Chapter

Geothermal Energy as an Alternative to Reduce Atmospheric Emissions and Provide Green Energy

Zayre I. González-Acevedo and Marco A. García-Zarate

Abstract

Recently, there has been a worldwide rise of concern regarding the increasing emissions of air pollutants and global climate change. In contrast, there are also concerns about the growing energy consumption and how to guarantee its supply. Renewable energies can help minimize the use of fossil fuels, this being a high priority on the political agenda of countries around the world. Within renewable energies, geothermal energy is one of the oldest and most well-known sources of energy to generate electricity. Its use started in 1904 in Italy, but it needs a high initial investment. Depending on the geothermal reservoir, fluids drawn from the deep Earth could liberate a mixture of gases such as carbon dioxide, hydrogen sulfide, methane, and ammonia. The aim of this work is to compare gas emission of renewable, clean, and conventional sources of energy to be able to elucidate if geothermal energy could be a suitable green energy to minimize gas emissions to the atmosphere.

Keywords: life-cycle assessment, gas emissions, geothermal energy, sustainability, renewable

1. Introduction

In recent years, the topic of energy has been present in environmental debates, as well as many national and international forums with a focus in creating agreements and action in preserving the environment. As mentioned in the Intergovernmental Panel on Climate Change or IPCC, some major effects have been shown in water pollution, soil acidification [1], greenhouse gas emissions, air pollution, and the damages these have brought onto human health [2–4]. These changes seek to incorporate relevant topics such as climate change, water scarcity, and residue management to energy planning [5]. In this context, some renewable energy sources such as biomass, hydraulic, Aeolic, solar, marine, and geothermal are being considered. The production of these types of energy is considered inexhaustible as opposed to fossil fuels, which run out in a considerably short period of time [6, 7].

Mainly from a political and economic point of view, many countries already promote and use renewable energy sources because they recognize the need to change current energy-related patterns and must protect the environment, which is why these are considered green energy. This concept covers not only the protection of the environment but also sustainability. This was defined at the end of the 1980s in the Brundtland's reunion as "meeting the needs of the present generation while not compromising the ability of future generations to meet their needs" [8].

Therefore, it is a great global concern these days with the decrease in fossil fuel reserves and the increase in the demand for energy [9]. Geothermal energy has then been identified as an important aspect in transitioning to sustainable energy systems for its reliability [10] and flexibility [11]. Research indicates that geothermal energy could provide around 3.5% of the world's population energy by 2050. Among the main geothermal energy producers are Japan and Iceland. The USA had the greatest installed capacity to create geothermal energy with 3450 MW by 2015. Iceland took the seventh place with 665 MW and Japan with a 519 MW capacity [12].

Sustainability evaluations of energy technologies often do not consider the social and cultural impacts along with the long-term repercussions of developing certain energy systems. Even though the economic and ecologic evaluations of energy systems may be hard to define [13], they are not any less important [14].

For geothermal energy, the term renewable corresponds to a property in the source of energy, while sustainable refers to the way the resource is used. Therefore, geothermal energy is sustainable as long as the steam extraction does not exceed the water supply. It is also renewable as long as the deposit continues to produce the same amount of electric energy for more than 100 years.

It involves damages on different scales; the development and frequent use of energy can have sustainable and significant implications on a multidimensional level [15, 16]. It is renewable because most of the time, the regeneration rate is faster than extraction. This clearly shows that we must control the extraction rate so that it is sustainable.

2. Geothermal energy

Geothermal studies cover the variations in temperature in the Earth's crust and the phenomenon that influences the distribution of internal heat in our planet. This study is made through exploration, evaluation, and exploitation of this type of energy. This type of energy manifests on the surface in the form of volcanoes, geysers, fumaroles, hot springs, etc. (**Figure 1**).

The Earth's thermal energy is vast, and only a small fraction has been used due to the limitations set by geological conditions (e.g., permeability) which impair the transportation of water in liquid or steam phase. The geothermal gradients reflect the movement of heat from deep areas toward the outer crust, which produces different changes in temperature at a different depth [17–19].

The geothermal resource has multiple applications according to the temperature and the enthalpy it represents. The temperatures of the fluid that vary in intervals of 100°C per kilometer are called systems of medium or low enthalpy. These resources are used directly or to create electricity with binary systems. When the temperature is higher than 180°C per kilometer, it is considered a system of high enthalpy. This enormous heat wave can usually heat great extensions of rock in deep settings where hydrothermal deposits or systems of hot dry rock form [20]. Hydrothermal formations rarely produce dry steam, which is ideal to produce electricity. They mostly have wet steam or geothermal corrosive brine with a high content of dissolved and suspended salts (**Figure 2**).

In the case of the hot dry rock formation, geothermal energy is used because they are generally free of fluids. A fluid is introduced in a well where the formation

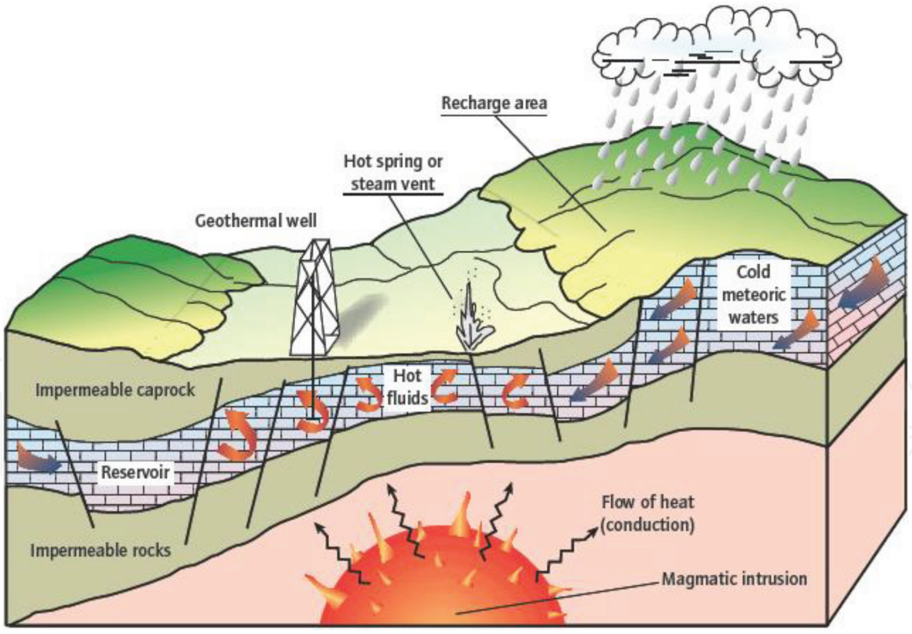

Figure 1.
Geothermal steamfield with its elements: recharge area, impermeable cover, reservoir, and heat source [17].

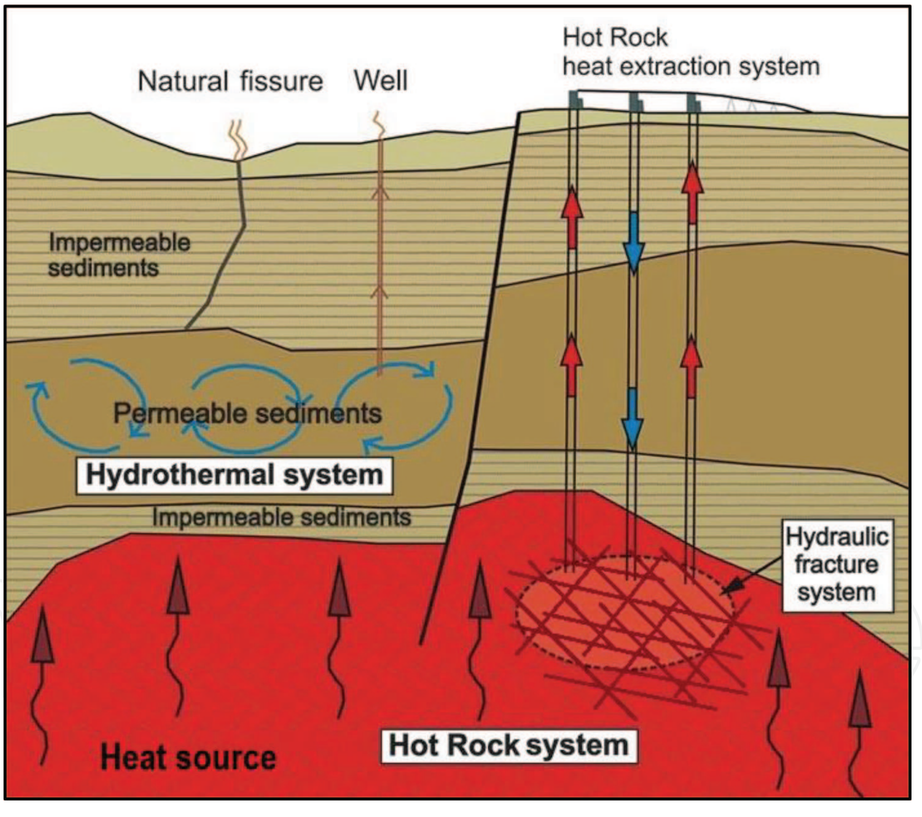

Figure 2.
Geological settings of hydrothermal and hot rock geothermal systems (modified from [21]).

vaporizes it creating a hot fluid that is collected to create electric energy. This is made through a binary conversion. For this type of formation, the limiting factors are its low permeability and low thermal conductivity that makes the exchange of heat difficult. Hydraulic fracturing has been proposed in this case to increase the superficial area available. These types of deposits are called enhanced or engineered geothermal systems (EGS) (**Figure 2**).

The different geothermal systems can be found in regions with a normal lightly superior geothermal gradient especially in places surrounding the plaque margins where the geothermal gradient can be significantly higher than average. This is the origin of geothermal resources.

Aside from a few setbacks, there are reasons to affirm that geothermal energy has a great advantage over other types of energy. For example, for its independence from climate and natural elements, it is available 24 hours a day 365 days a year, it is unmoved by the change of stations, the production area of 25 MW maximum is 1 acre, and geothermal stations are safe.

Also, it is important to point out that geothermal stations are reliable and work around 95% of the time, some even more than 99%. This can be compared to the 60%—70% for carbon-based and nuclear stations [22–24].

Geothermal energy is known as a renewable, immense, and practically inexhaustible source with a technological maturity that is solid, clean, versatile, and useful to generate electricity, among other applications [16, 25]. The use of geothermal resources has shown technical and economic viability to produce energy with a sustainable conscience, and in this context, it has been considered that the energy extracted from this system can be recuperated in a time scale similar to the process of its extraction [26]. In studies on the life-cycle analysis, it has been shown that the production of electricity affects the environment very mildly since its discharge is mainly wet steam and low gas emissions [27]. This makes it environmentally conscious.

3. Mexican case

The geothermal energy development in Mexico has been concentrating on producing energy in five geothermal electrical fields distributed around the country (**Figure 3**), from which the first four have been operated by the Federal Electricity Commission (CFE in Spanish), generating unit VI. Grupo Dragón owns the fifth field.

(a) Cerro Prieto, BC. It is the main and largest geothermal water field, and it is located in Baja California, a semiarid region, in the northwest of Mexico in the border with the USA (**Figure 4**). This geothermal field is located in a separable basin produced between the Cerro Prieto and the imperial active landslide faults

Figure 3.
Geothermal electrical fields in Mexico (modified from [28]). The fields in orange are operated by CFE, and the field in yellow is operated by Grupo Dragón.

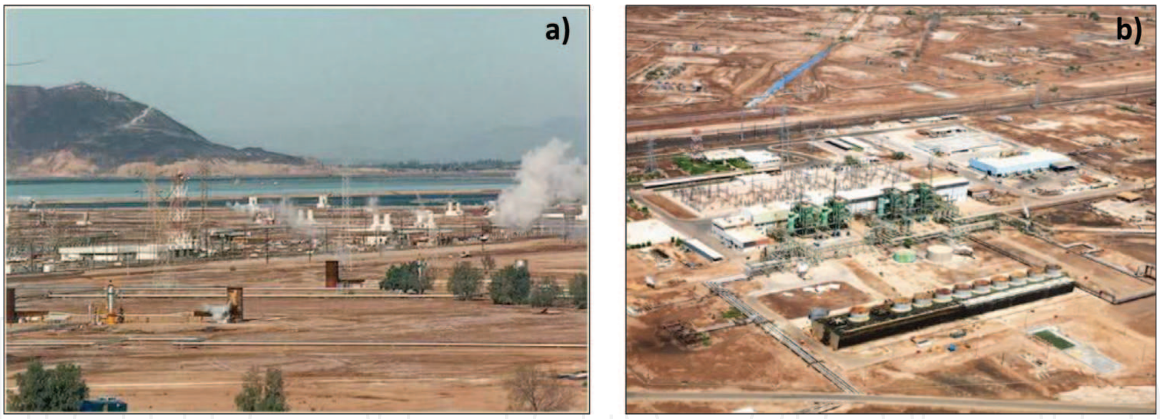

Figure 4.
(a) Cerro Prieto Geothermal Power Plant, evaporation pool, and Cerro Prieto Volcano (courtesy of CFE) and (b) Cerro Prieto geothermal power plant (courtesy of CFE).

that belong to the San Andreas Fault system. The heat source of the geothermal system is a thermal anomaly produced by a thinning of the continental crust in the basin. The geothermal fluids are contained in sedimentary rocks, mainly sandstones intercalated in a series of shales with a mean thickness of 2400 m [29].

This field is also the oldest in the country. It began working on April of 1973. By 2016, it had 150 producing wells and 30 reinjection wells. The capacity was of 570 MW made up of four flash evaporation units of 110 MW each, a low-pressure condensation unit of 30 MW, and four flash evaporation units of 25 MW each [30].

(b) Los Azufres, Mich. This geothermal field began operating in 1982. The producing rocks are of volcanic origin, typical of the Mexican Volcanic Belt which is a region covered by Pliocene-Quaternary volcanoes crossing from the Pacific Ocean to the Gulf of Mexico [31]. The field is located in a forest of pines, oyamels, and oaks, with subhumid temperate climate and semi-cold climate with summer rains (**Figure 5**).

By 2016 it had 44 producing wells and 6 reinjection wells. It is located in central Mexico, near the volcanic belt, with a capacity of 247.8 MW made up of six flash evaporation units (53.4 MW, 50 MW, and four of 26.6 MW each); it also has seven units of back pressure of 5 MW each and two units of binary cycle of 1.5 MW each. The operating capacity is 224.8 MW, since four of the back pressure units and two of the binary cycles are out of service [30].

(c) Los Humeros, Pue. This field began operating in 1990 and is located in central Mexico. This geothermal system is contained within volcanic rocks. The field lies in a Quaternary caldera. The geothermal fluids are hosted by tertiary

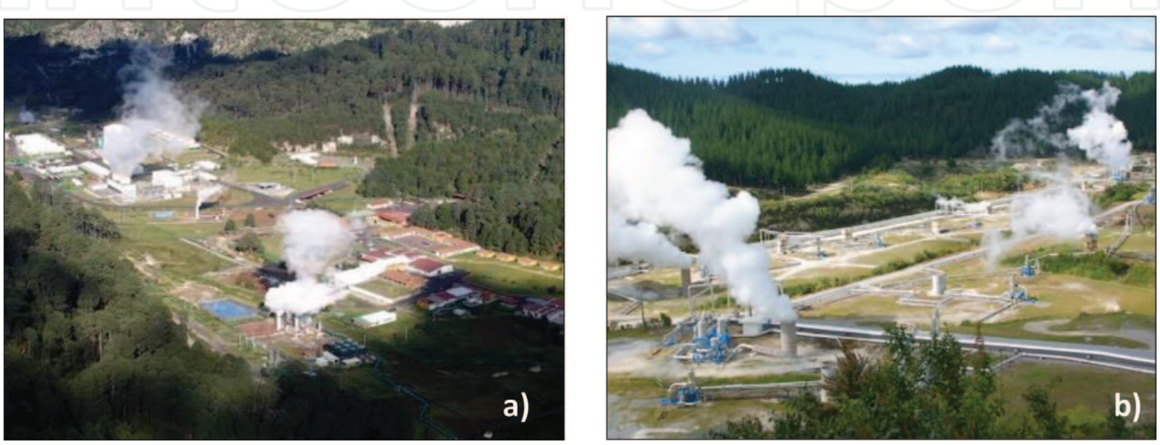

Figure 5.
(a) Los Azufres Geothermal Power Plant (courtesy of CFE) and (b) Los Azufres geothermal power plant (courtesy of CFE).

andesites, and the heat source is a magma chamber. This reservoir presents lower permeability than Los Azufres, but the temperature is up to 400°C in some wells, which is the highest, recorded in Mexican reservoirs [31]. The wells in Los Humeros produce usually low brine that is returned to the reservoir by injection wells [29]. In **Figure 6**, there are two pictures showing two different units of the geothermal power plant, some producing wells.

The power plant by 2016 had a capacity of 93.6 MW, with 23 producing wells and 2 of reinjection. It is made up of eight back pressure units of 5 MW each. The operating capacity is of 68.6 MW, since five of the back pressure units are out of service [30].

(d) Las Tres Vírgenes, BCS. This field is located in the north of Baja California Sur, in the Vizcaino Biosphere Reserve, and began operating in 2002. Las Tres Vírgenes is inside a Quaternary volcanic complex composed of three N-S aligned volcanoes. The heat source is related to the magma chamber of the La Virgen volcano, the youngest and southern of the volcanic complex. The geothermal fluids are hosted by intrusive rocks [29], with a low secondary permeability. These rocks are part of the regional intrusive basement and are overlain by volcano-sedimentary rocks [31].

By 2016, it had three producing wells and two reinjection wells with a capacity of 10 MW. It has two flash evaporation units of 5 MW each and a binary cycle of 2 MW to be built in the future [30]. In **Figure 7**, there are two pictures showing one unit of the geothermal power plant and a panoramic view.

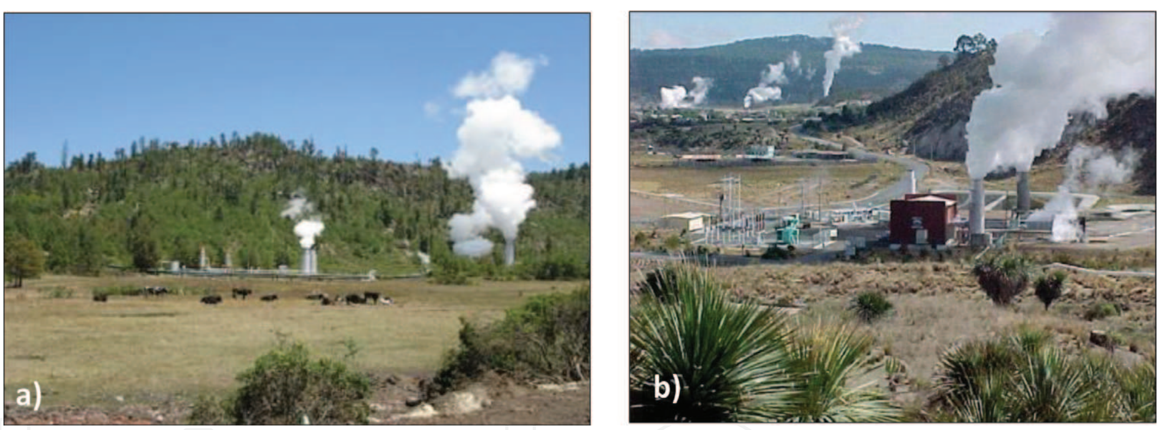

Figure 6.
(a) Los Humeros Geothermal Power Plant (CFE courtesy) and (b) Los Humeros geothermal power plant [32].

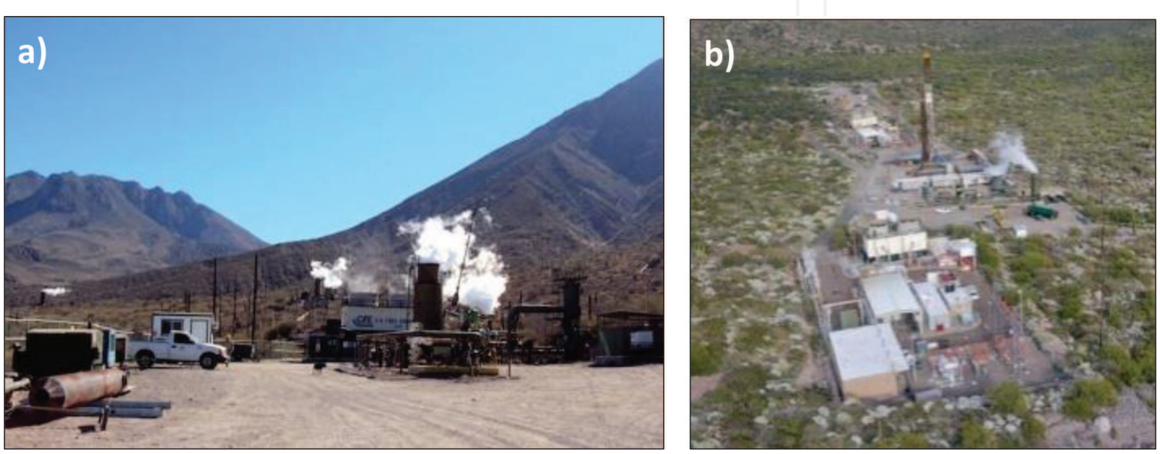

Figure 7.
(a) Las Tres Vírgenes geothermal power plant [33] and (b) Las Tres Vírgenes geothermal power plant [34].

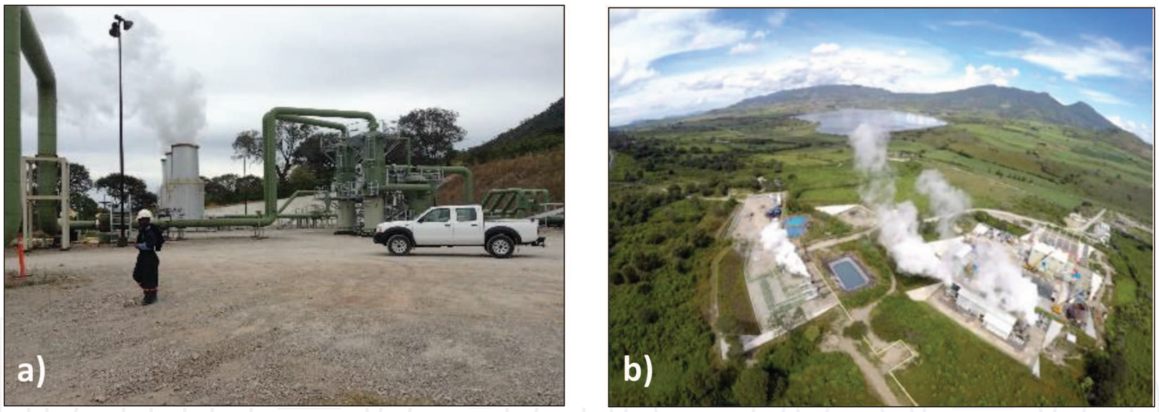

Figure 8.
(a) El Domo de San Pedro geothermal power plant [35] and (b) El Domo de San Pedro geothermal power plant (courtesy of Grupo Dragón).

(e) Domo de San Pedro, Nay. It is the most recent geothermal electrical field and started its operations in February 2015. It is the first geothermal field operated by a private producer Grupo Dragón. The field is currently operated for self-consumption, meaning that the energy is consumed by the entity that owns the plant, although not necessarily in the same location [35]. By 2016, it had a capacity of 35.5 MW, with four producing wells and three reinjection wells. It is made up of a flash evaporation unit of 25.5 MW and two inverse pressures of 5 MW each [30]. (**Figure 8**).

4. Gas emissions

Gas concentrations in the geothermal fluid vary according to the characteristics of the deposit that runs through the conventional geothermal cycle in energy stations. It has a certain amount of non-condensable gases (NCG) (CO_2, H_2S, NH_3, N_2, CH_4, etc.). These gases represent approximately 95% and the 1–2% maximum of the NCG content on geothermal fluids, respectively. The NH_3 and H_3BO_3 gases, which are water soluble, are mainly found in the aqueous phase, are transported to the atmosphere through the air separation (NH_3), and derive (NH_3 and H_3BO_3) from the cooling towers [36, 37].

The quantity and type of hydrogen sulfide reduction required in a geothermal energy plant vary considerably depending on the characteristics of the reservoirs and the design of the geothermal energy plant. The corresponding concentration of H_2S can vary dramatically from one reservoir to another and from one well to another within the same reservoir [38, 39]. The amount of H_2S that must be eliminated will depend on the specific environmental, health, and security requirements from the area in which the geothermal energy plant is located. The environmental regulations in the USA and Europe are very demanding since H_2S has a very low odor range and is very toxic in small concentrations 10–500 ppb [40]. Therefore, since the escape points of these devices are not generally high, it is conceivable to have odor or even lethal concentrations on the ground level [41–44].

In Mexico, there are no regulations for H_2S emissions in the geothermal industry. However, there is one for occupational exposure, which is of 15,000 μg m^{-3} within 8 h [45], in contrast to what the World Health Organization recommends which is 150 μg m^{-3} within 24 h [41].

The results of the H_2S emissions from the geothermal electrical fields from the Pollutant Release and Transfer Register (PRTR) of 2006 are shown in **Table 1**. From this table we can see that the geothermal electrical field with the highest H_2S

Site	ton H_2S /y	GWh/y	KWh/y	ton H_2S /KWh	g H_2S /KWh	g eq SO_2 /KWh*
Cerro Prieto	7136	3670.36	3,670,360,000	1.9442E-06	1.9442	3.65
Los Azufres	4588	1801.13	1,801,130,000	2.5472E-06	2.5473	4.78
Humeros	1570	507.66	507,660,000	3.0922E-06	3.0922	5.81
Tres Vírgenes	61	53.63	53,630,000	1.1392E-06	1.1393	2.14

**Acidification potential equivalent factor 1 g H_2S = 1.88 g eq SO_2 [53].*
Data reported by [52].

Table 1.
Calculations of H_2S emissions in 2016 of geothermal energy in Mexico.

emissions is Cerro Prieto. However, when the emissions are measured in KWh, the highest is Los Humeros, Pue. In addition, when calculating the acidification potential equivalent factor, which gives an overview of the possibility of causing acid rain in the area where the H_2S emissions are, the Los Humeros field is the one with the most potential for acidification, followed by Los Azufres, Cerro Prieto, and Las Tres Vírgenes. In the bibliography, the range of potential is located between 0.2 and 0.7 g eq SO_2 KWh-1 [46], but the reports come from enhanced or engineered geothermal systems (EGS) and geothermal life-cycle analysis normally coming from binary stations, which in theory should not have emissions to the atmosphere [47]. Even though the results shown in **Table 1** are emissions from the operation of geothermal electrical stations in 1 year, it is the first time they have been shown for this type of deposit. Aside from operation, the only stage where this type of gas is emitted is during perforations for the geothermal wells. These results evidently show that new technologies to lower H_2S emissions are needed [48–50] even if there are no any strict regulations like in other countries.

For example, H_2S emission control systems have been developed in Iceland, since its regulation is of 50 μg m^{-3} average in 24 h [51].

CO_2 emissions occurring during operation in geothermal electrical fields in Mexico in comparison to fossil fuel energy stations are presented in **Table 2**. On this table, it is shown that the plant with the highest CO_2 emissions per KWh is Los Azufres in contrast to other three geothermal electrical fields in Mexico. These values will include the emissions from natural gas-fueled stations; therefore, both technologies can be considered clean. In comparison to the carbon- or petroleum-fueled stations, the CO_2 emissions are lower.

Site/energy type	Tons CO_2/y	GWh/y	KWh/y	ton CO_2/KWh	g CO_2/KWh
Cerro Prieto	242,417	3670.36	3,670,360,000	6.6047E-05	66.05
Los Azufres	332,771	1801.13	1,801,130,000	1.8475E-04	184.76
Humeros	29553.857	507.66	507,660,000	5.8215E-05	58.22
Las Tres Vírgenes	1509	53.63	53,630,000	2.8137E-05	28.14
Geothermal (average)	606250.857	6032.78	6,032,780,000	1.0049E-04	84.29
Coal (a)					315
Oil (a)					260
Natural gas (a)					182

(Data reported by [54]): (a) [55].

Table 2.
Calculations of CO_2 emissions of renewable energies in Mexico.

The spread of the gas emissions depends on the meteorological conditions, the orography, the altitude of the emission points, and the gas temperature. Non-condensable gases are mainly emitted from the condenser after the reduction and the cooling towers' exit. If the recollection system is not efficient enough in redirecting the geothermal fluid from one plant to another, emissions might happen during the well drilling (discharge and degasification) and the plant's closing (free steam discharge). For this reason, it is required to make an environmental evaluation that would result in the start of an environmental project to predict and evaluate the consequences that might come from it and measure the possible damage caused around the area to dictate correcting measures or minimize the effects and impact [56].

A summary of the potential factors of climate change is shown in **Table 3**, based on the evaluation of the life cycle of renewable energies around the world. In this table, we can observe that the hydrothermal systems have more CO_2 emissions than the EGS. Within the EGS, the cogeneration and hot dry rock systems are the ones with less CO_2 emissions from all renewable energies, according to this table. In comparison to nuclear energy, binary stations emanate approximately the same emissions even though the hydrothermal systems emit a greater quantity of CO_2 per

Energy type	Conversion efficiency (%)	GWP g CO_2eq/KWh	Country	References
Geothermal energy				
Hydrothermal systems	n.r.	50–70	USA	[47]
Enhanced geothermal system (base case)	12 (ORC)	36.7	France	[58]
Binary plant	n.r. (ORC)	24.73–35.99	France	[59]
	9.7	42–62	Germany	[60]
Cogeneration plant	n.r. (ORC)	3.57–3.39	France	[59]
Hot dry rock	n.r.	3.39–3.57	France	[59]
Nuclear energy				
Fission power generation	33	22.25	Singapore	[61]
Solar panels				
Monocrystalline silicona	13.8	44.7	Italy	[62]
Polycrystalline silicona	13	72.4	USA	[63]
	14.4	8.74	Italy	[64]
	12.5	63	Germany	[65]
Amorphous silicon	6.3	34.3	USA	[63]
Wind turbines				
Onshore	90	7	Denmark	[66]
Horizontal axis	n.r.	12	Thailand	[67]
		179	New Zealand	[68]
Vertical axis	n.r.	46	France	[69]
Offshore	85	11	Denmark	[66]

Organic Rankine cycle (ORC); n.r., not reported.

Table 3.
Global warming potential (GWP) of life-cycle assessment for different renewable energies worldwide.

KWh in the production of electric energy. In the case of solar panels and wind turbines, while operating, there are evidently no gas emissions to the atmosphere. However, emissions occur during manufacture, transportation, installation, and disposing of the technology. When evaluating the life cycle of these technologies with a given life span of 25–30 years, then we can say that there are emissions of CO_2 per KWh in the production of electric energy. Some solar panels are even above the GWP reported for some binary geothermal stations or hydrothermal geothermal systems. This is the case for wind energy as well.

Now, in the matter of the efficiency of the technologies to convert to electric energy, it is seen that wind turbines are very efficient in comparison to the rest of the reported technologies. In the case of binary thermal stations, it varies in relation to the enthalpy of geothermal water and the external temperatures that can affect the energy necessary for cooling [57].

5. Environmental impact

The first formal lines to define the environmental characteristics related to geothermal development were published in 2016. There, the best practices to follow in the most important phases of a geothermal project were given, particularly in relation to creating electric energy and what is required for deep well drilling [70]. The development of sustainable energy is an emerging paradigm that implies the reduction of negative environmental impact and the efficient use of geothermal resources for long periods of time [71].

This emphasizes the need to establish new guidelines in public policy to include a simulation of the efficiency in energy production to ensure a reliable supply, security and energy diversity, economic efficiency, research development aid, and the development of improved technologies. Thereon, the term "renewable" is given to the resource, as well as the type of energy, and it implies a rhythm in which the system naturally rebuilds itself. The scale of time in which a natural geothermal system recharges is the main criteria to evaluate if the resource and geothermal energy are considered renewable; if the extracted geothermal energy is naturally substituted by an additional quantity of energy and this process takes place in a time period similar to the extraction time, then it will be renewable [72].

However, it is important to highlight that the use of geothermal energy does not only imply maintaining the production of each geothermal system individually. This is because sustainable development must incorporate all the aspects of human necessities and activities. Actually, sustainable usage implies an economic, social, and environmental integral development, just like the battle against climate change. Even then, the level of sustainable production of a geothermal resource increases with time as the knowledge on the resource also increases with technological advances. This means that, with exploration and continued monitoring, new exploration methods with innovative drilling technologies and efficiency may traduce in the increment of the production capacity of a geothermal well [73].

6. Challenges

The challenges in converting to sustainable energies are focused on providing access, particularly increasing the efficiency, minimizing the environmental impact, and promoting social acceptance and security. Although geothermal projects have a disadvantage in the long wait for development and high initial costs, this source of energy has a great increase in potential in the upcoming decades, and it is important to promote energy independence and reduce the use of fossil fuel by-products. Since geothermal energy is typically considered renewable, these resources must be ensured for future generations. This means that they must be renewed in time lapses acceptable for human societies. Thereon, the premature exhaustion of geothermal resources and the life span of a geothermal resource refer to the amount of time a geothermal resource can be exploited to produce electricity commercially. This brings up the matters of sustainability and energy security.

7. Conclusions

In a world that has shown great concern for the environment, there is also a greater attention to consider clean and sustainable sources of energy, such as geothermal. However, different technologies used in the production of geothermal energy result in different types of emission values to the atmosphere. The environmental effects of developing geothermal energy are linked to how geothermal energy stations operate. For example, the liberation of non-condensable gas is a problem in intermittent steam energy stations but not in binary fluid stations because it is not expected to have non-condensable gas as long as the geothermal fluids are pressurized. One of the disadvantages of the binary fluid stations is the need of external sources of refrigeration water.

Geothermal resources can be considered renewable as long as the system maintains a balance in regain with the help of cold or warm reinjection of the geothermal brine. Generally, the environmental impact from creating electric energy from geothermal resources is far less than other types of renewable, clean energies. One of the emissions that must be looked after is hydrogen sulfide, which is contained in most geothermal steam sources, as well as carbon dioxide, which have an impact on natural vegetation, habitants, and crops near the geothermal central at an approximately 5 km radius.

Due to the likelihood of expansion in geothermal energy in the further years, it will be needed to standardize the compliance of different environmental laws by incorporating environmental regulation guidelines in the process of policies and decision-making to create strategies to guide the geothermal development and ensure sustainable development and to also accept the need to conceptualize the relationship between economic development and natural and preservation of energy resources by providing a foundation to write legislations on geothermal resources around the world, from geothermal development and exploration to abandoning deposits.

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