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A COMPREHENSIVE REVIEW ON THE INTEGRATION OF GEOTHERMAL-SOLAR HYBRID ENERGY SYSTEMS FOR HYDROGEN PRODUCTION

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Nomenclatures

ACS	Absorption cooling system
AC	Alternating current
BTES	Borehole thermal energy storage
CCS	Carbon capture and storage
CPUE	cost per unit exergy
CSP	concentrated solar power
DC	Direct current
EGS	Enhanced Geothermal Systems
EVs	Electric vehicles
GE	Geothermal energy
GHE	Ground heat exchanger
GHG	Greenhouse gas
GPP	Geothermal power plant
GSHP	Ground source heat pump
GTES	Ground thermal energy storage
HTE	High-temperature electrolysis
ITHs	Internal heat exchangers.
LCOE	Levelized costs of energy
LHV	Lower heating value
LNG	Liquefied Natural Gas
MGS	Multi-Generation System
NG	Natural gas
ORC	Organic Rankine Cycle
PEC	Photo-electrochemical
P2H	Power-to-hydrogen
PVE	Photovoltaic electrolysis
RE	Renewable energy
RESs	Renewable energy systems
RC	Rankine cycle
SC	Solar collector

Abstract

An integrated system, harnessing solar and geothermal resources, is presented and evaluated. This review aims to produce H_2, from solar-geothermal resources. This integrated renewable energy system comprises solar PV/T modules as well as geothermal energy for H_2 synthesis. A review was carried out to examine the impact of different system design parameters on the energy and exergy efficiencies of both the overall system and its subsystems. Geothermal-solar hybrid systems for H_2 production integrate geothermal energy and solar power to create a sustainable and efficient method for hydrogen generation. These systems capitalize on the continuous and stable heat supply from geothermal sources combined with the intermittent yet potent energy from solar radiation. By leveraging the strengths of both energy sources, the hybrid system can achieve higher efficiency and reliability in hydrogen production. Geothermal energy provides a consistent base load, reducing the dependency on solar energy's variability, while solar power can be used during peak sunlight hours to boost production. This synergy not only enhances the overall energy output but also reduces GHG emissions, making it an environmentally friendly solution for meeting the growing demand for clean H_2.

Keywords: Geothermal Energy; Energy Efficiency, Exergy Efficiency; Hydrogen; Thermodynamic Analysis.

1. INTRODUCTION

The use of renewable energy (RE) is growing steadily due to the negative impact of fossil fuel sources on the ecosystem. Although there has been an increase in the utilization of RE, crude oil continues to be a significant contributor to energy production, accounting for around 82 % of the total energy generated [1]. CO_2 emissions, which are primarily responsible for recent climate changes, arise mostly from the combustion of fossil fuels. Considering the need for an alternative fossil fuel, it is important to explore the possibilities of using RE as geothermal and solar energy resource [2 - 3]. Geothermal energy (GE) is regarded as an attractive renewable energy source that may be used for many purposes such as generating electricity, providing heating and cooling, or producing H_2. The use of geothermal sources is mostly determined by the source of temperature. Geothermal resources with temperatures equal to or more than 150 °C are often used for generating electricity. Geothermal resources with temperatures ranging from 90 to 150 °C are well-suited for direct uses such as heating/cooling spaces, as well as other activities such as fish farming and aquaculture. Geothermal resources with temperatures equal to or less than 90 °C are also suitable for these direct applications. Utilizing high-temperature GE for multi-generation applications is clearly preferable. Producing many outputs from a single source will enhance the system's efficiency and improve its cost-effectiveness [5]. Researchers worldwide have lately shown interest in the multi-generation capacity of GE [8]. Non-condensable gas emission is a significant environmental concern when employing geothermal working fluids for power generation. The vent stacks in geothermal plants release CO_2 and CH_4, which are particularly worrisome due to their contribution to greenhouse gas (GHG) emissions [9]. The emissions from these sources are somewhat insignificant relative to those from fossil fuels, suggesting that their impact is essentially minimal [3]. Geothermal power facilities release elevated levels of hydrogen sulphide since it is a major component of geothermal fluids. This raises issues for both human health and the ecosystem [7]. Over a period, the geothermal resources might be exhausted, resulting in a decrease in energy production if not properly managed. The economic feasibility of manufacturing H_2 utilizing GE may be compromised due to its relatively higher cost when compared to other technologies. The present technique for transforming GE into H_2 is comparatively less efficient than other processes, such as electrolysis using wind or solar energy.

On the contrary, H_2 has emerged as a clear option for a carbon-neutral economy due to its ability to release no harmful substances into the environment (zero carbon) and

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therefore not encourage global warming [6], particularly when produced from renewable sources. In order to achieve greater efficiency, it is necessary to enhance the design of renewable-based energy systems [10]. An effective method to do this is to organize the system by using the methodologies of co-generation and particularly multi-generation. Multi-generational technologies offer improved efficiency, cost-effectiveness, and environmental benefits, leading to enhanced sustainability [4, 9]. Numerous studies [3 – 6, 8, 10 – 14] have been conducted on multi-generation technologies that rely on RE sources. Al-Ali et al. [15] proposed a system that combines geothermal and solar energy sources to provide several forms of energy production, including hot water, cooling, industrial heat, and electrical power. Extensive thermodynamic assessments were performed to evaluate the effectiveness of single generation, cogeneration, trigeneration, and multigeneration systems using exergy and energy techniques. The purpose was to evaluate the findings and demonstrate the efficiency of each technology. The energy efficiencies of single and multigeneration systems were determined to be 17.5 and 77.8 %. Similarly, the exergy efficiencies obtained were 27.1 and 37.2 %. Ezzat et al. [8] presented a novel energy technology that combines solar and geothermal sources to provide many forms of energy. Their technology comprises heat pump system, cooling system, drying system, thermal energy storage, a solitary flash geothermal cycle, hot water system, and a single-effect absorption. The primary objective of the research is to achieve five specific outcomes, which are cooling, electricity, hot water, drying, and heating. The total energy and exergy efficiencies were determined to be 70.01 % and 43.2 % respectively. Bicer and Dincer [13] presented an innovative technology that combines solar-geothermal energy to produce H_2, which consists of Pressure-volume/Temperature modules designed for H_2 production, heating, as well as GE sources used for cooling, electricity production. An evaluation was conducted to examine the efficiency of the cycle, specifically focusing on energy and exergy. The study also investigated how different system variables influenced the exergy and energy efficiency of the complete system. The findings indicate that the combination of systems may achieve energy and exergy efficiency up to 11.02 and 45.4 %, when the geothermal water temperature is 210 °C. Akrami et al. [1] developed a geothermal multigeneration energy technique to produce H_2, heating, electricity, and cooling, all at the same time. The mechanism comprises a domestic water heater, PEM electrolyzer, an ORC, and an absorption refrigeration cycle. The system was subjected to thorough energy and exergy evaluations, in addition to exergo-economic assessments. They examined the generator temperature, turbine inlet temperature, geothermal water mass flowrate, turbine inlet pressure, geothermal water temperature, and electrolyzer current density, on various parameters such as energies and exergies efficiency of the proposed system. The integrated system's energy efficiency was found to be around 35.88 %, while its exergy efficiency was determined to be around 49.22 %. Yuksel, et al. [9] proposed an integrated system that utilizes geothermal energy to generate hydrogen, heating, electricity, cooling, and domestic hot water. Energy efficiency, exergy destruction rates, and energy efficiency were established for both the whole system and its individual sub-systems. The findings indicate that the system's energy efficiency is 38.96% and its exergy efficiency is 44.87 %. Nikolaidis and Poullikkas [14] conducted research to compare the generation of

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H_2 from renewable resources. Supercritical gasification of biomass is recognized as the most efficient thermochemical method for producing H_2, based on their research. It has been observed that the cost of manufacturing H_2 from GE is lower compared to solar and wind power. Mehrpooya et al. [12] examined a composite system that incorporates an NH_3-H_2O absorption cooling sub-system, SOFC – gas turbine power plant, and a Rankine steam cycle. The suggested system is analyzed using energy and exergy techniques, as well as from an economic standpoint. Furthermore, the electrochemical model of the fuel cell that formed has been confirmed as accurate via the use of experimental data. Their findings indicate that the electrical efficiency of the combined system is 63.4%. Huang et al. [16] assessed the performance of a low temperature Organic Rankine Cycle (ORC) using R245fa as the working fluid. The use of the evacuated solar collector resulted in an overall power production efficiency of 4.3 %. Their findings highlighted the feasibility of using R245fa in a low-temperature solar energy-ORC system, with a satisfactory level of performance. Li et al. [17] have provided a thorough examination of hybrid solar geothermal systems. In their study, a thorough analysis was conducted on the various combinations of solar thermal, solar-PV, concentrating solar energy, and geothermal energy systems. The researchers provide an overview of the basic principles behind these systems and discuss the most recent advances in this field of study. They recognised that the incorporation of solar-geothermal power is very appealing from an energy perspective. Geothermal-solar energy integration is extensively studied and widely implemented, particularly in volcanic regions with abundant solar power. Solar energy may enhance GE by supplying extra energy during periods of strong sunlight, resulting in increased overall energy generation and enabling larger capacity for H_2 synthesis [18 – 20]. This combination method may alleviate the constraints of merely depending on geothermal resources. Integrating solar energy may facilitate the allocation of capital expenses and alleviate the financial strain linked to the development of geothermal wells [21]. It has the capacity to enhance the overall sustainability and efficiency of the systems by reducing the negative environmental impacts compared to GE extraction for hydrogen generation [22]. Astolfi et al. [23] conducted a review to examine the benefits and cost analysis of integrating solar and GE systems. They found that the notion of a solar-geothermal hybrid might be a promising prospect for generating power at a reduced cost. In addition, a previous study conducted by Suleman et al., 24] has verified that the integration of solar and GE offers several benefits. These include mitigating the disparity between energy demand and supply, reducing overall costs, enhancing overall efficiencies and minimizing emissions throughout the life cycle. H_2, which may be generated from renewables, is seen as a potentially major energy carrier in the future [24]. This research examines the manufacturing of hydrogen (H_2) using geothermal-solar energy. The main objective of this review is to provide a concise overview of the existing methods used in H_2 production, with a particular focus on the techno-economics, thermodynamics, and environmental consequences associated with solar-GE-assisted H_2 production. GE resources and characteristics/properties of H_2 are presented and discussed in detail in Sections 2 and 3, while Section 4 focuses on geothermal and geothermal hybrid systems integrated to producing H_2. Sections 5 discusses the applications/uses of H_2, while Section 6 covers the economic and

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environmental impact of the hybrid- system. Section 7 presents the future direction on the geothermal hybrid systems. Lastly, section 8 summarizes the conclusions and recommendation (s).

2. HYDROGEN PRODUCTION TECHNOLOGIES

3. GEOTHERMAL ENERGY SYSTEMS

GE is regarded as the most dependable and stable resource amongst all renewable energy systems (RESs) due to its high level of independence from the surrounding environment [25]. The integrity of the GE relies on several parameters, including grout material, depth, load and soil characteristics. GE has a broad range of applications, including cooling, energy storage, electricity generation, and heating (as shown in figure 1) [22, 26]. GE systems may be categorized as either shallow or deep, each requiring the construction of a production-injection well and ground heat exchanger (GHE). GE typically uses a ground source heat pump (GSHP) for heating and cooling, which operates on the traditional refrigeration cycle and is an enhanced version of the air source heat pump [6]. To do this task, GHE installation is necessary. The GHE comes in three main arrangements: horizontal, coiled, and vertical [27]. The coiled GHE may also be seen in the configuration of slinky and spiral/helical geometry. In GE systems with limited depth, it is necessary to encase GHE with grout material. This serves the dual purpose of safeguarding the heat exchanger from damaging and facilitating efficient heat transmission [28]. Therefore, it is essential for the group to possess both a high level of heat conductivity and mechanical strength. The selection of grout material may also impact on the necessary dimensions of the GHE and its initial cost. Phase change materials are currently used as contemporary substitutes for grout materials in order to enhance performance and provide greater reliability. A borehole heat exchanger (11,17,29) is an installation that combines grout with GHE. The earth-air heat exchanger is a less often used form of GE system for cooling and heating purposes [30]. This process involves the circulation of air under the earth by means of a conduit, facilitated by a blower or fan.

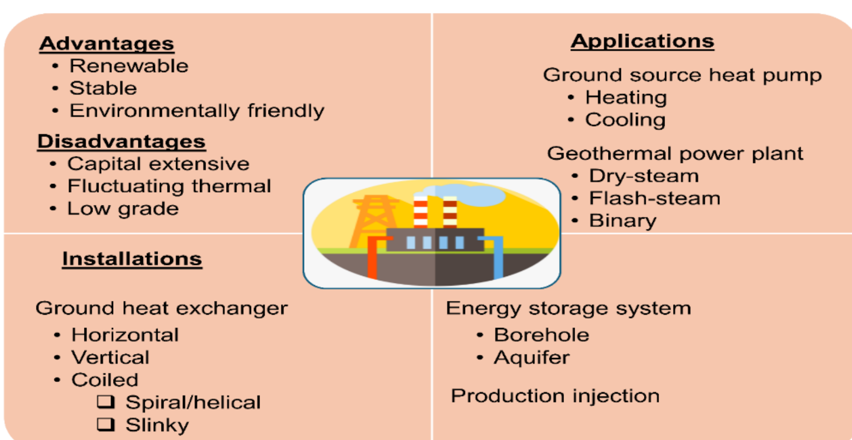

Figure 1: Properties of geothermal energy-related systems.

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In addition, the earth serves as a source of energy and can be used to store energy. Ground thermal energy storage (GTES) may be classified into borehole [22] and aquifer thermal [31]. These systems primarily store surplus energy from RES sources for later use. Using borehole thermal energy storage (BTES) to store heat from the ground has the advantage of reducing total energy loss since the earth itself is a well-insulated container [32]. Using the GTES as a seasonal BTES in combination with solar power has been shown to be significant in many investigations [16]. Energy may be transferred from the solar collector (SC) to the GHE with the help of a heat transfer fluid. This has the potential to increase the earth's efficiency and compensate for the heat that is removed from it [33]. Currently, the geothermal power plant (GPP) is the most recognized GE technology [12]. The GPP primarily relies on extracting high-temperature geothermal fluid from deep rock formations to drive the energy generation process, before returning it to the earth by reinjection. In general, GPPs may be classified into three main types: flash steam, binary cycles, and dry steam [34]. The dry and flash steam uses the geothermal fluid based on its existing properties, with the former being utilized when the fluid is present in the form of steam [35]. Nevertheless, flash steam harnesses the energy of hot geothermal water and transforms it to steam. One way to achieve this is by using a flash separator, which isolates the water and steam. This enables the steam to pass through the turbine(s) and generate electricity [36]. Flash cycles are primarily seen in the configuration of single and double, when one or two separators are employed, the multi-flash cycle, developed by investigators [23, 30, 33, 35, 36], is designed to function with multiple separators. This will optimize the extraction of electricity from the geothermal fluid prior to reinjection. Contrarily, the binary GPP does not necessarily use geothermal fluid, instead relying on flash cycle and steam. The primary focus is on the activation of an ORC, particularly when using a GE source with low-grade characteristics [37]. In this scenario, the geothermal fluid will heat the working fluid by flowing via a heat exchanger. The selection of a working fluid is a crucial factor in the cycles associated with these GPPs. The two indicated GPPs are of the typical kind; yet many changes have been implemented to these cycles in order to boost the efficiency of the systems. One approach that may be regarded as a heat recovery sub-system is the addition of internal heat exchangers (ITHs) [38]. Within the GPPs, there are two distinct methods for integrating the ITHs: recuperators and regenerators. The primary function of the ITHs is to facilitate the transfer of heat between the fluid that is leaving the turbine and the fluid that is leaving the pump. One way to improve GPP is by combining two cycles. In this configuration, the flash-steam is the primary cycle, while the binary cycle is the secondary cycle [19, 31, 39]. The primary concerns associated with shallow GE systems are variations in temperatures and thermal imbalance fluctuations [25]. When the demand exceeds the capacity of the geothermal source, the earth will not be able to replenish the energy that is captured. This will result in asymmetry in the ground, which may appear as either excessive heat buildup or a decrease in thermal energy, regardless of the specific use case. Therefore, an additional source might be used to create a hybrid GE system. It is important to avoid contamination of the earth or temperature imbalances and maintain consistency in terms of performance. The solar-geothermal combination is a widely used hybrid system that includes both geothermal and solar energy [14, 26, 40]. Studies have

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shown significant interest in this particular kind of hybridization because of its reliance on RES. Solar energy, which aligns well with the heat recovery requirements of the earth, has been particularly favored in this regard. Incorporating an additional source is advantageous in low-grade deep GE systems since it enables the geothermal fluid's temperature (s) to become acceptable for energy production.

2.1. Working fluids

Selecting a working fluid is crucial when it comes to GE-driven systems employed to produce H_2. Geothermal binary cycles often use ORC since the geothermal fluid typically has a low temperature in most instances [41]. Organic fluids could initiate power cycles using low-grade energy sources due to their favorable operating conditions. ORCs use fluids with lower boiling points than those used in traditional Rankine cycles. Ghaebi et al. [42] integrated a regenerative ORC into a geothermal co-generation with the purpose of generating electricity and H_2. Out of the working fluids that were evaluated, R245fa was best amongst others, with exergy and energy efficiencies of 67.54 and 3.412 %. Cao et al. [43] used parametric analysis to identify the right working fluid for GE-based H_2 generating systems. Based on their analysis, the scientists concluded that R123 is the most effective working fluid, next to isopentane. Specifically, R123 resulted in H_2 generation of 12.02 g/s, while isopentane resulted in 11.91 g/s. Isopentane had the lowest cost per unit of exergy at a rate of 37.00 $/GJ. The extracted electricity and geothermal water temperature have a significant impact on the cost and production. A comparison of working fluids by Gholamian et al. [44] found that R114 is best. Due to its cost per exergy and H_2 production, it is the most cost-effective working fluid. The system generated a total of 303.2 kgs of H_2/day, achieving an exergy efficiency of 56.22%. The system consisted of a PEM electrolyzer, geothermal-ORC, and a thermoelectric generator. The above combination results in a decrease in the cost of the product since the pace at which H_2 is produced is often directly related to the degree of superheating at the turbine intake. ORCs may employ zeotropic mixtures as working fluids to increase net output power and H_2 generation [45]. The mixtures may consist of multiple fluids, including isopentane, C_6H_{14}, R254fa, C_3H_8, C_4H_{10}, Butene, and iso-hexane. Compared to pure fluids, zeotropic blends reduce heat exchanger irreversibility. This reduction is mostly influenced by the mass fractions. The proportion of fluids used in the combination may also regulate the quantity of H_2 generated, thermal efficiencies and exergy extraction [10, 46]. For instance, selecting fluid that has a low boiling point enhances the production of H_2 and the extraction of exergy. Nevertheless, the thermal efficiency of the ORC is superior when using fluids having a higher boiling point. The environmental effect is a crucial consideration when selecting the working fluid. Energy-related systems often release significant quantities of carbon dioxide, which is considered as the most hazardous contaminant [15, 23, 47]. Therefore, carbon capture and storage (CCS) has been often used to reduce the environmental effect of this substance. Underground storage of carbon dioxide might potentially facilitate the activation of GPPs. One possible approach is to store carbon dioxide using CCS technology deep down. The carbon dioxide would be heated and pressurized rather than being emitted [16, 37]. Subsequently, the carbon dioxide might be used as a working fluid to generate H_2 with

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the assistance of GPP that will be linked to the electrolyzer [40, 45]. The combination of CCS with the GE-driven H_2 production system is an effective strategy for mitigating the environmental impact of CO_2.

4. PROPERTIES/CHARACTERISTICS OF HYDROGEN

H_2 has the most rapid burning rate among all fuels (Table 1), whether in gaseous or liquid form [44]. H_2 fuel cells provide a high-performance indication [48] considering that they are not limited by the thermal efficiency constraints of the Carnot cycle. H_2 possesses numerous benefits such as high LHV, efficient energy conversion, its capacity to be generated via H_2O splitting without emitting carbon, its flexibility as an intermediate fuel for syngas production, NH_3, etc. [49]. There are several techniques available for generating H_2. Electrolysis, natural gas reforming, photo biological process, high-temperature nuclear reactions, steam methane reforming, photoelectrochemical processes, coal gasification, and thermochemical fission are all methods used for H_2 production [50]. Converting CH_4 vapor into H_2 constitutes about 80% of the entire output. Chemical operations, such as chlor-alkali manufacture, account for 20%. Water electrolysis contributes to a minor proportion of commercial H_2 [51]. H_2 has been proposed as a fuel to help reduce global reliance on fossil fuels. It has been proposed as a means to decrease the amount of CO_2 emitted into the atmosphere [44].

Due to the use of RE resources such as GE, hydroelectric power, solar and wind energy, the production and usage of H_2 fuels is becoming more prevalent [26]. Renewable energy sources are used to produce carbon-neutral H_2, a process endorsed by organizations dedicated to conserving the environment. Most researchers are focusing on generating H_2 using renewable sources of energy.

Table 1: Properties of H_2 over other fuels [28, 32, 39. 41, 43. 45].

Characteristics	H_2	CH_4
Net Lower Heating value (MJ/kg)	119.9	45.8
Density (kg/m^3)	0.089	0.72
Auto-ignition temperature (K)	853	813
Boiling point (K)	20	111
Stoichiometry air/fuel mass ratio	34.4	17.2
Adiabatic flame temperature at NTP (K)	2480	2214
Flammability limits in air (% vol)	4–76	5.3–15

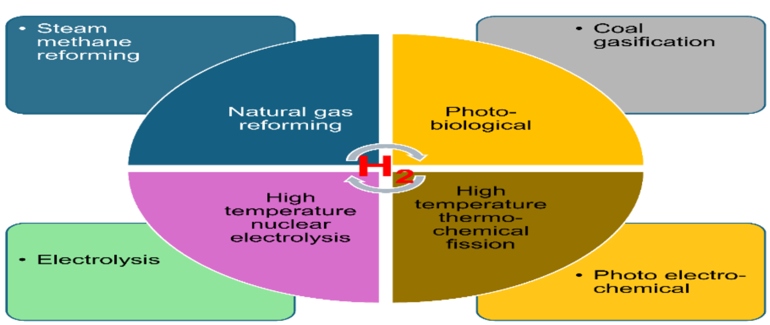

Figure 2: Hydrogen production methods.

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5. H_2 PRODUCTION PROCESSES FROM GEOTHERMAL RESOURCES

H_2 is obtained from both fossil fuels and renewable sources. Most of the H_2 is produced by burning fossil fuels. Nevertheless, the detrimental impact on the environment caused by these procedures makes them unsustainable. Additionally, these resources are rapidly diminishing [51]. In recent studies, there has been a focus on achieving ecologically friendly and pollution-free H_2 from renewable sources. This is because other options only make a little contribution to the production of H_2 [52]. The proliferation of RE sources, including wind, geothermal, solar and biofuels, has facilitated the development of more effective fuel production systems [17]. It provides a comprehensive examination of the essential methods for manufacturing H_2 from renewable sources, including electrolysis, solar, geothermal, hydro, wind and biomass. Additionally, it examines newer approaches to H_2 production from renewable energy, such as nuclear energy. Figure 4 illustrates the many techniques for producing H_2 from renewable sources.

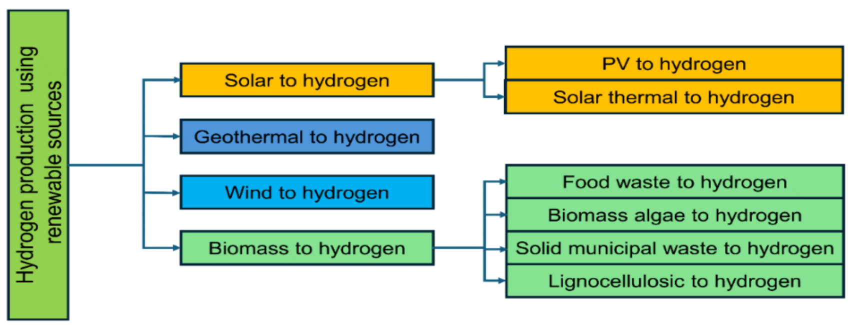

Figure 3: H_2 production methods by renewable resources.

4.1 Geothermal-to-H_2

GE is regarded as a very reliable and consistent RE source because to its ability to operate independently from its surrounding environment. GE is a sustainable energy source that is stored as heat inside the Earth's subsurface. GE has been harnessed for industrial use in areas where it is difficult to penetrate these underlying formations because of the high costs of drilling and other limitations [33]. Nevertheless, that has not been the case in other countries that have ample GE resources and where the process of pumping is less expensive. Thus, in order to bring this resource from the subsurface, a heat transfer carrier is necessary. This can be achieved in two stages: first, heat is transferred through the conduction of heat between rock formations, and subsequently, through heat transfer rate, an additional heat is provided to the ground [51 - 53]. Shallow and deep GE systems may be used for many applications such as heating, energy storage, cooling, and power generation. GE is seen as a viable remedy for the intensifying environmental issues. This renewable form of energy is very compatible with H2 generation and offers reasonable prices [3, 55]. The use of geothermal fluid and residual heat to warm H_2O, as well as the generation of electricity, are the two main methods by which GE is employed to produce H_2. Several investigators (41, 46, 56, 57) have studied the generation of H_2 using high-temperature electrolysis. Thermodynamic computations have also been conducted, showing that the energy efficiency for H_2

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synthesis exceeds 82 %. Furthermore, GE may be utilized for H_2 liquefaction, this basis can be improved that will enable GE to be employed in various applications such as co-generation structure for geothermal heat and electricity in the absorption chiller, H_2 liquefaction cycle, and the absorption cooling system [17, 33, 45, 58]. Most geothermal-powered hydrogen generation methods use PEM electrolyzers to separate H_2O into O_2 and H_2 [47]. The water temperature is the primary factor that determines the emergence of H_2, cost and the required power in the electrochemical reaction. Minimizing the optimum temperature of the electrochemical reaction will decrease the quantity of electricity needed, hence decreasing the cost of the H_2 generating system [56].In the second step, water and steam are separated in a flash splitter, and the steam is then used to generate electricity by driving a steam turbine. On the other hand, the energy obtained from heated water through an exchange is used to generate additional energy for the production of H_2 gas. The process of producing H_2 via GE is shown in Figure 5 [29], using several catalysts to improve O_2 and H_2O splitting. Purified water may reach elevated temperatures, hence enhancing process efficiency [50]. Utilizing geothermal water at 200° C may result in a 20 % reduction in the production cost of H_2. Recent experiments (37, 47, 51, 58) have shown that electrolyzers operating at 150 °C have a high level of efficiency. However, the management of impurities, such as H_2S, remains a major challenge when producing H_2 from a GE resource [15, 36].

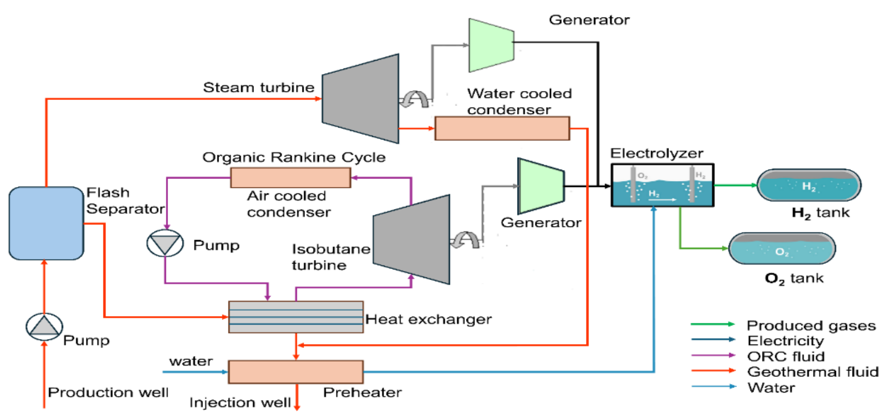

Figure 5: Process flow of geothermal H_2 production.

GE resources are a feasible option when considering the use of RE for H_2 generation. In regions where geothermal energy is widely used, producing hydrogen gas from geothermal sources might become a significant alternative [53]. Currently, the H_2 generating process can only achieve a heat input of around 200 - 250 °C when connected to a GE resource. However, it is possible that this might alter in the next decades [57]. It is important to mention that H_2 production and utilization technologies may easily be connected to GE sources and distributed energy systems. Using GE to generate H_2 may potentially reduce costs [15, 59]. Hydrogen generation utilizing GE has been the subject of many investigations [13, 45, 47, 51, 55]. In the context of H_2 generation methods in geothermal power plants, geothermal water has a dual role: generating energy via the power plant and providing heat to water. Initially, the geothermal water obtained from the

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operating well is directed via the geothermal power facility, after which the residual thermal energy is used for the purpose of heating water. Usually, a preheater is used to raise the temperature of the water that is being fed into the electrolyser [16]. The air preheater harnesses the surplus heat from the geothermal fluid and returns it to the ground. Yilmaz et al. [60] used an artificial neural network to investigate how heat affects electrolysis in a GE-powered H_2 production plant. The results from the empirical data demonstrate that as the temperature increases from 27 to 71 °C, the power required for H_2 production decreases from 44.3 to 43.1 kW/kg, resulting in a reduction of about 4.3 %. Yilmaz et al. [61] concluded that 0.245 g of H_2 is generated per kg of H_2O. The H_2 production rate was found to be 0.03 kg/s at a GE source of 165 °C and a fluid velocity of 105 kg/s. Yilmaz et al. [61] studied GE generation and H_2 liquefaction using numerous models. They establish several methodologies for conducting cost-benefit analysis of different scenarios. Based on their report, the projected range for the cost of H_2 generation and liquefaction is estimated to be between \$0.96/kg and \$2.60/kg. This study also investigated the impact of the geothermal water temperature on the costs associated with producing and converting H_2 into a liquid state. The results presented suggest that an increase in geothermal water temperature leads to a decrease in the cost associated with H_2 production and liquefaction. In addition, the capital expenses associated with models that include the liquefaction of H_2 are more compared to those that just need H_2 production.

Using geothermal fluid to generate heat, Balta et al. [55] studied an electrochemical technique that operates at high temperatures. Ingason et al. [56] examined the most efficient and economical techniques for producing H_2 only by the process of electrolysis from H_2O, using GE and hydro energy sources. The mixed integer algorithm technique facilitates the exploration of the most suitable options among a set of 24 potential power plants, consisting of 12 hydroelectric and 12 geothermal possibilities. Mansilla et al. [62] performed a techno-economic assessment of the higher heat exchanger system in a high-temperature electrochemical process for H_2 generation. Technology is connected to either a GE resource or high-temperature reactor in order to retrieve energy. The study investigates the capacity of GE in the western United States to generate power. This electricity would be used for the generation of H_2 [63]. Assareh et al. [64] examined geothermal H_2 generation units, their associated technology, and prospective uses. An energy evaluation using thermodynamics is conducted to evaluate the efficiency of a high-temperature electrochemical process that is connected to and powered by a GE resource.

The geothermal H_2-producing technique for enhanced hydrolysis has 87% and 85% energy efficiency. Arnason et al. [65] recommended the use of GE for H_2 generation on the Japanese island of Hachijo. The approach relies upon the outcomes of environmental impact study. The island will serve as a prototype for the global expansion of GE in other regions. Hai et al. [66] illustrated the process of H_2 decomposition using GE. In the context of electricity generation, an experimental binary GE plant was investigated. while the process of H_2 liquefaction was investigated using the cooled-down Linde-Hampson cycle. A methodology and set of assessments were developed for conducting such an investigation. Yuksel and Ozturk [67] conducted a study on a GE system that operates by

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generating energy and producing H_2. The research assesses how different operating conditions affect the efficiency of the systems. As the geothermal water increases from 160 to 200 °C, the energy production of the system also increases from 4.1 to 8.7 MW. The presence of H_2 affects the overall efficiency of the system.

The geothermal water temperature increased from 133 to 200 °C, resulting in an increase in the system's electrical energy output from 4.8 MW to 8.8 MW. Additionally, the generation of H_2 increased from 0.05 to 0.10 kg/s. Hadjiat et al. [68] modelled H_2 generation from a low-enthalpy GE resource. Hydrogen is generated by the electrolysis of water using this energy. The effectiveness of these methods with respect to the GE system was investigated using simulations. The system is modelled using the TRNSYS program at a spring temperature of 70 °C. According to the result, an annual output of 0.58 kg of H_2 per m^2 of thermal system was achieved.

The high-temperature electrochemical technique, which draws heat from geothermal fluid, was studied by Rahmouni et al. [69]. The techno-economic components involved in generating hydrogen gas from GE were examined by researchers. The use of geotherm H_2 produced by 1 kg of geothermal water heated to 210°C was investigated by Lund et al., [70]. Production of hydrogen from GE sources is summarized in Table 2.

Table 2: Geothermal to H_2 production studies.

Rate of H_2 produce	Assessment objective	Energy efficiency (%)	Solver	Electricity produced yearly (kWh)	Ref.
10.48 g/s	H_2 and heating fluid production	14.9	Equation Solver (ES)	2052 kWh	[71]
0.07 kg/s	H_2 and hot H_2O production	39.3	ES	–	[17]
0.07 kg/s	H_2, O_2, hot H_2O, and power production	41.5	ES	–	[14]
0.056 kg/s	Production of H_2 and liquefaction	–	ES	7922	[75]
332 tons/day	Production of H_2 and liquefaction	25.22	Aspen Plus	130000	[3]
–	Production of H_2 and liquefaction	4.91	ES	1571.1	[66]
14.4 kg/h	Production of H_2 and desalination	–	ES	3800	[20]
–	Production of H_2 and thermoelectric generation	–	ES	38.02	[61]
22.2 kg/h	Production of H_2 and thermoelectric generation	6	ES	4	[3]
0.38 kg/h	Production of H_2 and thermoelectric generation	19.8	MATLAB	–	[35]
3.5 Mkg/year	Production of H_2 and CO_2 Capture	–	GIS	–	[2]
1.13 kg/s	Production of H_2 and heating fluid.	3.8	Equation Solver	–	[11]
25.8 L/s	H_2 and Ice-making	–	MATLAB	415	[34]
–	H_2, power production	39.5	Equation Solver	1104	[55]

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Without a doubt, any nation with a substantial potential for GE can transition away from conventional fuels and towards renewable energy. Even with these renewable resources, there has to be a plan for storing and transporting electricity. The feasibility of generating H_2 is shown by the geothermal to H_2 technology.

4.1.1 Thermodynamic analysis

The use of RE sources is on the increase due to the growing dearth of crude oil and the adverse consequences on the environment. GE has been identified as a potential alternative when compared to other sources of renewables. GE enables the generation of electricity and the provision of heat energy in a cheap and environmentally friendly approach [63, 74]. GE application for H_2 generation is a highly efficient technology, as shown in Table 3. Posso et al [76] performed an assessment of the possibilities for H_2 generation utilising electrolysis from renewable energy. They evaluated several forms of RE, including hydropower, solar photovoltaic (PV), geothermal, and wind energy. The amount of H_2 produced using a PEM electrolyzer, having an efficiency of 75%, is roughly 4.59 × 108 kg per yr. Two unique applications have been proposed: (i) the use of H_2 in vehicle transportation as a substitute for diesel and petrol, and the substitution of firewood with H_2 for suburban energy purposes. According to the findings, H_2 has the potential as an alternative to 44% of the supplied diesel and 65 % petrol. Furthermore, the substitution of firewood with H_2 may be accomplished in 20 territories located in suburban regions. Moreover, a study has been conducted by [2, 86, 99] to examine the economic advancement and competition between conventional fuels and renewable energy in relation to advancements in renewable energy technologies. A model was proposed that explains the function biodiesel, solar, bio-H_2, tidal current, wind, H_2 fuel cell, and geothermal in power generation. The findings indicate that bio- H_2, wind power, and H_2 fuel cells operate adequately even without external support. Therefore, fuel cells and bio-H_2 may have a substantial impact in achieving a smooth transition towards renewable energy. In addition, the manufacturing techniques of H_2 based on GE, together with their advances and potential uses, have been evaluated by [74, 86]. A case study has been conducted on a high-temperature electrolysis (HTE) process that utilizes GE as its input energy source. Furthermore, in order to evaluate the system's operation, a thermodynamic study has been conducted. The exergy and energy efficiencies for H_2 generation have been calculated to be 87% and 88%, according to the findings. In addition, Cao et al. [43] assessed the utilization of GE for the liquefaction of H_2. Three distinct scenarios have been considered to analyze the technique. These models include the utilization of GE for the liquefaction cycle, the process of precooling gas before liquefaction using an absorption cooling system, and a combined heat and power system that uses geothermal energy to heat the absorption system. Kanoglu et al. [77] established a study on the integration of the HTE and GE processes, focusing on the analysis of exergy, exergoeconomic, and energy aspects. The authors examined several metrics in their research, such as exergy efficiency, heat transfer, power, and exergy destruction. In addition, Yilmaz et al. [61] conducted research on the generation of H_2 using PEM water electrolysis powered by GE. The study focused on exergy and energy assessments. Kanoglu et al. [77] have proposed four models for the use of GE in the

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production of H_2. The researchers examined the models from a thermodynamic perspective, taking into account both irreversible and reversible activities. Coskun et al., [79] introduced a multigeneration facility that incorporates a combined energy supply system consisting of a geothermal well and PV/T module. The energy conversion technique provided is specifically engineered to generate both H_2 and electricity. The exergy and energy efficiency for the period of cooling developed by a factor of 1.11 and 3.30, respectively. For the heating period, the exergy and energy efficiency improved by a factor of 4.20 and 1.20, respectively. Astolfi et al [80] conducted a study on the economic viability of solar-geothermal energy sources. They concluded that this coupling might lead to a cost reduction in power generation. According to Spadacini, et al [81], the integration of solar and GE will have many advantages, including reducing the gap between energy demand and supply, cutting emissions and costs during the life cycle, and improving overall efficiency. Musharavati, et al., [82] suggested the use of a new multiproduction facility that harnesses GE and parabolic solar collector technique. A Thermodynamic study was conducted on the equipment compared to a single-generation, cogeneration, and trigeneration plant. According to reports, implementing multigeneration may increase the overall energy efficiency from 15 % to over 85 % and greatly reduce losses. Additionally, research demonstrates that the multigeneration idea is much more eco-friendly compared to single-generation facilities. Cakici et al [83] simulated a geothermal well-parabolic solar collector hybrid system. They used thermodynamics to determine system performance. Calise et al [84] combined solar energy with GE to produce a new kind of microgrid. A system has been developed that provides freshwater heating, energy, and cooling to a small suburb. The system's overall energy efficiency was documented as 53.8%, while its exergy efficiency recorded as 45.9%. Caliskan et al [85] introduced a cogeneration system for H_2 and electricity production. This system harnesses renewable energy such as solar, geothermal and wind energy. The researchers examined the impact of various temperatures on exegetic analyses. The entire system efficiency is proportional to the temperatures. Rostamzadeh and colleagues [46] conducted a thermodynamic study of a hybrid RE system with a combination of GE and biogas to deliver cooling and heating, while also generating freshwater and H_2. A comprehensive analysis, which included a parametric study, was conducted to evaluate the general performance of the system. Additionally, the exergy efficiency of each component was determined. In addition, Karapekmez and Dincer [86] introduced a new method powered by solar and GE to produce H_2. The suggested system included an absorption system, an ORC, and an H_2 generation unit. The primary aim of this research was to remove H_2S from the geothermal resource. An evaluation was conducted to determine the general performance of the system. The results indicated that the highest energy and exergy efficiency was 79.07% and 57.44%. Additionally, Ebadollahi et al [33] conducted a study on a geothermal-driven Multi-Generation System (MGS) involving ORC, an ejector refrigeration cycle, PEM electrolyzer, and a Liquefied Natural Gas (LNG) system. The suggested MGS was analyzed from an energy and exergy perspective, and the heating capacity, output power, and cooling capacity were computed. Furthermore, the thermal and exergy efficiencies was 39.43% and 28.92 %.

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Table 3: Literature review on the investigation of H_2 production from renewables

Ref.	System	Method of investigation	Process of H_2 production	Observation of the overall energy and exergy efficiencies
89	Geothermal and RO desalination unit	Exergo-economic analysis	PEM electrolyzer with ORC cycle	The production cost of H_2 estimates was 4.20 \$/kg.
55	Geothermal	Exergo-economic analysis	Cu-Cl cycle	Energy efficiency: 49.5%; Exergy efficiency: 54.1%
42	Geothermal	Exergo-economic analysis	PEM electrolyzer	Energy efficiency: 3.11%; Exergy efficiency: 66.83%
59	Solar, Geothermal and Distillation unit	Exergoeconomic analysis	ORC cycle	Exergy efficiency: 52 %
77	Geothermal	Exergo-economic analysis	High temperature steam electrolysis	The energy required to produce H_2 is 133 kWh.
61	Binary Geothermal	Exergo-economic analysis	Electrolyzer	Energy efficiency: 46.7%; Exergy efficiency: 45.1%
1	Geothermal	Exergo-economic analysis	PEM electrolyzer with Rankine cycle	Energy efficiency: 34.47%; Exergy efficiency: 49.31%
90	Geothermal	Thermodynamic analysis	PEM electrolyzer with Kalina and Stirling cycle	The energy required to produce hydrogen is 378.84 kg/hr
86	Geothermal and Solar	Thermodynamic analysis	electrolyzer with ORC cycle	Energy efficiency: 83.47%; Exergy efficiency: 84.01%
91	Geothermal and Solar	Thermodynamic analysis	ORC cycle	Energy efficiency: 77.47%; Exergy efficiency: 38.91%
92	Solar and Geothermal	Thermodynamic analysis	ORC cycle	Energy efficiency: 53.57%; Exergy efficiency: 77.0%
53	Geothermal	Thermodynamic analysis	High temperature electrolysis and Cu-Cl cycle	Energy efficiency: 51.10%; Exergy efficiency: 59.29%
9	Geothermal	Thermodynamic analysis	PEM electrolyzer and Kalina cycle	Energy efficiency: 42.04%; Exergy efficiency: 49.91%
63	Geothermal	Thermodynamic analysis	High Temperature electrolysis	Energy efficiency: 86.97%; Exergy efficiency: 85.81%
52	Geothermal	Thermodynamic analysis	Four-step copper chlorine cycle	Energy efficiency: 21.77%; Exergy efficiency: 19.91%
33	Geothermal	Thermodynamic analysis	PEM electrolyzer with ORC cycle	Energy efficiency: 39.87%; Exergy efficiency: 29.94%
77	Geothermal	Thermodynamic analysis	Liquefaction cycle	Three cases were reported.
93	Geothermal	Thermodynamic analysis	PEM electrolyzer with ORC cycle	The working fluid is 60% C_4H_{10} and 40% C_3H_8
94	Geothermal	Thermodynamic analysis	Chole-Alkali cell with ORC cycle	Energy efficiency: 6.25%; Exergy efficiency: 23.04.94%

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36	Geothermal flash cycle	Thermodynamic analysis	Electrolyzer with Kalina cycle	Exergy efficiency: 26.25%.
50	Geothermal	Thermodynamic analysis	Electrolysis with ORC cycle	Energy efficiency: 11.75%; Exergy efficiency: 43.97%
67	Geothermal and absorption cooling system	Thermodynamic analysis	PEM electrolyzer	Energy efficiency: 47.25%; Exergy efficiency: 33.36.94%
39	Photovoltaic thermal and Geothermal	Thermodynamic analysis	PEM electrolyzer	Exergy efficiency increased by 2.12%
37	Geothermal	Thermodynamic analysis	PEM electrolyzer	Energy efficiency: 29.8%; Exergy efficiency: 57.44%
4	Parabolic solar and Geothermal	Thermodynamic analysis	ORC cycle	Exergy efficiency: 45%
11	Binary Geothermal	Thermodynamic analysis	PEM electrolyzer	Energy efficiency: 6.75%; Exergy efficiency: 23.98%
20	Geothermal-driven binary cycle	Thermodynamic analysis	High temperature electrolysis	Exergy efficiency: 38.2%
9	Geothermal	Thermodynamic analysis	Electrolyzer and ORC cycle	Energy efficiency: 39.11%; Exergy efficiency: 45.64%
10	Multi flash Geothermal system	Thermodynamic analysis	electrolyzer	Energy efficiency: 6.91%; Exergy efficiency: 47.24%
19	Geothermal and methanol synthesis unit	Thermodynamic analysis	PEM electrolyzer with S- Graz cycle	Energy efficiency: 14.09%; Exergy efficiency: 43.95%
52	Dora II Geothermal	Thermodynamic analysis	ORC cycle	Energy efficiency: 10.05%; Exergy efficiency: 28.99%
54	Geothermal system with CO_2 as working fluid	Thermodynamic analysis	Electrolyzer with Rankine cycle	Energy efficiency: 13.66%; Exergy efficiency: 35.53%
60	Double flash Geothermal system	Thermodynamic analysis	electrolyzer	H_2 production was achieved at 12.03 kg/day.
79	Geothermal	Thermodynamic analysis	Rankine cycle	Cooling season energy/exergy efficiency improved 3.50 and 1.13 times, and heating season 4.25 and 1.25 times.
85	Geothermal, Solar and Wind	Thermodynamic analysis	PEM electrolyzer	Energy efficiency: 3.34%; Exergy efficiency: 5.84%
1	Geothermal	Thermodynamic analysis	PEM electrolyzer with ORC cycle	Energy efficiency: 33.16%; Exergy efficiency: 45.84%

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4.2 Solar energy-to-H_2 production

Among RE sources, solar power has the best chance of satisfying the world's energy demands in the future [86–92]. Figure 6 shows that solar H_2 production is progressing well as a clean alternative fuel, which is encouraging, given solar energy's capacity to provide affordable power [93]. Despite the reliability and cost-effectiveness of converting solar energy into H_2, the fluctuating availability of solar energy is being addressed by developing a RE storage technologies [94]. One viable alternative to fossil fuels is solar H_2, which may be produced from sustainable energy sources like solar panels without contributing to global warming.

In the last forty years, scientists have examined the feasibility of using solar energy to power electrolysis as a potential viable method for producing H_2 from H_2O. Solar-driven water electrolysis can be achieved through two methods: photo-electrochemical (PEC) water splitting and photovoltaic electrolysis (PVE). PVE involves using separate PV modules to power individual electrolyzer units. On the other hand, PEC water splitting involves a single unit that absorbs direct sunlight in producing O_2 and H_2 respectively [46]. The most prevalent of the two primary system topologies is PEC water splitting. Solar-integrated H_2 generation methods enable the synthesis of H_2 in a way that does not release carbon into the atmosphere. Thus, they provide an alternate source of energy that has the potential to become extremely desirable among customers in the future. Hosseini and Wahid (1995) conducted an extensive investigation on methodologies for generating H_2 utilizing RE sources. Their work delved into the principle of green energy. A concise summary of the exergy evaluation of solar thermal systems that have been operational in the last three years was presented by Kalogirou et al. [96].

Their conclusion was that solar energy has potential applications in electricity generation systems, multigeneration systems, desalination, cooling systems, solar ponds, collection and storage of thermal energy, H_2 production, heating systems, and hybrid systems. Yilanci et al. [97] examined the present state of the techniques presently used to produce solar H_2. The researchers assessed PV-H_2/fuel system exergy efficiency and analysed stationary solar-PV H_2/fuel cell hybrid systems. Luqman et al. [98] developed a hybrid system that combines solar and wind energy to generate several forms of energy, including freshwater, oxygen, hydrogen, electricity, and heating.

This system operates on the principle of using solar panel and wind turbines. They primarily depended on wind turbines and solar collectors shaped like parabolic troughs as energy sources. Furthermore, they considered using a technique that can store thermal energy. Additionally, a PEM water electrolyzer was used to generate H_2. According to their argument, the recently developed system demonstrated 50% and 34 % energy and exergy efficiencies. The total energy consumption efficiency was determined to be 16%, while the exergy efficiency was 15%, specifically for energy generation. The apparatus used a vapour compression-based refrigeration mechanism that effectively utilized electrical energy. Meanwhile, a PEM electrolyzer was used to generate H_2, necessitating a substantial energy input.

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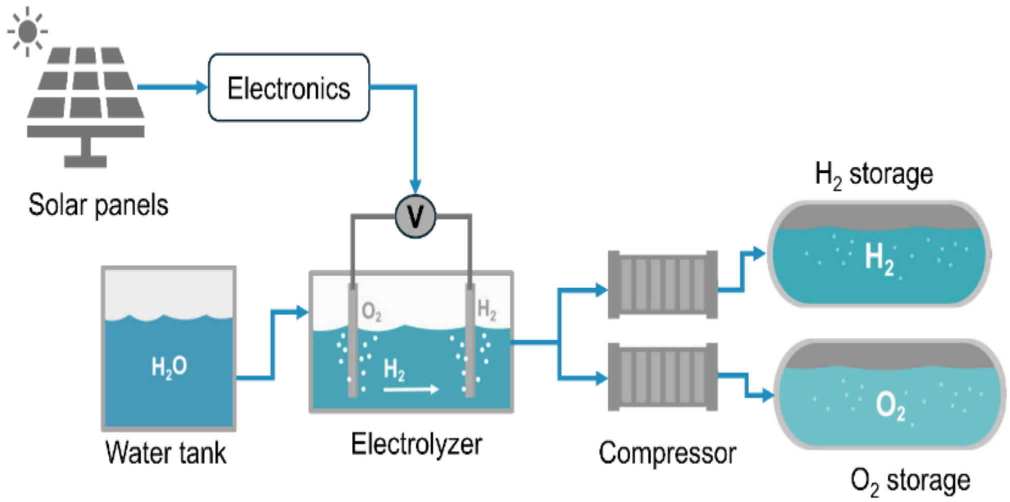

Figure 6: Solar energy integrated H_2 production systems

4.3 PV-to-hydrogen

PV energy production involves the conversion of solar energy into electricity using the piezoelectric effect. Photothermal energy generation, in contrast, makes use of heat exchangers to convert solar radiation into usable heat using installations of reflectors. The turbines may be powered by this heat in order to generate energy [99]. Figure 7 depicts the solar PV-electrolyzer method used to produce green H_2. Solar energy may be used to generate H_2 using water electrolysis. Suitable techniques for this process include PEM electrolysis, solid oxide electrolytic cells, and AWE. Electrolysis techniques are now the most attractive options for generating H_2. Among these, PEM stands out since it is not only compatible with renewable resources but also offers additional advantages [61, 100]. The basic principle of the PEM electrolysis may be shown by constructing an electrolytic cell using pure water and splitting it into two sections, namely the anode and cathode. Electrodes are then placed in each compartment [101].

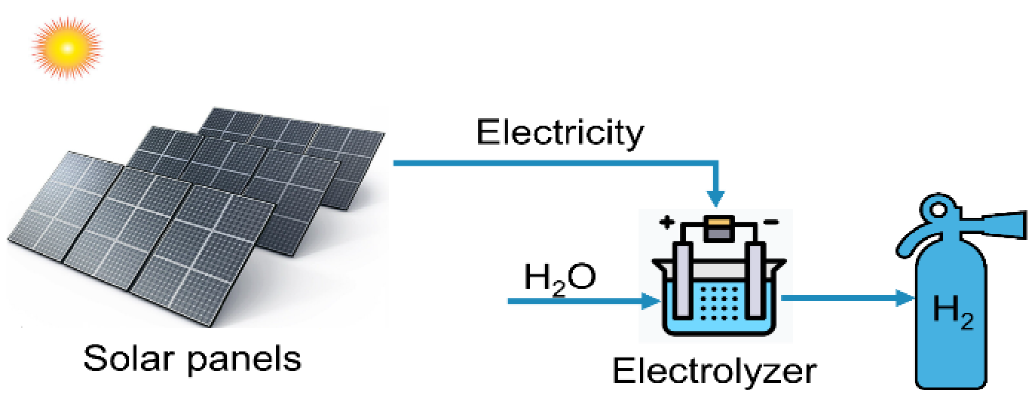

Figure 7: Schematic of solar H_2 production

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PV power generation is determined by calculating the solar energy intensity and other environmental variables, including temperature, humidity, and wind speed. The power output of the photovoltaic system can be calculated using equation (1), while the temperature of the photovoltaic cell can be estimated using equation (2) [103].

$$P_{pv} = C_{pv} D_{pv} \left[1 + \alpha p (T_c - T_\alpha)\right] \left(\frac{H_T}{H_S}\right) \quad (1)$$

$$T_c = T_a + H_T \left(1 - \frac{\eta c}{\tau \alpha}\right) \left(\frac{T_{C,NOCT} - T_{A,NCOT}}{H_{T,NOCT}}\right) \quad (2)$$

$$\tau \alpha H_T = \eta c H_T + U_L (T_C - T_a) \quad (3)$$

The rate of H_2 generated by the electrolyzer may be determined using equation (4). In addition, the amount of power required by the electrolyzer may be represented by equation (5) [102].

$$Q_{H_2} = \eta f \left(\frac{N_C I_e}{2F}\right) \quad (4)$$

$$I_E = A_E \cdot mH_2 + B_E \cdot m'_{H_2} \quad (5)$$

The energy required for compressing H_2 in the reservoir is represented by equation (6). The expected pressure within the H_2 reservoir as shown in equation (7) [103].

$$P_{com} = Q_{H_2} \cdot R \left[\left(\frac{P_{hto}}{P_{hti}}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right] \left(\frac{T_{htci}}{T_{htc}}\right) \left(\frac{\gamma - 1}{\gamma}\right) \quad (6)$$

$$P_{tank} = \left(\frac{R T_{htci}}{V_{htank}}\right) \eta_{htank} \quad (7)$$

Renewable parts like solar panels give direct current (DC) power, but the usual demand is for alternating current (AC). Hence, the converter is necessary to transform direct current (DC) into alternating current (AC). Moreover, the converter is integrated into the electrical system for the purpose of managing and controlling the flow of energy. The efficiency of the converters may be determined by using equation (8) [101].

$$\eta_{con} = \left(\frac{P_{ocon}}{P_{icon}}\right) \quad (8)$$

Various research has examined different methods of H_2 synthesis that rely on solar-PV energy evaluations [61, 83, 91, 95]. Rosner and Wagner [104] conducted a study on the production of H_2 from solar energy. The author used a distinct photocatalytic energy system that demonstrated the process of splitting water into its individual components using visible light irradiation. Furthermore, the integration of ZnS with semiconductors that have a small energy band gap has resulted in very efficient sulphide catalysts for the generation of H_2 in photovoltaic systems, particularly when electron donors are present. Joshi et al. [105] examined a solar H_2 generating system that utilises photovoltaic technology. After analysis, it was shown that the efficiency varies between 3.69% and 4.88%. It can be concluded that efficiency is low because of the PV's low efficiency. This approach is not economically efficient due to the high cost of PV technologies; further

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research is necessary in this domain. Some benefits of PV technology are its emission-free operation, easy maintenance, and noise-free operation. León et al. [106] assessed the sustainable generation of H_2 in a solar installation. The paper examines the production of green H_2 by a photovoltaic system working independently. The assessment of hourly productivity exposes discrepancies in global manufacturing that confirm the importance of the analyzed parameters which may be determined by other means. An interconnection between solar modules and hydrogen electrolyzers is proposed by Ahmad and Shenawy [107] as a means of producing hydrogen in a modular PV energy system. The test results indicated that using a maximum power point monitor instead of directly connecting the electrolyzer and solar modules resulted in consistently high amounts of H_2 generation. In order to determine and improve the thermodynamic and economic efficiency of large-scale solar PV using either stationary or mobile solar panels, Bilgen [108] designed a model. When solar modules are used, the total thermal efficiency of PV-electrolyzer systems may attain 11.95%, but with stationary panels it drops to 10.63%. Levelized H2 generation cost is significantly correlated with yearly sunlight irradiation on a level surface. Latitude, climate, and altitude have a little effect on this connection. Jamroen et al. [109] provide an independent system that utilises photovoltaic (PV) energy to monitor water quality and generate H_2. The findings demonstrated that the recommended system offered dependable communication, enabling the monitoring of H_2 production in near real-time, with a packet loss rate of 0.91 %. Temiz and Javani [110] examine the feasibility of a solar energy photovoltaic (PV) system that can produce electric power and H_2, using renewable resources. Photovoltaic electricity provides the necessary power for the load and also generates surplus energy for the operation of an electrolyzer and the generation of H_2. The findings indicate that H_2 is used to compensate for electric load via the production of energy using fuel cells. Wang et al. [111] established a model for a PV grid-connected/H_2 manufacturing system. This model involves generating H_2 by electrolyzing water, which serves as a local load. According to the study, the low-frequency resonating peak reduces gradually as the number of inverters increases, but the high-frequency resonating peak stays constant. Generally, the modal analysis technique is a superior approach for studying the fundamental resonance issue of a system compared to the frequency evaluation method. Additional publications on solar PV-H_2 generation may be found in the following references: [12, 33, 50, 67, 95, 100]. Utilizing solar PV power for H_2 synthesis effectively addresses the problem of costly water electrolysis by optimizing solar resources. Moreover, it offers an economical, carbon-neutral, and eco-friendly approach to H_2 generation. Furthermore, the affordable cost of electrolyzing water, which is the most environmentally friendly technique for generating H_2, has hindered its advancement.

4.4 Solar thermal-to-H_2

Hydrogen fuels may be produced using a chemical process known as water splitting, which involves the use of concentrated solar energy to maintain a high temperature in a chemical reactor. This process is known as solar thermal water electrolysis (Figure 8). Solar thermal facilities all over the globe have benefited from the development and distribution of various solar collector and receiver types [18, 38, 66, 118].

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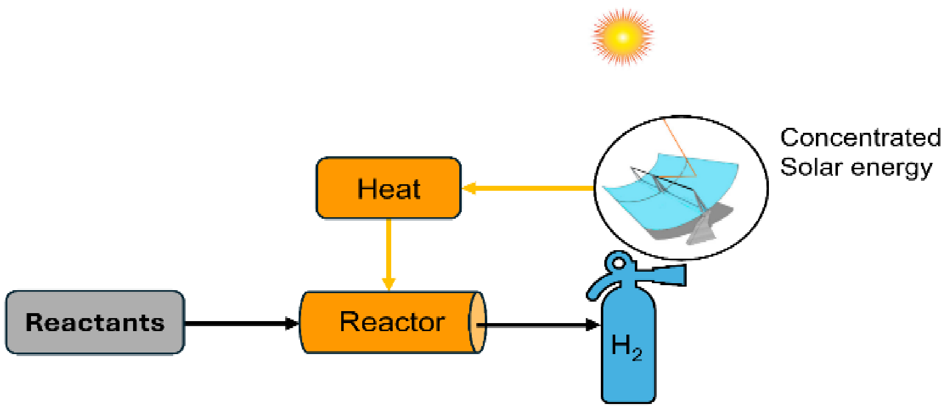

Figure 8: Schematic of solar-thermal H_2 production.

The amount of solar irradiation converted into H_2 gas, as demonstrated in equation (9), is the efficiency of solar thermal H_2 production.

$$S_{th} = \frac{LHV_{H_2}}{\sum_i^n \quad Q_{solar,i}} \cdot 100 \tag{9}$$

$$Q_{solar,i} = \frac{Q_{in,i}}{\Omega_{opt}\left(1-\frac{\varphi T_i^4}{I \cdot C_i}\right)} \tag{10}$$

Numerous investigations have evaluated the technical and economic feasibility of different solar thermal energy-based hydrogen generation technologies in terms of their potential to contribute to future hydrogen supplies [53, 67, 89, 103]. One potential method of producing hydrogen gas from solar heat is examined by Pregger et al. [112]. They concluded that H_2 would emerge as a major power source before the year 2050. Graf et al. [113] performed a cost-benefit study on the generation of H_2 utilising electroplating and thermo-chemical cycles. Both methods use concentrated solar thermal energy for the multi-stage generation of H_2. The study highlighted the advantages of using commercial electrolysis instead of sustainable H_2 production by solar energy and thermochemical cycles. As a result, the cost to manufacture 1 kg of H_2 using electrolysis might vary from €2.1 to €6.8. In order to create carbon-free H_2 in South Africa, Hoffmann [114] examined some techniques of integrating solar thermal technology.

It is possible that South Africa might become the world leader in hydrogen production due to its massive solar resource. Solar thermal H_2 has lower production costs compared to other methods due to the high capital expenditures associated with solar thermal energy. Solar thermal H_2 is not predicted to capture a significant portion of the market in the next decade, but improvements in production processes and increased production volumes might lead to cheaper production in the long run, perhaps bridging the gap. Baykara [115] states that the methods for determining the techniques include water electrolysis, a high-temperature H_2 extractant, and steam co-generation, and/or combining these three processes with high-temperature electrolysis. These processes are thermally efficient, which may lead to lower costs of H_2 production. Based on this research, 172 GJ is the

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minimum yearly plant capacity level, which can be attained by using chemical plant modules and natural thermal water degradation that is championed by a large dish-type solar array for H_2 synthesis. From a thermodynamic point of view, the method proposed by Joshi et al. [116] for a solar-based thermally-driven hydrogen generating system is examined and assessed. Research is undertaken to analyse the effectiveness of this system, focusing on energy and exergy efficiencies. The results suggest that the concentrator performs well when there is more solar radiation, higher reflectance of the reflecting surface, greater concentration factors, higher absorptive coefficients of the heat exchanger, collector surface energy and lower heat loss coefficients. In order to produce heat and electricity, Zamfirescu et al. [117] designed specialized concentrated solar heat turbines with modest capacities. In addition, they conducted comprehensive evaluations of the systems' maximal energy, ecological, and economic aspects in order to evaluate and analyze their performance in practical applications.

A comprehensive and up-to-date evaluation of many H_2 generating methods was carried out by Yilan et al. [118]. A RE system for energy storage that combines solar power with H_2, and fuel cells was the subject of a research in Denizli, Turkey. According to their findings, the system's overall energy efficiency may range from 0.79 to 9.9 %, with a range of 0.90 to 9.9 % for the system's overall energy performance indicators. Several researchers [53, 67, 89, 103] have examined several ways for producing H_2 using solar thermal energy. They have assessed the technical and economic potential of these systems and evaluated their potential contribution to future H_2 resources.

In their study, Pregger et al. [112] examine the potential for producing hydrogen by solar thermal methods. They concluded that H2 will emerge as a substantial power source prior to the year 2050. Graf et al. [113] conducted a cost-benefit analysis on the generation of H_2 utilizing electroplating and thermo-chemical cycles. Both methods use concentrated solar thermal energy for the multi-stage generation of H_2. The study highlighted the advantages of using commercial electrolysis instead of sustainable H_2 production by solar energy and thermochemical cycles. The cost of electrolysis to create 1 kilogram of hydrogen typically falls within the range of €2.1–6.8. Hoffmann [114] examines several methods of incorporating solar thermal technology into South Africa's energy infrastructure to generate carbon-free hydrogen. South Africa's abundant solar resources indicate that the nation has the potential to become a leading player in the hydrogen (H_2) sector.

The cost of producing H_2 with solar thermal energy is lower compared to other production methods due to the significant initial investment required for solar thermal technology. The market share of solar thermal H_2 is not anticipated to significantly increase in the next ten years. However, the implementation of improved production techniques and increased production volumes may eventually lead to cost reductions and narrow the gap. Avanade and Flamant [119] examine the process of solar thermal breakdown to produce H_2. The focus of the project was to develop a solar reactor with a capacity of 12 kW, utilizing indirect heating. The results showed that CH_4 conversion and H_2 production achieved a rate of 97.3% and 91.4%. Additionally, C_2H_2, with a maximum mole of 5.69%,

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was found to be the most important by-product. The research revealed that the temperature was uniformly distributed over the collection, allowing for the identification of thermal equilibrium. Liu et al. propose an innovative approach for producing solar H_2 by combining CH_3OH steaming reformation with solar energy at relatively low temperature [120]. As a result, the conversion rate of CH_3OH into other chemicals may exceed 91.3 %, and the proportion of H_2 in the gaseous products can be 68.5% higher than solar irradiation of 585 W/m^2. The favorable results suggest that this solar-powered technique for producing H_2 can be accomplished. Table 4 is a compilation of research that has examined the process of solar thermal H_2 generation.

Table 4: Literature review of solar-thermal H_2 works.

Cycle Type	Rate of H_2 produced	Energy efficiency (%)	Hydrogen cost	Electricity production	By-product	References
Rankine cycle (RC)	363 kg/day	–	–	51.50 MW	Steam: 14.98 kg/s	[121]
RC	1530 kg/day	–	–	48.68 GW	Heat: 456.82 GWh/yr	[122]
					Freshwater: 160390 ton/yr	
RC	34.0/kg/day	–	–	–	–	[123]
RC	26650 tons/yr	38.8	–	–	CH_3OH	[124]
RC	100 tons/day	25	–	–	–	[125]
RC	–	35.66	–	–	Heat	[126]
RC	–	38	–	–	Heat	[127]
RC	1533 kg/h	28.78	$6.76/kg	–	Heat	[128]
RC	0.2 kg/s	24	–	42 MW	Steam: 13.4 kg/s	[129]
					O_2: 0.79 kg/s	
RC	2144.45 tons/year	22.9	2.59$/kg	1239 MW	Fresh H_2O: 5333.79 tons/yr	[130]
					Thermal energy: 843 MWh	
RC	1034.18 tons/year	52.6	–	422.08 GW	Fresh H_2O:120964.04 tons/yr	[131]
					Thermal energy:132.26 GWh	
RC	491.26 kg/h	45.07		43.36 MW	Steam:10.79 kg/s	[132]
Rankine cycle	59.45 mol/s	29.9	–	8.3 MW	–	[133]

By optimizing the use of solar resources, the generation of H_2 using solar thermal energy not only resolves the issue of highly expensive electrolysis water, but also provides a cost-efficient, carbon-neutral, and environmentally favorable method of H_2 production.

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4.5. Solar-geothermal- H_2 production

For optimal efficiency, it is essential to enhance the design of systems that rely on RE sources. An effective strategy to accomplish this objective is to develop the system, to integrate the principles of cogeneration, particularly multigeneration. Intergenerational systems are becoming increasingly common because they are able to provide better sustainability via higher efficiency, eco-friendliness, and cost-efficiency [35,]. The use of hybrid technologies may be advantageous for solar and GE resources as a result of the inherent benefits in energy types and properties [76, 89]. A hybrid system is useful when designing power plants since it performs well in both isolated and stand-alone modes. Power plant configurations might benefit from this hybrid system [6, 96]. The hybrid power plant has the capacity to generate more energy, but this can only happen if it is fully used. This phenomenon may be attributed to an increase in solar irradiation, an increase in geothermal fluid temperature, or a decrease in the ambient air temperature. Furthermore, these systems possess the capacity to be economically feasible. Several investigations have demonstrated that solar-geothermal systems have substantial capacity for providing long-term solutions, including the desalinated water, production of cooling, H_2, electricity, heating etc. [57].

Alirahmi et al. [134] suggested a multi-system that combines a steam Rankine cycle with an ORC to provide cooling, electricity, H_2 and fresh water. Subsequently, they examined the energy and exergoeconomic features of the system. This system would use GE-solar energy (hybrid energy) as its source of energy. In addition, they enhanced the efficiency of their system by using a GE and concluded that the maximum achievable exergy efficiency is 30.05%. Alternatively, the cost per unit of energy (CPUE) is approximately 128.9 $/gigajoule (GJ). The existing literature proposes the following fundamental classifications for the design of an integrated geothermal-solar facility. To heat the brine, a solar preheating system boosts the steam's enthalpy, using solar energy. A solar superheating system is used when the geothermal fluid is heated to a higher temperature employing solar energy. An ORC's feedwater is preheated using a geothermal preheating apparatus. Research on combined geothermal-solar systems were summarized [57]. Several research have been conducted to enhance the temperature of the geothermal fluid prior to its use for H_2 manufacturing, particularly when GE is regarded as a low-grade heat source.

Therefore, it is essential to use an alternative energy source, preferably an RE source such as solar, in order to maintain a completely eco-friendly system [134]. Utilizing additional sources of energy may augment the power output and improve the efficiency of the plant by pre-heating or re-heating the geothermal or working fluid. Table 5 provides a concise overview of all the solar-geothermal systems that have been examined for the purpose of H_2 production. Trigeneration is an enhanced version of the cogeneration system, offering three distinct outputs compared to the two outputs from cogeneration system. Siddiqui and Dincer [135] introduced a hybrid MGS called a solar integrated NH_3 fuel cell and GE system, which consists of six sub-systems: ACS, ORC, revised osmosis desalination, geothermal flash, solar-based NH3 fuel cell, and electrolysis. The

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system generates four distinct outputs, namely freshwater, cooling, electricity, and H_2. The system's energy and exergy efficiencies are 43.2% and 21.5% respectively. Within the proposed design, GE was assigned to initiate the ACS and flash cycle, while the heat required for the ORC was supplied by both GE and solar energy. Nevertheless, the NH_3 fuel cell and the RO desalination machine were exclusively powered by solar energy.

Table 5: Review of H_2 generation by solar-geothermal energy systems.

Ref.	Year	Technique	Production	Efficiencies	Remark
[15]	2017	Microsoft Excel and EES	103 kW_e	$22\%_{en}$	Integrating solar-geothermal plant with FC
[38]	2021	EES	2756.69 g_h/day and 417.89 MJ_e/day	$5.69\%_{en}$ & $7.50\%_{ex}$	Evaluating the impacts of several solar cells
[13]	2015	EES	19.03 kg_h/h	$11\%_{en}$ & $47.1\%_{ex}$	Supplying H_2, power, cooling, and heating,
[86]	2021	EES	157 g_h/s	$79.07\%_{en}$ & $57.30\%_{ex}$	Multigeneration system development
[122]	2021	EES	–	$28.29\%_{ex}$	Addition of a concentrated PV recuperator
[135]	2021	EES	0.47 mol_h/s, 4629 kW_e and 1490 kW_c	$41.1\%_{en}$ & $23.9\%_{ex}$	Electricity production, H_2, fresh water, and cooling
[136]	2020	Aspen Plus & EES	33.2 mol_h/s, 3399 kW_e & 605.1 kW_c	$20.9\%_{en}$ & $20.8\%_{ex}$	Production of a trigenerational system
[125]	2021	HOMER and EES	7940 kg_h/yr, 1640 MWh_e/yr and 490 MWh_{th}/yr	$17.1\%_{en}$ & $15.4\%_{ex}$	Desalination, electricity generation, H_2, and district heating.

A techno-economic analysis of solar-geothermal heating systems has been provided in the literature. Figure 9 illustrates the integration of a PEM electrolyzer, GE source, an evaporator, an ORC, and a solar energy collector to generate H_2. The geothermal fluid with a relatively low to medium enthalpy, obtained from the geothermal well, is directed towards the solar collectors (stage 2).

At stage 3, the collector transfers hot fluid (s) to the evaporator in order to power the ORC. Within the ORC system, the vaporized n-C_4H_{10}, acting as the working fluid, undergoes expansion over the turbine, generating energy that is utilized in the PEM electrolysis process (stage 5).

Subsequently, at stage 4, the fluid inside the turbine is directed towards the condenser, thus transforming into a liquid state that is then recycled. As part of an essential operation to maintain optimum output, it is vital to expel the extra heat from the ORC. At stage 7, the hydrogen generated in the system is stored with the aid of a compressor.

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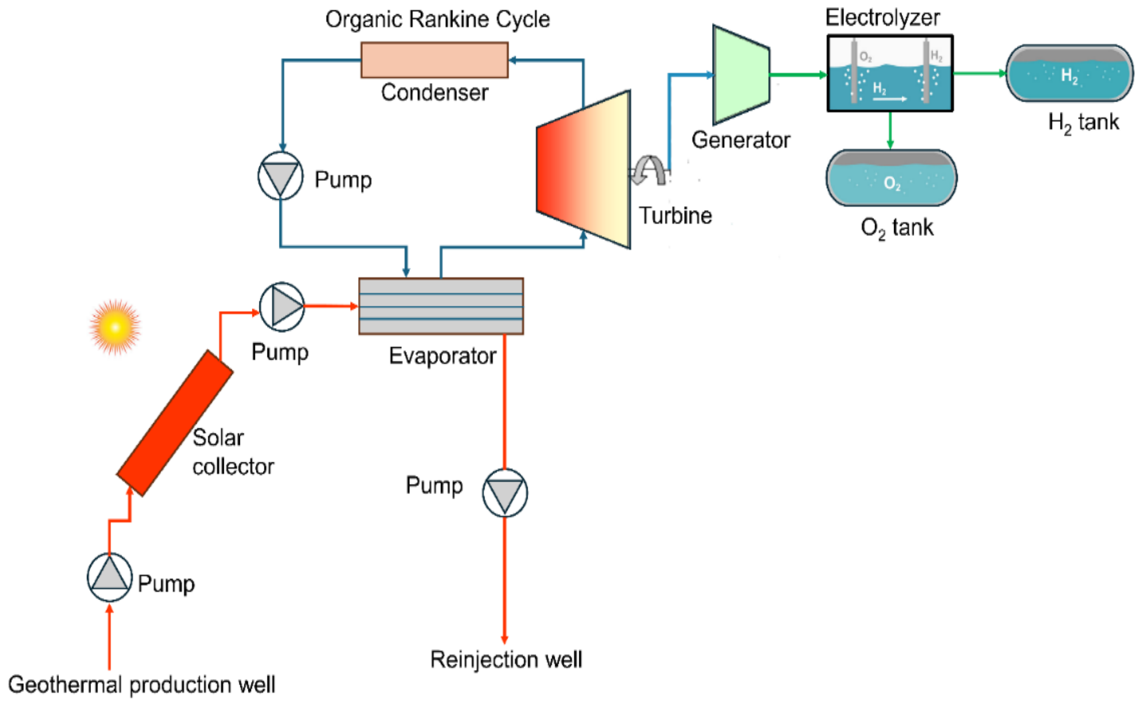

Figure 9: Geothermal-solar integrated hydrogen production system.

6. APPLICATIONS OF H_2

H_2 can be used for power generation, steel manufacture, transportation, refining, medicines, chemical process industry [19]. The advantages of hydrogen gas (H_2) may be enumerated as follows: The capacity to store and transport H_2 using existing natural gas (NG) pipelines is a significant distinguishing factor between H_2 and other forms of energy storage [41]. The facilities used for NG can be readily adapted for transporting H_2.H_2 has the potential for reducing carbon emissions in the environment [71]. The adoption of NG-vehicles, H_2 fuel cell cars (HFCVs), and electric vehicles (EVs), could potentially be promoted by the hybrid electricity/H_2/gas/refueling station, which plays a vital role in fostering environmental advancement [32, 61, 79]. H_2 has numerous advantages over other energy storage systems. Renewable power-to-hydrogen (P2H) could be a highly effective solution for addressing the barriers of transitioning to RE sources. These obstacles include the need for reliable, efficient, cost-effective, and long-term storage capacity [10, 94].

H_2 may be used as a source of electricity for heating systems in buildings. Hydrogen-fueled fuel cells have the potential to provide the energy required by buildings [85, 104]. H_2 emerges as a prominent heating method, given that buildings contribute to approximately thirty percent of global primary energy use, with the majority of this being attributed to heating needs. By integrating H_2 into the existing NG infrastructure, it will be possible to use H_2 for heating in the near future. Ultimately, it is feasible to modify the existing NG infrastructure to operate exclusively on H_2. Indoor heating heat pumps may

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be powered by H_2 [14, 69]. In regions characterized by dense populations, the use of H_2 energy in heat pumps is employed. Recent findings indicate that a combination of H_2 technologies, such as H_2 tanks, fuel cells, and electrolyzers, may potentially substitute the battery bank. Nevertheless, it should be noted that this alternative comes at a greater cost, mostly due to the rising capital price of the components [16, 39, 70]. The H_2 value chain is gaining worldwide recognition, which is expected to contribute to cost reduction. H_2 is a favorable option due to its lower rate of loss compared to batteries, which makes it well-suited for long-term energy storage and reliable electricity supply [2]. H_2 can be used as both feedstock and energy source in the industrial use sector. H_2 can provide the need for both warmth and electricity. Hydrogen offers a significant advantage over electricity in areas where electricity has challenges in terms of competitiveness, such as cement, steel, refineries, and aluminum [101, 137]. H_2 may be used for heating various industrial processes at elevated temperatures, such as drying, melting, gasification and other applications.

6.1 Economic and Environmental Analysis of H_2 Energy

The emergence of the H_2 economy is anticipated to originate from ongoing research on H_2 energy. The global economy implies a scenario where the global economic system is dependent only on H_2 as a fuel source. As a result, the industrial sector will be powered by H_2 instead of the existing electrically driven equipment. Hydrogen will be used to power the majority of devices and applications. Power plants, transportation, and H_2-fueled automobiles will all be affected by this [31, 85]. To enhance the compelling qualities of GE-solar hybrid system technologies, continuous efforts are made to enhance its performance, aiming to maximize earnings while maintaining operating expenses at an acceptable level. Geothermal-solar hybrid energy integrated H_2 production systems have shown less environmental problems compared to energy sources. Consequently, researchers examined the many factors that affect the environmental consequences of H_2 generating systems according to their sources. Geothermal and solar energy have always been seen as the most ecologically sustainable energy sources [36, 78]. Rahmouni et al. [69] performed an environmental evaluation on a geothermal system that integrates H_2 production with the use of CO_2 as a working fluid. Reports indicate that the proposed system has the capability to generate 22 kg/h of H_2, with a carbon dioxide mass flow rate of 40.0 kg/s at 300.0 K. From an economic perspective, the cost of producing H_2 is 8.24 dollars per kg of H_2, which is much more than the present price. Nevertheless, the inclusion of the carbon fee might enhance competitiveness.

Ingason et al [56] investigated the most efficient techniques for generating H_2 by electrolysis of water, using power derived from solar and GE sources. Furthermore, Johnson et al. [137] have published research that assesses the possibility of using GE for H_2 production. The researchers investigated the impact of using a high-temperature steam electrolysis method called HOT ELLY, which was conducted within 800 to 1000°C. According to the findings, the use of the HOT ELLY process with geothermal steam at 200°C may lead to a significant 20 % reduction in the cost of H_2 generation. Yilmaz et al. [60] conducted a study on the liquefaction process using GE, and they also performed

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thermodynamic and economic assessments. The H_2 generation and liquefaction per unit mass of geothermal water, as well as the cost of producing and liquefying a unit mass of H_2, have been quantified. The authors also analyzed the impact of geothermal water temperature on the related costs of H_2 generation and liquefaction procedures. Boyaghchi and Safari [39] conducted a multi-objective optimization study on a geothermal power plant with many generations. Following optimization, the exergy destruction and cost rate may be reduced by a factor of 3 and 5 %.

Additionally, there is a 17% increase in the overall cost compared to the initial condition. A study conducted by Ahmadi et al [138] examined the techno-economic viability of generating H_2 from a binary geothermal power plant. According to the report, increasing geothermal temperatures result in greater energy and exergy efficiency of the entire plant. Furthermore, economic studies have shown that there is a direct correlation between the cost of H_2 generation and the cost of energy. The authors used a GE to optimize the newly introduced H_2 manufacturing process. The H_2 production costs may be influenced by many factors, including taxes, subsidies, the H_2 generating plant's location, the energy source, and governmental promotions. Table 6, displays the LCOE for several RE.

Table 6: LCOE of different sources of energy.

Source	Type	LCOE ($/kWh)
Natural gas	Combined cycle	0.058
Solar	PVs	0.087
	thermal	0.243
Biomass	-	0.101
Geothermal	-	0.048
Wind	Offshore	0.159
	Onshore	0.640

7. TECHNICAL CHALLENGES

The integration of geothermal and solar energy systems for H_2 generation offers numerous advantages but also presents several technical challenges. These challenges need to be addressed to ensure the efficiency, reliability, and economic viability of hybrid systems. The following sections delve into the primary technical challenges associated with this integration.

(a). Resource Availability and Site Selection:

- **Geographical Limitations:** The success of geothermal-solar hybrid systems depends significantly on the geographical availability of both geothermal and solar resources. Geothermal resources are typically found in specific regions with tectonic activity, such as the Pacific Ring of Fire, Iceland, and certain parts of the United States. Similarly, optimal solar resources are concentrated in regions with high solar insolation, such as deserts and tropical areas. Finding locations with both abundant geothermal and solar resources can be challenging, limiting the potential sites for hybrid systems.

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- **Resource Assessment:** Accurate assessment of geothermal and solar resources is crucial for site selection and system design. This involves comprehensive geological surveys, drilling for geothermal resource confirmation, and solar irradiance mapping. Inaccurate resource assessment can lead to suboptimal site selection, impacting system performance and economic viability.

(b). Technological Integration:

- **Thermal Compatibility:** Integrating geothermal and solar thermal systems involves managing different temperature regimes. Geothermal fluids typically have lower temperatures compared to the high temperatures achieved by concentrated solar power (CSP) systems. Ensuring thermal compatibility and optimizing the heat exchange processes between these systems require advanced engineering solutions.
- **System Synchronization:** Synchronizing the operation of geothermal and solar systems to ensure a stable and continuous energy supply is complex. Solar energy is intermittent, with output varying based on weather conditions and time of day. In contrast, geothermal energy provides a continuous base load power. Effective system synchronization and load balancing are essential to maintain consistent hydrogen production rates.
- **Control Systems:** Advanced control systems are necessary to manage the integration of geothermal and solar energy inputs, optimize the operation of electrolysis units, and ensure grid stability. These control systems must be capable of real-time monitoring and adjustment to respond to fluctuations in energy supply and demand.

(c). Hydrogen Production and Storage:

- **Electrolysis Efficiency:** The efficiency of H_2 generation through electrolysis is influenced by the temperature and pressure conditions of the energy input. Integrating geothermal and solar energy sources to achieve optimal conditions for electrolysis is challenging. Research and development are needed to improve the efficiency of electrolysis units operating under hybrid energy inputs.
- **Hydrogen Storage:** Storing hydrogen efficiently and safely is a critical challenge. Hydrogen has low volumetric energy density, requiring high-pressure tanks, cryogenic storage, or advanced materials for solid-state storage. The integration of storage solutions with geothermal-solar hybrid systems must consider these technical and safety challenges.

(d). Economic Viability and Initial Investment:

- **High Capital Costs:** The initial capital investment for geothermal-solar hybrid systems can be substantial. Geothermal energy development involves significant costs related to drilling, reservoir assessment, and plant construction. Similarly, solar power installations, especially CSP systems, require considerable upfront investment. The high initial costs can be a barrier to adoption, despite potential long-term cost savings.

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- **Financing and Incentives:** Securing financing for hybrid projects can be challenging due to the high risks and uncertainties associated with resource assessment, technology integration, and market conditions. Government incentives, subsidies, and favorable policies are essential to attract investment and reduce financial barriers.

(e). Environmental and Regulatory Challenges:

- **Environmental Impact:** The development of geothermal resources can have environmental impacts, including land subsidence, induced seismicity, and potential contamination of groundwater. Mitigating these impacts requires careful planning, monitoring, and regulatory compliance.
- *Regulatory Framework:* Navigating the regulatory landscape for geothermal and solar energy projects can be complex. Different regions have varying regulations and permitting processes for renewable energy development. Harmonizing these regulatory requirements and ensuring compliance can pose significant challenges.

(f). Grid Integration and Stability:

- *Grid Compatibility:* Integrating hybrid energy systems with the existing power grid requires ensuring compatibility with grid infrastructure and stability requirements. The intermittent nature of solar energy and the continuous base load from geothermal sources must be balanced to prevent grid instability.
- *Energy Storage Solutions:* Effective energy storage solutions, such as batteries or thermal storage, are crucial for managing the variability of solar energy and ensuring a stable energy supply. Developing and integrating these storage solutions with hybrid systems involves technical and economic challenges.

8. FUTURE DIRECTIONS IN GEOTHERMAL-SOLAR H_2 GENERATION

The integration of geothermal and solar energy for H_2 generation presents an innovative approach to sustainable energy systems. Future directions in geothermal-solar hydrogen production are poised to be transformative, leveraging advancements in technology, economic strategies, and policy frameworks. At the technological forefront, Enhanced Geothermal Systems (EGS) represent a significant leap, enabling the extraction of geothermal energy from areas with low permeability and porosity through fluid injection techniques. This advancement can vastly expand the geographical applicability of geothermal resources. Additionally, the integration of concentrated solar power (CSP) systems with geothermal energy can achieve the high temperatures needed for thermochemical water splitting, a process that efficiently produces H_2 [32, 114]. Innovations in photovoltaic (PV) technologies and materials science are also critical, enhancing efficiency and reducing the costs of solar energy systems used in this hybrid approach.

Economic viability is another key factor driving the future of geothermal-solar hydrogen production. Reducing the costs associated with both geothermal and solar technologies, such as through improved drilling techniques and more affordable solar collectors, is

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essential for making this approach commercially competitive [88, 93]. Achieving economies of scale as deployment increases will further reduce costs, enhancing economic feasibility. Supportive policies, including government incentives and subsidies, are crucial to accelerate the adoption of geothermal-solar H_2 production. These policies not only provide financial support but also create a stable market environment that encourages investment and innovation [49, 101]. Clear regulatory frameworks that address resource management, environmental impacts, and safety standards will also play a pivotal role in facilitating sustainable development [33].

Environmental and social considerations are equally important in shaping the future of geothermal-solar hydrogen production. Sustainable management of geothermal and solar resources is crucial to prevent depletion and minimize environmental impacts [22, 95]. This includes careful monitoring and mitigation of potential effects on local ecosystems and communities. Building public acceptance through education and transparent communication about the benefits and risks of geothermal-solar hydrogen production is essential for its widespread adoption. Moreover, integrating these systems with existing energy infrastructure, including smart grids and hybrid renewable energy networks, can enhance overall energy resilience and flexibility. Ongoing research and development, coupled with pilot projects, are vital for refining technologies, addressing challenges, and providing real-world data to inform large-scale implementation. These efforts collectively contribute to the global transition toward cleaner, more sustainable energy systems.

9. CONCLUSION

The integration of geothermal-solar hybrid energy systems for H_2 generation is a compelling and viable solution to meet the increasing demand for clean and sustainable energy. It represents a promising advancement in the pursuit of sustainable and renewable energy solutions. This comprehensive review highlights the multifaceted benefits, technical challenges, and future potential of such hybrid systems. Combining geothermal and solar energy sources can significantly improve the overall efficiency of hydrogen production. Geothermal energy provides a stable, continuous power output, which complements the intermittent nature of solar energy.

This synergy ensures a more reliable and consistent energy supply, essential for continuous hydrogen production. The Hybrid systems can reduce operational costs by maximizing the use of available renewable resources. By leveraging the high-capacity factor of geothermal energy and the cost reductions in solar photovoltaics and solar thermal technologies, these systems can achieve lower levelized costs of energy (LCOE) compared to standalone renewable energy systems. Utilizing geothermal and solar energy for H_2 production substantially reduces GHG emissions compared to fossil fuel-based hydrogen production methods. This shift contributes to global decarbonization efforts and helps mitigate climate change. While there are notable challenges to overcome, the potential benefits in terms of efficiency, cost savings, and environmental impact make it a worthwhile pursuit. Continued advancements in technology, coupled

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with supportive policies and incentives, will be crucial in unlocking the full potential of these hybrid systems. As we move towards a more sustainable future, the role of geothermal-solar hybrid systems in hydrogen production is poised to become increasingly significant, driving progress in renewable energy integration and contributing to global decarbonization efforts.

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