

A modified hydrogen liquefaction cycle integrated with geothermal energy and an absorption refrigeration cycle

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Abstract: Scientific discussions are gaining momentum on renewable energy, geothermal energy in specific. Researchers are seeking to propose different methods for energy storage systems that are more efficient and environment-friendly. The objective here is to propose an innovative approach where geothermal energy is consumed to fulfill different requirements first, and be stored in liquid hydrogen and consumed cold energy generated from geothermal sources through an absorption refrigeration cycle for pre-cooling, next. This liquid hydrogen is gasified before entering the liquefaction cycle. This multipurpose system produces hot water, freshwater, and power through geothermal energy. The geothermal flow enters the ammonia water absorption cooling unit, first, where its temperature is reduced, and enters the organic Rankine power generation unit equipped with a heat exchanger to produce hot water. The system is assessed by running energy, exergy, and economic analyses, with a focus on the hydrogen liquefaction cycle. The total estimated annual cost of the system is \$1.62 million, with a minimum selling price of \$2.96. The specific energy consumption in the multipurpose system is computed as 8.78 kWh p/kg of liquid hydrogen produced.

keywords: Hydrogen, Geothermal, Solar energy, PEM, Water-ammonia absorption.

1 Introduction

The increase in energy demand and the negative effects of fossil fuel types consumption on the environment have led to the development of energy conversion and storage systems, especially for renewable energy sources (Faramarzi et al. 2021a; Faramarzi et al. 2021). Geothermal energy is consumed as a permanent and sustainable energy source to generate electricity. Minimizing carbon emissions through different processes and converting energy sources by environment-friendly processes is gaining momentum (Faramarzi et al. 2024; Faramarzi and Khavari 2023).

One of the advantages of geothermal energy is the absence of environmental pollutants. The studies on geothermal waters as a source of energy storage systems are many (Faramarzi et al. 2024; Ghorbani et al. 2019).

The temperature of the geothermal output flow source can vary from 50 °C to 350 °C

(Ghorbani et al. 2020). Due to the existence of many heat sources in different places and industries, it is estimated that the trend of consuming renewable energies will increase in the future. The studies on geothermal energy sources for different cogeneration systems are many. Abdolalipouradl et al. (2020) assessed a cogeneration system through a geothermal energy source. They proposed a system to produce electricity, fresh water, and hydrogen gas. They applied energy and exergy analysis to find the best key variables. The multi-purpose process produced power, fresh water, and hydrogen gas. Hürdoğan and Kara (2022) applied geothermal heat exchangers to produce fresh water and applied polymer electrolyte membrane electrolyzers and photovoltaic-thermal panels to meet the requirements of the hydrogen production cycle. Soil temperature, solar radiation, and mass flow rate are the main parameters that affect the process. Faramarzi et

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al. (2021b) modeled a heat exchanger with boundary conditions in the hydrogen liquefaction cycle. Neon gas is consumed to reduce the temperature difference in the exchanger. In the heat exchanger, exergy destruction is caused by: pressure drop, hot and cold temperature difference, and the phenomenon of conversion of ortho hydrogen to para. Exergy destruction caused by the pressure drop in the converter is less effective than in other cases. The organic Rankine cycle applies heat sources like renewable sources and waste heat to produce electricity (Ghorbani et al. 2020).

Many researchers have assessed the organic Rankine systems integrated in geothermal sources in detail. Desalination systems can consume geothermal energy (Abdollahi et al. 2024; Nikzad et al. 2024). Excess salt and minerals are removed from the salt water through this energy (Okampo and Nwulu 2021). Among the different approaches in the world, the most practical methods are adopted in seawater desalination in medium and high volumes. Systems based on reverse osmosis are among the most popular methods (Qasim et al. 2019). The reverse osmosis system requires less thermal energy compared to other methods, which are based on heating (Qasim et al. 2019). Hoseinzadeh et al. (2020) proposed a reverse osmosis desalination system integrated with geothermal energy, a carbon dioxide turbine, and a sodium hypochlorite generator. A 10% drop is observed in the overall cost rate compared to the general state. Moradi Nafchi et al. (2019) applied renewable energy types to supply the required power of a proton membrane electrolysis. The efficiency of their proposed cycle had an exergy efficiency of 41.25%. Yilmaz (2018) studied the consumption of geothermal energy in the absorption pre-cooling unit of a liquid hydrogen production system. The power obtained from geothermal energy is consumed in hydrogen liquefaction cycle compressors. A GA is run to minimize the energy consumption of the cycle. Seyam et al. (2020) proposed an innovative system to convert geothermal energy into power and liquid hydrogen. Claude cycle is applied in the cooling part of the liquefaction system, while in the pre-cooling system, nitrogen gas is consumed to reduce the hydrogen gas temperature. The power consumption of the liquefaction unit is 107 MW and different volumes of hydrogen mass flow rate and pressure are assessed.

The presented cycles are many, but to date, studies on the possibility of the simultaneous production of several products in a combined system equipped with an energy storage system are few. In this article, a multi-objective system is presented with a focus on the hydrogen liquefaction cycle, in its economic aspect. The thermodynamic performance of a multi-purpose system, including a geothermal energy system, electrolyzer, and hydrogen liquefaction cycle, is

analyzed here. The innovation of this cycle is based on a multi-generation system that stores geothermal energy in the form of liquid hydrogen, and the geothermal system that pre-cools hydrogen gas through the cooling output from a water-ammonia refrigeration cycle.

2 System description

There are six central units involved in this process: 1) the geothermal water enters the absorption system, which pre-cools the hydrogen stream, 2) the heat from the geothermal flow increases the temperature of the water flow to the operating temperature of the electrolyzer, 3) the organic Rankine cycle converts the geothermal water energy into electricity, which powers the desalination unit and hydrogen liquefaction cycle, 4) ORC unit is simulated according to (Abdolalipouradl et al. 2020), 5) once separated from water in the electrolyzer, hydrogen enters the hydrogen liquefaction cycle, and 6) the geothermal water is heated up to the operating temperature and returns to the injection well. The information about the geothermal flows and absorption system is based on (Kanoglu et al. 2016). The flow streams and equipment of the liquefaction unit and absorption cooling section are diagrammed in Fig. (1).

The geothermal flow, known as flow named 1, Fig. (1), enters the absorption refrigeration cycle at 200 °C. The required thermal energy is provided by geothermal hot water. In the absorption system, in orange, Fig. (1), the hydrogen flow, or flow number 27, is cooled from 25 °C to minus 27 °C. In this cooling process, the cold energy from the absorption system is consumed which allows the hydrogen liquefaction cycle to avoid the need for more electricity. After pure ammonia is evaporated in the evaporator, water is consumed to absorb the ammonia in the absorber. The water flow cools the solution, and the rich ammonia, or flow number 32, enters the generator. The gaseous hydrogen that exits the electrolyzer is pre-cooled in the hydrogen liquefaction cycle through five heat exchangers. The first heat exchanger is for pre-cooling, and the rest consume a combined refrigerant including hydrogen, helium, and neon. The negative temperature of 253 °C cools the hydrogen to make it liquid. Two modified Benedict Webb-Rubin equations of state are applied here to simulate the pure hydrogen flows, and Peng-Robinson equations of state are applied to simulate the other flows. The ASPEN hysys 10 software is applied to simulate the hydrogen liquefaction cycle and absorption cooling unit. The thermodynamic properties of the simulated flows are computed in the Haysis software, and validated by comparing them with the findings in (Faramarzi et al. 2021; Faramarzi et al. 2021). The characteristics of the main currents used in this process are tabulated in Table 1.

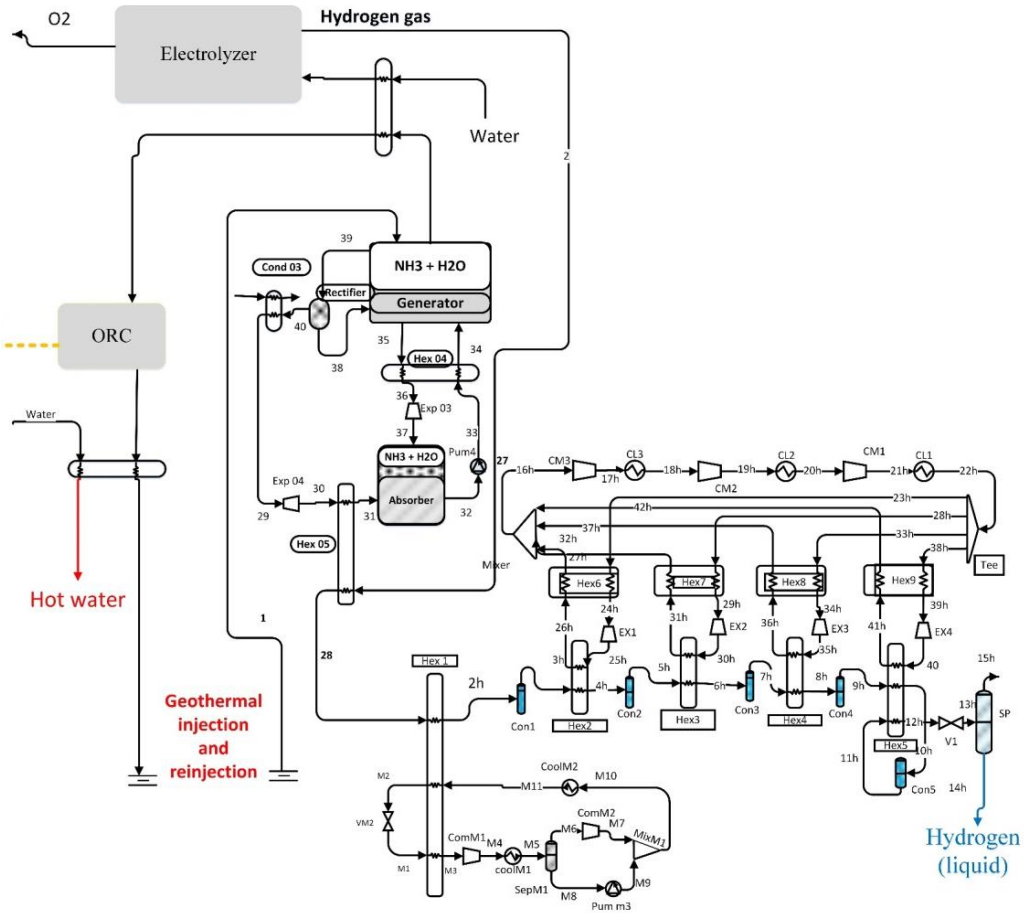


Fig. 1. Flow diagram of this proposed multi-generation system

Table 1. Detailed components of main flow streams applied in the proposed system

Flow streams				
W1	16h	28	M1	Components
0	4	100	0	Hydrogen
0	0	0	6	i-Pentane
0	0	0	17	Ethylene
0	64	0	0	Helium
0	0	0	53	Nitrogen
0	0	0	15	Methane
0	32	0	0	Neon
0	0	0	9	Propane
100	0	0	0	Water

2 Governing equations

Energy analysis based on mass and energy balance is as follows (Faramarzi et al. 2022; Golchoobian et al. 2018):

$$\dot{Q}_{cv} + \sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} + W_{cv} \quad (1)$$

where \dot{m} is the mass flow rate. SEC and coefficient of performance (COP) for the hydrogen

liquefaction cycle are computed to compare it with other similar cycles. The performance parameters are as follows (Golchoobian et al. 2021; Nourbakhsh et al. 2021):

$$SEC = \frac{P_{net}}{\dot{m}_l} \quad (2)$$

$$COP = \frac{Q_c}{P_{net}} \quad (3)$$

where P_{net} is the power consumption in compressors. Exergy analysis is based on the following equations (Faramarzi et al 2021; Fratzscher 1997; Ghorbani et al. 2020a):

$$Ex = Ex^{ph} + Ex^{ch} \quad (4)$$

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

$$Ex_m^{ch} = \sum_j x_j Ex_j^{ch} + \bar{R}T_0 \sum_j x_j \ln x_j \quad (6)$$

$$Ex_i + Ex_{Qi} = Ex_o + Ex_{Qo} + W_{sh} + I \quad (7)$$

$$\eta_{cycle} = 1 - \frac{I_{total}}{P_{net}} \quad (8)$$

where h is the enthalpy and s is the entropy, I is the irreversibility and η is the total exergy efficiency. Investment cost and annual maintenance cost are computed to estimate the annual cost of liquid hydrogen production. The economic parameters are computed based on the cost estimation method proposed by Cardella et al. (2017). The equations of economic analysis are as follows (Golchoobian et al. 2019; Cardella et al. 2017):

$$C_{CAPEX,a} = C_{CAPEX,t} \frac{A \cdot (1 + A)^b}{(1 + A)^b - 1} \quad (9)$$

$$SLC = \frac{C_{OPEX,a} + C_{OPEX,t} + C_{O\&M,a}}{\dot{m}_{LH2,a}} \quad (10)$$

where b is the payment period, A is the annual interest rate. Considering the capital

payback time, three years in this study, the minimum selling price of liquid hydrogen is computed to evaluate the proposed cycle.

3 Results

The characteristics of different flows are tabulated in Table 2. The energy and exergy analysis results are applied to identify the optimal initial values. According to the exergy analysis results, some equipment has high exergy destruction rates. The exergy efficiency of different equipment, which indicates that the expanders are the equipment with the lowest exergy efficiency in the hydrogen liquefaction cycle is shown in Fig. (2). The exergy destruction of different equipment, indicating that the coolers have the highest overall exergy destruction ratio among all the equipment in the hydrogen liquefaction cycle are compared in bar charts in Fig. (3).

The effect of the maximum working pressure of the refrigerant of the liquefaction cycle cooling unit is plotted in Fig. (4). The change in the mass flow rate of the combined refrigerant in the overall performance of the liquefaction cycle, is plotted in Fig. (5). As observed in Fig. (6), an increase in the maximum pressure within the 3300 to 4200 kPa range decreases SEC.

Table 2. Thermodynamic properties of main flow streams applied in this proposed system

Flow stream	$\dot{m} \left(\frac{\text{kg}}{\text{h}} \right)$	T (°C)	P (kPa)
H2	80	-141	1968
H4	80	-207	1903
H6	80	-231	1903
H8	80	-238	1843
H10	80	-248	1843
27	80	25	2000
28	80	-27	2000
29	17	-26	1501
30	17	-30	101
31	17	-30	101
32	90	25	101
33	90	58	1501
34	90	100	1501
35	71	131	1501
36	71	78	1501
37	71	47	1501
38	71	131	1501
39	90	131	1501
40	17	131	1501

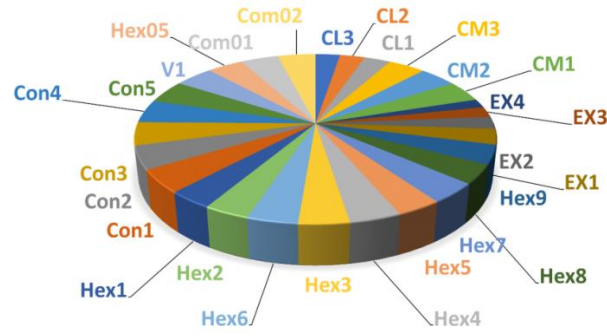


Fig. 2. Exergy efficiency of different components

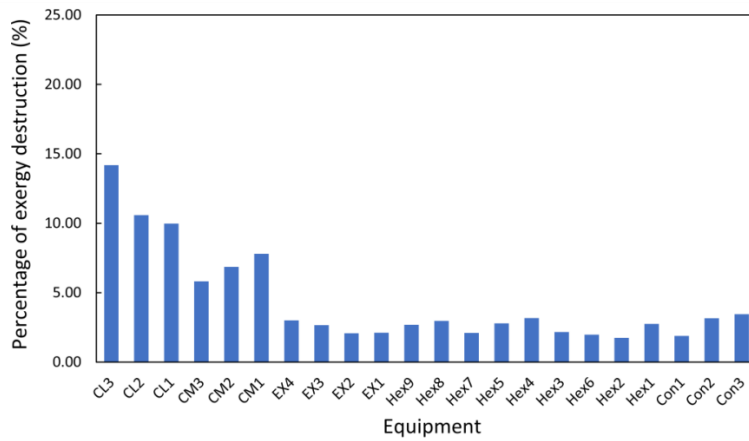


Fig. 3. Exergy destruction proportion of different equipment

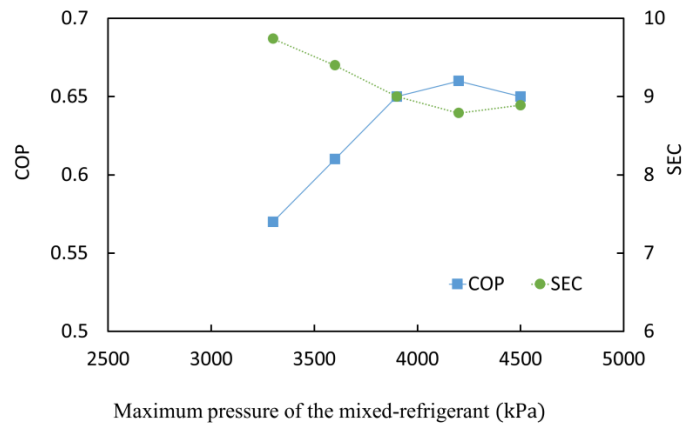


Fig. 4. Effect of changes of pressure work of the mixed refrigerant applied in the hydrogen liquefaction cycle on COP and SEC

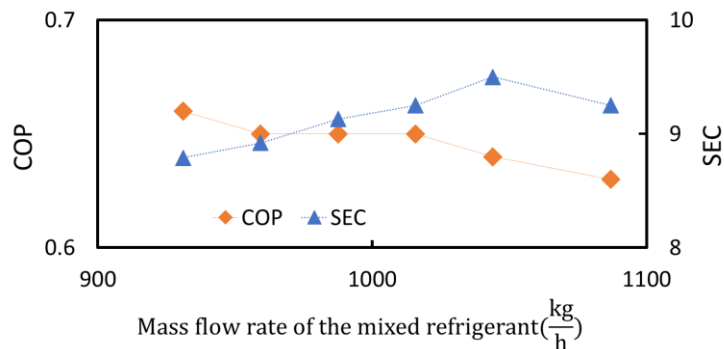


Fig. 5. Effect of changes in mass flow rate of the mixed refrigerant applied in the hydrogen liquefaction cycle on COP and SEC

That an increase in the flow rate of the mixed refrigerant leads to an increase in SEC with a minor effect on the exergy efficiency is shown in Fig. (5). The optimal performance of the liquefaction cycle is achieved when the refrigerant mixture flows at 931 kg/h rate in the pre-cooling stage. The impact of geothermal temperature changes on specific energy consumption is shown in Fig. (6), where, SEC increases as the geothermal temperature rises from 150°C to 300°C. The slope of the line changes gradually at 200°C.

The total annual cost of the hydrogen liquefaction cycle and its performance with the minimum proximity temperature in the converters are compared in Fig. (7). The annual investment cost including equipment and other capital costs, with an annual interest rate of 7 %

and a payment period of 20 years is computed. To compute the minimum selling price of liquid hydrogen, a three-year payback time is considered for the proposed cycle in this study. Though the specific energy consumption of this cycle is 8.78, it is notable that this study applies a small-scale hydrogen liquefaction cycle. Compared to other big-scale cycles that produce liquid hydrogen, this cycle has a higher capital cost for hydrogen production, which is predictable. The characteristics of the cycle assessed in this study are compared with that of (Yang et al. 2019). In this study, hydrogen gas enters the liquefaction unit at -27 °C due to pre-cooling in the absorption cooling section, thus, the outstanding point of this study.

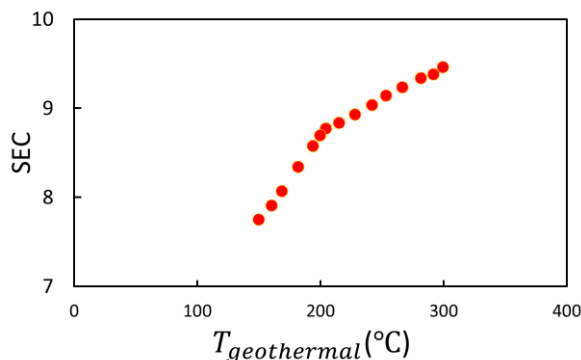


Fig. 6. Effect of changes in geothermal temperature on SEC of the hydrogen liquefaction cycle

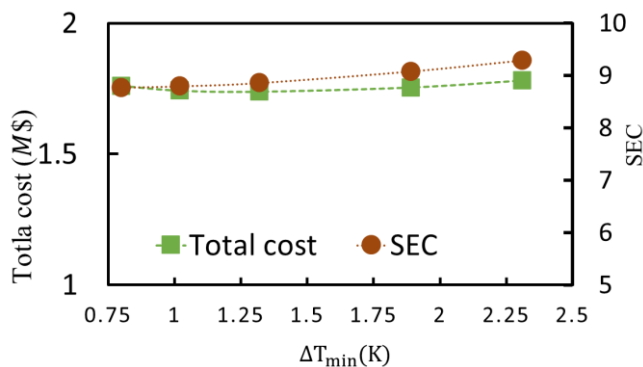


Fig. 7. Effect of changes of minimum temperature difference applied in the hydrogen liquefaction cycle on total cost and SEC

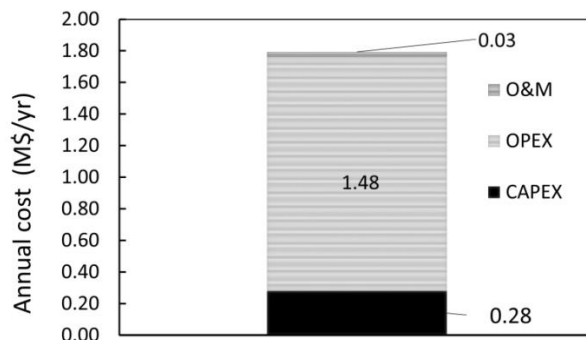


Fig. 8. Different annual costs of the hydrogen liquefaction cycle (COPEX, OPEX, O&M)

Table 3 Comparison of the proposed multi-generation system with other similar cycles (Yang et al. 2019)

Performance parameter	(Yang et al. 2019)	This study	Improvement compared with (Yang et al. 2019)
SEC (kWh/kg)	11.04	8.78	+19 %
Minimum selling price (\$/kg)	2.53	2.96	- 15.6 %

4 Conclusion

A multi-objective process involving an electrolyzer applied to separate hydrogen from water is assessed here. Geothermal water heat is consumed in the water-ammonia absorption cycle to cool the hydrogen gas flow entering the hydrogen liquefaction cycle. The focus here is on the hydrogen liquefaction cycle, which is added to a multi-purpose system to store geothermal energy as liquid hydrogen. The efficiency of the hydrogen liquefaction cycle is analyzed by running energy, exergy, economic, and sensitivity analysis. The proposed cycle applies a geothermal energy source at 200 °C to feed different units. At this temperature, the production capacity of liquid hydrogen is 80 kg/h. The mass flow rate of the produced hydrogen is limited by the power provided in the geothermal system. The higher the temperature of the geothermal flow, the higher the mass flow rate of the produced hydrogen. Geothermal energy is consumed to power equipment like electrolyzers, desalination units, and hydrogen liquefaction cycle compressors. Based on the analysis, the expanders in the equipment have the lowest exergy efficiency, while the coolers have the highest overall exergy destruction ratio compared to other components in the hydrogen liquefaction cycle. The economic analysis reveals that the total annual cost amounts to \$1.79 million, and based on the capacity of the liquefaction unit, the production cost of liquid hydrogen is \$2.31 p/kg. Considering the three-year payback period, the minimum sales cost for liquid hydrogen is \$2.96 p/kg.

5 Recommendations for future works

It is suggested to assess this proposed system in terms of exego-economic analysis to estimate the cost of exergy in hydrogen production and compare it with other methods. Other types of renewable energy like solar energy can be applied instead of geothermal energy.

Nomenclature

Symbols

- C* Cost (\$)
- e* Exergy (kW)
- h* Specific enthalpy (kJ/ kg)
- P_{net}* Net power (kW)
- s* entropy (kJ/kgK)
- t* Process lifetime (year)
- I* Exergy destruction (kW)
- V* Voltage of electrolyzer (V)
- W_{com}* Work of compressor (kW)
- Y_a* Annual rate of cycle activity

η Exergy efficiency (%)

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