



## Techno-Economic Analysis of Kamojang Geothermal Power Plant as A Green Hydrogen Producer

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### Abstract.

The utilization of renewable energy is becoming increasingly important in addressing the challenges of climate change and the need for clean energy. The potential to produce hydrogen from renewable energy sources, such as geothermal, offers an attractive solution to support the transition to clean energy. In this paper, the author uses a case study approach to analyze the hydrogen production potential of the Kamojang Geothermal Power Plant. The analysis method includes modeling the potential for hydrogen production based on the characteristics of the Kamojang Geothermal Power Plant, while the economic analysis includes planning investment costs, operational and maintenance costs, and Levelized Cost of Hydrogen. Based on the operational condition, it shows that the Kamojang Geothermal Power Plant has the potential to produce hydrogen using Alkaline Water Electrolysis technology. The economic analysis reveals that the hydrogen production infrastructure requires investment costs for Green Hydrogen Plant Infrastructure, operational costs must be considered to optimize LCOH and revenue from hydrogen sales can increase company profits in line with the PLN Group's Beyond kWh program. The results of this study are the basis for consideration, both from technical and economic aspects, in planning and implementing hydrogen production projects from renewable energy sources. The implication of this analysis is that the Kamojang Geothermal Power Plant has the potential to become a hydrogen producer in the future, where the hydrogen can be used commercially to support the PLN Group's Beyond kWh program and provide benefits to the environment by producing low-emission electrical energy fuel.

**Keywords:** *Green Hydrogen Plant (GHP), Alkaline Water Electrolysis (AWE), Levelized Cost of Hydrogen (LCOH), Capital Expenditure (CAPEX), Operation Expenditure (OPEX)*

### 1 Introduction

Fossil fuels have been powering energy systems globally for thousands of years now. The continuous use of fossil fuels as the main source of energy in various industries poses a threat to the earth's climate due to the greenhouse gas emissions

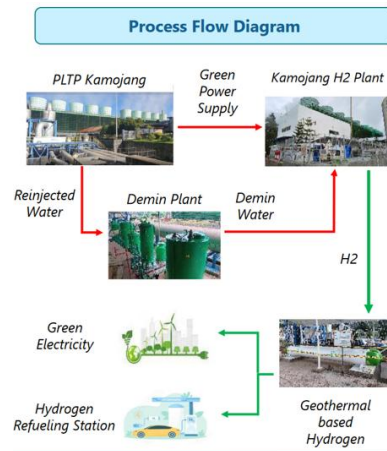
associated with it. In order to decarbonize economies, reduce the significant amounts of greenhouse gases emitted, and save earth's climate, there needs to be modifications in the utilization of the various energy sources (Sarpong Mensah, 2023).

Hydrogen, being a clean energy carrier, concurrently decarbonizes the commercial, residential, industrial, and transportation sectors (Sarpong Mensah, 2023). Most of the hydrogen currently used in Indonesia comes from natural gas and is used in the industrial sector, especially as a raw material for fertilizer. Hydrogen consumption in Indonesia is currently around 1.75 million tons per year, dominated by the use of urea (88%), ammonia (4%), and oil refineries (2%). Indonesia needs to gradually develop low-carbon hydrogen to replace hydrogen currently produced from fossil fuels. In the future, hydrogen will not only be used in the industrial sector, but will be widely used in other sectors, such as transportation and electricity generation, and has the potential to be traded as a commodity in the domestic market (Isa et al., 2021).

## **2 Research and Innovation**

The development of hydrogen technology in Indonesia is currently still in the research stage. Several stages still need to be carried out, such as pilot-scale projects to encourage the hydrogen ecosystem to enter the commercial scale stage. In 2023, a combination of battery and fuel cell technology was discovered for renewable power plants (Dewi et al., 2023).

Hydrogen can be produced through various methods and technologies. Hydrogen is not a primary energy carrier so it needs to be produced from primary sources such as coal, natural gas, wind, sun, and other energy sources. Currently, 97% of the world's hydrogen is produced from fossil fuels, especially natural gas. Hydrogen can be classified based on: (1) production process; (2) raw materials; (3) energy sources; and (4) emissions produced (Dewi et al., 2021). The general classification that is often used today is based on energy sources which are categorized by color.



**Figure 1** Process Flow Diagram of Green Hydrogen Production in Kamojang Geothermal Power Plant (Nur Rakhman, 2024).

The process starts at the Kamojang Geothermal Power Plant, which generates green electricity from geothermal steam. This electricity is transmitted to the Kamojang H<sub>2</sub> Plant to power the hydrogen production system. The geothermal process also involves a Demin (Demineralization) Plant that produces high-purity demineralized water, essential for electrolysis. This demin water is sent to the Kamojang H<sub>2</sub> Plant for hydrogen production. At the Kamojang H<sub>2</sub> Plant, electrolyzers use green electricity and demin water to perform electrolysis, producing hydrogen (H<sub>2</sub>). The produced green hydrogen is clean and carbon-free because it is powered entirely by renewable geothermal energy. The green hydrogen is then directed to a Hydrogen Refueling Station, where it can be used for fueling hydrogen-powered vehicles or stored for other uses. Simultaneously, excess green electricity can be supplied to other systems or applications. After use in the power generation process, geothermal water is re-injected back into the earth, maintaining geothermal reservoir sustainability.

|                                 | Grey Hydrogen   | Brown Hydrogen   | Blue Hydrogen w/ Thermal   | Low-CO2 H2  |   |   |   |
|---------------------------------|---|--|--|---|---|---|---|
|                                 | Grey Hydrogen   | Brown Hydrogen   | Blue Hydrogen w/ Thermal   | Blue Hydrogen   | Green Hydrogen  | Pink Hydrogen   | Turquoise Hydrogen  |
| <b>Raw material used</b>        | Natural gas and water   | Coal and water   | Water and electricity  | Natural gas or Coal and water   | Water and renewables  | Water, uranium  | Methane   |
| <b>Production process</b>       | Split natural gas into H <sub>2</sub> and CO <sub>2</sub> through steam methane reforming (SMR)   | Gasify coal into H <sub>2</sub> and CO through high-temperature, high-pressure gasification  | Split water into H <sub>2</sub> and O <sub>2</sub> in an electrolyzer that is powered by electricity grid with CCS | Similar to Grey or Brown H <sub>2</sub> but additionally capture, potentially use, and store CO <sub>2</sub>          | Split water into H <sub>2</sub> and O <sub>2</sub> in an electrolyzer that is powered by renewables | Split water into H <sub>2</sub> and O <sub>2</sub> in an electrolyzer that is powered by nuclear energy | Pyrolysis using a thermal/metal reactor – soot as a by-product<br>Pyrolysis using a plasma reactor - carbon black as a by-product |
| <b>By-product</b>               | CO <sub>2</sub>   | CO / CO <sub>2</sub>   | Water + CO <sub>2</sub> (if no CCS)  | CO <sub>2</sub> not captured by CCS (~10% of total)   | Water   | Water   | Carbon soot or graphite or carbon black   |
| <b>Purity of H<sub>2</sub></b>  | ~70%  | 70-96% (if double-treated)   | ~100%  | ~70%  | ~100%   | ~95%  | ~95%  |
| <b>CO<sub>2</sub> emissions</b> | As natural gas splits into H <sub>2</sub> and CO <sub>2</sub> in presence of water, 5.5 tonnes of CO <sub>2</sub> is released per tonne of H <sub>2</sub> | As coal gasifies into H <sub>2</sub> and CO in presence of steam, 19 tonnes of CO <sub>2</sub> is released per tonne of H <sub>2</sub> | CO <sub>2</sub> is emitted by the grid if CO <sub>2</sub> is not captured by the H <sub>2</sub> production process | CO <sub>2</sub> produced in the steam methane reforming process is stored and buried using Carbon Capture and Storage | No CO <sub>2</sub> is produced and emitted  | No CO <sub>2</sub> is produced and emitted  | In the absence of Oxygen, Methane is broken down into Carbon and H <sub>2</sub> , and hence no CO <sub>2</sub> is emitted         |
| <b>Fit to PLN</b>               | Limited gas supply, no value from PLN if using SMR  | High coal availability, however limited market due to CO <sub>2</sub> intensity  | Usage of over-capacity in Java, potential to combine with CCS  | Higher fit if coal is used, given limited gas in Indonesia  | PLN can provide the renewables for generation, however at higher cost than coal                     | Potential nuclear in Indonesia only post-2040   | Unproven technology   |

**Figure 2** Hydrogen Classification based on Energy Sources (Nur Rakhman, 2024)

This image provides a comparison of various hydrogen production methods based on key factors such as raw materials, production process, by-products, hydrogen purity, CO<sub>2</sub> emissions, and suitability for PLN (Indonesia's state-owned electricity company). Grey Hydrogen is produced from natural gas using steam methane reforming (SMR), which emits a large amount of CO<sub>2</sub> (~5.5 tons per ton of H<sub>2</sub>). The hydrogen purity is about 70%. It has limited relevance for PLN due to Indonesia's limited gas supply and high emissions. Brown Hydrogen uses coal and water, producing even higher CO<sub>2</sub> emissions (~19 tons per ton of H<sub>2</sub>). It may be feasible due to Indonesia's coal availability but is not environmentally sustainable. Blue Hydrogen uses either natural gas or coal but includes Carbon Capture and Storage (CCS) to reduce emissions. However, about 10% of CO<sub>2</sub> may still escape. Hydrogen purity is around 70%. Blue Hydrogen with Thermal uses electricity (with optional CCS) to split water into H<sub>2</sub> and O<sub>2</sub>. It produces nearly 100% pure hydrogen. It may fit in Java, where there is grid overcapacity. Green Hydrogen (highlighted) is produced by splitting water using electricity from renewable energy sources such as geothermal or solar. It produces no CO<sub>2</sub> and has ~100% hydrogen purity. It is the cleanest method and is suitable for PLN, though the cost is higher compared to coal-based options. Pink Hydrogen uses nuclear power for electrolysis and has ~95% hydrogen purity with no CO<sub>2</sub> emissions. It is only viable in Indonesia after 2040. Turquoise Hydrogen involves methane pyrolysis and produces solid carbon (soot or carbon black) instead of CO<sub>2</sub>. It is still considered unproven technology. In summary, green hydrogen is the most environmentally friendly and future-proof option for Indonesia's energy transition, especially if supported by renewable electricity sources like geothermal.

### 3 Techno-Economic Calculation

In technical and economic calculations, several data are required, consisting of manufacturer data, operational data, and several assumptions. Economic calculations are carried out in sequential stages. The LCOH calculation method uses equations from the literature (Deutsch et al., 2023).

| Generator Capacity               |   |          |          |  |  |
|----------------------------------|---|----------|----------|--|--|
|                                  | HMXT-50   | HMXT-100 | HMXT-200 |  |  |
| <b>Feed water</b>                |   |          |          |  |  |
| Minimum resistivity              | 200k $\Omega$ -cm   |          |          |  |  |
| <b>Maximum consumption</b>       |   |          |          |  |  |
| liter per hour                   | 3   | 6        | 11       |  |  |
| gallon per hour                  | 0.8   | 1.6      | 2.9      |  |  |
| <b>Process Cooling Water</b>     |   |          |          |  |  |
| Max allowable temperature        | 40°C (104°F)  |          |          |  |  |
| Max allowable pressure           | 100 psig (7 kg/cm <sup>2</sup> )  |          |          |  |  |
| Max required flow                | 40 liter/min (11 GPM)   |          |          |  |  |
| Pressure drop at max flow        | 10 psig (0.35 kg/cm <sup>2</sup> )  |          |          |  |  |
| <b>Maximum heat load</b>         |   |          |          |  |  |
| kW                               | 8   | 15       | 25       |  |  |
| kBtu/hr                          | 27.3  | 51.2     | 85.4     |  |  |
| <b>Condenser Cooling Water</b>   |   |          |          |  |  |
| Max allowable temperature        | 40°C (104°F)  |          |          |  |  |
| Max allowable pressure           | 100 psig (7 kg/cm <sup>2</sup> )  |          |          |  |  |
| Required flow                    | 4 liter/min (1 GPM)   |          |          |  |  |
| Pressure drop at max flow        | 7 psig (0.5 kg/cm <sup>2</sup> )  |          |          |  |  |
| Maximum heat load                | 1 kW (3000 Btu/hr)  |          |          |  |  |
| <b>Electrical Power Supply</b>   |   |          |          |  |  |
| Nominal input voltage            | Universal or Made to match supply voltage (380 Volt Minimum)  |          |          |  |  |
| <b>Phase</b>                     |   |          |          |  |  |
| Nominal AC KVA                   | 30  | 60       | 120      |  |  |
| <b>Ambient Temperature Range</b> |   |          |          |  |  |
| Minimum allowable                | 0.6°C (33°F)  |          |          |  |  |
| Maximum allowable                | 50°C (120°F)  |          |          |  |  |
| <b>Nitrogen Purge</b>            |   |          |          |  |  |
| <b>Pressure Range</b>            |   |          |          |  |  |
| Consumption                      | 50 to 350 psig (3.5 to 25 kg/cm <sup>2</sup> )<br>100 Std liters / day dependent on number of off / on cycles |          |          |  |  |

**Figure 3** Specification of Hydrogen Generator in Kamojang Geothermal Power Plant (Nur Rakhman, 2024).

Several equations used in the techno-economic calculation of Green Hydrogen Production (Deutsch et al., 2023).

1. Annuity Factor

$$\text{Annuity Factor} = \frac{\text{Discount Rate} \times (1 + \text{Discount Rate})^{\text{Lifetime Electrolyzer System}}}{(1 + \text{Discount Rate})^{\text{Lifetime Electrolyzer System} - 1}} \quad (1)$$

2. Energy Consumption

$$\text{Energy Consumption} = \text{Sepcific Energy Consumption} + \text{Energy Demand per kgH}_2 \quad (2)$$

3. Full Load Hours

$$\text{Full Load Hours} = \text{Capacity Factor} \times 365 \times 24$$

4. Levelized Cost of Hydrogen (LCOH)

$$\frac{\text{CAPEX Depreciation}}{\text{LHV}} = \frac{\text{LHV}}{\text{Energy Consumption}} \times \frac{\text{Total CAPEX}}{\text{Energy Consumption} \times \text{Lifetime Electrolyzer}} \quad (3)$$

$$\text{OPEX per kgH}_2 = \frac{\text{LHV}}{\text{Energy Consumption}} \times \frac{\text{OPEX (\%)} \times \text{CAPEX}}{\text{Full Load Hours}} \quad (4)$$

$$\text{Electricity Costs per kgH}_2 = \frac{LHV}{LHV/\text{Energy Consumption}} \times \frac{\text{Electricity Costs}}{1000} \quad (5)$$

$$\begin{aligned} &\text{Cost of Capital per kgH}_2 \\ &= \frac{(\text{CAPEX Free User Input} \times \text{Annuity Factor} - (\text{CAPEX Free User Input} / \text{Lifetime Electrolyzer System}))}{\text{Full Load Hours}} \times \text{Energy Consumption} \end{aligned} \quad (6)$$

$$LCOH = \text{CAPEX Depreciation per kgH}_2 + \text{OPEX per kgH}_2 + \text{Electricity Costs per kgH}_2 + \text{Cost of Capital per kgH}_2 \quad (7)$$

5. Energy Demand per kWh

$$\text{Energy Demand per kgH}_2 = \frac{c_p}{T_\infty} \times \frac{\text{Inlet Pressure}}{\text{Outlet Pressure}} \frac{1 - \text{Heat Capacity Ratio}}{\text{Heat Capacity Ratio}}^{-1} \quad (8)$$

6. Major Costs Driver LCOH

$$\begin{aligned} &\text{Discount Rate} - 40\% \\ &= \left( \frac{LHV}{LHV/\text{Energy Consumption}} \times (\text{Discount Rate} (-20\%)) \right. \\ &\quad \left. + \text{OPEX} (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Cost}}{1000} \right) \\ &- \left( \frac{LHV}{LHV/\text{Energy Consumption}} \times (\text{Annuity Factor} \right. \\ &\quad \left. + \text{OPEX} (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \right) \end{aligned} \quad (9)$$

$$\begin{aligned} &\text{Discount Rate} + 40\% \\ &= \left( \frac{LHV}{LHV/\text{Energy Consumption}} \times (\text{Discount Rate} (+20\%)) \right. \\ &\quad \left. + \text{OPEX} (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Cost}}{1000} \right) \\ &- \left( \frac{LHV}{LHV/\text{Energy Consumption}} \times (\text{Annuity Factor} \right. \\ &\quad \left. + \text{OPEX} (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \right) \end{aligned} \quad (10)$$

$$\begin{aligned}
 & \text{CAPEX} - 40\% \\
 & = \left( \frac{\text{LHV}}{\text{LHV}/\text{Energy Consumption}} \times \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX} (\%) \times \left( \frac{\text{Total CAPEX} \times (1 - \text{Sensitivies} (\%))}{\text{Full Load Hours}} \right) \right. \right. \\
 & \quad \left. \left. + \frac{\text{Electricity Cost}}{1000} \right) \right) \\
 & - \left( \frac{\text{LHV}}{\text{LHV}/\text{Energy Consumption}} \times \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX} (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \right) \right)
 \end{aligned} \tag{11}$$

$$\begin{aligned}
 & \text{CAPEX} + 40\% \\
 & = \left( \frac{\text{LHV}}{\text{LHV}/\text{Energy Consumption}} \times \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX} (\%) \times \left( \frac{\text{Total CAPEX} \times (1 + \text{Sensitivies} (\%))}{\text{Full Load Hours}} \right) \right. \right. \\
 & \quad \left. \left. + \frac{\text{Electricity Cost}}{1000} \right) \right) \\
 & - \left( \frac{\text{LHV}}{\text{LHV}/\text{Energy Consumption}} \times \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX} (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \right) \right)
 \end{aligned} \tag{12}$$

$$\begin{aligned}
 & \text{OPEX} - 40\% = \left( \frac{\text{LHV}}{\text{LHV}/\text{Energy Consumption}} \times \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX} (\%) \times (1 - \text{Sensitivies} (\%)) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} \right. \right. \\
 & \quad \left. \left. + \frac{\text{Electricity Cost}}{1000} \right) \right) \\
 & - \left( \frac{\text{LHV}}{\text{LHV}/\text{Energy Consumption}} \times \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX} (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \right) \right)
 \end{aligned} \tag{13}$$

$$\begin{aligned}
 OPEX + 40\% = & \left( \frac{LHV}{LHV/Energy\ Consumption} \times (Annuity\ Factor \right. \\
 & + OPEX\ (\%) \times (1 + Sensitivies\ (\%)) \times \frac{Total\ CAPEX}{Full\ Load\ Hours} \\
 & \left. + \frac{Electricity\ Cost}{1000} \right) \\
 & - \left( \frac{LHV}{LHV/Energy\ Consumption} \times (Annuity\ Factor \right. \\
 & + OPEX\ (\%) \times \frac{Total\ CAPEX}{Full\ Load\ Hours} + \frac{Electricity\ Costs}{1000} \left. \right)
 \end{aligned} \tag{14}$$

*Lifetime Electrolysis System – 40%*

$$\begin{aligned}
 = & \left( \frac{LHV}{LHV/Energy\ Consumption} \times (Lifetime\ Electrolysis\ System\ (-20\%) \right. \\
 & + OPEX\ (\%) \times \frac{Total\ CAPEX}{Full\ Load\ Hours} + \frac{Electricity\ Cost}{1000} \left. \right) \\
 & - \left( \frac{LHV}{LHV/Energy\ Consumption} \times (Annuity\ Factor + OPEX\ (\%)) \times \frac{Total\ CAPEX}{Full\ Load\ Hours} \right. \\
 & \left. + \frac{Electricity\ Costs}{1000} \right)
 \end{aligned} \tag{15}$$

*Lifetime Electrolysis System + 40%*

$$\begin{aligned}
 = & \left( \frac{LHV}{LHV/Energy\ Consumption} \times (Lifetime\ Electrolysis\ System\ (+20\%) \right. \\
 & + OPEX\ (\%) \times \frac{Total\ CAPEX}{Full\ Load\ Hours} + \frac{Electricity\ Cost}{1000} \left. \right) \\
 & - \left( \frac{LHV}{LHV/Energy\ Consumption} \times (Annuity\ Factor + OPEX\ (\%)) \times \frac{Total\ CAPEX}{Full\ Load\ Hours} \right. \\
 & \left. + \frac{Electricity\ Costs}{1000} \right)
 \end{aligned} \tag{16}$$

*Full Load Hours – 40%*

$$\begin{aligned}
 = & \left( \frac{LHV}{LHV/Energy\ Consumption} \times \left( (Annuity\ Factor \right. \right. \\
 & + OPEX\ (\%) \times \left( \frac{Total\ CAPEX}{Full\ Load\ Hours} \times (1 - Sensitivities\ (\%)) \right) \\
 & \left. \left. + \frac{Electricity\ Cost}{1000} \right) \right) \\
 & - \left( \frac{LHV}{LHV/Energy\ Consumption} \times (Annuity\ Factor \right. \\
 & + OPEX\ (\%) \times \frac{Total\ CAPEX}{Full\ Load\ Hours} + \frac{Electricity\ Costs}{1000} \left. \right)
 \end{aligned} \tag{17}$$

Full Load Hours + 40%

$$\begin{aligned}
 &= \left( \frac{LHV}{LHV/Energy\ Consumption} \times \left( \left( \text{Annuity Factor} \right. \right. \right. \\
 &+ OPEX (\%) \times \left( \frac{\text{Total CAPEX}}{\text{Full Load Hours}} \times (1 - \text{Sensitivities} (\%)) \right) \\
 &\left. \left. \left. + \frac{\text{Electricity Cost}}{1000} \right) \right) \right) \\
 &- \left( \frac{LHV}{LHV/Energy\ Consumption} \times (\text{Annuity Factor} \right. \\
 &+ OPEX (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \left. \right)
 \end{aligned} \tag{18}$$

Electricity Cost - 40%

$$\begin{aligned}
 &= \left( \frac{LHV}{LHV/Energy\ Consumption} \times \left( \left( \text{Annuity Factor} \right. \right. \right. \\
 &+ OPEX (\%) \times \left( \frac{\text{Total CAPEX}}{\text{Full Load Hours}} \times \right) \\
 &\left. \left. \left. + \frac{\text{Electricity Cost}}{1000} \times (1 - \text{Sensitivities} (\%)) \right) \right) \right) \\
 &- \left( \frac{LHV}{LHV/Energy\ Consumption} \times (\text{Annuity Factor} \right. \\
 &+ OPEX (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \left. \right)
 \end{aligned} \tag{19}$$

Electricity Cost + 40%

$$\begin{aligned}
 &= \left( \frac{LHV}{LHV/Energy\ Consumption} \times \left( \left( \text{Annuity Factor} \right. \right. \right. \\
 &+ OPEX (\%) \times \left( \frac{\text{Total CAPEX}}{\text{Full Load Hours}} \times \right) \\
 &\left. \left. \left. + \frac{\text{Electricity Cost}}{1000} \times (1 + \text{Sensitivities} (\%)) \right) \right) \right) \\
 &- \left( \frac{LHV}{LHV/Energy\ Consumption} \times (\text{Annuity Factor} \right. \\
 &+ OPEX (\%) \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \left. \right)
 \end{aligned} \tag{20}$$

$$\begin{aligned}
 & \text{Specific Energy Consumption} - 40\% \\
 & = \left( \frac{LHV}{LHV/ \text{Energy Consumption}} \times (1 \right. \\
 & \quad \left. - \text{Sensitivities (\%)} \right) \times \left( \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX (\%)} \times \left( \frac{\text{Total CAPEX}}{\text{Full Load Hours}} \times \right) + \frac{\text{Electricity Cost}}{1000} \right) \right) \\
 & - \left( \frac{LHV}{LHV/ \text{Energy Consumption}} \times (\text{Annuity Factor} \right. \\
 & \quad \left. + \text{OPEX (\%)} \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \right)
 \end{aligned} \tag{21}$$

$$\begin{aligned}
 & \text{Specific Energy Consumption} + 40\% \\
 & = \left( \frac{LHV}{LHV/ \text{Energy Consumption}} \times (1 \right. \\
 & \quad \left. - \text{Sensitivities (\%)} \right) \times \left( \left( \text{Annuity Factor} \right. \right. \\
 & \quad \left. \left. + \text{OPEX (\%)} \times \left( \frac{\text{Total CAPEX}}{\text{Full Load Hours}} \times \right) + \frac{\text{Electricity Cost}}{1000} \right) \right) \\
 & - \left( \frac{LHV}{LHV/ \text{Energy Consumption}} \times (\text{Annuity Factor} \right. \\
 & \quad \left. + \text{OPEX (\%)} \times \frac{\text{Total CAPEX}}{\text{Full Load Hours}} + \frac{\text{Electricity Costs}}{1000} \right)
 \end{aligned} \tag{22}$$

$$\begin{aligned}
 & \text{Discount Rate} - 20\% \\
 & = \frac{\text{Discount Rate (\%)} \times (1 - \text{sensitivities (\%)}) \times (1 + (\text{Discount Rate (\%)}(1 - \text{Input Sensitivities (\%)}))^{\text{Lifetime Electrolysis System}})}{(1 + (\text{Discount Rate (\%)}(1 - \text{Input Sensitivities (\%)}))^{\text{Lifetime Electrolysis System}} - 1}
 \end{aligned} \tag{23}$$

$$\begin{aligned}
 & \text{Discount Rate} + 20\% \\
 & = \frac{\text{Discount Rate (\%)} \times (1 + \text{sensitivities (\%)}) \times (1 + (\text{Discount Rate (\%)}(1 + \text{Input Sensitivities (\%)}))^{\text{Lifetime Electrolysis System}})}{(1 + (\text{Discount Rate (\%)}(1 + \text{Input Sensitivities (\%)}))^{\text{Lifetime Electrolysis System}} - 1}
 \end{aligned} \tag{24}$$

$$\begin{aligned}
 & \text{Lifetime Electrolysis System} - 20\% \\
 & = \frac{\text{Discount Rate (\%)} \times (1 + \text{Discount Rate (\%)})^{\text{Lifetime Electrolysis System}} \times (1 - \text{Input Sensitivities (\%)})}{(1 + \text{Discount Rate (\%)})^{\text{Lifetime Electrolysis System}} \times (1 - \text{Input Sensitivities (\%)}) - 1}
 \end{aligned} \tag{25}$$

$$\begin{aligned}
 & \text{Lifetime Electrolysis System} + 20\% \\
 & = \frac{\text{Discount Rate (\%)} \times (1 + \text{Discount Rate (\%)})^{\text{Lifetime Electrolysis System}} \times (1 + \text{Input Sensitivities (\%)})}{(1 + \text{Discount Rate (\%)})^{\text{Lifetime Electrolysis System}} \times (1 + \text{Input Sensitivities (\%)}) - 1}
 \end{aligned} \tag{26}$$

## 7. Sensitivities of The Cost Shares

$$\begin{aligned}
 \text{CAPEX Depreciation \%} &= \frac{\text{CAPEX Depreciation per kgH}_2}{\text{LCOH}} \\
 \text{OPEX \%} &= \frac{\text{OPEX per kgH}_2}{\text{LCOH}} \\
 \text{Electricity Cost \%} &= \frac{\text{Electricity Cost per kgH}_2}{\text{LCOH}} \\
 \text{Cost of Capital \%} &= \frac{\text{OPEX per kgH}_2}{\text{LCOH}}
 \end{aligned}
 \tag{27}$$

8. Total Shares of LCOH Cost

$$\begin{aligned}
 &\frac{\text{CAPEX Depreciation}}{\text{LHV}} \times \frac{\text{CAPEX Free User Input}}{\text{Full Load Hours} \times \text{Lifetime Electrolysis System}} \\
 \text{OPEX} &= \frac{\text{LHV}}{\text{Energy Consumption}} \times \frac{\text{OPEX (\%)} \times \text{CAPEX}}{\text{Full Load Hours}} \\
 \text{Electricity Costs} &= \frac{\text{LHV}}{\text{Energy Consumption}} \times \frac{\text{Electricity Costs}}{1000} \\
 \text{Cost of Capital} &= \frac{(\text{CAPEX Free User Input} \times \text{Annuity Factor} - (\text{CAPEX Free User Input} / \text{Lifetime Electrolyzer System}))}{\text{Full Load Hours}} \times \text{Energy Consumption}
 \end{aligned}
 \tag{28}$$

4 Results and Discussion

Base on specification of Hydrogen Generator and several data, it can be summarized essential data for calculation.

Table 1 Data for Calculation

| DATA CALCULATION             |                                  |
|------------------------------|----------------------------------|
| Discount Rate                | 8%                               |
| Lifetime Electrolyzer System | 25 years                         |
| Lifetime Stack               | 80000 hours                      |
| Annuity Factor               | 0.093678779                      |
| Specific Energy Consumption  | 63 kWh/kgH <sub>2</sub>          |
| Energy Consumption           | 63.52969645 kWh/kgH <sub>2</sub> |
| Capacity Factor              | 85.30%                           |
| Full Load Hours              | 7472.28                          |
| System Pressure              | 11.61 bar                        |
| Compressor Efficiency        | 70%                              |
| Electricity Cost             | 107.31 Euro/MWh                  |
| OPEX                         | 3%                               |

Discount Rate is obtained from general economic assumptions or project finance standards, commonly used in techno-economic analyses. Lifetime of Electrolyzer System is obtained from manufacturer's data, reflecting the expected operational lifespan of a complete electrolyzer unit. Lifetime of Stack is taken from literature, representing the standard or typical value used in hydrogen system studies. Annuity Factor is calculated from the discount rate and project lifetime using standard annuity formulas. Specific Energy Consumption is referenced from literature sources (ranges between 59–66 kWh/kgH<sub>2</sub>), representing the energy

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required to produce one kilogram of hydrogen. Energy Consumption is derived value or average from literature within the mentioned range. Capacity Factor is taken from corporate or project-specific data, reflecting system utilization over time. Full Load Hours is calculated from the capacity factor and the number of hours in a year, specific to the system being modeled. System Pressure is provided by the manufacturer, or represents an average value from literature related to typical hydrogen generation systems. Compressor Efficiency is based on literature, representing average values for hydrogen compression systems. Electricity Cost is converted from Rp 122/MWh to Euro/MWh, based on exchange rates and literature-reported electricity prices. OPEX is taken from literature, with a typical range of 1.5% to 3%. A source should be clarified if this is for academic reporting.

**Table 2** LCOH Calculation

| INPUT CAPEX                         |             |                       |
|-------------------------------------|-------------|-----------------------|
| Lifetime Stack                      | 10.70623692 |                       |
| Capex Fee User Input                | 895.77      | Euro/MWh              |
| Total CAPEX                         | 895.77      | Euro/MWh              |
| LCOH                                |             |                       |
| CAPEX Depreciation/kgH <sub>2</sub> | 0.304635245 | Euro/kgH <sub>2</sub> |
| OPEX/kgH <sub>2</sub>               | 0.228476434 | Euro/kgH <sub>2</sub> |
| Electricity Costs/kgH <sub>2</sub>  | 6.817371726 | Euro/kgH <sub>2</sub> |
| Cost of Capital/kgH <sub>2</sub>    | 0.4088112   | Euro/kgH <sub>2</sub> |
| LCOH                                | 7.759294604 | Euro/kgH <sub>2</sub> |

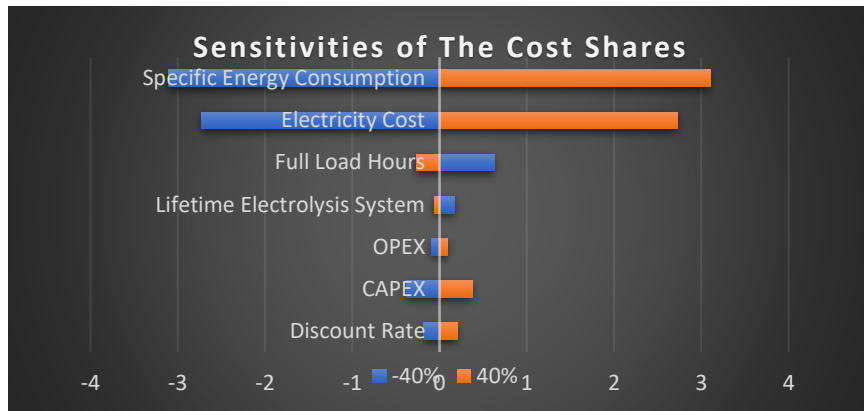
From the data calculation, it can be calculated LCOH from Capex Depreciation/kgH<sub>2</sub>, OPEX/kgH<sub>2</sub>, Electricity Cost/kgH<sub>2</sub>, and Cost of Capital/kgH<sub>2</sub>. However, for illustrate the calculation to the graphics, it is needed to calculate the Energy Demand and several calculation of Sensitivity of The Cost Shares, Total Shares of LCOH Cost, and Major Costs Driver LCOH. Then, the calculation are presented to the graphics to see which affects the LCOH.

**Table 3** Technical Calculation

| CALCULATION COMPRESSION                           |                                  |
|---|----------------------------------|
| Outlet Pressure                                   | 30 bar                           |
| Inlet Pressure                                    | 11.61 bar                        |
| Heat Capacity at Constant Pressure H <sub>2</sub> | 14.3 kJ/kg.K                     |
| Heat Capacity at Constant Volume H <sub>2</sub>   | 10.2 kJ/kg.K                     |
| Heat Capacity Ratio                               | 1.401960784                      |
| Total Efficiency                                  | 70%                              |
| Ambient Temperature                               | 298.15 K                         |
| Energy Demand per kg H <sub>2</sub>               | 0.529696446 kWh/kgH <sub>2</sub> |

**Table 4** Calculation of Sensitivity of The Cost Shares

| CALCULATION TORNADO DIAGRAM         | -40%        | 40%         | -40%         | 40%       |
|-------------------------------------|-------------|-------------|--------------|-----------|
| Discount Rate                       | 7.57543296  | 7.96339343  | -0.183861644 | 0.204099  |
| CAPEX                               | 7.382525453 | 8.136063755 | -0.376769151 | 0.376769  |
| OPEX                                | 7.667904031 | 7.850685178 | -0.091390573 | 0.091391  |
| Lifetime Electrolysis System        | 7.935608085 | 7.699315622 | 0.176313481  | -0.059979 |
| Full Load Hours                     | 8.38724319  | 7.490173782 | 0.627948586  | -0.269121 |
| Electricity Cost                    | 5.032345914 | 10.48624329 | -2.72694869  | 2.726949  |
| Specific Energy Consumption         | 4.655576762 | 10.86301245 | -3.103717842 | 3.103718  |
| Discount Rate (-20%)                | 0.069536905 |             |              |           |
| Discount Rate (+20%)                | 0.120477888 |             |              |           |
| Lifetime Electrolysis System (-20%) | 0.116829545 |             |              |           |
| Lifetime Electrolysis System (+20%) | 0.085803265 |             |              |           |

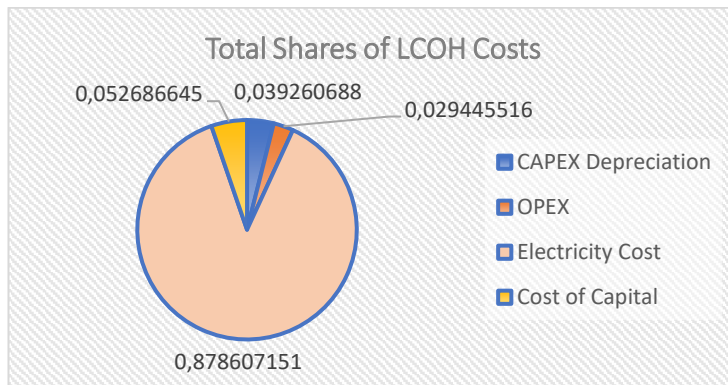


**Figure 4** Sensitivity of The Cost Shares

This chart analyzes the sensitivity of each cost parameter by simulating a  $\pm 40\%$  change in each factor and its effect on LCOH. Specific Energy Consumption and Electricity Cost are the most sensitive parameters. A  $\pm 40\%$  change causes the highest variation in LCOH. Full Load Hours and Electrolyzer Lifetime have moderate influence. OPEX, CAPEX, and Discount Rate show relatively lower sensitivity.

**Table 5** Calculation of Total Shares of LCOH Costs

| PIE CHART          |             |
|--------------------|-------------|
| CAPEX Depreciation | 0.039260688 |
| OPEX               | 0.029445516 |
| Electricity Cost   | 0.878607151 |
| Cost of Capital    | 0.052686645 |

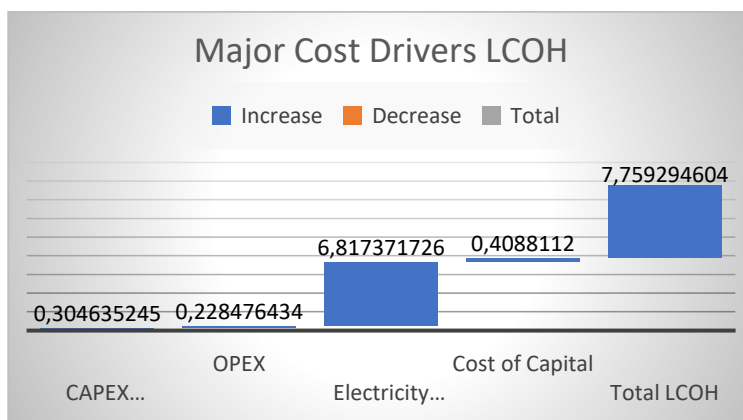


**Figure 5** Chart of Comparison of Total Shares of LCOH Costs

This chart illustrates the proportion of each cost component contributing to the Levelized Cost of Hydrogen (LCOH). Electricity is the dominant contributor, making up 87.86% of the total LCOH. OPEX (Operational Expenditures) contributes 9.93%. CAPEX Depreciation accounts for 5.23%. Cost of Capital contributes the least at 2.94%.

**Table 6** Calculation of Major Cost Drivers LCOH

| WATERFALL DIAGRAM  |             |
|--------------------|-------------|
| CAPEX Depreciation | 0.304635245 |
| OPEX               | 0.228476434 |
| Electricity Cost   | 6.817371726 |
| Cost of Capital    | 0.4088112   |
| Total LCOH         | 7.759294604 |



**Figure 6** Comparison of Major Cost Drivers LCOH

This chart illustrates the proportion of each cost component contributing to the Levelized Cost of Hydrogen (LCOH). Electricity Cost is the dominant contributor, making up 87.86% of the total LCOH. OPEX (Operational Expenditures) contributes 9.93%. CAPEX Depreciation accounts for 5.23%. Cost of Capital contributes the least at 2.94%.

## 5 Conclusion

Based on chart of sensitivity of the cost shares, the cost of hydrogen is highly sensitive to specific energy consumption and electricity prices. Improving system efficiency and securing low-cost energy sources are crucial for economic viability. Chart of the total shares of LCOH cost shows that electricity cost is the most dominant component, accounting for nearly 88% of total LCOH. Reducing energy cost will significantly impact hydrogen production cost. Chart of the major costs driver LCOH has almost similar result with chart of the total shares of LCOH cost. Electricity cost is by far the largest cost driver in hydrogen

production, while other components like CAPEX and OPEX play a minor role in the total cost. From the three charts, it can be concluded the electricity cost is the largest contributor and most sensitive variable in determining the LCOH. Efficiency improvements (especially specific energy consumption) can substantially lower hydrogen costs. Capital investment and financial factors have less impact, though still relevant for optimization.

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