Life cycle assessment of green hydrogen production via geothermal energy-driven electrolysis

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***Abstract*—This study investigates green hydrogen production using a closed-loop geothermal system integrated with an organic Rankine cycle (ORC). Geothermal energy powers the ORC turbine, generating electricity for hydrogen production through water electrolysis. The study quantifies the global warming potential (GWP) of the production of green hydrogen. Notably, the GWP is low at 3.67 kg CO_2eq per kg of hydrogen, promoting a cleaner alternative. The results highlight the system's sustainability, offering valuable insights for policymakers and stakeholders in the pursuit of a greener energy future.**

***Index Terms*—geothermal, hydrogen, proton exchange membrane electrolyzer, life cycle assessment**

I. Introduction

As the world strives to mitigate climate change and reduce the dependency on fossil fuels, the need for sustainable energy generation technologies has gained traction. Hydrogen has emerged as a potential energy carrier to supersede fossil fuels in different energy verticals. Hydrogen acts as an environmentally friendly energy carrier between renewable energy resources and energy consumers [1]. It can be generated through a range of energy sources, encompassing both renewable and non-renewable resources. These include fossil fuels with specific techniques like steam reforming of methane, oil/naphtha reforming, and coal gasification, as well as renewable sources such as biomass and biological sources. Additionally, hydrogen production through water electrolysis is also a significant method in this context [2]. Fig. 1 shows various hydrogen production methods from different sources.

In the process of water electrolysis, water serves as the input and undergoes dissociation into hydrogen and oxygen with the aid of direct current. Various electrolyte systems have been devised for water electrolysis, such as alkaline water electrolysis (AWE), proton exchange membranes (PEMs), alkaline anion exchange membranes (AEMs), and solid oxide water electrolysis (SOE). While these systems employ different materials and operating conditions, their fundamental principles remain consistent. Additionally, depending on the operating temperatures utilized, both low- and high-temperature water electrolysis are feasible [3].

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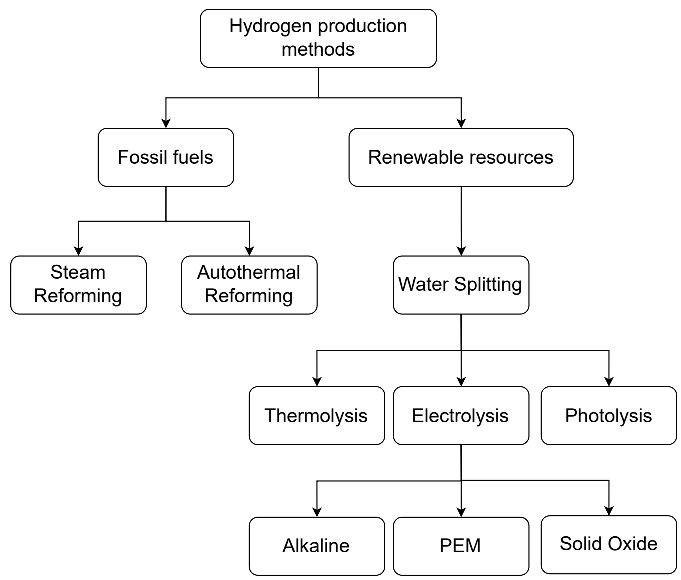

Fig. 1. Hydrogen production methods.

Conventional AWE has been successfully commercialized for hydrogen production. Nevertheless, its extensive adoption is hindered by limitations in current density, energy efficiency, and operating pressure.

In recent times, proton exchange membrane electrolyzer cells (PEMECs) have received significant attention due to several advantages they offer, including high-purity hydrogen production, swift system response, broad current density operation range, and compact design. However, PEMECs still face challenges in achieving cost competitiveness with other conventional energy technologies due to their high manufacturing cost [4].

In this regard, the integration of low-temperature geothermal resources for the production of hydrogen is of great significance. Tapping into the potential of low-temperature geothermal resources can unlock a pathway for green hydrogen generation. From the perspective of life cycle assessment (LCA), utilizing electricity generated from wind or hydro power for electrolysis stands out as one of the most favorable hydrogen production methods as compared to those relying on the conventional grid electricity mix or fossil fuel feedstocks [2]. However, little research focusing on the LCA of geothermal-driven hydrogen has been done to this date. It is essential to investigate this aspect as the presence of geothermal energy is growing in the global renewable energy mix.

ORCs are the most common power plant concepts for power generation from low- and medium-temperature geothermal resources [5], with an installed capacity of 3.5 GW worldwide [6]. A detailed overview of studies regarding geothermal energy for hydrogen production is presented in [7]. Hasani et al. [8] present a detailed evaluation of various ORC configurations and working fluids for geothermal-driven hydrogen production. The authors of that work identify the ORC working fluid R-113 as an optimal choice. However due to the significant GWP and ozone depletion potential (ODP) of R-113, the fluid suggestion is questionable under environmental considerations, since several studies have proven the pivotal negative effect of high-GWP ORC working fluids caused by leakages (e.g. [9], [10], [11], [12]).

The aim of this study is to provide an environmental impact assessment by using LCA for a geothermal-driven hydrogen production system. The results provide valuable insights into deep geothermal-driven hydrogen production and show that it is an attractive option for the production of green hydrogen.

In Section II, the system for hydrogen production is introduced. Section III presents the process of the LCA carried out. The results are presented and discussed in Section IV. Section V concludes the paper.

II. System Description

The proposed system consists of a closed-loop heat exchanger system, an ORC and a PEM electrolyzer as visualized in Fig. 2. This system for geothermal heat extraction is set up as described in [13].

The heat extraction fluid remains in the pipes without coming in direct contact with the subsurface [14]. It is circulated via the thermosiphon effect without requiring a downhole pump. The vertical depth of production and reinjection wells is chosen to be 4 km. The lateral drilling length of the subsurface heat exchanger is set to 82.4 km as given in the literature [13]. A subcritical one-staged ORC system is considered for power generation. R-1233zdE is applied as a working fluid since it has been experimentally proven as a promising low-GWP working fluid for geothermal ORC systems [15]. This ORC system uses an air-cooled condenser. More detailed information about the method and assumptions is available in [16].

A typical state-of-the-art PEM electrolyzer is considered to be driven by the electricity generated from the geothermal resource as shown in Fig. 2: The heat energy extracted by the closed loop sub-surface heat exchanger drives the ORC which generates electricity. This electricity is then fed into the PEM electrolyzer.

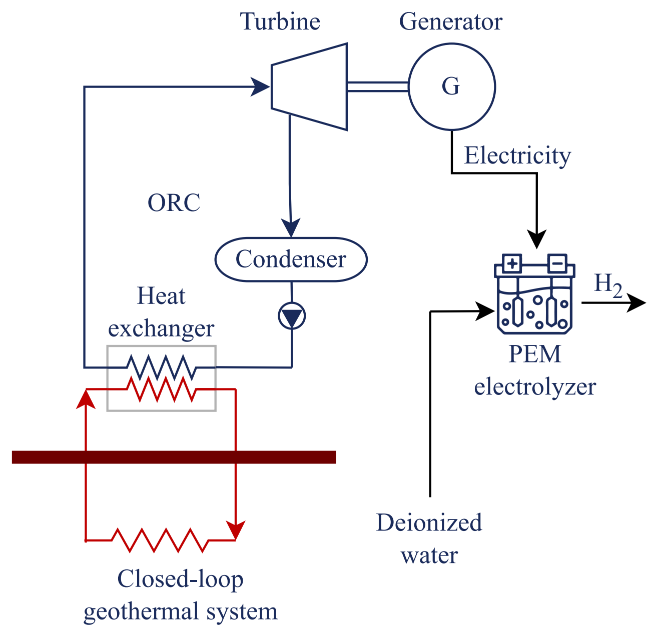

Fig. 2. Closed-loop geothermal-driven hydrogen production system.

The temperature input of the geothermal brine to the ORC is assumed as 150 °C and the reinjection temperature is set to 80 °C. The brine flow rate is 40 kg/s. From these considerations, the heat available for the ORC is estimated at 11.7 MW_{th}. The net ORC efficiency has been found to be 9.1 % as per our simulations. This implies that a surface-level ORC plant of 1.06 MW_e net capacity can be driven with the available temperature.

The operation parameters of state-of-art PEM electrolyzers have been taken from the literature ([2], [17]). The conversion efficiency of an electrolyzer falls within a range of 67 % to 82 %. The PEM electrolyzer has a specific energy consumption of 4.5 $kWh/(N\,m^3)$ to 7.5 $kWh/(N\,m^3)$ [2]. In this study, we chose an efficiency of 75 % and energy demand of 4.7 $kWh/(N\,m^3)$, which is equivalent to 52.2 kWh for production of 1 kg of H_2 [17]. The deionized water consumption of the electrolyzer is chosen to be 260 kg/h. Table I summarizes the main considerations and performance data of the system.

TABLE I
Main considerations and performance data of the system.

Parameter	Value	Unit
Considerations		
Vertical depth of the geothermal system	4	km
Length of horizontal drilling	82.4	km
Brine temperature	150	°C
Brine flow rate	40	kg/s
ORC turbine efficiency	75	%
ORC pump efficiency	80	%
ORC superheating	3	K
Min. ORC pinch point temperature difference	3	K
Capacity factor	95	%
PEM electrolyzer efficiency	75	%

III. Life Cycle Analysis

In this study, the environmental impact assessment of the closed-loop heat exchanger system is carried out as per the International Organization for Standardization (ISO) guidelines for conducting LCA within series ISO 14040 and 14044 [18]. LCA comprises four steps: (a) goal and scope definition, (b) life cycle inventory (LCI) analysis, (c) life cycle impact assessment (LCIA), and (d) life cycle interpretation.

a) Goal and scope definition: The goal of the LCA in this study is to quantify the GWP of geothermal hydrogen production. We used ReCiPe [19] which is a method to transform LCI results into a limited number of indicator scores including 18 impact categories at the midpoint level and three impact categories at the endpoint level. One of the midpoint indicators is the GWP. The functional unit is fixed as 1 kg of hydrogen produced. The system boundaries are set from "cradle-to-gate" which includes raw material extraction, material processing, equipment production, shipping to the site, power plant construction, and operation, but not end-of-life, as depicted in Fig. 3. The analysis period is set to 30 years to harmonize with other geothermal energy LCA studies [20].

PEM electrolysis plant components such as circulation pumps, heat exchangers, or deoxidizer are not included in the scope of this study due to the inventory availability limitations.

Including those specific material inputs in the future could slightly alter the current findings and act as an extension and improvement to this study.

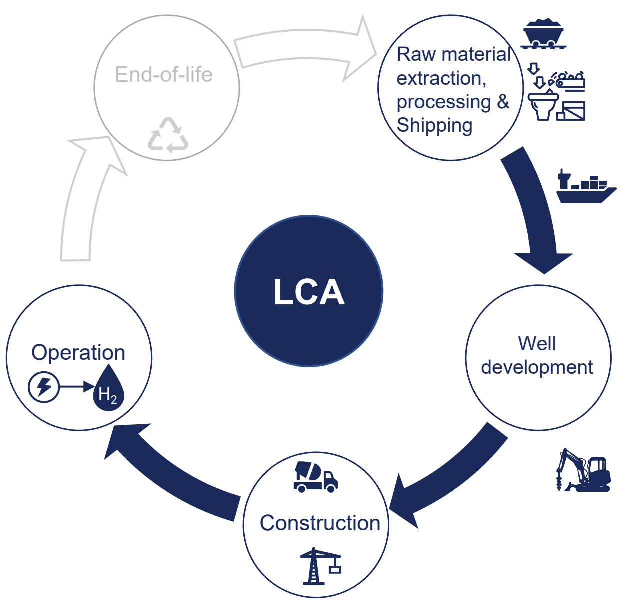

Fig. 3. LCA system boundaries.

b) LCI analysis: The LCI data is derived from the Ecoinvent 3.5 database [21] and compiled by the software SimaPro®[1]. The material requirements for the closed-loop geothermal ORC have been calculated in [13], [14]. The vertical depths of production and injection wells are chosen as 4 km each, while the lateral drilling length of the subsurface heat exchanger pipes is set to 82.4 km. High-density polyethylene (HDPE) is considered the proxy for the piping material as the novel high-temperature resistant pipe (proprietary Rock-Pipe) composition is not available. The vertical wells are considered to be cemented and cased using steel [22]. The main material considerations are tabulated in Table II.

[1]https://simapro.com/

Bareiß et al. [23] presented a near-future estimate of the material requirements of a 1 MW_e PEM electrolyzer and "balance of plant (BoP)" equipment which comprises auxiliary components and systems of a power plant. The material inputs used in the LCA are tabulated in Table III. Nafion® (a sulfonated tetrafluoroethylene-based fluoropolymer-copolymer) is not available in any of the inventories. Hence, a proxy material has been created with a composition of tetrafluoroethylene and sulphuric acid as per the weights calculated in [24].

The lifetime of the PEM electrolyzer is 60 000 h. In this study, we consider that four PEM electrolyzer stacks of 1 MW_e are required over 30 years. The PEM electrolyzer's demand for deionized water is chosen as 260 kg/h [17].

TABLE II
Closed-loop geothermal ORC inventory.

Material	Quantity	Unit
Drilling for well development		
Diesel for drilling	37 300	GJ
Drilling mud	1 570	m^3
Cement	1 271	tonnes
Casing Steel	842	tonnes
Piping Material	1 096	tonnes
ORC equipment		
Carbon steel	46 036	kg
Stainless steel	3 180	kg
Aluminum	8	kg
Copper	1 278	kg
Mineral wool	53	kg
Plastic	1 431	kg
Organic chemicals	4 664	kg
Power plant construction		
Concrete	74 201	kg
Carbon steel	10 600	kg
Stainless steel	663	kg
Aluminum	613	kg
Copper	159	kg
Mineral wool	6 300	kg
Plastic	763	kg

c) Life cycle impact assessment: This step evaluates the environmental impact. The GWP has been estimated using SimaPro®. The resulting GWP of hydrogen production from the closed loop geothermal system is 3.67 kg CO_2eq per kg of H_2 produced.

d) LCA results interpretation: The LCA results show that the electricity generated from the geothermal-driven ORC contributes to 83 % of the GWP, as represented in Fig. 4.

TABLE III
1-MW PEM ELECTROLYZER INVENTORY.

Material	Quantity	Unit
PEM electrolyzer stack		
Titanium	37	kg
Stainless steel	40	kg
Aluminum	54	kg
Copper	9	kg
Nafion® (proxy)	2	kg
Activated carbon	4.5	kg
Iridium	37	g
Platinum	10	g
BoP equipment		
Low-alloyed steel	4.8	tonnes
High-alloyed steel	1.9	tonnes
Aluminum	0.1	tonnes
Copper	0.1	tonnes
Concrete	5.6	tonnes
Plastic	0.3	tonnes
Lubricant	0.2	tonnes

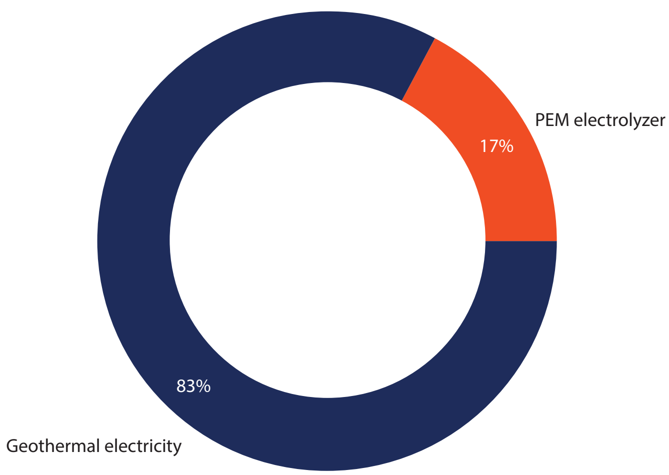

Fig. 4. Share of the processes of the total GWP.

The emissions stemming from the manufacturing of the PEM electrolyzer stack are of negligible magnitude, which is inline with the findings of [23]. The primary portion of emissions associated with the PEM electrolyzer is traced back to the utilization of deionized water during the PEM electrolyzer's operational phase. Collectively, the PEM electrolyzer accounts for 17 % of the GWP.

IV. Results and Discussion

As per our simulation, the resulting annual electricity generation from the subcritical one-staged ORC is 8.9 GWh. Feeding this electricity into the PEM electrolyzer with the technical specifications shown in Section II, produces 170 metric tonnes of hydrogen annually.

The resulting GWP of 3.67 kg CO_2eq per kg of H_2 produced by the proposed system is very low as compared to hydrogen production from grid electricity in most countries. Our LCA results show that the GWP of hydrogen production is highly dependent on the emissions from the electricity that is used for electrolysis, as shown in Fig. 4. This is in line with [23] where it was shown that if the PEM electrolyzer was driven by electricity generated from a mix of renewable sources, the GWP of the hydrogen produced would only amount to 3.3 kg CO_2eq per kg H_2 produced, whereas using grid electricity would result in considerably higher emissions.

Accordingly, our calculations yield that with the average grid emission factor of the countries in Asia and Australasia of 480 g CO_2eq/kWh [25], the resulting GWP would be 36 kg CO_2eq per kg H_2, which is about ten times as high as for the proposed system.

The GWP of hydrogen produced by electrolysis using electricity generated from renewable electricity generators as assessed by [2] and [23] is shown in Fig. 5 along with the GWP from geothermal electricity-driven electrolysis assessed in our study.

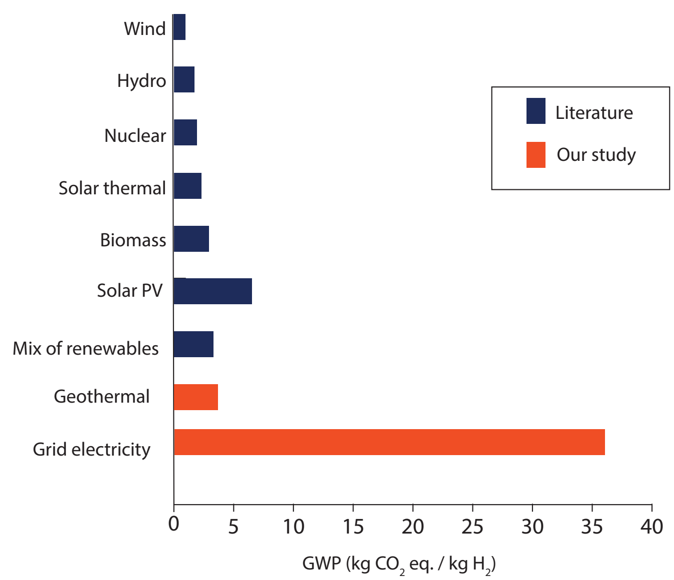

Fig. 5. GWP of hydrogen production from different sources (modified after [2], "mix of renewables" modified after [23]) and our our study (orange)

The results show that the production of green hydrogen from closed loop geothermal power generation is viable from a GWP perspective. This suggests that geothermal power can indeed be considered as a pathway to produce green hydrogen.

Though geothermal power is not considered an intermittent renewable source, the well productivity might fall over the years due to thermal drawdown or cooling down of the rock which is surrounding the subsurface heat exchanger [13]. In this study, we have assumed that the well productivity does not fall over 30 years.

The current analysis does not include end-of-life phase of the system due to data availability limitations. Bringing the end-of-life phase into LCA in the future can vary the GWP value of hydrogen generated. But it also shows the possibilities of selecting materials that promote circular economy.

Furthermore, as an extension to the current analysis, a cascading system to extract heat from the geothermal brine leaving the ORC by passing it through a multi-effect distillation cycle that requires a heat source of 70 °C [26] can be studied. In this way, seawater can be desalinated and used for electrolysis. This helps avoid a competition between water demand for drinking and electrolysis.

V. Conclusion

In this paper, we presented a closed loop heat exchanger system with an ORC and a PEM electrolyzer for extraction and conversion of geothermal heat to electricity for hydrogen production via electrolysis. The GWP of the system was determined by LCA using ReCiPe and SimaPro®. The resulting GWP is 3.67 kg CO_2eq per kg of hydrogen produced. This is in the same range as hydrogen production from biomass or solar power, and considerably lower than using electricity from the power grid in most countries.

The thermal energy extracted from the effluent brine exiting the ORC heat exchanger could be effectively employed to power a multi-effect distillation water desalination facility, or alternatively, harnessed for preheating industrial feedwater.

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