear power reduced several environmental consequences and that CO_2 collection and storage raised the number of non GHG impacts. The production of low-carbon technologies was crucial and could serve as an early indicator of the most desirable technology. The geothermal power plant used in this analysis was expected to last for a long lifetime and had a high load factor. This resulted in less pollution throughout manufacturing. When comparing GHG, toxicity, particulate matter emissions, photochemical ozone production and acidification, direct emissions were at least an order of magnitude greater than indirect emissions. The high geogenic emissions were the cause of this situation: 83 gCO_2/kWh, 0.1587 gSO_2/kWh, 0.75 gCH_4/kWh, 0.06 gNH_3/kWh and 4 gHg/MWh. As most environmental impacts were caused by direct site-specific emissions from the geothermal fluid during the plant operation, these assumptions could be considered conservative, especially for human toxicity and freshwater ecotoxicity, for which the characterization factor of Hg was one of the highest across all substances [39].

The LCA of a binary-cycle power plant that used high-enthalpy geothermal resources and a closed-loop GHP system that used low-enthalpy resources has been considered. Geothermal electricity is suitable enough to replace fossil-derived electricity, according to the LCA of binary-cycle power plants that use high-enthalpy geothermal resources. Figure 8 shows the overall findings including Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Ozone Layer Depletion Potential (ODP), Photochemical Oxidant Formation Potential (POFP), Acidification Potential (ACP), Eutrophication Potential (EP) and Cumulative Energy Demand (CED). Even though geothermal power systems had a positive environmental profile and life cycle energy balance, their performances might be improved by minimizing the material requirements of site operation activities such as drilling and casing using environmentally friendly working fluids. The life cycle assessment of low-enthalpy geothermal resource closed-loop GHP heat generating revealed that high power demand and heat generation usage were the elements that define the environmental performance of geothermal heat systems. The availability of more ecologically friendly electrical networks was a major issue in mitigating the impact of geothermal heat, notwithstanding geothermal heat's more favorable GWP and lower non-renewable energy consumption than fossil heat. Despite the fact that more efforts must be required to ensure environmental sustainability, the authors believe that geothermal energy systems will play an important part in the future energy systems because of its capacity to deliver energy with low environmental effect [40].

A critical issue in order to minimize the impact of geothermal heat is a more environmentally friendly electrical grid. To this end, Marriott et al., explored the potential impacts of the energy mix on the results of an LCA case study. The findings showed that regional variations in the local generation mix could significantly affect GHG emission estimates. Similarly, GHG for certain sectors and scenarios could change by more than 100%. Finally, the authors advised practitioners to account for the uncertainties associated with mix choice [41]. In the spirit of improved results, the following articles investigate new methods for conducting an LCA. Martin Pehnt investigated the potential of a dynamic approach on LCA on the grounds that background system impacts such as supply of materials or the demanded energy for production systems had the potential to be improved over time. The findings showed, therefore, that the inputs of finite energy resources and GHG emissions were significantly lower than in the conventional system. Concerning other environmental effects, the results did not provide a definitive judgement in favor of or against renewable energies [42].

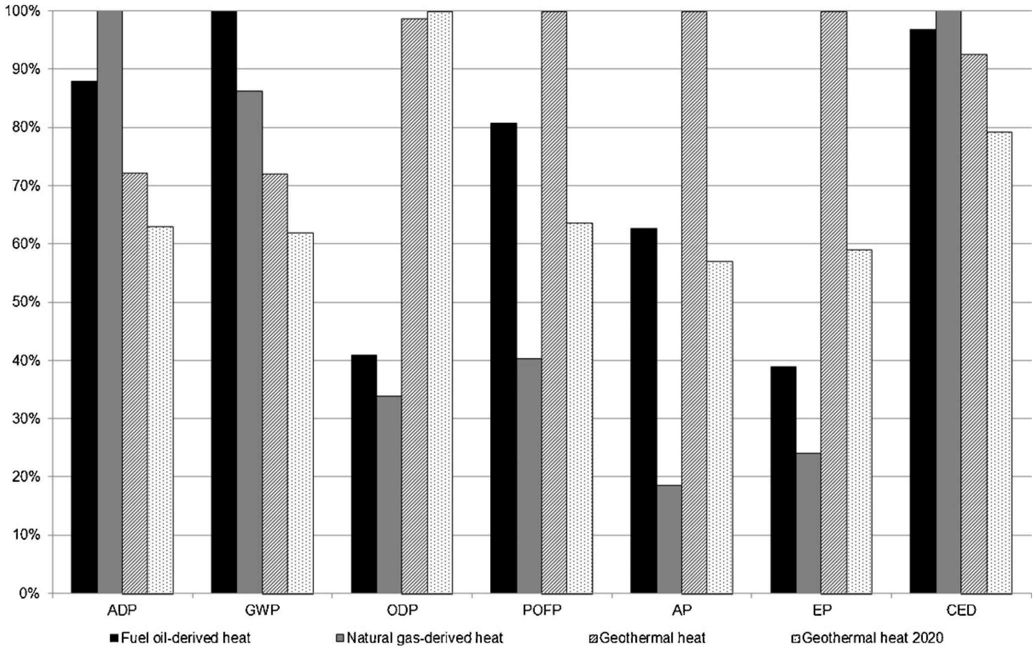

Figure 8. Comparison of the environmental impacts of geothermal heat and fossil-derived thermal energy for the studied technologies [40].

Onshore and offshore wind, hydropower, marine technologies (wave power and tidal energy), geothermal, PV, solar thermal, biomass, waste and heat pumps have all been the subject of LCA studies, and these studies have been reviewed with remarkable thoroughness. The major focus of that analysis was to show how inconsistent previous LCA studies were in their reporting of GHG emissions from the generation of electricity and heat using Renewable Energy Sources (RES). Figures 9 and 10 show that the review found offshore wind to have the lowest GHG emissions (with potential mean life cycle GHG emissions of 5.3–13 gCO_2eq/kWh). Thus, estimates of GHG emissions from the combustion of fossil fuels to generate heat and electricity were compared with the actual GHG emissions, suggesting that conventional sources produced more GHG over the course of their life cycles than renewable ones do, with the exception of nuclear power. However, depending on the feedstock, the chosen limit and the inputs needed to produce it, energy from waste and Dedicated Biomass Technologies (DBTs) were shown to have potentially large GHG emissions, with ranges of 97.2–1000 and 14.4–650.0 gCO_2eq/kWh, respectively. Existing life cycle GHG emission estimates for power and heat generation from renewable energy sources were shown to differ remarkably. Some of these variations might be attributable to changes in real GHG emissions, while others might be related to discrepancies in assumptions and modeling choices. These variations revealed areas for improvement and opportunities for standardization. Future projects in developing renewable energy technology for electricity and heat generation can benefit from the evaluated results by providing appropriate baseline estimations [43].

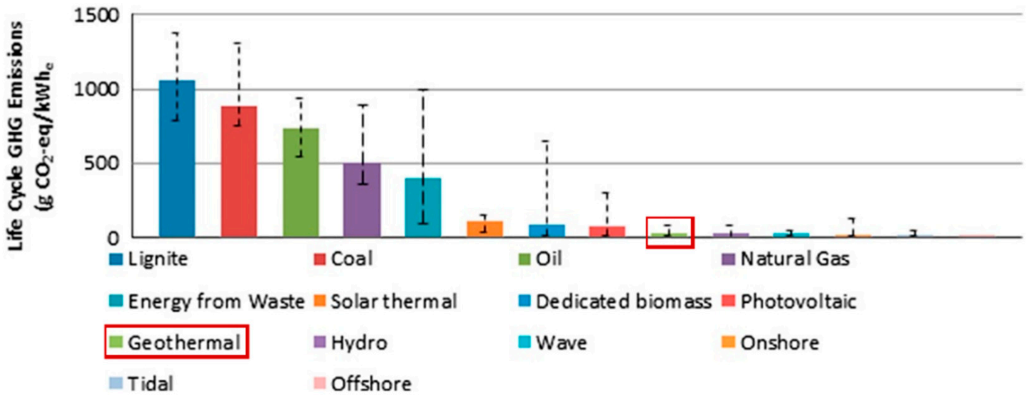

Figure 9. Life cycle GHG emission estimates from various electricity generation methods [43].

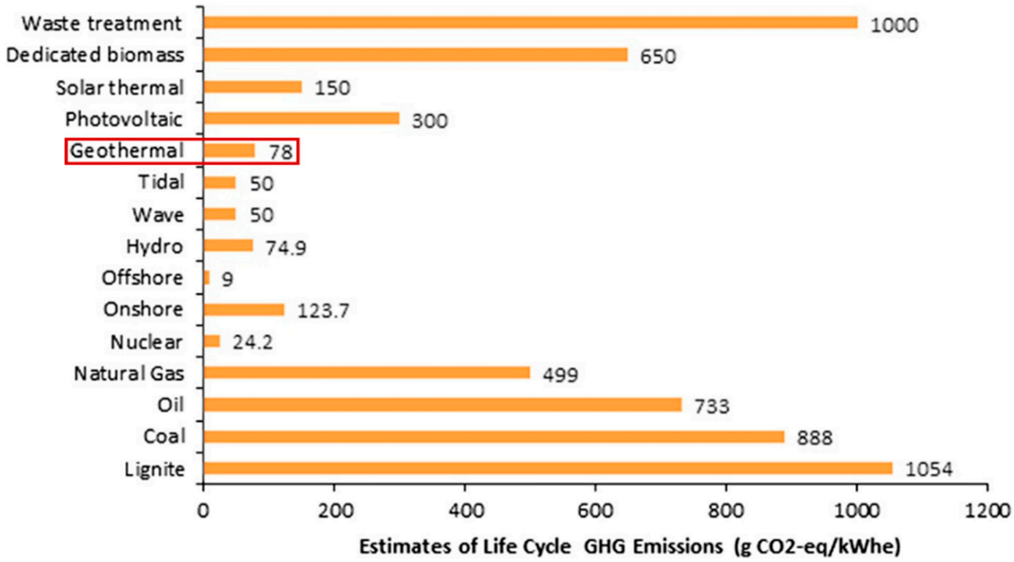

Figure 10. Maximum GHG emission levels from various electricity generation methods [43].

The possible environmental impacts of geothermal power plants during their lifetime have been thoroughly investigated. According to the authors, there is a lack of LCA studies on the topic of geothermal power production, and the ones that exist tend to be conducted on a country or even regional scale. Life cycle fugitive emissions, geological hazard risk and the consequences of water and land usage are also very time dependent factors. Emissions and resource consumption ranges for present global geothermal power generation were offered based on their analysis. They did the same thing when they defined a universal case approximating the mean. The data obtained might be used to feed LCIs, however they were not yet fully formed. Local and regional environmental impacts of potential emissions of key harmful compounds such as mercury, boron and arsenic were not sufficiently addressed on a worldwide basis [44].

Furthermore, a new simplified model based on an LCA study of environmental performance variability of energy pathways deserves attention as a separate but related topic. An EGS power plant life cycle GHG emission estimation model with simplified parameterization has been developed using this technology. The model may be used with a wide variety of plant layouts. The research revealed a two-parameter model to evaluate EGS GHG emissions. In order to characterize a large number of potential EGS power plants in central Europe, a parameterized reference model was built. Using GSA on this baseline model, the impact of changes in installed power capacity, drilling depth and the number of wells as the primary contributors to the observed variation in GHG values were identified. Comparison results of published EGS and LCAs confirmed the representativeness of this new simplified model. Overall, the simplified model allowed for a fast and easy estimation of the environmental performance of an EGS power plant, without resorting to the LCA technique in its entirety. To this end, it provided a straightforward resource for EGS industry stakeholders and decision makers, with the goal of advancing the discussion surrounding the efficacy of this developing technology and the environmental consequences it might have [45].

4.5. Environmental Studies on Pre-Existing Power Plants

The electricity production phases of four geothermal electricity plants in the Mount Amiata area in Tuscany, Italy has been evaluated. Back then, the authors claimed that geothermal power contributed for 1.8% of the total electricity production in Italy and the global trend towards renewable energy sources. This study sought to provide light on the environmental implications of geothermal power generation and propose strategies for mitigating such effects. All aspects of the power plants' life cycle were considered in an airborne emissions assessment. GWP, ACP and Human Toxicology Potential (HTP) were all taken into account, with 1 MWh of generated electricity serving as the functional unit. They resulted that the power generated by geothermal units in the Mount Amiata region could not be called carbon free. While HTP did not produce any alarming numbers, GHG emissions were found to be greater than those of natural gas plants and close to those of coal plants in some cases. Furthermore, the studied geothermal plants produced power with an ACP that was 2.2 times greater than those produced by coal plants. In an example, the disparity grew by a ratio of 4.4, reaching over 28 times the ACP of a natural gas power station. Environmental considerations made the idea of minimization of impacts (through the complete reinjection of incondensable fluids into the reservoir) a promising avenue for future geothermal power plants, as the authors argue, even though binary-cycle technology was not the best solution at the present time from an efficiency and cost perspective [46].

On the other hand, Hanbury and Vasquez [47] investigated the potential environmental benefits of using a renewable power source, in this case geothermal power, for transportation. In particular, they considered LNGV for Liquefied Natural Gas Vehicle, E85 for an 85% mixture of ethanol and gasoline, HEV for a Hybrid Electric Vehicle and FCV H_2 for a Fuel Cell Vehicle that runs on hydrogen gas. The electric vehicle in this case was the same vehicle as in the geothermal column, but it used a standard mix of electricity common in the US (coal, natural gas, nuclear, etc.). A plant in northern Nevada (Blue Mountain) was studied with a capacity of approximately 484 MW of geothermal power. Following this case study, they analyzed the life cycle of transportation vehicles using geothermal energy. Geothermal power had large variations between plants, owing to differences in the hydrothermal reservoir chemistry and thermodynamic conditions, so the authors used a stochastic approach to determine the amount of variation that is usually applied when using this energy source. Figure 11 shows the results, implying that geothermal power has a low environmental impact relative to other methods of energy production for transportation use.

Another study performed a cradle-to-grave LCA of the Italian flash technology Bagnore power plant system based on an accurate life cycle inventory of primary data, which were supplied by the plant manufacturer and operator Enel Green Power, reporting every life cycle stage. The dominant stages were the operating and commissioning phase, with a contribution of 84% and more than 11%, respectively, of the considered environmental impacts. On the contrary, maintenance, decommissioning and EoL phases indicated negligible values. Finally, the comparison with the average Italian electricity mix showed that geothermal energy production had the lower environmental impact, except in the climate change category [48].

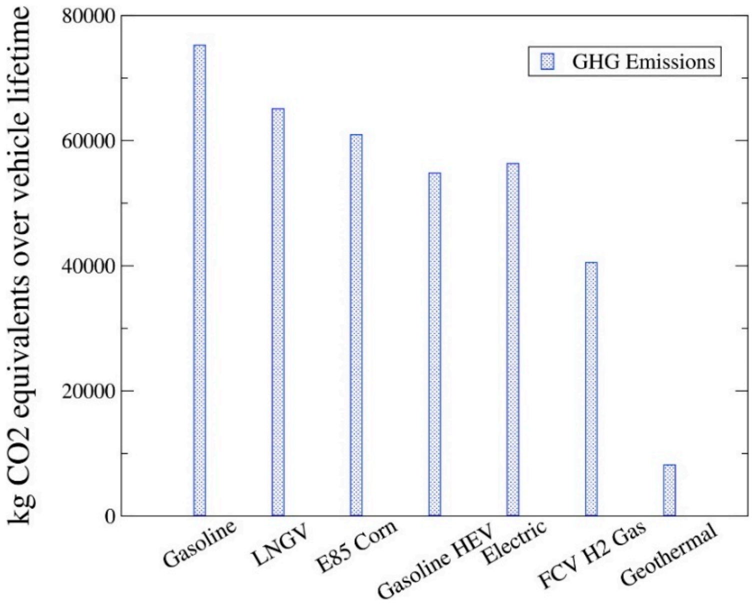

Figure 11. Comparison of GHG emissions for different vehicle types [47].

4.6. Greenhouse Heating Systems

In order to evaluate the efficiency of an integrated system PV GHP, an environmental analysis had been applied by encountering the PV-GH as a greenhouse heating system, compared with a conventional hot air generator using Liquefied Petroleum Gas (LPG-HG). Tests were carried out in twin experimental greenhouses in the Mediterranean area, specifically in Valenzano, Italy. The two technologies already encouraged by Italian policies for the reduction of GHG emissions were studied. Experimental tests, and subsequently a comparison of microclimatic conditions and environmental performances, were realized. Under a technological scenario, GHP was also examined by assuming that electricity was not provided by solar panels but from the Italian national grid. The microclimatic conditions in the two greenhouses along with 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 an LCA method, according to ISO 14040 standard [36]. The interpretation of the results using CML2001 as LCIA methodology showed that neither system was environmentally beneficial and that the GHP scenario had the higher environmental burdens. Limiting the analysis to the emissions responsible for the greenhouse effect, the plant with the GHP and PV panels reduced carbon emissions by 50%. In order to assess the sustainability of the GHP plant, the estimated payback time for energy and for CO_2 emissions were 1 and 2.25 years, respectively [49].

4.7. Improvement of Existing Technologies of Geothermal Systems

Among several articles that investigate the effects of specific changes to the existing geothermal technology, in order to improve it, there is an approach for a new solution: protecting the steel turbine components of geothermal power plants against aggressive corrosion by coating with multi-composite layers. This research aimed to design and synthesize novel complex powder mixtures of NiCr/NiCoCr with varying additions of ZrO_2 stabilized with Y_2O_3 to generate protective layers with enhanced wear, thermal shock and abrasion resistance. The plasma jet technique utilized by the study team gave the tested layer deposits exceptional resistance to wear and corrosion. Similar to how the layer deposits hold up when used on precision components, this was also true when applied to high-precision parts. The technology-neutral testing approach was employed to evaluate a wide range of deposit materials in multi-layer composites [50].

Using a considerable amount of research conducted at the University of Pisa, Grassi et al., [51] chose to highlight key aspects of the GSHP's architecture. In particular, they prioritized a method that minimized their impact on the environment by optimizing their performance throughout the course of their full service life. To meet the remaining energy needs and to adjust the power peaks, the suggested technique investigated design and management options to discover the best amount of exploitation of the ground source. The strategy was called holistic, taking into account the complete system rather than just the parts that were commonly thought of as being the most crucial. To simulate the operational performances of the entire GSHP system, an optimization method was employed to model each component and connect it to the others. Component sizing, life cycle performance evaluation, optimization procedure and feasibility analysis were all included in the proposed approach. The authors of this study additionally reviewed related works to see what kind of results existed about the proposed methodology's potential use cases. Lastly, the objectives of ongoing studies and those of planned ones are outlined.

Scharrer et al. [52] studied the environmental profile of an innovative storage system for excess electricity combined of a heat pump, a heat storage and an ORC build in Germany. The analysis indicated that the higher impacts were the drilling and the borehole cementing. The pump production dominated in the operation phase due to its short service life. Finally, in terms of LCA, Bonamente and Aquino [53] presented a novel system for space conditioning in an industrial building already in use. The configuration consisted of a GSHP with upstream TS. Consequently, the building was provided with the necessary thermal energy by a geothermal installation in reduced size. Three scenarios were implemented: the baseline where the system was working in conventional mode, the alternative where the system was working in alternative mode and an improved scenario where an upgrade of the storage was proposed. The corresponding values for GWP impact category were calculated as 0.156, 0.187 and 0.160 $kgCO_2eq/kWh_{th}$ for the baseline, storage and improved scenario, respectively.

4.8. Water Consumption

For a planet with limited water resources, knowing how water is consumed at each stage of the power generating process is crucial.

As depicted in Figure 12, Meldrum et al., combined estimates of water withdrawal and water consumption throughout the whole life cycle of a few different power generation systems. 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. Regarding the abbreviations in Figure 11, PV stands for PhotoVoltaics; C-Si for Crystalline Silicone; EGS for Enhanced Geothermal System; CSP for Concentrating Solar Power; CT for Combustion Turbine; CC for Combined Cycle; IGCC for Integrated Gasification Combined Cycle; PC for Pulverized Coal, sub-critical. Component production, fuel procurement, processing, transport, power plant operation and decommissioning were all part of the process under examination. Water needed for the cooling of thermoelectric power plants dominates the life cycle water usage in most cases, while the coal, natural gas and nuclear fuel cycles demanded considerable water per MWh. Concentrating solar, geothermal, PV and wind generating facilities also demanded a high volume of life cycle water usage per MWh during their production and installation [54]. In another article, a remarkable amount of water was required, although almost 98% of this amount was used for water evaporation in the cooling tower [10].

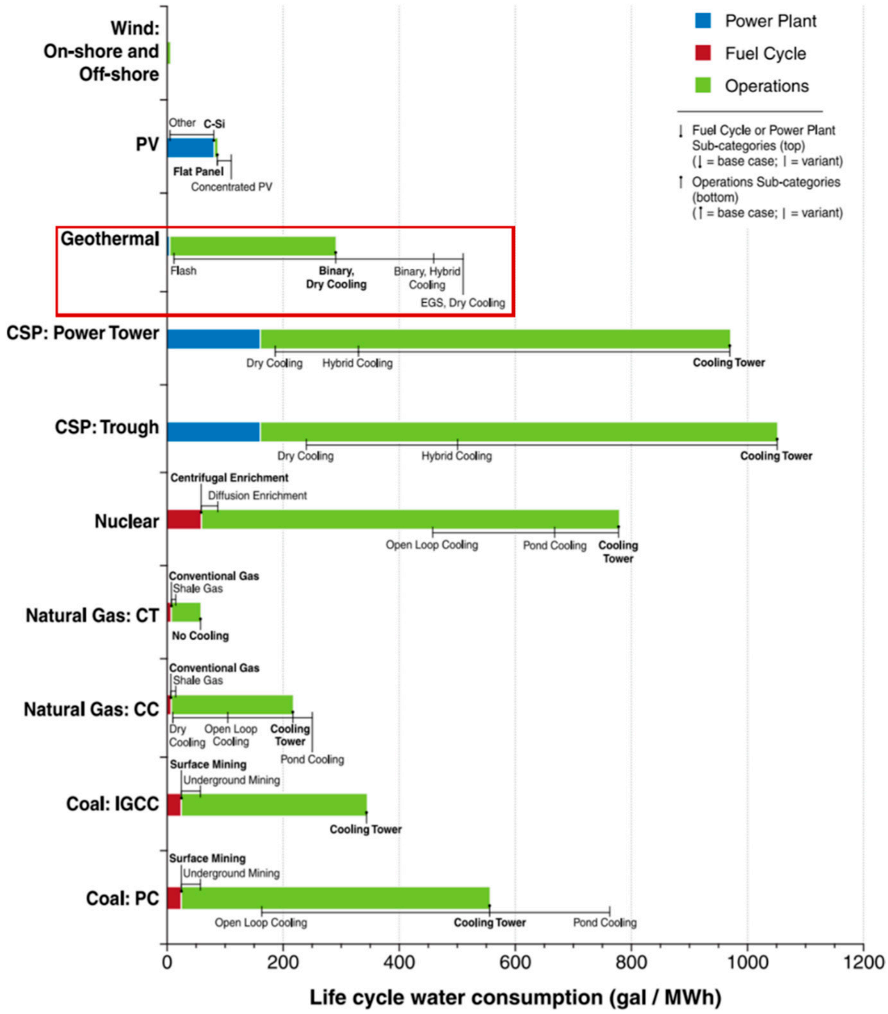

Figure 12. Estimated life cycle water consumption factors for selected electricity generation technologies, based on median harmonized estimates, demonstrate significant variability with respect to technology choices [54].

5. Conclusions

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

On the one hand, the advantages of geothermal energy are:

- It is a renewable energy.
- Geothermal power plants can work 24 h a day, seven days a week without stopping.
- Geothermal power plants are not affected by the weather conditions or other natural phenomena.
- Newer technological improvements increase the number of potential geothermal sites that can be exploited.
- Certain technologies of geothermal power generation have almost zero GHG emissions during their operational phases (e.g., EGS).
- It has a broad spectrum of possible applications, from a small scale such as water and space heating (e.g., GSHP) to a large scale such as electricity generation; electricity generation from geothermal power plants is concentrated in its form, not widespread such as photovoltaic or wind power and as a result it is more easily combined with the currently existing electricity transfer grid.
- High-grade geothermal resources are available in over 80 countries around the world, with a potential generating capacity of 11,000 ± 1300 TWh/year. The feasible potential is

estimated at 8100 TWh/year, with a total theoretical potential of around 400,000 TWh/year. This is much larger than the current production level of 2600 TWh/year [26].

On the other hand, the disadvantages of geothermal energy are:

- Its high construction costs.
- Its high material requirements.
- Some electrical power generation geothermal technologies have GHG emissions during their operation phase (e.g., HT-Flash).
- GSHP are inevitably connected to the national power grid, which can cause GHG emissions during their operation phase.
- There is the risk of increased seismicity among other environmental impacts: surface disturbances, physical consequences such as ground subsidence due to fluid withdrawal, noise, thermal pollution and the discharge of unpleasant chemicals are all side effects of generating electricity from geothermal sources. Nevertheless, there are significant technologically dependent variances between sites [26].

Summing up, geothermal energy is a renewable form of energy that is not based on 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 plant operation phase. Geothermal power provides benefits both for the environment and for dependability in electricity generation. Although a lot of steel and concrete are needed to produce a certain quantity of electricity, EGSs have one of the lowest GHG emissions of the renewable systems investigated per kWh produced throughout its lifespan [29]. Likewise, geothermal power shows the lowest possible prices of electricity generation, along with hydro power [26].

Another of its most important aspects is its capability of space heating, using low enthalpy reservoirs that exist practically everywhere. A lot of research 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 renewable energy systems. Geothermal energy can play a vital role in the zero GHG emissions societies of the future if certain steps are accomplished: the improvement of the electricity generation mix; innovations in borehole drilling and transportation, which will cause mitigated environmental impacts in the construction phase of the technologies; improvements in the design of various components; reinjection of harmful emissions of existing geothermal power plants, which not only cause a mitigation in environmental impacts, but also increase the life expectancy of the geothermal source.

Just as any other technology of renewable sources, geothermal energy is not the panacea for the future. Nevertheless, it is an extremely viable alternative that, combined with other renewable energy systems, may produce good and solid results for mitigating the negative effects of the existing electricity generation grid on the planet's environment.

Author Contributions: M.M.: conceptualization, writing the original paper and editing; A.P.: conceptualization, methodology, writing; A.P.V.: methodology, results, diagrams; G.M.: writing and editing; M.S.: methodology, writing, editing and supervision; S.P.: methodology, writing, editing and supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research is part of the findings of the project entitled "Save Checker Tool (SECT)" and has been financed by the Operational Program Western Greece 2014–2020 under the call "RIS3 Energy Applications" (project code: ΔEP7-0019898).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ADP	Abiotic Depletion Potential
ACP	Acidification Potential
ASHP	Air-Source Heat Pump
BHE	Borehole Heat Exchanger
CC	Combined Cycle
CCHP	Combined Cooling, Heating and Power
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
COP	Coefficient of Performance
C-Si	Crystalline Silicone
CSP	Concentrating Solar Power
CT	Combustion Turbine
DBT	Dedicated Biomass Technologies
EBPD	European Building Performance Directive
EGS	Enhanced Geothermal Systems
EMA	Emergy Analysis
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FCV	Fuel Cell Vehicle
GDHS	Geothermal District Heating System
GHG	Greenhouse Gas
GHP	Geothermal Heat Pump
GPGE	Geo Pressured Gas and Electric
GSA	Global Sensitivity Analysis
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
H/C-EGS	Heating/Cooling Energy Generation System
HDR	Hot Dry Rock
HTP	Human Toxicology Potential
HVAC	Heating, Ventilation and Air Conditioning
IGCC	Integrated Gasification Combined Cycle
IO-LCA	Input–Output Life Cycle Assessment
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
LNGV	Liquefied Natural Gas Vehicle
LPG	Liquefied Petroleum Gas
NCG	Non-Condensable Gases
NPV	Net Present Value
ODP	Ozone Layer Depletion Potential
ORC	Organic Rankine Cycle
PC	Pulverized Coal
POFP	Photochemical Oxidant Formation Potential
RES	Renewable Energy Sources
PV	PhotoVoltaic
SA	Sensitivity Analysis
SCOP	Seasonal Coefficient of Performance
UEV	Unit Emergy Value

References

1. Ristimäki, M.; Säynäjoki, A.; Heinonen, J.; Junnila, S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy* **2013**, *63*, 168–179. [CrossRef]
2. ISO 15686-8:2017, Buildings and Constructed Assets-Service Life Planning-Part 5: Life-Cycle Costing. Available online: https://www.sis.se/api/document/preview/922173/ (accessed on 25 July 2022).

3. Koroneos, C.; Tsarouhis, M. Exergy analysis and life cycle assessment of solar heating and cooling systems in the building environment. *J. Clean. Prod.* **2012**, *32*, 52–60. [CrossRef]
4. Abusoglu, A.; Sedeeq, M.S. Comparative exergoenvironmental analysis and assessment of various residential heating systems. *Energ. Build.* **2013**, *62*, 268–277. [CrossRef]
5. Lacirignola, M.; Blanc, P.; Girard, R.; Pérez-López, P.; Blanc, I. LCA of emerging technologies: Addressing high uncertainty on inputs' variability when performing global sensitivity analysis. *Sci. Total Environ.* **2017**, *578*, 268–280. [CrossRef] [PubMed]
6. Buonocore, E.; Vanoli, L.; Carotenuto, A.; Ulgiati, S. Integrating life cycle assessment and emergy synthesis for the evalua-tion of a dry steam geothermal power plant in Italy. *Energy* **2015**, *86*, 476–487. [CrossRef]
7. Rugani, B.; Benetto, E. Improvements to emergy evaluations by using life cycle assessment. *Environ. Sci. Technol.* **2012**, *46*, 4701–4712. [CrossRef]
8. Tomasini-Montenegro, C.; Santoyo-Castelazo, E.; Gujba, H.; Romero, R.J.; Santoyo, E. Life cycle assessment of geothermal power generation technologies: An updated review. *Appl. Therm. Eng.* **2017**, *114*, 1119–1136. [CrossRef]
9. Moret, S.; Peduzzi, E.; Gerber, L.; Maréchal, F. Integration of deep geothermal energy and woody biomass conversion pathways in urban systems. *Energy Convers. Manag.* **2016**, *129*, 305–318. [CrossRef]
10. Stoppato, A.; Benato, A. Life cycle assessment of a commercially available organic Rankine cycle unit coupled with a biomass boiler. *Energies* **2020**, *13*, 1835. [CrossRef]
11. Arat, H.; Arslan, O. Exergoeconomic analysis of district heating system boosted by the geothermal heat pump. *Energy* **2017**, *119*, 1159–1170. [CrossRef]
12. Keçebaş, A. Exergoenvironmental analysis for a geothermal district heating system: An application. *Energy* **2016**, *94*, 391–400. [CrossRef]
13. Douziech, M.; Tosti, L.; Ferrara, N.; Parisi, M.L.; Pérez-López, P.; Ravier, G. Applying Harmonised Geothermal Life Cycle Assessment Guidelines to the Rittershoffen Geothermal Heat Plant. *Energies* **2021**, *14*, 3820. [CrossRef]
14. Nitkiewicz, A.; Sekret, R. Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler. *Energy Convers. Manag.* **2014**, *87*, 647–652. [CrossRef]
15. Saner, D.; Juraske, R.; Kübert, M.; Blum, P.; Hellweg, S.; Bayer, P. Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems. *Renew. Sust. Energ. Rev.* **2010**, *14*, 1798–1813. [CrossRef]
16. Simons, A.; Firth, S.K. Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building us-ing water-based sensible heat storage. *Energ. Build.* **2011**, *43*, 1231–1240. [CrossRef]
17. Koroneos, C.J.; Nanaki, E.A. Environmental impact assessment of a ground source heat pump system in Greece. *Geothermics* **2017**, *65*, 1–9. [CrossRef]
18. Karagiorgas, M.; Mendrinos, D.; Karytsas, C. Solar and geothermal heating and cooling of the European Centre for Public Law building in Greece. *Renew. Energy* **2004**, *29*, 461–470. [CrossRef]
19. Mohamed, A.; Hamdy, M.; Hasan, A.; Sirén, K. The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions. *Appl. Energy* **2015**, *152*, 94–108. [CrossRef]
20. Zheng, X.; Li, H.Q.; Yu, M.; Li, G.; Shang, Q.M. Benefit analysis of air conditioning systems using multiple energy sources in public buildings. *Appl. Therm. Eng.* **2016**, *107*, 709–718. [CrossRef]
21. Bartolini, N.; Casasso, A.; Bianco, C.; Sethi, R. Environmental and economic impact of the antifreeze agents in geothermal heat exchangers. *Energies* **2020**, *13*, 5653. [CrossRef]
22. Huang, B.; Mauerhofer, V. Life cycle sustainability assessment of ground source heat pump in Shanghai, China. *J. Clean. Prod.* **2016**, *119*, 207–214. [CrossRef]
23. Chang, Y.; Gu, Y.; Zhang, L.; Wu, C.; Liang, L. Energy and environmental implications of using geothermal heat pumps in buildings: An example from north China. *J. Clean. Prod.* **2018**, *167*, 484–492. [CrossRef]
24. Chiasson, A.; Center, G.H. *Life-Cycle Cost Study of a Geothermal Heat Pump System*; Geo-Heat Center, BIA Office BLDG: Winnebago, NE, USA, 2006.
25. Junghans, L. Evaluation of the economic and environmental feasibility of heat pump systems in residential buildings, with varying qualities of the building envelope. *Renew. Energy* **2015**, *76*, 699–705. [CrossRef]
26. Evans, A.; Strezov, V. A Sustainability Assessment of Electricity Generation. In Proceedings of the 2010 International Conference on Biosciences, Cancun, Mexico, 7–13 March 2010; pp. 106–111.
27. Evans, A.; Strezov, V.; Evans, T.J. Assessment of sustainability indicators for renewable energy technologies. *Renew. Sust. Energ. Rev.* **2009**, *13*, 1082–1088. [CrossRef]
28. Asdrubali, F.; Baldinelli, G.; D'Alessandro, F.; Scrucca, F. Life Cycle Assessment of Electricity Production from Re-newable Energies: Review and Results Harmonization. *Renew. Sust. Energ. Rev.* **2015**, *42*, 1113–1122. [CrossRef]
29. Sullivan, J.L.; Clark, C.E.; Han, J.; Wang, M. *DE-AC02-06CH11357*; *Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems*; Argonne National Lab.: Argonne, IL, USA, 2010; pp. 10–15.
30. Sullivan, J.L.; Clark, C.E.; Han, J.; Wang, M. *ANL/ESD/11-12*; *Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems: Part II*; Argonne National Lab.: Argonne, IL, USA, 2011; pp. 11–12.
31. Sullivan, J.L.; Wang, M.Q. Life cycle greenhouse gas emissions from geothermal electricity production. *J. Renew. Sustain. Energy* **2014**, *5*, 063122. [CrossRef]

32. Clark, C.; Sullivan, J.; Harto, C.; Han, J.; Wang, M. Life Cycle environmental impacts of geothermal systems. In Proceedings of the Proceedings Thirty Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, USA, 30 January–1 February 2012; Volume 30, p. 194.
33. Lacirignola, M.; Blanc, I. Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment. *Renew. Energy* **2013**, *50*, 901–914. [CrossRef]
34. Gerber, L.; Maréchal, F. Environomic optimal configurations of geothermal energy conversion systems: Application to the future construction of Enhanced Geothermal Systems in Switzerland. *Energy* **2012**, *45*, 908–923. [CrossRef]
35. Frick, S.; Kaltschmitt, M.; Schröder, G. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. *Energy* **2010**, *35*, 2281–2294. [CrossRef]
36. ISO 14040:2006, Environmental Management—Life Cycle Assessment—Principles and Framework. 2006. Available online: https://www.alz.org/alzheimers-dementia/what-is-dementia (accessed on 25 July 2022).
37. Martínez-Corona, J.I.; Gibon, T.; Hertwich, E.G.; Parra-Saldívar, R. Hybrid life cycle assessment of a geothermal plant: From physical to monetary inventory accounting. *J. Clean. Prod.* **2017**, *142*, 2509–2523. [CrossRef]
38. Heberle, F.; Schifflechner, C.; Brüggemann, D. Life cycle assessment of Organic Rankine Cycles for geothermal power gen-eration considering low-GWP working fluids. *Geothermics* **2016**, *64*, 392–400. [CrossRef]
39. Gibon, T.; Arvesen, A.; Hertwich, E.G. Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renew. Sust. Energ. Rev.* **2017**, *76*, 1283–1290. [CrossRef]
40. Martín-Gamboa, M.; Iribarren, D.; Dufour, J. On the environmental suitability of high- and low-enthalpy geothermal sys-tems. *Geothermics* **2015**, *53*, 27–37. [CrossRef]
41. Marriott, J.; Matthews, H.S.; Hendrickson, C.T. Impact of Power Generation Mix on Life Cycle Assessment and Carbon Footprint Greenhouse Gas Results. *J. Ind. Ecol.* **2010**, *14*, 919–928. [CrossRef]
42. Pehnt, M. Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renew. Energy* **2006**, *31*, 55–71. [CrossRef]
43. Amponsah, N.Y.; Troldborg, M.; Kington, B.; Aalders, I.; Hough, R.L. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. *Renew. Sust. Energ. Rev.* **2014**, *39*, 461–475. [CrossRef]
44. Bayer, P.; Rybach, L.; Blum, P.; Brauchler, R. Review on life cycle environmental effects of geothermal power generation. *Renew. Sust. Energ. Rev.* **2013**, *26*, 446–463. [CrossRef]
45. Lacirignola, M.; Meany, B.H.; Padey, P.; Blanc, I. A simplified model for the estimation of life-cycle greenhouse gas emis-sions of enhanced geothermal systems. *Geotherm. Energy* **2014**, *2*, 1–19. [CrossRef]
46. Bravi, M.; Basosi, R. Environmental impact of electricity from selected geothermal power plants in Italy. *J. Clean. Prod.* **2014**, *66*, 301–308. [CrossRef]
47. Hanbury, O.; Vasquez, V.R. Life cycle analysis of geothermal energy for power and transportation: A stochastic approach. *Renew. Energy* **2018**, *115*, 371–381. [CrossRef]
48. Tosti, L.; Ferrara, N.; Basosi, R.; Parisi, M.L. Complete data inventory of a geothermal power plant for robust cradle-to-grave life cycle assessment results. *Energies* **2020**, *13*, 2839. [CrossRef]
49. Russo, G.; Anifantis, A.S.; Verdiani, G.; Mugnozza, G.S. Environmental analysis of geothermal heat pump and LPG green-house heating systems. *Biosyst. Eng.* **2014**, *127*, 11–23. [CrossRef]
50. Buzăianu, A.; Moţoiu, P.; Csaki, I.; Popescu, G.; Ragnarstottir, K.; Guðlaugsson, S.; Guðmundsson, D.; Arnbjornsson, A. Experiments on life cycle extensions of geothermal turbines by multi composite technology. *Geothermics* **2015**, *57*, 1–7. [CrossRef]
51. Grassi, W.; Conti, P.; Schito, E.; Testi, D. On sustainable and efficient design of ground-source heat pump systems. *J. Phys. Conf. Ser* **2015**, *655*, 012003. [CrossRef]
52. Scharrer, D. Life cycle assessment of a reversible heat pump-Organic rankine cycle-Heat storage system with geothermal heat supply. *Energies* **2020**, *13*, 3253. [CrossRef]
53. Bonamente, E.; Aquino, A. Life-cycle assessment of an innovative ground-source heat pump system with upstream thermal storage. *Energies* **2017**, *10*, 1854. [CrossRef]
54. Meldrum, J.; Nettles-Anderson, S.; Heath, G.; Macknick, J. Life cycle water use for photovoltaic electricity generation: A review and harmonization of literature estimates. *Environ. Res. Lett.* **2013**, *8*, 015031. [CrossRef]