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Techno-economic analysis of green hydrogen production, storage, and waste heat recovery plant in the context of Nepal

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ABSTRACT

Alkaline water electrolysis (AWE) operated by surplus electricity is suitable for producing green hydrogen in Nepal. Simulation models are built using DWSIM software for AWE, multistage compression, and the Organic Rankine Cycle (ORC). The AWE system's Capital Expenditure (CAPEX) is determined to be $47 million and Operational Expenditure (OPEX) of $7.65 million/year. The storage system, including the multistage compression system and Type IV cylinders, has a CAPEX of $52 million and an OPEX of $17 million/year. The ORC has a CAPEX of $500,000 and an OPEX of $200,000/year. The thermal power generated from AWE and multistage compression can be converted to electricity by the ORC and supplied to the AWE system. This process decreases the Levelized Cost of Hydrogen (LCOH) from $3.5141/kg over 5 years to $3.4725/kg over 25 years. The techno-economic analysis performed confirms the feasibility of implementing these plants in Nepal.

1. Introduction

Human society relies entirely on natural resources and fossil fuels. Conventional fuels such as petroleum, firewood, coal, and natural gases are significant sources of energy, which are non-renewable sources with carbon and greenhouse gas (GHG) emissions, which are a major concern today to be solved [1]. Considering such a problem, we should look for a better alternative to fossil fuel, which has the potential to be a game changer in the sector of energy storage. Hydrogen has many unique properties that make it the best alternative to fossil fuels like petroleum and natural gas [2]. Hydrogen is a clean, economical, and highly safe renewable energy source that would be ideal to replace fossil fuels because it is light, available in excess amounts, and forms water as a byproduct, which is environmentally benign. The hydrogen economy has emerged as a promising alternative to the current hydrocarbon economy [3]. Hydrogen has been proven to be an alternative fuel that will potentially replace fossil energy due to many attributes like increased energy density, abundance, ease of transportation, and a variety of different processes from clean renewable energy fuels with zero or negligible emissions [4].

Currently, grey hydrogen and blue hydrogen are widely popular as renewable energy. Still, in reality, they are generated from fossil fuels, and the most important task to achieve a hydrogen-based society is the development of a green hydrogen production system [5]. Green hydrogen is a type of hydrogen generated by using renewable energy sources. Hydrogen that is generated through water electrolysis can be used as an alternative fuel with a high gravimetric energy density and high energy production potential, which can solve conventional fossil

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Abbreviations: AWE, Alkaline Water Electrolysis; AEL, Alkaline Electrolyzer; ORC, Organic Rankine Cycle; LCOH, Levelized Cost of Hydrogen; CAPEX, Capital Expenditure; OPEX, Optimal Expenditure; SE, Surplus electricity; MW, Megawatt; PEM, Proton Exchange Membrane; H_2, Hydrogen; NEA, Nepal Electricity Authority.

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fuel exhaustion and degradation of the environment [6]. Powering electrochemical reactions created by renewable electricity produced from distributed mechanical energy can lead to commercial electric energy savings and cost reductions [7]. Nepal has a huge potential to generate green hydrogen to be a hydrogen-backed economy and rise in the global fuel market. Nepal's hydropower resource can produce green hydrogen as an energy storage medium and electrify the transportation sector [8]. Since Nepal is expected to have about a 3000 MW electricity surplus by the year 2030, it is time to practice alternative electricity use to make hydropower projects financially feasible [9].

Numerous studies have demonstrated Nepal's significant potential for producing hydrogen from excess hydroelectricity. 753 MW of new generating capacity were added to the grid in the fiscal year 2021–2022, according to the NEA [10]. Around 11.6 billion NPR have been made from energy sales during off-peak hours since June 2022 [11]. In 2021/22, hydroelectric plants sold 493.6 GWh of power to India NEA Generation Directorate [12]. Nepal expects to handle surplus electricity well, but worries about possible overproduction remain. Ale and Bade Shrestha (2008) investigated the use of hydroelectricity during off-peak hours to produce green hydrogen, estimating a capacity of 27 kt to 140 kt by 2020. Based on projections, surplus hydropower capacity is expected to reach 10,000 MW by 2030 and 39,000 MW by 2040. This may potentially lead to the production of hydrogen for less than $1 per kilogram by 2050. In the fiscal year 2021–2022, green hydrogen might help Nepal's chemical industry by fulfilling fertilizer demands and perhaps exceeding imports [13,14]. The techno-economics of producing urea using hydropower was evaluated by Devkota et al. [15], who found that the levelized costs of ammonia and hydrogen varied. A Capital Expenditure (CAPEX) of $25,546,417, an Operational Expenditure (OPEX) of $236,497,554/year and a minimum Levelized Cost of Hydrogen (LCOH) of $2340/ton, or $2.58/kg, is predicted to be the cost of hydrogen. Such value of LCOH and economic analysis conducted in past studies prove that it is cost-effective to use the electricity surplus to supply hydrogen. There are also other ways to use the surplus electricity generated from hydropower. Nepal, if it utilizes the surplus electricity generated to produce hydrogen, can help it become a hydrogen-rich economy. It would support Nepal to decrease its reliance on countries like India to import fuels like petroleum and coal and grow its economy by exporting the produced hydrogen n in the form of ammonia and urea [15]. Similarly, the use of electricity through the establishment of many new industries can help Nepal grow its economy rapidly.

Electrolysis of water, especially alkaline water electrolysis (AWE), is the most promising method used to produce hydrogen because of its economic benefits and no effect on the environment. Following the envisaged growth in renewables, producing hydrogen using electrolysis using renewable electricity in combination with different methods of storage of the produced hydrogen can create short-term, seasonal, or long-term benefits for re-electrification in multiple areas [16]. The electrolysis method of hydrogen production is the most suitable means of hydrogen production in Nepal. With several hydropower projects due to be completed in upcoming years and the time-of-day meter already being implemented in many industries of the country, an automated plant with few to no personnel would be suitable for economic hydrogen (H_2) production [17]. Further, the annual hydrogen production is determined by applying hydrogen production efficiency to the annually available surplus hydropower. This production efficiency of Nepal is taken as 50 kWh/kg H_2 for 2025 and is assumed to remain unchanged for simplicity [18]. Utilization of such potential through AWE, which is the most advanced and green technology, can help Nepal upgrade its economy and reduce its dependency on other countries for fuel.

The problems of hydrogen transportation and storage have restricted the application of hydrogen energy, which has become a major factor in the progress and utilization of hydrogen energy [19]. Low energy density, cryogenic storage requirements, material compatibility, embrittlement, safety concerns, limited infrastructure, and cost are major problems associated with hydrogen. Many researchers and engineers are actively working on addressing these problems and challenges through various storage methods, such as solid-state storage, metal hydrides, chemical storage, and advanced composite materials. The storage of hydrogen in advanced composite materials has been a topic of attention in recent years because this method of storage is widely thought to be one of the most promising solutions to the problem of storing hydrogen for use as an alternative energy carrier in a safe, compact, and affordable form [20]. Different processes for hydrogen storage are available, including multistage compression and storage, high-pressure and cryogenic-liquid storage, adsorptive storage on high-surface-area adsorbents, chemical storage in metal hydrides and complex hydrides, and storage in boranes [21]. However, storage in type-4 cylinders after compression by multistage compression at very high pressure is the most advanced and applicable method of storage of produced hydrogen gas for use in vehicle refueling stations.

The compression of hydrogen typically involves the use of compressors in multiple stages that cause an increase in the pressure of the gas by reducing its volume connected with some other devices for cooling heat management and storage of compressed products. The ultimate goal is to achieve highly compressed hydrogen gas in the final tank with a very low volume compared to the initial feed hydrogen gas. The stages through which hydrogen passes throughout the compression system are the inlet stage, intermediate stage, and final stage. A hydrogen supply system for an ionic liquid compressor can be designed for charging hydrogen into storage vehicles to fill hydrogen into vehicles [22] using the same compression system. Also, the developed and stored hydrogen can be utilized to create ammonia and urea in Nepal to decrease its import of urea from other countries. However, the timeline for large-scale implementation remains to be determined which when Nepal will be utilized on a full scale, which, if it succeeds, could be the backbone of Nepal's progress. Still, the Nepali government needs to be fully conscious of the potential of Nepal's water resources, and no national project for the development of plants for hydrogen generation has been started in Nepal. There is a significant need to attract the attention of relevant stakeholders, including private investors and government authorities, to initiate projects that can effectively utilize Nepal's capacity for hydrogen production.

Both electrolyzer and multistage compressor systems produce a significant quantity of heat that must be recycled. To recycle such waste heat produced, an Organic Rankine Cycle (ORC) can be used. The ORC is a proven method to convert heat sources at low and medium temperatures in the range of 50–300 °C into electricity and has been recognized as a viable approach that converts waste heat into electricity [23,24]. ORC is a power generation technology that uses organic working fluids instead of water to convert low-grade heat into electricity. ORC systems have many benefits, including:

Efficiency: ORC systems are more efficient than other power generation technologies, such as the steam Rankine cycle, when converting low-grade heat into useful electricity. This is because organic working fluids have lower boiling points than water, which means that they can vaporize at lower temperatures, which helps to increase their efficiency.

Flexibility: ORC systems can be used with multiple sources of heat, including waste heat from industrial processes, geothermal energy, and solar energy. Overall, the ORC system is a versatile technology for diverse applications.

Scalability: ORC systems can be scaled from small units to large power plants. This makes ORC systems suitable for a variety of applications, from distributed generation to utility-scale power generation. For large-scale heat recycling, ORC can be used.

Environmental benefits: ORC systems can help to reduce greenhouse gas emissions by converting waste heat into electricity. This can diminish the need for fossil fuel-fired power plants.

The generated electricity from reusing the waste heat from the electrolyzer can be used to be connected to the electric supply line of the electrolyzer which can help in reducing the cost of electricity and ultimately overall OPEX. Overheating of an electrolyzer can reduce efficiency, degrade materials, and decrease hydrogen purity. It can also cause safety risks, such as leaks or explosions and damage to components. Though Nepal produces very cheap hydroelectricity using its water resources, this technology can be a useful way of recycling the generated heat from electrolyzers and multistage compressors, which can surely help reduce electricity expenses. It can be a highly useful technology in countries where the cost of electricity is very high for running a business. Till today, research articles have yet to be published that involve the utilization of waste heat in the context of Nepal reduced from alkaline water electrolyzers and storage systems. Also, there are no scientific articles published regarding storage methods like multistage compression systems in the context of Nepal.

A few previous studies have explored utilizing Nepal's hydropower for green hydrogen production. One study analyzed the potential for hydrogen generation from 2022 to 2030 under 20–100% surplus energy utilization scenarios [9]. Significant production ranges from 63,072 to 3,153,360 tons in 2030 were found, with a hydrogen production cost as low as $1.17/kg. Another study developed hydropower generation and demand profiles under low, medium, and high growth scenarios [25]. The surplus electricity was used for hydrogen production, and costs ranged from $4.07-$4.82 per kg, depending on the scenario. A study in 2008 investigated utilizing off-peak hydropower for hydrogen production to replace transportation fuels and meet peak demand [26]. Approximately 50% of off-peak hydroelectricity could produce 27–140 kilotons of hydrogen by 2020. One analysis performed a techno-economic assessment of ammonia production for green urea production in Nepal using hydropower [15]. Economic, sensitivity, and uncertainty analyses determined hydrogen and ammonia costs varied between $2845–4361/ton and $634–1018/ton, respectively, with a minimum hydrogen cost of $2340/ton. Numerous global studies have economically evaluated integrating alkaline electrolyzers with solar, wind, and hydroelectric sources. One of the analyses developed an electrolysis model for a system considering energy usage and flows [27]. The model showed high accuracy compared to experimental data.

Another research investigation delved into the integration of wind energy alongside alkaline electrolysis. The studies revealed initial hydrogen costs ranged between $2.118–2.261/kg [28] and $9.4–10/kg in 2015, decreasing to $6.2–6.5/kg by 2030 [29] as technology advanced. One analysis used solar power, with electricity costs of $18–21/MWh and electrolyzer usage from 49 to 54 kWh/kg. Calculated hydrogen costs were $2.20/kg in 2018 and projected to decrease to $1.67/kg by 2025 [30]. A study of the Oman PV-hydrogen system calculated annual hydrogen production of 90,910 kg at an investment cost of €5,301,760 and a hydrogen cost of €6.2/kg [31]. One Venezuelan study assessed the importance of electricity cost in overall hydrogen production costs, which varied significantly between 17 and 45% of total cost depending on year and population [32]. A study of Slovenian run-of-river hydropower found hydrogen cogeneration could provide hydrogen at $4.16/kg, highlighting its potential cost-effectiveness [33].

In the study [34], the author investigates the techno-economic potential of waste heat recovery from a large-scale 10 MW green hydrogen production process using proton exchange membrane electrolysis. The authors model the electrolysis system and integrate a heat recovery system to capture waste heat from the electrolyzer stack and gas streams. An ORC is then used to convert the recovered low-grade heat into electricity. Technical simulation results show that the heat recovery system can increase the overall electrolyzer efficiency from 71.4% to 98%. The study also conducts an economic analysis to calculate the LCOH under different scenarios and assess the feasibility of implementing waste heat recovery coupled with an ORC. This study demonstrates the viability of recovering usually wasted low-grade heat from large-scale hydrogen production for power generation purposes.

2. Aim and novelty

This research aims to assess the economic potential of green hydrogen production in Nepal, deliver the results of the analysis obtained on the economic potential of Nepal of the generation of green hydrogen using AWE, and determine various parameters to evaluate the cost of hydrogen generation and storage using AWE and a multistage compression system following storage respectively, along with an evaluation of the potential of Nepal to replace its vehicles with FCEVs soon. This research mentions the use of a technology involving high novelty, as explained by the flowchart in Fig. 1, which shows the use of the waste heat produced by the AWE system and the multi-stage hydrogen compression system into the ORC for generating the electricity and using the same electricity in the AWE system which ultimately affects the LCOH of hydrogen. The study has presented an idea of how the LCOH price can be reduced in hydrogen production by utilizing the waste heat produced during the hydrogen production using alkaline water electrolysis and compression process. In addition, the models of the AWE system and multistage compressor system were developed using DWSIM software, which previous research works have yet to use. Similarly, the AWE system itself is a newly proposed model that has followed the different methodologies and equations of previously published research works. Overall, the methodology used in this study offers a novel approach and a breakthrough in solving the problem of hydrogen storage and also reducing the LCOH of hydrogen in the context of Nepal (see Fig. 1).

This research focuses on the production of hydrogen on a large scale by implementation in the hydropower plants in Nepal. Although PEM (Proton Exchange Membrane) electrolyzers offer better efficiency, have small size, and fast reactions, however, they lack the durability of an AWE system, and this research work intends to suggest an idea for the hydrogen production process that requires lower investment and has higher durability. Nepal being a developing country with a weak economy, an affordable system as AWE than PEM electrolysis and more durable means of producing hydrogen from surplus electricity would be favorable.

3. Methodology

3.1. Alkaline water electrolysis model

The AWE model was simulated using open-source DWSIM software that calculated the hydrogen generation capacity per second of fed water and potassium hydroxide as an alkali. A custom Python-based alkaline electrolyzer model was integrated into DWSIM to calculate the hydrogen generation by applying various equations that used overall alkaline water electrolysis principles using a stacked cell. A stack is a series of cells that are connected mechanically and operate using electricity which helps to increase the voltage and the hydrogen and oxygen production rates. The custom model used the basic principle of electrolysis, and various parameters and values could be determined using the equations discussed below.

A semi-empirical model was used to determine the polarization curve. The model, as presented in Eq. (1), could calculate the concentration overpotentials that occur at very high current densities above the normal operating range of an electrolyzer [35].

$$V_{cell} = V_{rev} + \left[(r_1 + d_1) + r_2.T + d_2.p\right] i + s\cdot\left(\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)\cdot i + 1\right) \tag{1}$$

where.

V_{cell} = real cell voltage
V_{rev} = reversible cell voltage = 1.23 V at standard conditions
$r_1 = 4.45153 \times 10^{-5}\ \Omega\ m^2$
$r_2 = 6.88874 \times 10^{-9}\ \Omega\ m^2\ °C^{-1}$
$d_1 = 3.12996 \times 10^{-6}\ \Omega\ m^2$
$d_2 = 4.47137 \times 10^{-7}\ \Omega\ m^2\ bar^{-1}$
$s = 0.33824$ V

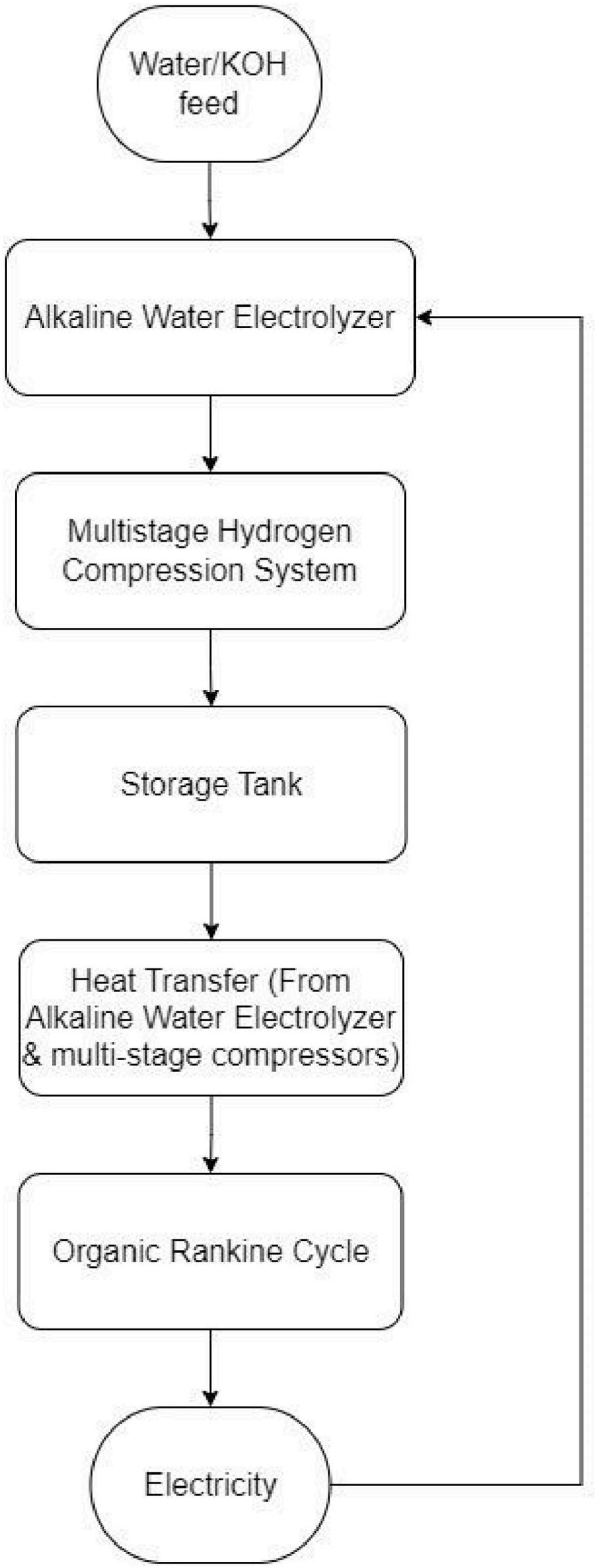


Fig. 1. Flowchart of the overall process.

$t_1 = -0.01539 \times m^2\,A^{-1}$
$t_2 = 2.00181\ m^2\,°C\,A^{-1}$
$t_3 = 15.24178\ m^2\,°C^2\,A^{-1}$
T = temperature maintained in stack cells
i = current density

The real voltage (V_{cell}) is the sum of reversible voltage, and each of these overpotentials ($\widehat{\eta}$), activation overvoltages ($\widehat{\eta}_{cat}$, $\widehat{\eta}_{an}$), ohmic overpotentials ($\widehat{\eta}_{ohm}$) and concentration overpotentials ($\widehat{\eta}_{conc}$), which is shown below by Eq. (2) [35]:

$$V_{cell} = V_{rev} + \left(\widehat{\eta}_{cat} + \widehat{\eta}_{an} + \widehat{\eta}_{ohm} + \widehat{\eta}_{conc}\right) \tag{2}$$

Faraday's efficiency was determined by an empirical expression for a given temperature using parameters as shown in Eq. (3) [35,36]:

$$\eta_F = \left(\frac{i^2}{f_{11} + f_{12}.T + i^2}\right).(f_{21} + f_{22}.T) \tag{3}$$

Where.

$f_{11} = 478645.74\ A^2 m^{-4}$
$f_{12} = -2953.15\ A^2\,m^{-4}\,°C^{-1}$
$f_{21} = 1.03960$
$f_{22} = -0.00104\ °C^{-1}$

The content of hydrogen in oxygen (HTO) at the specified temperature as a product was determined based on information provided in previous research works [35,37,38].

$$HTO = \left[C_1 + C_2.T + C_3.T^2 + \left(C_4 + C_5.T + C_6.T^2\right).exp\left(\frac{C_7 + C_8.T + C_9.T^2}{i}\right)\right] + \left[E_1 + E_2.p + E_3.p^2 + \left(E_4 + E_5.p + E_6.p^2\right).exp\left(\frac{E_7 + E_8.p + E_9.p^2}{i}\right)\right] \tag{4}$$

where.

$C_1 = 0.09901$
$C_2 = -0.00207\ °C^{-1}$
$C_3 = 1.31064\ °C^2$
$C_4 = -0.08483$
$C_5 = 0.00179\ °C^{-1}$
$C_6 = -1.13390\ °C^2$
$C_7 = 1481.45\ A\,m^{-2}$
$C_8 = -23.60345\ A\,m^{-2}\,°C^{-1}$
$C_9 = -0.25774\ A\,m^{-2}\,°C^{-2}$
$E_1 = 3.71417$
$E_2 = -0.03963\ bar^{-1}$
$E_3 = 0.05817\ bar^{-2}$
$E_4 = -3.72068$
$E_5 = 0.93219\ bar^{-1}$
$E_6 = -0.05826\ bar^{-2}$
$E_7 = -18.38215\ A\,m^{-2}$
$E_8 = 5.87316\ A\,m^{-2}\,bar^{-1}$
$E_9 = -0.46425\ A\,m^{-2}\,bar^{-2}$

- T = temperature maintained in a stack
- p = pressure maintained inside electrolyzer
- i = current density

Constants.

F: Faraday constant (in Coulombs/mol)
M_{H_2} = Molar mass of hydrogen (in g/mol)
M_{KOH} = Molar mass of KOH (in g/mol)
M_{H_2O} = Molar mass of water (in g/mol)

The values for water and KOH were determined in tons/day. To work with consistent units, we convert these quantities to kg/s:

The water supply and KOH from tons/day to kg/s was converted as follows:

$$Water_{kg/hour} = water_{tons/day} \times \frac{1000}{24} \tag{5}$$

Convert KOH supply from tons/day to kg/s

$$KOH_{kg/s} = KOH_{tons/day} \times \frac{1000}{24} \tag{6}$$

3.1.1. Calculation of moles of KOH and H_2O

The amount of KOH and water supplied in kg/s was converted to moles/s using their respective molar masses:

$$n_{KOH} = \frac{KOH_{kg/s}}{M_{KOH}} \tag{7}$$

$$n_{H_2O} = \frac{Water_{kg/s}}{M_{H_2O}} \tag{8}$$

Calculation of current density

$$\text{Current density} = \frac{Current\ (I)}{Total\ Area\ (A)} \tag{9}$$

3.1.2. Calculation of current efficiency

The current efficiency was calculated based on the percentage efficiency input provided by the user:

$$i_{efficiency} = \frac{current}{100} \times efficiency \tag{10}$$

3.1.3. Calculation of moles of H_2 produced

The moles of hydrogen gas (H_2) produced during electrolysis were determined using Faraday's law of electrolysis, where the number of moles of electrons involved in the reaction for hydrogen gas is 2, as shown by equation (14) below [35]. The following equations are used to calculate the yield product on outlet streams:

$$n_{H_2,prod=}\ n_F \times N \times \frac{1}{Z.F} \tag{11}$$

where: Z = Parameter for electrochemical behavior of cells, N is the number of cells, n_F is the Faraday efficiency, Z is electrochemical equivalence, and F is the Faraday constant

$$n_{H_2,cat} = n_{H_2,prod} \tag{12}$$

$$n_{H_2,an} = n_{HTO} \tag{13}$$

$$n_{O_2,an} = n_{O_2,prod} = \frac{1}{2} n_{H_2,prod} \tag{14}$$

$$n_{H_2O} = n_{H_2,prod} \tag{15}$$

The mass of hydrogen gas (H_2) produced in kg/s was calculated using its molar mass and moles of hydrogen $n_{H_2,cat}$ generated at the cathode:

$$m_{H_2} = n_{H_2,cat} \times M_{H_2} \tag{16}$$

Convert kg/s to tons/day:

The mass of hydrogen gas produced was converted back to tons/day for easier interpretation of the result:

$$H_{2_{tons/day}} = m_{H_2} \times \frac{86400}{1000} \tag{17}$$

3.1.4. Calculation of remaining KOH and H_2O

The moles of KOH and H_2O remaining after the electrolysis process based on the stoichiometry of the reaction were calculated as

$$n_{KOH_{remaining:}} = n_{KOH} - \frac{n_{H_2}}{2} \tag{18}$$

$$n_{H_{2_{remaining}}} = n_{H_2O} - n_{H_2} \tag{19}$$

3.1.5. Calculation of Heat generated by the electrolyzer

The heat generated by the electrolyzer was calculated by using the following formula [35]:

Heat generated = (Operating voltage - Thermoneutral voltage) × Current (20)

where.

- Operating voltage is the voltage applied to the electrolyzer.
- Thermoneutral voltage is the voltage required for water electrolysis at a given temperature and pressure. Equation (1) gives the value of V_{cell}. At standard conditions, the value of thermoneutral voltage is equal to 1.482. On the increasing temperature, this value only changes slightly to 1.473 V at 80 °C and 1 bar of pressure and remains unchanged up to 30 bar of pressure at the same temperature [39].
- Current is the current flowing through the electrolyzer.

The moles of KOH and H_2O remaining were converted back to mass in kg and then to tons/day for easy interpretation:

$$m_{KOH_{remaining}} = n_{KOH_{remaining}} \times M_{KOH} \tag{21}$$

which calculates the mass of KOH remaining

$$m_{H_2O_{remaining}} = n_{H_2O_{remaining}} \times M_{H_2O} \tag{22}$$

The output stream from the custom model of the electrolyzer contained $KOH_{\ remaining}$, $H_2O_{remaining}$ hydrogen, and oxygen, which were further separated.

As mentioned in Table 1 below, the different parameters were used for developing the AWE model as shown in Fig. 2.

35 wt% of KOH dissolved in 100 L/min of water generated 86.389 tons/day of hydrogen, and the electrolyzer in this process was found to produce a thermal power of 314.140 W.

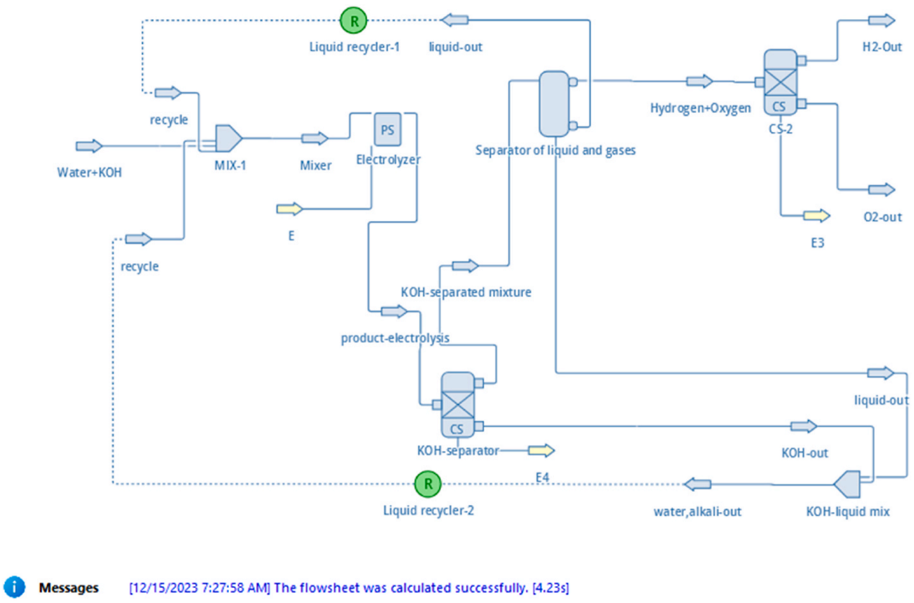
3.2. Hydrogen compression and storage

To address the hydrogen storage, the utilization of a multistage hydrogen compression and storage system, as detailed by Wang et al. [22], was used. The hydrogen, produced from the AWE process, experiences expansion during the collection period, having an initial

Table 1

Parameters for AWE process for both input and output.

Parameters	Value
Number of cells	5000
Current	1000 A
Voltage	10,000 V
Area of each cell	0.020 m^2/cell
Total Area	100.52254 m^2
%Efficiency	70%
Water (feed)	100 L/min (100 kg/s)
KOH (feed)	30% (feed)
Plant capacity (Power)	10 MW
H_2 product from plant	● 3598.717 kg/h (86.369 tons/day) ● 59978.617 L/min ● 1.000 kg/s
Temperature	298.15 K
Pressure	1 bar
Current density	0.1050 A/m^2
V_{cell}	1.82 V
Power generated	314.140 W



[12/15/2023 7:27:58 AM] The flowsheet was calculated successfully. [4.23s]

Fig. 2. DWSIM's simulation of alkaline water electrolysis plant.

pressure of 7 bar and a temperature of 298.15 K that was assumed to be expanded to 1 bar and having the same temperature of 298.15 K.

For the calculation of the temperature and pressure required to compress hydrogen at an initial pressure of 1 bar–400 bar using a multistage compressor having 3 stages for hydrogen compression, the isentropic process was assumed [22], and the following steps were employed.

1. The overall pressure ratio was calculated, which was the outlet pressure to the inlet pressure. In this case, the overall pressure ratio is 400 bar/1 bar = 400.
2. Then, the outlet temperature for each stage was determined using equation (23), and the same temperature values were used in coolers 'CL-1, CL-2, and CL-3′ in the 3 stages, as shown in Fig. 3.
3. The pressure in each stage was determined using equation (24)
4. Finally, the temperature and pressure for each stage using the following formula for the isentropic process [40]:

$$Temperature\ (^{\circ}C) = \frac{T_1 \times (P_2/P_1)^{\left(\frac{1-\gamma}{\gamma}\right)} - 1}{\gamma - 1} \tag{23}$$

$$Pressure\ (bar) = P_1 \times \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} \tag{24}$$

Where.

- T_1 is the initial temperature (°C)
- T_2 is the outlet temperature (°C) in each stage
- P_1 is the initial pressure (bar)
- P_2 is the outlet pressure (bar) in each stage
- γ is the specific heat ratio of hydrogen (1.41)

Using the above formulae, we calculated the pressure for each stage

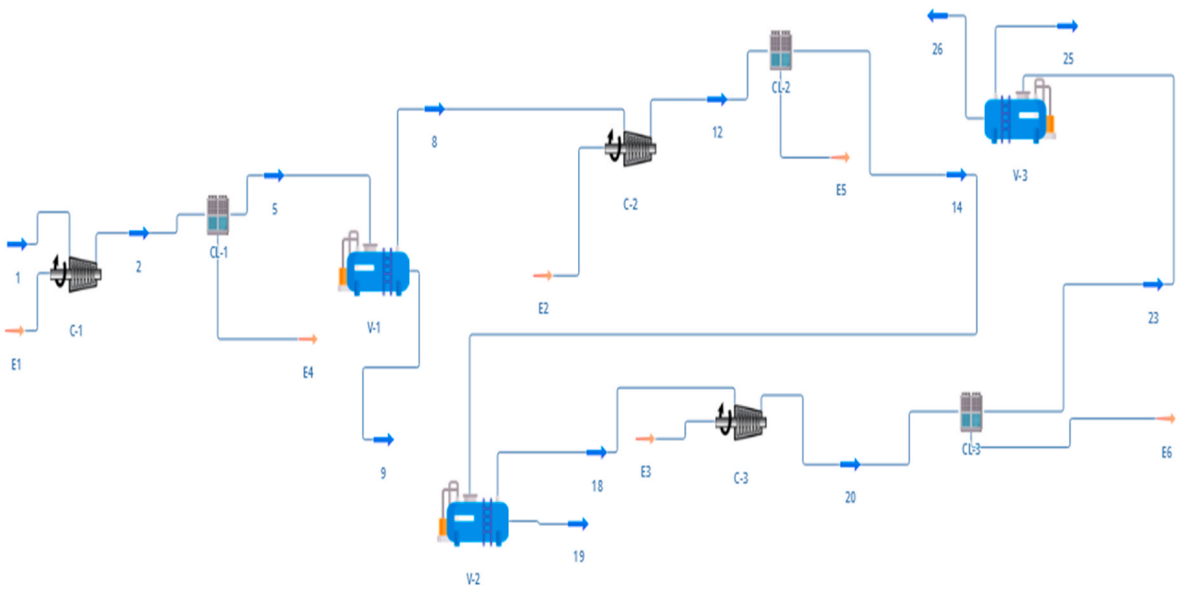


Fig. 3. Multi-stage compression model.

of the multistage compressor using temperature and pressure values in coolers and compressors 'CL-1, CL-2, and CL-3′ and 'C-1, C-2, and C-3′, respectively. The values of temperature and pressure used in these devices in different stages are mentioned in Table 2 below.

The amount of hydrogen generated per hour from the alkaline water electrolyzer was used as a feed in the simulation model built in DWSIM, as shown in Fig. 3 above. The hydrogen was at a temperature of 298.15 K and pressure of 1 bar after production from AWE, and it was obtained at a volume of 156.20 m^3/s generated by the AWE system. Then, the hydrogen was compressed using the multi-stage compressor model as shown in Fig. 3. As shown in Fig. 3, C-1, CL-1, and V-1 represent the compressor, cooler, and gas-liquid separator, respectively in the first stage of compression, C-2, CL-2, and V-2 represent the compressor, cooler and gas-liquid separator respectively in the second stage of compression and C-3, CL-3 and V-3 respectively represent the compressor, cooler and gas-liquid separator in the third stage of compression. Stream '1' is the inlet of hydrogen gas feed, and stream '25′ is the outlet.

The amount of heat generated in the three stages of the compressor system was added to the heat generated by the electrolyzer, as tabulated in Table 3 below.

Hence, from the simulation modeled in DWSIM, it was found that turbines can generate 126.49 kW of electrical power. This electricity could be connected to the electrical supply line of the electrolyzer. As shown in Fig. 4, the three phases of compression generated a significant amount of heat that could be utilized to produce useful power using an ORC.

As shown by the data above, the volumetric flow rate was highly lowered from 33.7766 m^3/s to 0.130591 m^3/s at the output stream of the multistage compressor. This showed that hydrogen can be stored with a lower volume which can highly decrease the cost of storage.

After the compression, Type IV tanks are utilized, which are the most suitable tanks for storing the compressed hydrogen. Type IV hydrogen storage tanks have properties like high storage density, lightweight, durability, and a high level of safety, which make them suitable for storing compressed hydrogen under high pressure.

3.3. ORC for heat recovery

The heat generated from the electrolyzer and multistage compression system can be utilized to generate useful power. As described by the research [31,34], the ORC can be a useful technology to recycle the heat generated during compression at multiple stages. Their research recommends utilizing R254a as the optimal working fluid for modeling this process [31]. Employing the same approach, a model was developed using the DWSIM software to simulate this concept.

The heat generated was used to generate useful electricity, which could be connected to the electrical power supply of the electrolyzer.

The total efficiency ($\eta_{efficiency}$) of the ORC system [31] was calculated as follows:

$$\eta_{efficiency} = \frac{W_{turbine} - W_{pump}}{Q_{in}} \tag{25}$$

where: Q_{in} = Heat transferred into the system

$W_{turbine}$ = work of turbine
W_{pump} = work of turbine

Table 2
Temperature and pressure at different stages of compression.

Stage	Pressure (bar)	Temperature (°C)
1	7.36	30
2	54.16	80
3	400	150

Table 3
Thermal power generation results.

Source of thermal power	Waste thermal power generation	Percentage of power generated
Stage first of multistage compressor	66998 kW	39.29%
Stage second of multistage compressor	34400.9 kW	20.16%
Stage third of multistage compressor	69170.1 kW	40.55%
Electrolyzer	0.314140 kW	0.000184%
Total thermal power	170569.314 kW	100%

As shown in Fig. 5 below, a DWSIM model of ORC was used to determine the electrical power generation from the recycling of waste thermal power.

When 170,569.31 kW of heat was supplied from the source for the use of 7.47 kg/s feed of the organic compound R254a at feed stream 'Organic Compound', the value of turbine power was found to be 126.49 kW. Similarly, 75 kg/s of the organic compound R254a gave 2558.43 kW, 100 kg/s gave 2558.43 kW, 200 kg/s gave 2902.27 kW, and 500 kg/s gave 2902.27 kW, which showed within a certain value of the concentration of organic compound used, the amount of electricity generated was mainly influenced by it.

3.4. Model validation

The model employed the concept of an electrolyzer for hydrogen generation as described by Ref. [35,37,38], incorporating general principles based on the fundamental working mechanisms of electrolyzers. Experimental data from Ref. [35] were analyzed and compared with the results of the electrolyzer model, as shown in Table 4, alongside experimental data from various other sources.

The bar diagrams in Fig. 6 show the comparison between the experimental results and developed model's results of hydrogen production rate and waste thermal power.

The multistage compressor model was based on the Aspen Plus model simulation from Ref. [34,36] and analysis from Ref. [36], which verifies the applicability of the model for estimating hydrogen compression capacity.

The ORC model was built concerning [41,42]. The ORC model can be verified for its applicability from research by Ref. [34,43], where the Aspen Plus software-based model was verified experimentally. The same model type was developed in DWSIM as developed in Aspen Plus [43].

3.5. Sensitivity analysis

The sensitivity analysis was performed for the simulation models of AWE, multistage compression system, and ORC, as discussed below.

3.5.1. AWE model

The heat generation at the outlet of the cathode of the electrolyzer was observed as it was the main output variable needed for use in ORC. Each of the two input parameters, current supplied and area of electrolyzer, was varied by ±20% of the original value used as input for the original model designed by us so that V_{cell} and heat generated by the electrolyzer were determined for each varied parameter. The generated plots illustrated the heat generated was constant concerning area and increased linearly with current, reflecting a direct proportionality to current. Meanwhile, V_{cell} remained nearly constant across different currents and areas, indicating that the inherent properties of the cell primarily influence cell voltage and are not significantly affected by changes in either area or current. These relationships highlighted that heat generation is directly dependent on current, while both thermal power (heat generated) and V_{cell} are less dependent on cell area.

The results of such sensitivity study of AWE model is shown in Fig. 7 below.

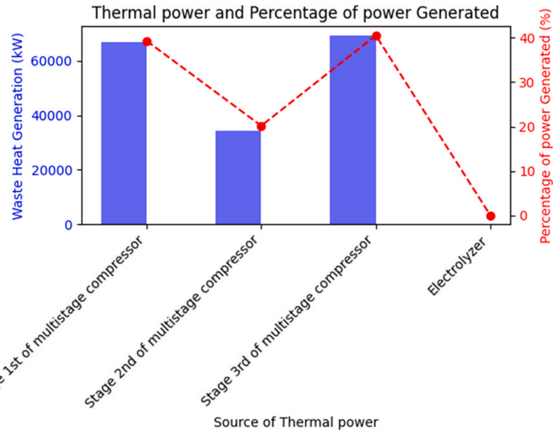


Fig. 4. Bar diagram for output heat generated during different stages of compression.

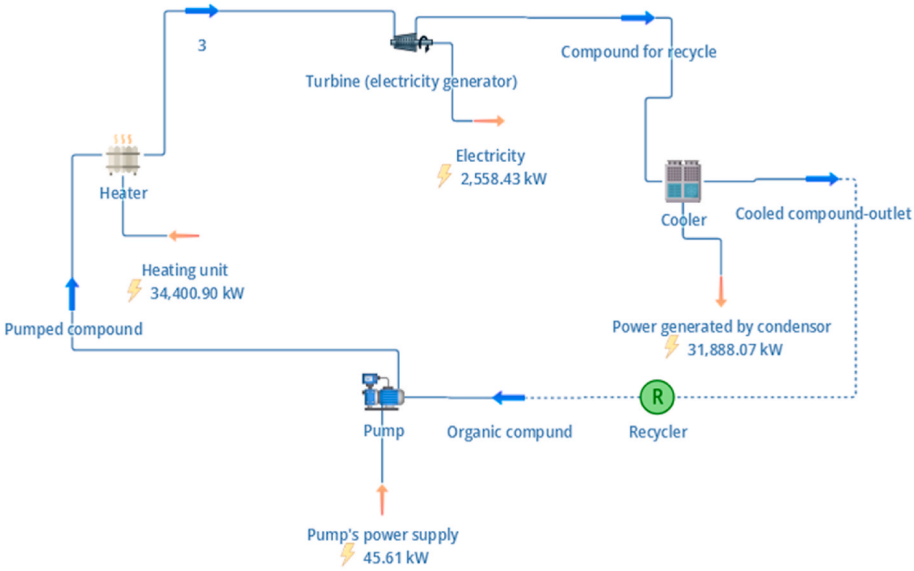


Fig. 5. DWSIM's model for ORC.

3.5.2. *Hydrogen compression*

Similarly, sensitivity analysis was performed for a multistage hydrogen compression system, taking the volumetric flow rate of inlet stream '1' as an independent variable and the volumetric flow rate at the outlet stream '25' as the dependent variable in DWSIM. The data were obtained for the volumetric flow rate at the outlet stream, which varied linearly with the volumetric flow of feed, which showed that the model's results were as accurate as desired and that the model can be applicable for determining the storage feasibility of hydrogen. The linear plot obtained through the same data is shown below in Fig. 8.

3.5.3. *ORC model*

Similarly, the ORC's model was tested for its accuracy. By keeping the input thermal power at 'Heater' as an independent variable and turbine power at the 'Electricity' energy stream as a dependent variable, the sensitivity analysis was performed. The change in values of the independent variable of power supplied by the heater by ±20% showed no variation with change in values of dependent input variables, and a plot of the graph was obtained as shown below. The change in the value of independent variables by ±20% for the cycle input thermal power at 'Heater' and molar flow rate of organic compound R254a (at 'Organic Compound' stream) both by ±20% showed linear variation with dependent variable turbine power at 'Electricity' stream. The resulting plot shown in Fig. 9 proved a variation in such a way that the Turbine's Power increases up to a certain limiting value of the molar flow of organic compound at stream 'Organic Compound' and thermal power supplied and then decreases, and such result of variation obtained proved that the model built was highly accurate and feasible for the determination of power generated from waste heat using the model of ORC as shown in Fig. 5.

3.6. *Economic analysis*

3.6.1. *Levelized cost of hydrogen*

The LCOH is the cost per unit of hydrogen generated by the process, which is the discounted lifetime cost of constructing and running a hydrogen facility. It is determined to compare the viability of different hydrogen production technologies and to evaluate hydrogen's competitiveness as a fuel. It is an indicator of the average cost of producing hydrogen over the lifetime of a hydrogen production plant.

The LCOH was calculated by taking the total cost of constructing and operating a hydrogen production plant, which was divided by the total amount of hydrogen produced over the plant's lifetime. The total cost included capital costs, such as the cost of the electrolyzer, compressor, and other equipment, as well as operating costs, such as the cost of electricity, water, and maintenance. The approach was used to

Table 4
Comparison of model results with experimental results from various sources.

Experimental data	Model data and results	References for experimental data
● Pressure 7 bar, temperature 25.49 °C, number of cells 12, surface area of cells 1000 $\mathrm{cm}^{2,}$ feed water 1.730 kg^{-1}, 35 wt% KOH, cell voltage 1.23 V, current density 0.42 Acm^{-2} ● Hydrogen production rate 0.17 kg/h and waste thermal power 2392.8 Watt	● Pressure 7 bar, temperature 25.49 °C, mass flow rate of, number of cells 12, Cell voltage 1.23 V, surface area of cells 1000 $\mathrm{cm}^{2,}$ feed water 1.730 kg^{-1}, 35 wt% KOH, current density 0.42 Acm^{-2} ● Hydrogen production rate 0.1643 kg/h and waste thermal power 2246.7503 Watt	[35]

Table 5
Cost category with percentage.

Cost Category	Percentage
Direct Costs	
Equipment (Total Purchase Cost)	35%
Equipment Erection	10%
Piping	5%
Instrumentation	4%
Electrical	4%
Process Buildings	3%
Utilities	4%
Storages	5%
Site Preparation	5%
Auxiliary Buildings	4%
Indirect Costs	
Design and Engineering	7%
Contractor's Fee	7%
Contingency	7%

determine the economic feasibility of implementing waste heat recovery that was intended to power the electrolyzer system through the supply of electrical power. The LCOH of the system was calculated first by calculating the OPEX of the system without the recovery of waste heat, and then when the heat recovery was assumed to be implemented, OPEX was again determined for the next few years. It includes all pertinent expenses incurred during the lifespan of the system, such as CAPEX, OPEX, and electricity costs.

Table 6
Items and value distributions.

Items	Value	Unit
System CAPEX	47,000,000	$
Electric Cost	0.069	$/kWh
Discount Rate (r)	8	%
Tax Rate (TR) [51]	20	% of Revenue
Stack Lifetime (N)	8690	h
Plant Capacity Factor (PCF)	50	%
Degradation Rate (DR)	0.525	%/year
Hydrogen SP [52]	7.5	$/kg

Table 7
LCOH value calculation.

Project lifetime (years)	LCOH ($/kg)
5	3.5141
10	3.4734
15	3.4725
20	3.4725
25	3.4725

To elaborate on Equation (26), we utilized a proposed approach, resulting in Equation (27). Equation (27) demonstrates how various parameters, including the cost of capital (CAPEX), cost of operations (OPEX), tax rate (TR), revenue from hydrogen sales (REVHn), discount factor (r), system degradation rate (DR), and annual mass of hydrogen produced, impact the LCOH.

In this context.

- CAPEX encompassed the electrolyzer's balance of plant (BOP), installation, and other setup costs.
- OPEX covered the annual operating and maintenance costs, including electrical charges.
- Income tax was factored into the LCOH formula and applied to revenue from hydrogen sales (oxygen was excluded).
- The system's degradation rate (DR) implied that 10% of the system would be degraded after 86,900 h of plant operation, contributing to a steady degradation over time.

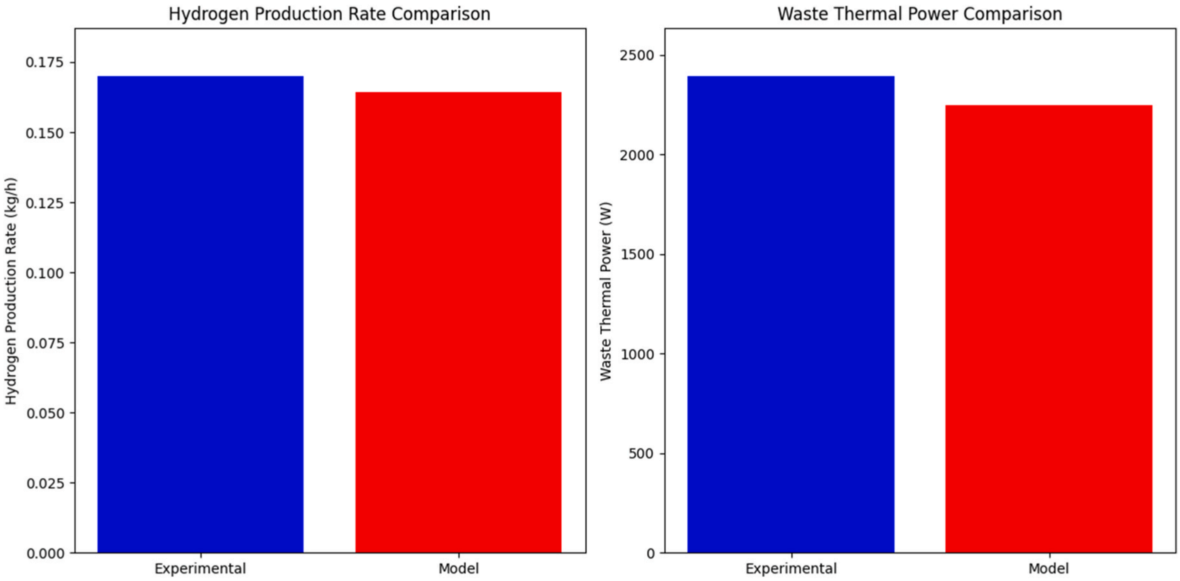


Fig. 6. Comparison of proposed model's data vs experimental data [35].

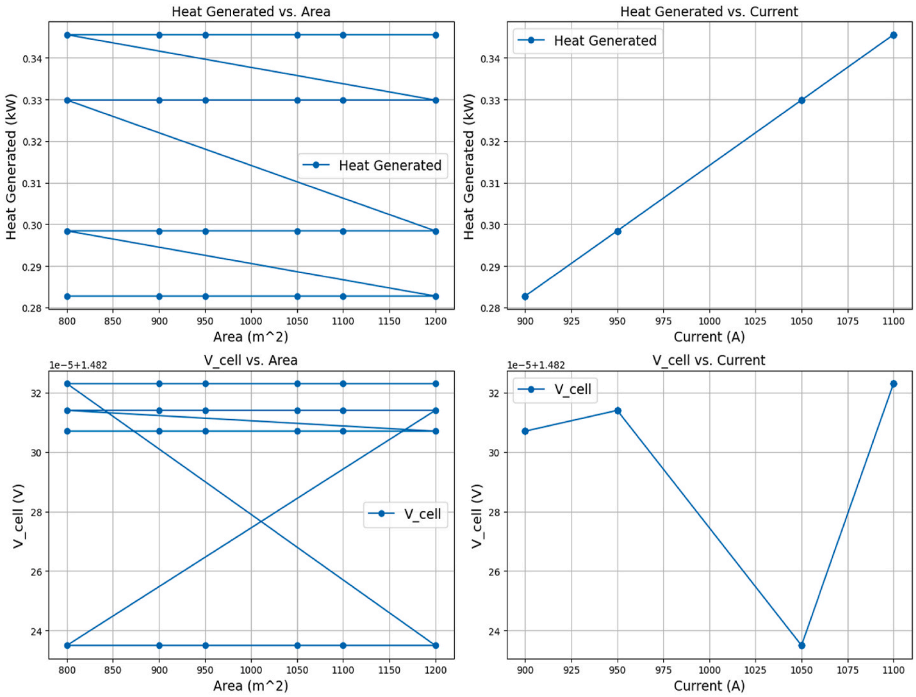


Fig. 7. Variation of hydrogen production rate and cell voltage with current supplied and water feed rate.

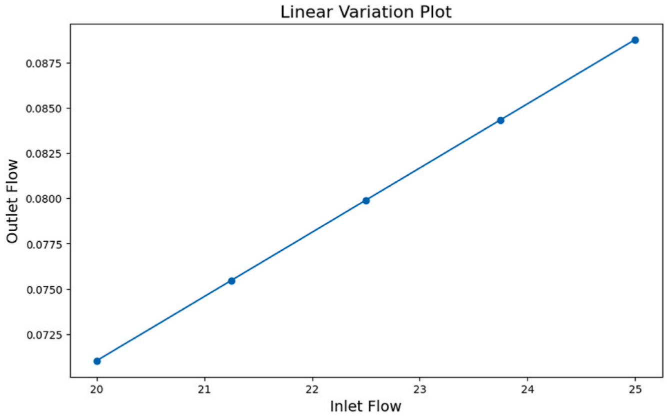


Fig. 8. Sensitivity analysis plot of model for inlet and outlet hydrogen volumetric flow.

The formulas utilized are as follows:

$$LCOH=\frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ H_2\ Production} \tag{26}$$

$$LCOH=\frac{CAPEX+\sum_{n=1}^{N}\frac{OPEX_n}{(1+r)^n}+TR\sum_{n=1}^{N}\frac{REVH_n}{(1+r)^n}}{\sum_{n=1}^{N}\frac{m_{h2}(1-DR)^n}{(1+r)^n}} \tag{27}$$

$$\sum_{n=1}^{N}\frac{REVH_n}{(1+r)^n}=\sum_{n=1}^{N}\frac{m_{H2}(1-DR)^n.SP_{H_2}}{(1+r)^n} \tag{28}$$

The cost of an electrolyzer was tough to calculate and a challenge as the study was aimed at calculating LCOH for various values of SE over a number of years. This condition was overcome by using a solution system proposed by using the values of the CAPEX projection equation that is mentioned. The above equation helps determine the cost of an electrolyzer.

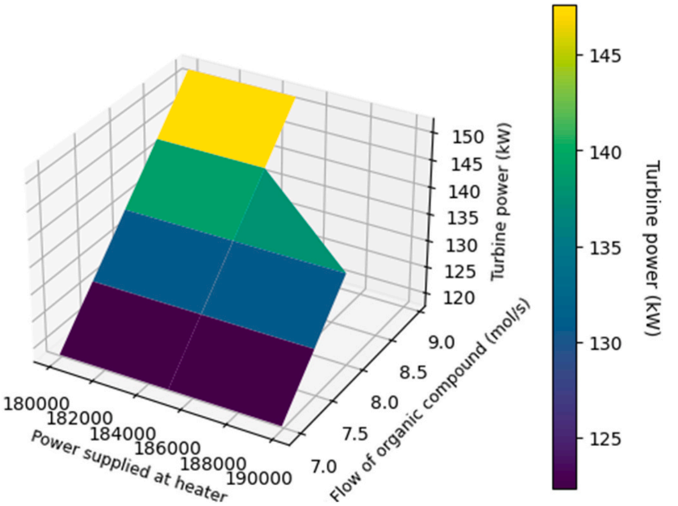


Fig. 9. Variation of turbine power with power supplied at heater and molar flow of organic compound.

The parameters outlined in Table 5 were utilized to ascertain the CAPEX employing the DWSIM capital cost estimator. DWSIM's capital cost estimator uses all the fundamental equations of chemical engineering and concepts to determine the capital cost [44]. The plant's base location was set in India in the same capital estimator tool, considering the cost using current exchange rates for Nepal. All equipment costs were computed, excluding the electrolyzer. Notably, the DWSIM model integrated a custom-built Python model for the electrolyzer, externally added. The estimated cost derived from the DWSIM model, as depicted in Fig. 1, without considering the cost of the electrolyzer was calculated by setting base location as India using DWSIM's capital cost estimator. The cost computation involved the various items for estimating the CAPEX as detailed in the capital cost estimation presented in Table 5 below.

3.6.2. Calculation of economic parameters

The capital cost of the electrolyzer was determined for the year 2023 by using the chemical engineering plant cost index (CEPCI) using equation (29) [43].

$$C_2 = C_1 \left(\frac{I_2}{I_1}\right) \tag{29}$$

For determining the capital cost, the CAPEX value was determined for the alkaline water electrolyzer for the year 2019, which was equal to \$424/kW, according to Proost (Proost. 2019). So, for a 10,000 kW (10 MW) electrolyzer, the average cost without considering the remaining equipment was calculated to be \$4.24 × 10^6.

The CEPCI value (I_1) value for 2019 was equal to 607.5 [45], and the CEPCI value for the year 2023, which was used as the annual average for the CEPCI value I_2, was equal to 797.9 [46]. Thus, using equation (29), the cost of the 10 MW electrolyzer without considering the plants' remaining equipment components in 2023 was found to be \$5,570, 192.13. Similarly, for the remaining components of the plant, the CAPEX was determined using DWSIM's capital cost estimator setting base location to India, so the total CAPEX of the plant was found to be approximately \$47,000,000 in the context of Nepal for the year 2023 when the cost found in the context of India was slightly raised as the cost in Nepal is usually higher for establishing plant than in India.

The electricity cost per kilowatt-hour (kWh) in Nepal is 5.79 Nepalese Rupees (NPR) for households and 9.21 NPR for businesses at the present date [47]. According to Google Finance, the exchange rate at the present date is 1 NPR = \$0.0076 [48]. Therefore, the cost of electricity per kWh in \$ was: For businesses: 9.21 NPR/kWh × 0.0076 \$/NPR = 0.069 \$/kWh.

A stream factor is an actual factor for operating time of total operating time (8690 h) [49]. The unit price of electricity was \$0.069 per kWh for businesses in Nepal [47], which included all components of the electricity bill, such as the cost of power, distribution, and taxes. The price of electricity was calculated by multiplying the yearly required power for H_2 production, which is 10 × 8690 MWh, and the unit electricity price, which resulted in a cost equal to \$5,999,100/kg H_2. Full-time labor expenses were set at \$5520 annually, with part-time labor costs amounting to \$2670 annually. Assuming one full-time and one part-time employee for a 10 MW water electrolysis operation, maintenance expenses were estimated at 2.5% of the Alkaline Water Electrolysis (AWE) value.

Additionally, other costs were calculated at 1% of AWE, resulting in figures of \$1,175,000 and \$470,000, respectively. According to the information accessed from the Nepal Electricity Authority (NEA) [50], the rise in electricity cost per year was 2.5% per unit. So, the cost of electricity due to the annual price increment and waste heat recovery by ORC was determined using equation (30) below.

$$\text{Electricity's expense in the n}^{\text{th}}\text{ year} = \text{Expense in 2023} + \sum_{1}^{n} \left[(\textit{Expense in previous year} \times 1.025) \times 0.9874\right] \tag{30}$$

This equation gave the expense of electricity in the second year of operation to be \$6,217,758.45. Using the same equation (30) and assuming a 15% change in OPEX value per year due to inflation and other causes, the following bar graph was drawn for the change in the cost of each item for the next, as shown in Fig. 10 could be obtained representing the cost for 10 years for parameters to determine LCOH.

Now, in order to calculate the LCOH following parameters could be used as mentioned in Table 6 below:

A different approach was applied to calculate the LCOH value. In equation (27) for calculating LCOH, the term $\sum_{n=1}^{N} \frac{OPEX_n}{(1+r)^n} + TR \sum_{n=1}^{N} \frac{REVH_n}{(1+r)^n}$ was replaced by $OPEX_1 + \sum_{n=1}^{N-1} \frac{OPEX_{n+1}}{(1+r)^n} + TR \sum_{n=1}^{N} \frac{REVH_n}{(1+r)^n}$ where $OPEX_1$ was the OPEX for the first year of operation assumes 8690 h of operation per year and the value was expected to be affected by the reduction in OPEX for the next 20 years of plant operation due to the electrical power supply by the ORC plant connected to the electricity supply line from the second year of operation.

The expense on electricity in the second year of operation was calculated to be \$6,217,758.45. So, the OPEX for the second year of operation would be \$7,652,290 - \$5,999,100 + \$6,217,758.45 = \$7,870,948.45 when organic compound R254a used in the ORC was 7.46 kg/s. Thus, using equations (27) and (28), the LCOH value was found to be 3.4725 \$/kg of H_2 for 20 years of operation. Similarly, when the organic compound R254a used was 75 kg/s, 100 kg/s, 200 kg/s, and 500 kg/s, the LCOH was found to be decreased with the increase in the concentration of organic compounds for the 20 years of operation. It means the efficiency of ORC increases as the concentration of organic compound increases to a certain limiting value. So, the analysis showed that by using ORC with an adequate quantity of organic compounds, the LCOH can be greatly reduced.

For the number of years of operation of 5, 10, 15, 20, and 25 years of project life for 7.47 kg/s of organic compound R254a used in ORC, the following data mentioned in Table 7 was determined and plotted as shown in Fig. 11 below. The LCOH was found to be decreased from \$3.5141/kg for a 5-year project to \$3.4734/kg for a 10-year project and further to \$3.4725/kg for 15, 20, and 25-year project lifetime. This reduction was seen because spreading the initial capital costs over a longer project lifetime lowers the per-unit cost of hydrogen. The most significant decrease was seen between 5 and 10 years, with minimal changes beyond 15 years, indicating a stabilization of cost efficiency over extended periods.

It can be observed from the above table and graph that the value of LCOH reaches a constant value after a fixed lifetime. As shown above, in Fig. 11, the value of the LCOH becomes constant after the 15th project year.

Similarly, setting the base location as India in the DWSIM capital cost estimator, the capital cost (CAPEX) for the compression system was determined according to expenses on the following percentage of items in Table 8.

Thus, the CAPEX of the multistage compression plant for the above items in Table 8 was found to be \$51,167,217.52 using DWSIM's capital cost estimator, setting the base location as India.

Regarding storage after compression, Type IV cylinders are the safest, most portable, lighter, and most advanced cylinders for storing hydrogen. They can be imported from other countries like South Korea, China, the United States of America, etc. It is common practice to store hydrogen at slightly lower pressures than the rated pressure of the cylinder to allow for a safety margin. This is because pressure in hydrogen gas fluctuates depending on temperature and other factors. So, we used Type IV cylinders with a pressure of 450 bar to store hydrogen, which

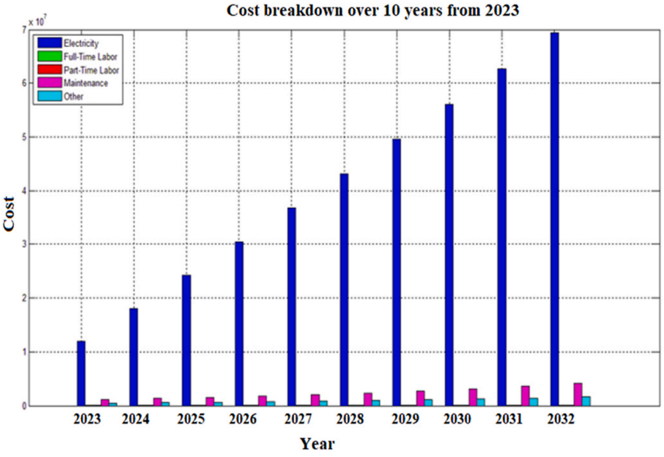


Fig. 10. Cost breakdown over 10 years.

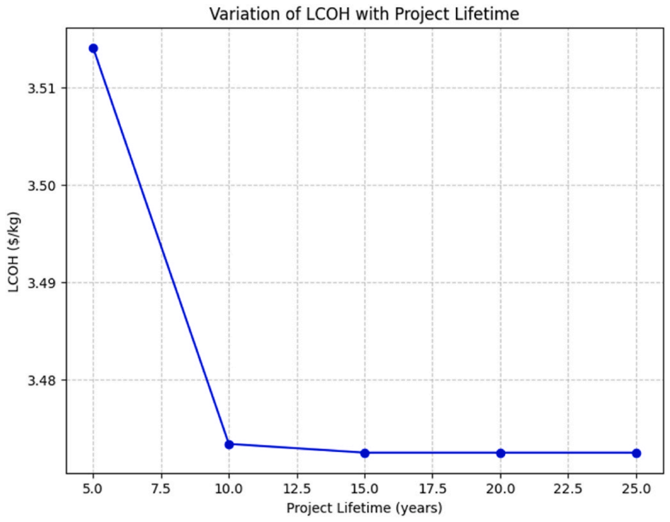


Fig. 11. LCOH ($/kg) decrement with increment on project life.

was compressed to 400 bar. The report [50] discusses that current costs for Type IV compressed hydrogen systems that store 5.6 kg of useable H_2 are projected within 95% certainty to range between $12-$16/kWh (μ = $13/kWh) and $16 - $20/kWh (μ = $17/kWh) for 350-bar and 700-bar working pressures, respectively. It was considered the cost to be higher in Nepal due to shipping and other charges, including the cost for regular inspection for safety, total cost was estimated to be quite higher than that for multi-stage compression plants. So, the cost of the cylinders was added to our CAPEX, and the total cost of storage was concluded to be approximately $52 million.

Similarly, the DWSIM capital cost estimator was used to determine the OPEX for a multistage compressor system setting base location as India, which approximated the cost to be $16 970, $469.52/year when the base location was set to India. Since prices can fluctuate between Nepal and India, hence, the OPEX was approximated at $17 million/year for expenses on maintenance, operation, laboratory, supervision, plant overheads, capital charges, rate/taxes, insurance and licensing fees/royalty payments as fixed costs, raw materials costs, other materials, utilities, and shipping and packaging as variable costs and sales expenses, and general overhead as miscellaneous costs.

Finally, the CAPEX and OPEX values were calculated for the ORC plant using the DWSIM capital cost estimator, setting the base location as India; the CAPEX was found to be $418,161.43, which was approximated to be $500,000 for Nepal, influenced by various factors such as shipping and transportation costs for the various categories of expenses shown in Table 9.

Similarly, the OPEX for the plant was found to be $188,261.66/year for expenses on maintenance, operation, laboratory, supervision, plant overheads, capital charges, rate/taxes, insurance and licensing fees/royalty payments as fixed costs, raw materials costs, other materials, utilities, and shipping and packaging as variable costs and sales expenses, and general overhead as miscellaneous costs, which was approximated to be $200,000/year for Nepal, influenced by various factors like rate of inflation and location.

4. Results and discussion

The above study presents a standardized 10 MW alkaline water electrolyzer model along with a multistage hydrogen compression system integrated with a waste heat recovery system. It aligns with an advanced and modern system for hydrogen generation, storage, and heat recycling. The alkaline water electrolyzer is modeled in a Python custom model. Despite the extreme novelty of the model and calculation process involved in this research, the model could generate satisfactory results, as shown by detailed techno-economic analysis. The hydrogen was generated at 3598.717 kg/h (86.369 tons/day) by the model for complete electrolysis, separation, and water and alkali recycling system.

CAPEX for the AWE system was found to be $47 million, which is the capital cost, investable, and OPEX values were also determined for the first year and decreased due to the usage of stored electricity in the second year generated by ORC from the first year.

The amount of hydrogen that can be stored in a Type IV cylinder by maintaining a high level of safety as the volumetric flow rate was found to be decreased to 0.554653 m^3/s from 156.20 m^3/s using the modeled multistage compression system. The storage system consisting of both the multistage compression system and Type IV cylinder was determined to have a CAPEX of $52 million, with OPEX of $17 million/year.

Finally, the CAPEX and OPEX values were calculated for the ORC plant using the DWSIM capital cost estimator, setting the base location as India. The CAPEX was found to be $418,161.43, which was approximated to be $500,000 for Nepal, and OPEX for the plant was found to be $200,000/year.

The ORC model simulated in DWSIM generated quite a good amount of electricity, which can be used in electrolyzers, which is an excellent example of power recovery and recycling processes in process plants. The OPEX due to electricity generated from ORC could compensate for the electricity required to operate the electrolyzer, reducing the OPEX from $7,870,948.45/year in the first year of operation to $6,217,758.45/year for the use of organic compounds at very low concentrations. It was found that when the value of organic compound R254a′s concentration increases up to a certain limiting value, the LCOH gets reduced accordingly.

The sensitivity analysis for all three proposed modeled systems showed a high level of accuracy and satisfactory results. This shows the feasibility of implementing such models practically to develop pilot projects to utilize the immense potential of hydrogen generation from

Table 8
Cost & Percentage breakdown.

Cost Category	Percentage
Direct Costs	
Equipment (Total Purchased Cost)	35%
Equipment Erection	10%
Piping	5%
Instrumentation	3%
Electrical	4%
Process Buildings	3%
Utilities	5%
Site Preparation and safety	10%
Auxiliary Buildings	4%
Indirect Costs	
Design and Engineering	7%
Contractor's Fee	7%
Contingency	7%

Table 9
Costs & Percentage of different categories.

Cost Category	Percentage
Direct Costs	
Equipment (Total Purchase Cost)	35%
Equipment Erection	10%
Piping	5%
Instrumentation	5%
Electrical	4%
Process Buildings	3%
Utilities	5%
Site Preparation	8%
Auxiliary Buildings	4%
Indirect Costs	
Design and Engineering	7%
Contractor's Fee	7%
Contingency	7%

surplus electricity in Nepal.

The ORC process can help reduce the LCOH by a good amount, which we have found to be dependent on the concentration of organic compound R254a used for the process. Ultimately, the techno-economic analysis showed that when implementing waste heat recovery coupled with ORC, we get a more effective system with the overall benefit of lower electricity prices for countries with a high amount of electricity generation capacity. However, when the price of electricity is higher, and for countries with high electricity expenses, the ORC system is an economically feasible and highly efficient process. The overall techno-economic analysis showed that the AWE, multistage hydrogen compression and storage, and ORC processes are feasible to be implemented in Nepal, and the proposed method of heat recovery can be beneficial to reduce the LCOH to increase the sales of hydrogen and generate a good revenue from the sales.

5. Conclusion

The developed processes using the simulation models in DWSIM software demonstrate a strong feasibility for utilizing ORC in recycling the heat produced by the electrolyzer and the multistage compression process for reducing LCOH. The overall process has the potential to reduce the LCOH significantly. Implementing this process in a developing country such as Nepal could produce hydrogen at a reduced cost. In addition to it, the proposed method of storage of hydrogen has been determined feasible to be implemented in Nepal through economic analysis which can help in storing the green hydrogen if produced on a large scale in Nepal if safety measures are properly followed.

The produced hydrogen could assist in powering vehicles, resulting in decreased emissions of greenhouse gasses from older vehicles running on petrol and diesel. Consequently, this initiative holds the potential to contribute to the sustainable and economic development of Nepal.

CRediT authorship contribution statement

Bishwash Paneru: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anup Paudel:** Writing – review & editing, Software, Investigation, Conceptualization, Formal analysis, Visualization. **Biplov Paneru:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Software, Methodology. **Vikram Alexander:** Writing – review & editing, Visualization, Software. **D.P. Mainali:** Supervision. **Sameep Karki:** Writing – review & editing, Supervision, Project administration. **Seemant Karki:** Conceptualization. **Sarthak Bikram Thapa:** Project administration. **Khem Narayan Poudyal:** Writing – review & editing, Supervision, Project administration. **Ramhari Poudyal:** Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

There are no additional relationships or activities to declare. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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