Proposing a Hydrogen Liquefaction Cycle for Geothermal Energy Storage in an Innovative Multi-Generation System

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Article Information

Abstract

Energy storage has become a critical focus area, especially within the renewable energy sector. Among these, geothermal energy has gained attention for its environmentally friendly characteristics. Researchers are increasingly working to develop more efficient energy storage systems using a variety of innovative methods. This research project focuses on two core aspects: the innovative use of geothermal energy to produce liquid hydrogen for storage and the application of geothermal cooling via an absorption refrigeration cycle to cool hydrogen gas. The proposed multi-generation system leverages geothermal energy to generate hot water, fresh water, hydrogen, and power. As the geothermal flow passes through the ammonia water absorption cooling unit, its temperature is reduced before it enters the organic Rankine cycle power generation unit and heat exchanger, where it is used to produce power and hot water. The system is thoroughly analyzed using energy, exergy, and economic assessments, with a specific focus on the hydrogen liquefaction unit. The total annual cost of the system is estimated at 1.49\$ million, with a minimum selling price of 2.71\$ per kilogram. The specific energy consumption of the multi-generation system is calculated to be 8.51 kWh per kilogram of liquid hydrogen.

1   Introduction

In recent years, the growing energy demands and challenges associated with fossil fuel usage have driven significant advancements in conversion and storage systems, especially for renewable energy sources. Geothermal energy has emerged as a prominent and abundant source of power generation, known for its stability and reliability. Extensive research has focused on reducing carbon emissions and improving the efficiency of geothermal systems to maximize energy production. Geothermal energy provides several advantages, including zero pollutant emissions and the capability to simultaneously produce heat and power. Numerous studies have investigated the potential of geothermal systems as efficient energy storage solutions. Geothermal systems operate at temperatures ranging from 50 °C to 350 °C. With the abundance of geothermal resources and their versatility across various applications, the use of geothermal systems is anticipated to grow significantly in the coming years.

Numerous studies have highlighted the effectiveness of geothermal systems in cogeneration scenarios. For instance, Abdolalipouradl et al. [1] investigated a cogeneration system designed to simultaneously produce electricity, potable water, and hydrogen Exergy analysis was employed to ascertain the primary factor influencing the efficiency of the aforementioned system. Hürdoğan et. al. [2] also utilized geothermal technology for potable water production. Additionally, polymer membrane electrolyzers and photovoltaic panels were integrated to link the hydrogen production cycle with the primary cycle The findings revealed that the soil temperature, solar radiation, and mass flow rate ratio were the most significant parameters, significantly influencing the performance of the cycle.

Faramarzi et al. [3] developed a hydrogen liquefaction heat exchanger model utilizing neon as the refrigerant cycle. The study investigated exergy destruction related to pressure drop, temperature difference between cold and hot sources, and hydrogen formation. The findings indicated that the exergy destruction rate due to pressure drop was negligible. Furthermore, several researchers have explored the integration of the organic Rankine cycle with geothermal systems to generate electricity from the waste heat of the cycle.

Geothermal sources are extensively utilized in desalination systems worldwide, serving as the primary energy source for high-volume production applications [4,5]. Among the various desalination methods, reverse osmosis systems are the most commonly used.These systems can effectively utilize geothermal sources and require lower energy inputs at high temperatures compared to alternative methods [6]. Hoseinzadeh et al. [7] proposed a model that combines reverse osmosis desalination with carbon dioxide and sodium hypochlorite turbines. The geothermal energy-powered cycle in this model offers a 10 percent cost reduction compared to other designs.

In their study, Nafchi et al [8] introduced a novel approach that harnesses geothermal sources to power a proton exchange electrolyzer. The proposed cycle demonstrated an exergy efficiency of 41.25 percent. Similarly, Yilmaz [9] integrated geothermal energy into his design for the precooler of a liquid nitrogen production plant. This study explores the potential of geothermal systems as a reliable and consistent energy source. Unlike previous studies, it focuses on the implementation of a liquid nitrogen cycle for geothermal energy storage. The proposed cycle not only generates electricity but also produces fresh water and heat. What distinguishes this study is the use of a water-ammonia absorption cycle to precool the hydrogen, thereby reducing the energy required for the main hydrogen liquefaction cycle. As a result, the minimum cost of liquid hydrogen in this method is significantly lower, at 2.71$, compared to other similar cycles.

2   Materials and Methods

Figure 1 illustrates the suggested sequence comprising six primary sub-cycles. Initially, the geothermal energy-heated hot water undergoes the absorption cycle for pre-cooling. The heat from the geothermal source is used to raise the water's temperature, preparing it for use in the electrolyzer. This heated water is then employed in the organic Rankine cycle to generate electricity and support the hydrogen liquefaction cycle [1].
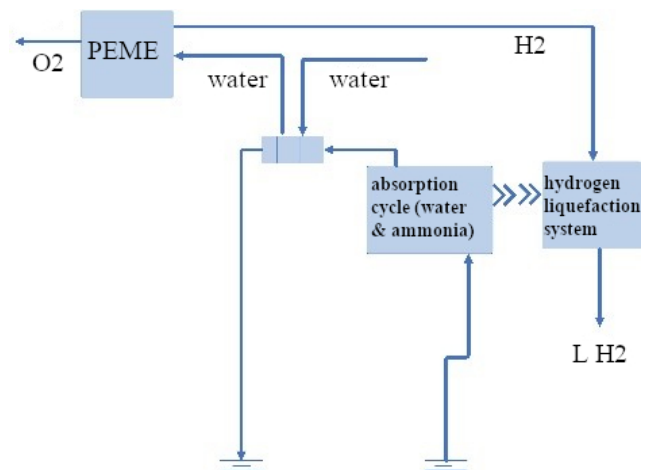

Fig. 1. Schematic of the proposed cycle.

Upon completion of the electrolysis process, the resulting hydrogen is directed to the hydrogen liquefaction system. The water is then cooled to a temperature of $60\,°C$ before being reintroduced into the geothermal well for reheating. The research conducted by Kanoglu [10] serves as a reference for the overall cycle. Figure 2 provides a detailed schematic of the system, including the mass flow rate for each section of the cycle. According to the diagram, the flow from the geothermal well is heated to a temperature of $200\,°C$ before being directed to the absorption cycle. Within the absorption refrigeration cycle, the hydrogen is cooled, reducing its temperature from $25\,°C$ to $-27\,°C$. This cooled hydrogen is then transferred to the hydrogen liquefaction cycle. Notably, the hydrogen produced by the electrolyzer is initially in a gaseous state and undergoes pre-cooling in the absorption refrigeration cycle. The hydrogen liquefaction cycle includes five heat exchangers: the first acts as a precooler, while the remaining four further cool the hydrogen to a temperature of $-253\,°C$.
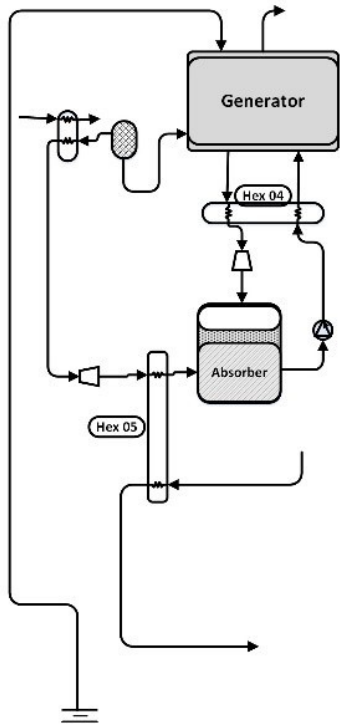

Fig. 2. Mass flow rate of the proposed cycle.

This study utilizes two different equations of state, namely the modified Benedict-Robin for simulating pure hydrogen and the Peng-Robinson for other fluid flows. The cycle simulation is conducted using ASPEN HYSYS 11 software. The properties of each segment of the cycle are summarized in Table 1. The simulation results are cross-validated with the findings from reference [11].

Table 1. Propertise of each flow for the proposed cycle.

Component of flow	Flow name and fracion			
	M1	28	16h	W1
Hydrogen	0	100	3	0
i-Pentane	7	0	0	0
Ethylene	16	0	0	0
Helium	0	0	63	0
Nitrogen	51	0	0	0
Methane	17	0	0	0
Neon	0	0	34	0
Propane	9	0	0	0
Water	0	0	0	100

2.1 Energy, Exergy and Economical Analysis

The energy analysis and continuity can be described as follows [12].

$$\dot{Q}_{sv} + \sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} + W_{sv}\,. \qquad (1)$$

Equations (2) and (3) can be utilized to determine the specific energy consumption and coefficient of performance for the hydrogen liquefaction process.

$$\mathrm{COP} = \frac{Q_c}{W_{net}}\,, \qquad (2)$$

$$\mathrm{SEC} = \frac{W_{net}}{\dot{m}_l}\,. \qquad (3)$$

Exergy analysis is based on the following equations:

$$\mathrm{Ex} = \mathrm{Ex}^{ph} + \mathrm{Ex}^{ch}\,, \qquad (4)$$

$$\mathrm{Ex}^{ph} = h - h_0 - T(S - S_0)\,, \qquad (5)$$

$$\mathrm{Ex}^{ch}_m = \sum_j x_j \mathrm{Ex}^{ch}_j + \bar{R}T_0 \sum_j x_j \ln x_j\,, \qquad (6)$$

$$\mathrm{Ex}_i + \mathrm{Ex}_{Qi} = \mathrm{Ex}_o + \mathrm{Ex}_{Qo} + W_{sh} + I\,, \qquad (7)$$

$$\eta_{cycle} = 1 - \frac{I_{total}}{p_{net}}\,. \qquad (8)$$

Enthalpy, entropy, and irreversibility are denoted by H, S, and I, respectively. To determine the yearly expenses of the process, Equations (9) through (12) can be employed. The cost associated with the hydrogen liquefaction process is determined using Equation (9):

$$C_{\mathrm{CAPEX},t} = C_{devices}(1 + a_1 + a_2 + a_3 + a_4 + a_5 + a_6)\,. \qquad (9)$$

The constants a_1 through a_6 represent various factors including installation and insulation (0.1), piping (0.15), installation location (0.1), control and electrical systems (0.14), unforeseen costs (0.16), and test and commissioning costs. These constants are used in

the calculation of main equipment, such as heat exchangers, compressors, and turbines, which can be determined separately using equations 10 to 12 [13, 14].

$$c_{\text{hex}} = 0.1 \left[8500 + 409 \left(A_{\text{hex}} \frac{U_A}{U_{OH}} \right)^{0.83} \right], \quad (10)$$

$$c_{\text{com}} = 7900 \left(w_{\text{com}} \right)^{0.62}. \quad (11)$$

According to Equation (10), the cost of the heat exchanger is determined by its surface area. The cost of additional components, such as the turbine and compressor, is approximated as a fraction of the main equipment cost. In this study, this fraction is set at 35% of the total cost of the compressor, turbine, and heat exchanger. The annual cycle cost can be computed using Equation (12):

$$c_{\text{tur}} = 378 (w_{\text{tur}})^{0.81}. \quad (12)$$

In Equation (12), c_{el} represents the electricity cost associated with the operation of the cycle, while $c_{\text{feed,in}}$ denotes the yearly cost of the cycle with respect to raw materials. Additionally, the maintenance cost is assumed to be 2% of the initial capital cost of the cycle. By applying Equation (12), the production cost for a single kilogram of liquid hydrogen can be determined.

3 Results and Discussion

Table 2 presents the results related to the flow and characteristics observed at each stage of the cycle. The energy and exergy analysis results, shown in Figure 3, reveal the rate of exergy destruction for each piece of equipment, as well as the exergy efficiency. It is clear from Figure 3 that the equipment responsible for expanding the flow exhibits lower exergy efficiency within the cycle. Furthermore, Figure 4 illustrates the exergy destruction rate for each equipment, with coolers identified as having the highest exergy destruction rate among all the equipment involved in the cycle.
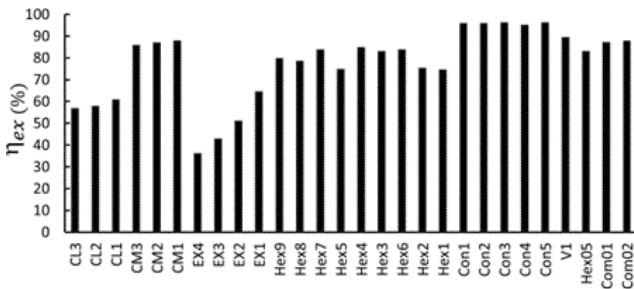

Fig. 3. Exergy efficiency of each equipment in cycle.

Table 2. Thermodynamic propertise of main flows in cycle.

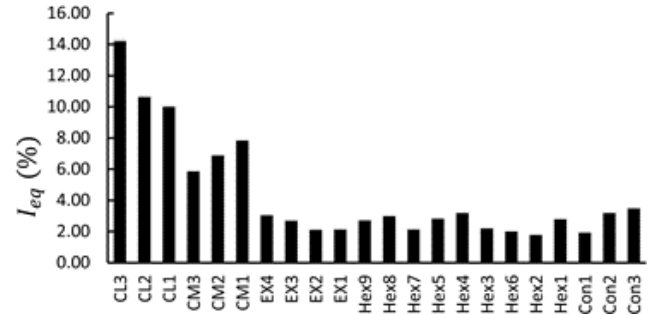| Flow	Pressure (kPa)	Temperature (°C)	Mass flow rate (kg/h)
h_2	1970	−142	79
h_4	1910	−206	79
h_6	1910	−230	79
h_8	1850	−237	79
h_{10}	2000	−248	79
27	2000	25	79
28	1501	−27	79
29	101	25	18
30	101	−29	18
31	101	−29	18
32	1501	25	89
33	1501	58	89
34	1501	100	89
35	1501	131	71
36	1501	78	71
37	1501	47	71
38	1501	131	71
39	1501	131	89
40	1501	131	18

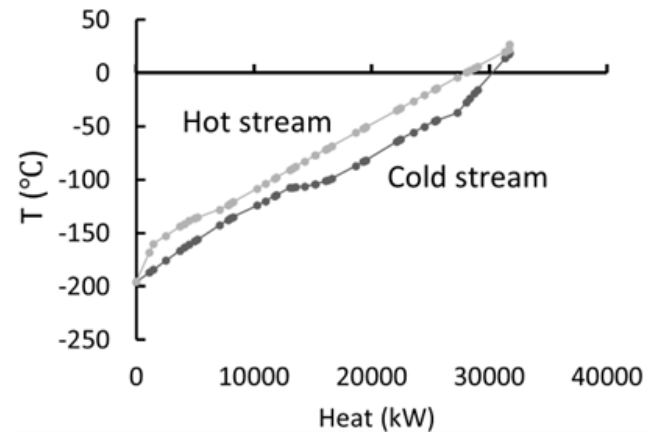**Fig. 4. Exergy destruction rate of each equipment in cycle.**

Fig. 5. Compound figure for precooler heat exchangers.

Figure 6 clearly demonstrates that increasing the pressure within the range of 3300 to 4200 kPa results in a reduction of the SEC. Figure 7, on the other hand, shows that the SEC is influenced by the increasing mass flow rate of the refrigerant. However, it is worth noting that a mass flow rate of 931 kg/h exhibits the optimal performance for the liquefaction cycle.
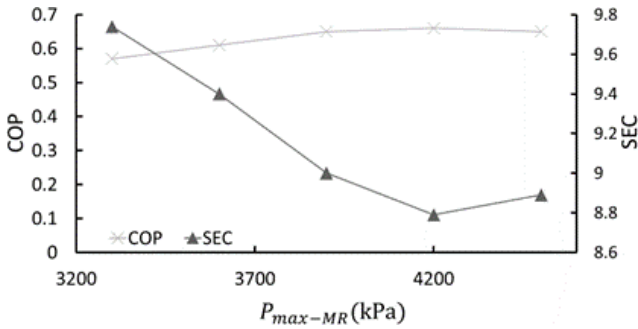

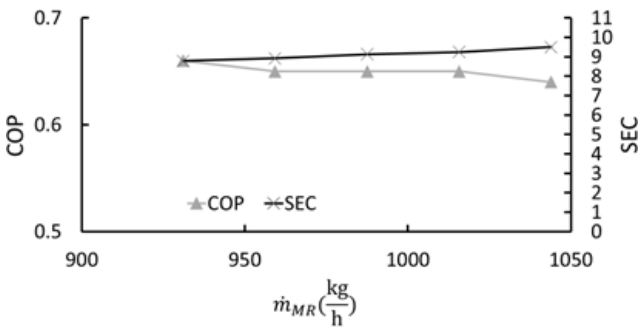**Fig. 6. Comparison of pressure of refrigerant on liquification cycle performance.**

Fig. 7. Mass flow rate of refrigerant impact on liquification cycle performance.

Figure 8 illustrates the impact of geothermal source temperature on SEC. As the geothermal source temperature increases from 150 °C to 300 °C, there is a significant rise in SEC. Nevertheless, the rate of change slows down considerably around 200 °C. The data from Figure 8 suggests that lowering the geothermal source temperature results in improved performance of the liquification cycle. However, since this stream is utilized in the electricity production cycle, reducing the temperature may disrupt the cycle's functionality. Therefore, it can be concluded that the optimal temperature is 200 °C.

Figures 9 and 10 illustrate the contrast between the annular cost of the cycle and the influence of the minimum heat exchanger working temperature difference on the cycle's performance. It is important to note that the annual cost includes a 7 percent profit margin over a 20-year payback period.
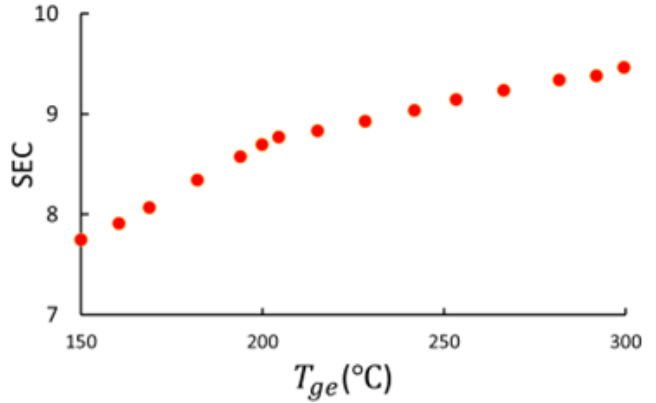

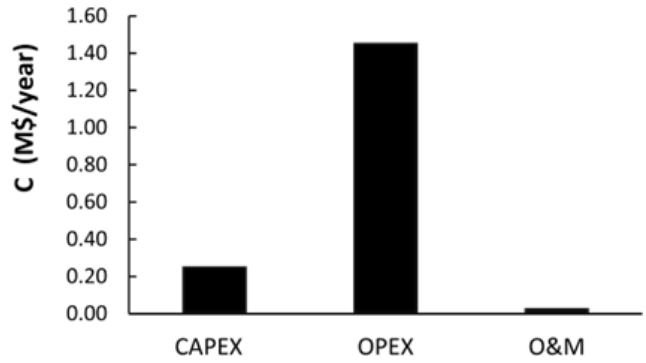**Fig. 8. Compound figure for precooler heat exchangers.**

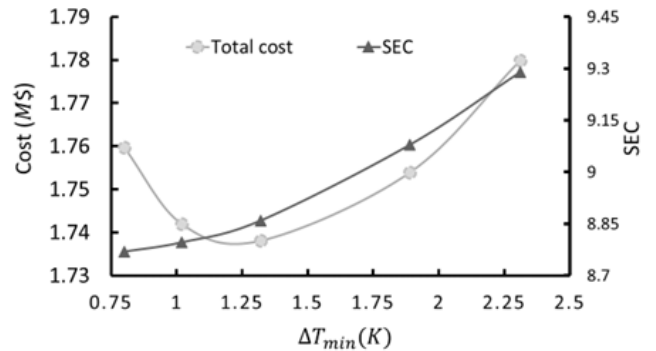**Fig. 9. Comparison of annular cost of the cycle.**

Fig. 10. Impact of minimum temperature difference of heat exchanger on SEC.

Table 3 compares the results of the current study with those of Yung [15], focusing on a three-year payback period. The Specific Energy Consumption (SEC) of the cycle in the current study is 8.51. Yung [15] reported that hydrogen enters the liquefaction cycle at a temperature of 23 °C, whereas in the current study, hydrogen is precooled to −27 °C before entering the liquefaction cycle. This significant difference in the initial temperature of the hydrogen is the primary fac-

tor contributing to the lower SEC observed in the current cycle. Utilizing compression as an alternative to liquification can offer potential advantages. However, it is important to recognize the significant safety concerns associated with this method, as well as the lower heating value of the resulting gas compared to liquefaction. As a result, hydrogen liquefaction stands out as a viable alternative for storing renewable energy, despite the potential high-cost impact of battery stor-age. In hydrogen systems, the integration of cogeneration capabilities enables the production of heat, power, and other valuable by-products, thereby improving the overall efficiency of the cycle. In the context of this study, a geothermal system is utilized as a renewable energy source, and a proposed cycle is introduced to effectively store this energy while simultaneously generating heat, electricity, and fresh water.

Table 3. Comparison of present work with similar cycles [15].

Parameter	Units	Present Work	Ref. [15]	Difference
SEC	kWh/kg	8.51	11.05	+23%
Minimum Cost of hydrogen	$/kg	2.71	2.53	-7%

4   Conclusions

This study proposes a modified hydrogen liquefaction cycle that utilizes renewable geothermal energy to power the process. Hydrogen is produced through the electrolysis of water, with the process beginning by heating water using geothermal heat. The resulting hot water is then employed in an absorption refrigeration cycle to precool the hydrogen. Afterward, the pre-cooled hydrogen undergoes liquefaction in a dedicated cycle. To evaluate the performance of the cycle, an energy, exergy, and economic analysis was conducted. The goal of this analysis is to assess the impact of various parameters on the cycle's efficiency. The results show that by heating the water to a temperature of $200\,^{\circ}\mathrm{C}$, the cycle is able to produce 79 kg/h of liquid hydrogen. Notably, as the temperature increases, hydrogen production also rises. However, this increase in temperature is accompanied by limitations on the mass flow rate of hydrogen. Furthermore, the exergy-economic analysis indicates that the total cost of the cycle is 1.49 million dollars. Considering the production capacity of the cycle, this translates to a cost of 2.71$ per kilogram of liquid hydrogen, with a return on investment period of 2 years. These findings suggest that hydrogen liquefaction cycles provide a viable and efficient method for storing renewable energy, while also enabling the cogeneration of heat, power, and valuable by-products such as fresh water.

Acknowledgements

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