



Contents list available at CBIORE journal website

International Journal of Renewable Energy Development

Journal homepage: <https://ijred.cbiore.id>



Research Article

Financial viability analysis for green hydrogen production opportunity from hydropower plant's excess power in Indonesia

Hendy Eka Hardana^{a*}, Pupung Adiwibowo^b, Yos Sunitiyoso^a, Tri Edi Kusuma Kurniawan^c

^aMaster Program of Business Administration, School of Business and Management Institut Teknologi Bandung, Jakarta, Indonesia

^bMaster Program of Business Administration, Hult International Business School, Cambridge, MA United States

^cPT PLN Indonesia Power, Indonesia

Abstract. The research presents a comprehensive analysis of the financial viability of producing green hydrogen from excess power generated by small hydropower plants in Indonesia. It highlights Indonesia's commitment to increasing renewable energy sources to achieve net zero emissions by 2060 and the role of Perusahaan Listrik Negara (PLN) in this transition. The study examines the potential of utilizing dormant excess power from retroactive small hydropower plants to produce green hydrogen, which could significantly decarbonize hard-to-abate sectors and enhance energy security. The authors conducted a financial analysis using the NREL H2A Production Model to determine the optimal technical arrangement and financial simulation for green hydrogen production. The paper discusses various electrolyzer technologies, with a focus on alkaline water electrolyzers due to their high technology readiness level and low capital expenditure. It also explores the sensitivity of the levelized cost of hydrogen to different factors, particularly the cost of utilities. The findings suggest that green hydrogen production from small hydropower plants is economically feasible in Indonesia, with the potential to contribute to the global hydrogen market and support the country's green circular economy. The study concludes that green hydrogen production using excess electricity from small hydropower plants is a viable method for decarbonization and offers scalability for future energy production in Indonesia, with the first initial step being as a green hydrogen and natural gas co-firing fuel mixing in gas turbines.

Keywords: Green hydrogen, Hydropower plants, Excess power, Alkaline electrolyzer, LCOH, Financial viability analysis



@ The author(s). Published by CBIORE. This is an open access article under the CC BY-SA license (<http://creativecommons.org/licenses/by-sa/4.0/>).

Received: 8th May 2024; Revised: 28th June 2024; Accepted: 6th July 2024; Available online: 14th July 2024

1. Introduction

According to (The World Bank Group, 2023), Indonesia, highly susceptible to climate change impacts such as flooding and extreme heat, ranks among the top third of countries for climate risk. Projections suggest an increased population exposure to hazards like extreme river floods and permanent sea-level rise flooding. Acknowledging the economic disruption caused by climate shocks, Indonesia emphasizes the need for adaptation measures. The country is transitioning towards a low-carbon, climate-resilient growth model to balance emission cuts with economic progress.

Stakeholders in Indonesia express the perspective that, in the short term, the implementation of climate policies remains unlikely. The government's current focus centers on economic development, emphasizing growth, employment and equality, which may take precedence over immediate environmental concerns. Furthermore, the conflict between economic development objectives and climate policies impedes the integration of climate policies into Indonesia's development agenda. The successful adjustment to climate change necessitates the participation of a variety of stakeholders, encompassing both the public and private sectors, to put into action measures that reduce greenhouse gas (GHG) emissions.

It is crucial to more seamlessly incorporate considerations of climate risks and the necessities of adaptation into the routine operations of these key stakeholders, form connections between climate change adaptation strategies and local policies at both national and regional scales for the efficient control of GHG emissions (Rakhmindyarto, 2020; Sebos *et al.*, 2023) Sukmara *et al.*, 2024).

Based on report by (The World Bank Group, 2023), Indonesia has set forth a plan to curtail its GHG emissions by modifying its primary energy composition, with the objective of diminishing the proportions of coal and oil and augmenting the proportion of renewable energy (RE) sources. The nation's goal is to decrease the coal contribution from 43% to 30% and oil from 31% to 25% in the decade from 2020 to 2030, while elevating the contribution of renewables from 6.1% to 25%. Moreover, as part of its Enhanced Nationally Determined Contributions (E-NDC), Indonesia has pledged to achieve a 31.9% reduction in GHG emissions by 2030. (Rahman *et al.*, 2023) describe that RE has the potential to tackle all three identified energy trilemma. This is in line with the policy of using RE in power sector mitigation in IPCC category 1A1a (Martin-Ortega *et al.*, 2024). Nonetheless, to handle the constraint of energy affordability, continuous investment and commitment from the government are necessary, especially if the existing

* Corresponding author
Email: hendy_hardana@sbm-itb.ac.id (H. E. Hardana)

public-led market mechanism is to continue. The aspect of energy affordability is paramount in gaining societal approval for renewables.

Despite the global impact of the COVID-19 pandemic, (Buechler *et al.*, 2022) reveals significant heterogeneity in the effects on electricity consumption. Across continents, countries exhibited diverse initial responses, ranging from extreme/severe to mild, with varying rates of recovery. The research highlights the interplay between electricity consumption changes and key factors, including COVID-19 deaths, government restrictions, individual mobility shifts, GDP fluctuations and electricity system characteristics. Based on data from (Enerdata, 2023), electricity demand declined in several regions due to the COVID-19. However, Asia stood out as an exception, experiencing no decline in electricity consumption during this period.

The pandemic had a paradoxical impact on electricity demand in Indonesia. Economic activities slowed due to lockdowns, yet residential electricity consumption surged as people stayed home, increasing usage of household appliances, lighting and electronic devices. Remote work and online education further heightened energy consumption (Novianto *et al.*, 2022; Sari & Pinassang, 2023). Despite a 5% decline in demand from the industrial sector in 2020, the total electricity demand increased by 2% compared to the previous year and continued to increase after COVID-19 as shown in Figure 1.

The electricity sector in Indonesia has crucial role in achieving electrification and climate change mitigation goals necessitates enhancing its climate resilience. The initial move towards a low-carbon, climate-resilient electricity sector involves recognizing its climate vulnerability and incorporating its adaptation plans into national climate change strategies. It's vital for electric utilities to integrate climate adaptation into their long-term strategies and capacity building. Raising stakeholder awareness about the impact of climate change on business sustainability is a key step. Collaborative efforts in achieving environmental sustainability, prioritizing efficiency and using RE in the electricity system can minimize long-term losses. (Buana *et al.*, 2023; Handayani *et al.*, 2019).

The proportion of RE sources in Indonesia, mostly hydropower and geothermal energy, stands at approximately 15%. Indonesia's energy demand is predicted to increase significantly due to economic growth, urbanization and the expansion of electricity usage. This presents a difficulty in the process of reducing carbon emissions in the power industry and accomplishing the aim of 2060 to net zero emissions (NZE) or sooner (IEA, 2022). Coal yet the primary source of power in Indonesia, making up about 60% of the total generation and contributing approximately 80% of the CO₂ emissions.

Perusahaan Listrik Negara (PLN) is a government-owned corporation responsible for supplying electricity to the whole Indonesian archipelago with a motto: Electricity for a Better Life. PLN operates in multiple sectors of the electrical industry, encompassing power generation, transmission, distribution and marketing. PLN is thoroughly owned by the Government of Indonesia and plays a crucial role in bolstering national growth (PLN, 2022). Accordingly, the Indonesian government has pledged to gradually phase out unabated coal to fulfill the Paris Agreement's target and has acknowledged that it will require international assistance to do so. The international community's pressure on the electrical sector to move to RE sources immediately is PLN's challenge. PLN is committed to providing environmentally sustainable electricity to the community while maintaining system dependability and financial health (IESR, 2023).

(Sunitiyoso *et al.*, 2020) described that in Indonesia, the incorporation of New and Renewable Energy (NRE) into the electrical sector is vital for ensuring long-term and environmentally sustainable economic development. Although local governments and the central government are eager to promote the construction of NRE infrastructure, eventually it is funded by PLN earnings and the national budget. Regrettably, the revenues of PLN are constrained by the power tariff, subsidy amount and IPP electricity procurement mandated by Ministry of Energy and Mineral Resources (MEMR) feed-in tariff restriction, while national budget allocation is limited. Despite the waiting for financing cooperation mechanism, PLN must implement its internally developed breakthrough solution in decarbonization. Meanwhile, in carrying out its sustainability strategy, PLN aims to achieve NZE by 2060 with plans for 69% of electricity production to come from RE sources, 15% from gas, 8% to come from coal and gas plants, that have carbon capture storage facilities and 7% comes from new energy. By the 2050s coal and gas will be gradually eliminated, with the exception of those facilities that are fitted with carbon capture, utilization and storage (CCUS) technology. Electricity generated from low-emission sources, such as nuclear power, ammonia and hydrogen, also contribute to the overall energy mix (PLN, 2023; IEA, 2022).

PLN is dedicated to expediting the transition process to sustainable energy sources to reach NZE by 2060. PLN has further solidified its position as a leader and key player in supplying sustainable energy for the nation, with a specific emphasis on the advancement of novel and sustainable energy sources. Based on PLN's NZE aspirations in 2060, hydrogen co-firing is included as PLN's long-term target for 2031-2060, by means of gas turbine (GT) and diesel engine power plants implementation either. Adding hydrogen to ordinary natural gas in the combustors of GT, a process known as co-firing, can lead to substantial reductions in GHG emissions (Jaeger & deBiasi, 2022; PLN, 2022; Alhuyi Nazari *et al.*, 2022). To achieve this target, with the aid of innovation, funding and policy, PLN aspires to develop its own capabilities and new technologies. However, challenges remain, including limitations on PLN's earnings due to government-regulated tariffs and subsidies, requiring innovative solutions for decarbonization (PLN, 2022).

Hydrogen possesses the most potential as an energy source in the future. Nevertheless, its carbon emissions exhibit significant variability, contingent upon the manufacturing techniques employed and the scopes considered for emission calculations. Currently, there are three types of hydrogen that may be produced using existing technology: grey hydrogen, which is derived from coal gasification; blue hydrogen, which is obtained by steam methane reforming (SMR); and green hydrogen (GH₂), which is generated through the process of electrolysis utilizing RE sources. Purple hydrogen is also created by the electrolysis of water from nuclear power. Varying production methods have varying carbon footprints, which affects the climate (Cheng & Lee, 2022).

Hydrogen as a new alternative NRE in Indonesia, has been included in energy transition scenario, (KESDM, 2023; Zahra, 2022; Sulistyono *et al.*, 2023) explained that in contrast to other colors, GH₂ is vital in the energy transition and could decarbonize difficult-to-abate sectors significantly. Supply of GH₂ from NRE planned to start at 2031, will decarbonize at about 388 million tons CO₂. Based on report by (IRENA, 2022), hydrogen can enhance the resilience of isolated communities, ranging from villages situated in remote mountainous regions to segregated islands. These localities encounter distinct energy security obstacles. They frequently rely heavily on foreign fossil

fuels, whereas their energy infrastructures are typically modest and dependent on diesel generators to provide auxiliary power inspite of possess some of the most exceptional RE resources.

However, current widespread implementation of hydrogen technology in Indonesia is hindered by its classification as a chemical substance for industry. Approximately 96% of the hydrogen is produced so far came through the fossil fuels (Manullang & Sinaga, 2022). Likewise, the industry sector retail selling price of blue hydrogen through SMR in Indonesia based on (Murti & Pratomo, 2022) is still about ±40.36 USD/kg. GH₂ is produced by electrolyzing water in an electrolyzer utilizing RE sources such as hydro, wind and sun. The GH₂ generated can thereafter be utilized for a multitude of uses. Examples of applications for GH₂ include fuel cells, industrial operations and storage (Maka & Mehmood, 2024). To further reduce the cost of producing GH₂, using affordable RE sources besides geothermal allows GH₂ energy utilization faster and achieve zero carbon emissions sooner (Zahra, 2022).

Low-carbon hydrogen has three possible applications in the Indonesian electricity sector as described in the national hydrogen strategy document (KESDM, 2023b). One potential method to reduce carbon emissions is co-firing low-carbon hydrogen or ammonia in fossil-based power plants, though it is less impactful than co-firing with biomass. This alternative may become viable between 2030 and 2050 if there is a reduction in non-RE availability, a drop in low-carbon hydrogen production costs making it competitive, or a significant rise in carbon costs. Additionally, hydrogen can serve as a storage solution for off-grid power generation, aiding the goal of complete electrification, although it is not the primary focus. Lastly, hydrogen can help mitigate the intermittency of NRE generation in the national electricity grid, particularly beyond 2040 when the cost of NRE-based electricity generation is expected to become highly competitive.

Studies in several GH₂ production by (Reksten et al., 2022; Zun & McLellan, 2023; Shahabuddin et al., 2023) presented a prediction of the cost of electrolyser plants, considering factors like scale-up, manufacturing volumes and technology improvements. It also includes a comprehensive hydrogen production, compression, storage and transportation: a technical and economic evaluation, along with a sensitivity analysis of the levelized cost of hydrogen (LCOH). Various electrolyzer technology along with it's technology readiness level (TRL) explained by (KESDM, 2023; Krishnan et al., 2023; Rey et al., 2023), currently there are four production technology:

alkaline water electrolyzer (AE), proton exchange membrane electrolyzer (PEM), solid oxide electrolyzer (SOE) and anion exchange membrane electrolyzer (AEM). Among GH₂ electrolyzers, AE stand out due to their longest lifespans, lowest capital expenditures (CAPEX) and highest TRL. This durability, with lifespans surpassing 30 years and high scalability because have been supported by most manufacturers since the early 1900s (IRENA, 2020). Report by (Energy Sector Management Assistance Program (ESMAP) et al., 2024; Accenture & China Hydrogen Alliance, 2023), outline for example, China, which has advanced AE technology, can produce and install electrolyzer systems for as low as \$400/kW, while costs in Europe tend to be higher. In line to research by (KESDM, 2023b; Rey et al., 2023), AE has achieved a TRL score of 9, indicating that this technology has been validated through successful operational deployment and highest maturity, unlike other electrolyzer technologies. Table 1 shows the electrolyzer comparison.

Research by (Tambunan et al., 2020; Sunitiyoso et al., 2020) represent that RE source potency in Indonesia as a developing country has prodigious potential while modest utilisation, still ranging below 7% of its potential. The gap between potential and utilization indicates an opportunity for Indonesia to tap into its vast RE resources more effectively. The first potential come from solar power by 207,898 MW with 0.04% utilisation and the second come from hydropower plants (HPP) by 75,091 MW with 6.4% utilisation also small hydropower (SHP) by 19,385 MW with 1% utilisation. The third and the rest followed by wind, bioenergy and geothermal consecutively. Drawing upon the inherent strength of Indonesia's internal NRE context, we can explore the potential benefits. According to recent research by (Fokeer et al., 2024), developing countries have strategic opportunities to produce GH₂ using renewable energy resources to improve energy security, reduce vulnerability to external shocks, participate in the global hydrogen market, achieve net zero industrial development, generate local value-added, create wealth and create employment opportunities. Indonesia can participate in the global hydrogen market and improve their energy security through producing GH₂, which could meet up to 25% of global demand by 2050. This involvement strengthens economic resilience and promotes the growth of diverse, knowledge-based economies in addition to providing opportunities for net-zero industrial development and local value addition.

Our GH₂ initiative outlines novel business practices based on comprehensive research in Indonesia, an area that had

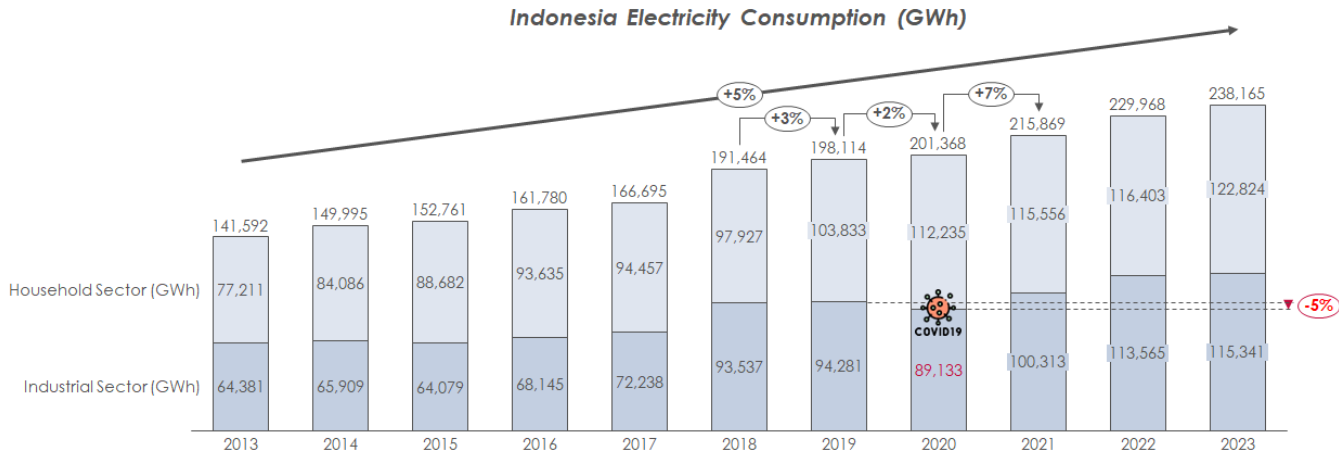


Fig 1. Indonesia electricity consumption 2013-2023 (Source: author analysis from KESDM, 2023a)

previously received limited attention in academic publications. We investigate key factors influencing the economic viability of GH₂ production, focusing on market demand readiness and CAPEX. These initiatives not only spur innovation but also support the energy transition, providing significant insights for global adoption that can be emulated by other countries. The study assesses the feasibility of GH₂ production facilities by optimizing untapped SHPs and creating GH₂ clusters across Indonesia's islands. As noted by (Pambudi et al., 2023), nearly all Indonesian provinces have dispersed hydro energy potential, making this approach significant for establishing economically feasible GH₂ prices using excess SHP power. These networks aim to serve the burgeoning market and contribute to the GH₂ supply chain. Additionally, the research explores large-scale production systems that fundamentally transform the energy transition process. It emphasizes the critical role of regulatory frameworks and international collaboration in advancing sustainable energy and meeting NZE goals.

The study presents a proof-of-concept for the scalability of GH₂ in Indonesia, proposing that hydropower to GH₂ co-firing with gas turbines and diesel/gas engines could be a feasible approach. Indonesia's geographical features support integrated energy production from hydropower, wind and solar sources, fostering a green circular economy and reducing fossil fuel dependence. A thorough financial analysis of electrolysis-based GH₂ production was conducted using the NREL H2A Production Model to achieve the best and most efficient system configuration. Furthermore, it might be developed for EV charging infrastructure, where GH₂ could provide hydrogen for fuel cell-based EV charging stations, seen as a promising strategy for reducing emissions. A future ecosystem capable of bolstering national energy security during the energy transition era, aligning with the Indonesian government's NZE program.

2. Literature Review

2.1 LCOH

The LCOH is a key metric used to evaluate the cost of producing and delivering hydrogen over its entire lifecycle. LCOH is defined as the cost per unit of hydrogen that a project must incur over its entire lifecycle to achieve a Net Present Value (NPV) of zero. In other casual words, LCOH refers to the

minimum price per kilogram of hydrogen that an investor must achieve in the market in order to cover the expenses related to the initial investment in capacity and all ongoing operating costs. GH₂'s economic feasibility is considerably increased when the inaugural investment is intended as an hybrid system that integrates electrolyzer with RE source (Agora Industry and Umlaut, 2023; Friedl et al., 2023; Zun & McLellan, 2023).

LCOH calculated through discounted cash flow (DCF) model yielding a predetermined internal return rate of return (IRR) using H2A production model by (Penev et al., 2018). Simulations can be conducted utilizing default technological input values generated from existing production technology examples include capital costs, operational expenses and capacity factors, or by employing customized input values. Based on (Li et al., 2024) as shown in Figure 2, the DCF model performs a comprehensive evaluation of all projected future cash inflows and outflows. By incorporating revenue, operating expenses, capital expenditures and other financial elements, it offers a reliable estimate of the LCOH. The benefits of utilizing the LCOH as an economic performance indicator are twofold: it facilitates the comparison of diverse production and delivery technologies with varying lifetimes, project scales, capital expenditures and capacities; it provides a benchmark for policymakers to develop incentives by enabling the comparison of multiple alternative energy projects.

LCOH include estimated power costs, the number of full-load hours, the cost of capital and the capital expenses for electrolyzers. Optimal integration within the energy system tends to reduce full-load hours, thereby increasing the proportion of capital investment in the overall cost of green hydrogen production. The major cost driver of LCOH shown in Figure 3 and the highest variable are electricity costs. For instance, widely-referenced German energy forecasts predict that electrolyzers will operate for approximately 3,000 full-load hours by 2030, corresponding to a utilization rate of around 34%, with a gradual increase anticipated until 2045. As the number of full-load hours declines, the relative significance of electrolysis investment expenses escalates (Agora Industry and Umlaut, 2023).

The latest scholarly investigations forecast the cost projection of Alkaline (AE) and Proton Exchange Membrane (PEM) electrolyzers, account for ongoing advancement in

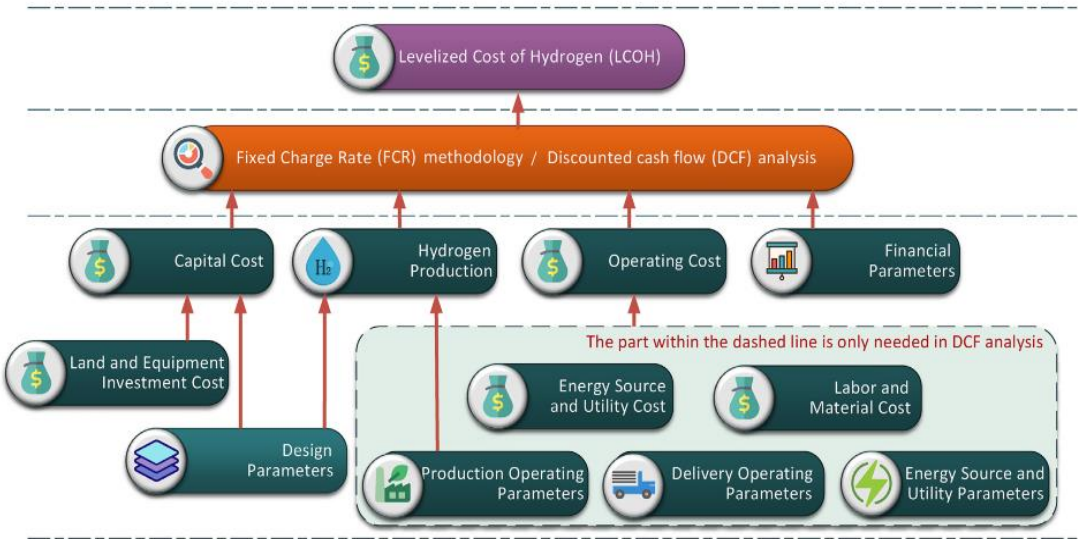


Fig 2. Methods of figuring the LCOH and the required data (Source: Li et al., 2024)

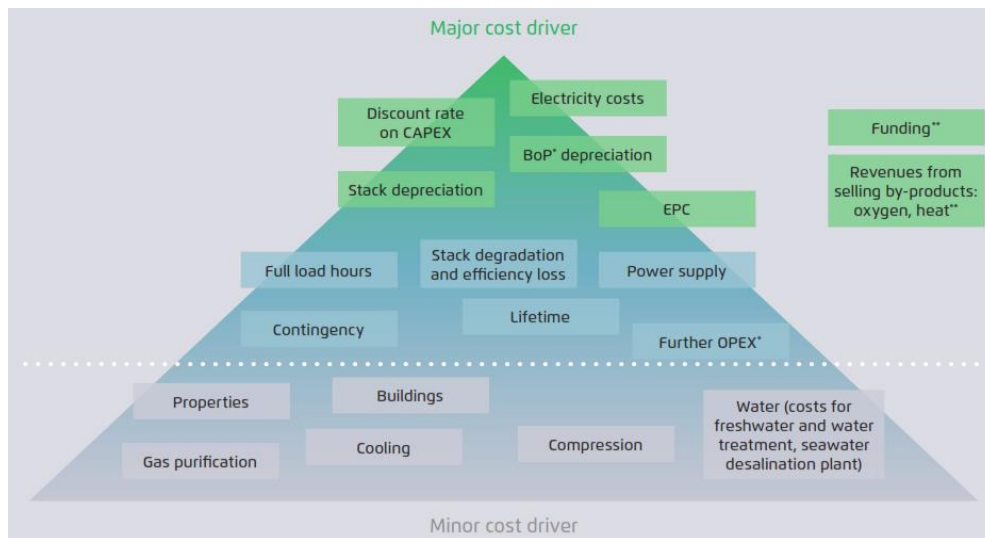


Fig 3. Cost driver on LCOH (Source: Agora Industry and Umlaut, 2023)

research and development (R&D), scale effects and observational learning. These factors subsequently influence the LCOH projections. By 2030, the global LCOH for GH_2 is predicted to be less than 5 USD/kg for solar, onshore wind and offshore wind energy sources due to lower electrolyzer costs and the Levelized Cost of Electricity (LCOE) in both scenarios. Equation 1 defines the LCOH where LCOE, N , r and M represent the levelized cost of electricity, plant life, inflation rate and mass number of produced hydrogen (Zun & McLellan, 2023).

$$LCOH = \frac{\sum_{n=1}^N \frac{CAPEX}{(1+r)^n} + \frac{OPEX}{(1+r)^n} + \frac{Others}{(1+r)^n} + LCOE}{\sum_{n=1}^N \frac{MH_2}{(1+r)^n}} \quad (1)$$

2.2 Hydropower Plant

Hydropower is the most well-established form of RE technology used for generating electricity. Nevertheless, the advancement of large-scale hydropower systems, specifically those of significant capacity dams are frequently linked to major environmental and socioeconomic challenges, such as the land flooding, the relocation of communities and the potential for disasters caused by dam leaks and social conflict. Hydropower with large reservoirs are influenced by climate change either, as mentioned by (Handayani *et al.*, 2019), how water inflow could flood the reservoir and spill or even drought and all of this weather impact can affect the operation scheme of the plant. SHP, such as run-of-river systems, is characterized by its lower size and fewer disadvantages compared to larger HPPs (Rospriandana *et al.*, 2023).

The inception of Indonesia's electricity can be traced back to the late 19th century. Originally, the primary intention of the first power plant in Indonesia was to supply electricity to factories. The construction of it was carried out by a Dutch sugar mill and tea factory. The public gained access to electricity with the founding of the *Nederlandse Indische Electriciteit Maatschappij* (NIEM) power company. The Netherlands is the location of the company's main office. Gambir, in Batavia, is where NIEM built a steam power plant along the banks of the Ciliwung River. (ESMAP & The World Bank, 2017) explains that about 500 projects with a combined capacity of more than 2 GW are found on Sumatera or Jawa Islands, accounting for more

than half of SHP. Java Island's production capacity is 890 MW from 241 projects.

In 1927, the Dutch government established s'Lands Waterkracht Bedrijven (LWB). The company is a government-owned electricity company responsible for overseeing the operation of multiple SHPs throughout various regions in Indonesia. The mentioned power plants include Plengan, Lamajan, Bengkok Dago, Ubrug, and Kracak in West Java, Giringan in Madiun, Tes in Bengkulu and Tonsea Lama in North Sulawesi (Islam & Febrian, 2020). Furthermore, municipal electricity corporations were established in various municipalities.

The initial generation of SHP was created utilising European Francis and Pelton turbines. During the period of 1900s-1945, it had a significant role in the first development of electrification in the East Indies, namely in the vicinity of Bandung, the capital city of the West Java province. The virtual tour from CSR Hero (PLN Indonesia Power, 2021) provides a glimpse memory of all the heritage SHPs by the Dutch East Indies in West Java. Figure 4 shows the identified SHP projects in west java region which is being and will be developed.

SHP is considered key, according to (Langer *et al.*, 2021; Rospriandana *et al.*, 2023), that SHP in Indonesia is a reliable RE source with high yield and low environmental impact. It has evolved from the East Indies era to a key solution for rural

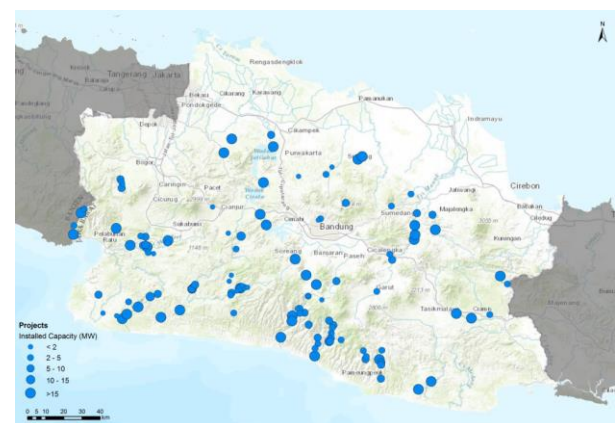


Fig 4. Identified SHP across West Java nearby Jakarta (Source: ESMAP & The World Bank, 2017)

electrification and community empowerment. Despite barriers like lack of foreign investment, limited infrastructure and as described by (Ratnaningsih *et al.*, 2019) that rivers are currently heavily polluted by domestic waste where mostly in West Java, the upscaling of SHP is endorsed due to its lower costs, local proficiency, reliable power production and its successful implementation could smooth the shift towards alternative energy sources in isolated regions, moving away from diesel and other non-renewable fuels.

2.3 Hydrogen Co-firing

Hydrogen's life-cycle emissions depend on the energy source used for production. Currently, most global hydrogen supply comes from fossil fuels. GH_2 holds significant promise for the energy transition due to its lack of GHG emission (Blohm & Dettner, 2023). The application of hydrogen in GT has emerged as a possible substitute for conventional fuels like oil and coal. This transition is motivated by the growing apprehensions surrounding the utilization of conventional fuels and the consequent release of GHG emissions. Hydrogen, due to its substantial energy content and absence of emissions, presents a superior alternative that is both cleaner and more efficient.

(Abdin, 2024) explained that GH_2 co-firing, which considered as gas-gas co-firing, is a technology that is becoming more important because of the emphasis on hydrogen. It involves burning gaseous fuels, such as hydrogen and natural gas mixing. This approach exploits the distinctive characteristics of hydrogen, specifically its high energy density, to enhance the energy content of the fuel mixture. Combusting hydrogen with natural gas yields a flame that exhibits increased temperature and uniformity, hence improving the efficiency and quality in generation of energy.

Studies by (Miyamoto *et al.*, 2018; Laget *et al.*, 2022) discuss the development of a large GT with hydrogen and natural gas co-firing capabilities of Mitsubishi Hitachi Power Systems, Ltd (MHPS) and ENGIE. The research on MHPS reports the successful completion of a 30 vol% hydrogen co-firing test using a recently constructed combustor. Comparing this co-firing capability to a traditional natural gas thermal power plant yields a 10% reduction in carbon dioxide (CO_2) emissions. It also examines the performance of GT operating in both simple and combined cycle designs using natural gas, hydrogen, or a combination of the two in great detail and quantitatively. Also, promising research on ENGIE, only found fractional effects on flame position, figuration and also NO_x emission were observed for hydrogen concentrations less than 30%.

Accordingly, GT have the inherent ability to use different types of fuel, such as GH_2 or similar alternatives. They can be designed to run on these fuels from the start or modified even after being operated for a long time with traditional fuels like natural gas. The extent of the necessary adjustments to design a GT for hydrogen operation is contingent upon the intended hydrogen content in the fuel, the initial GT arrangement and the entire plant balance (GE Vernova, 2023; Kawasaki, 2022).

Moreover, (Alhuyi Nazari *et al.*, 2022) explained that introducing hydrogen into regular fuels can decrease CO and NO_x emissions, enhance the flame's stability and the regularity of combustion and in some situations, improve the efficiency of energy utilization. The performance and practicality of hydrogen-fired GT can be influenced by various aspects such as hydrogen generation technologies, system designs, operating circumstances and economic considerations. In order to increase the capacity and decrease carbon dioxide emissions, hydrogen-powered GT can be combined with other power production systems, such as solar PV cells, electrolyzers, and

biomass systems. A recent study by (Wade *et al.*, 2023), in order to provide low-carbon electricity, the study also attempted to size a power supply system made up of a hydrogen-fired GT power plant, a wind power plant, an electrolysis plant, a compressor and a storage tank. This technology avoids oversizing the system and delivers savings in terms of costs, area and water consumption in addition to providing the dispatchable power supply system that is necessary to provide flexibility on the grid.

Hydrogen co-firing in GT power plants presents a viable and sustainable solution for power generation. With its high energy content and zero-emission characteristic, hydrogen can significantly reduce GHG emissions and contribute to the decarbonization of the energy sector. Further research and development in this field can pave the way for more efficient and sustainable power generation systems.

2.4 Excess Power

Excess power in HPP facilities is the surplus electricity generated when there is a greater amount of water flow than required to meet the current demand. The importance of hydropower and its capacity to harness excess energy is vital for grid stabilisation, particularly in conjunction with the incorporation of other renewable resources (Hafner & Luciani, 2022). Related to SHP which has the potential for excess power, according to (Das *et al.*, 2024; Prawitasari *et al.*, 2024), as energy that is not used as a burden or demand, should be utilized through a more sustainable value creation method. To find the energy savings, we compared the excess energy values of each proposed system to the existing and baseline values.

The new solution and technologies are needed to ensure and enable the storage excess energy. Power-to-Gas (P2G) is a method, for converting excess power generated from renewable electrical energy into hydrogen. P2G technology uses electricity to perform electrolysis, which is the process of shattering water into hydrogen and oxygen. Study from (Bamisile *et al.*, 2020), a conceptual model is developed for generating hydrogen using electricity from hydropower plants in China. This is followed by a year-long investigation into the production of hydrogen from water by four distinct HPP in Southwestern China that had surplus or unused electricity. By using the hydropower potential, GH_2 production can devote significantly to reduce GHG emissions. Also as described by (Jovan *et al.*, 2021), that the run-of-river HPP in Slovenia utilises a control algorithm to estimate the cogeneration of GH_2 from excess hydropower. This algorithm limits the amount of hydrogen production, taking into account the specified schedule and the actual water accumulation in order to enhance the financial returns of the HPP operations.

Hydrogen production is one strategy that can effectively handle excess electricity in a HPP facility. (Zwickl-Bernhard & Auer, 2022) explores the potential business case for producing GH_2 using hydropower and profitable market for GH_2 produced from hydropower in the future. Upon by reviewing the literature and forecasting future trends in energy system decarbonization, it can be inferred that excess power from hydropower stands out as the viable RE technology for producing GH_2 .

2.5 Electrolyzer Technology

The importance of GH_2 in meeting long-term net-zero climate targets has been widely recognized. RE sources are anticipated to be crucial to this transition. However, these sources are unpredictable and reliant on the weather.

Table 1
AE, PEM, SOE and AEM comparison

Technology	Abbreviation	Temp. Range	Electrolyte	Catalysts	Advantages	Challenges	TRL	Notes
Proton Exchange Membrane	PEM	~ 50° – 80°C	polymer membrane H+ conducting	PGM-based (e.g., Pt, Ir)	a. Commercial technology b. High current density at high efficiency c. Differential pressure operation d. Dynamic operation capability	a. Use of critical materials (e.g., Ti, Ir, Pt, PFAS) b. Temperature-limited efficiency	8	
Liquid Alkaline	AE	~ 70° - 90°C	aqueous solution OH- conducting	PGM-free (e.g., Ni-based)	a. Commercial technology b. Low-cost materials c. Proven long lifetime d. Established supply chain and manufacturing processes	a. Corrosive electrolyte b. Dynamic operation limitations c. Low performance d. Differential pressure operations difficult e. Temperature-limited efficiency	9	
Oxide-ion Conducting Solid Oxide	O-SOE	~ 700° - 850°C	ceramic membrane O2 conducting	PGM-free	a. Early commercial technology b. High electrical efficiency c. Thermal energy integration, e.g., with nuclear or solar	a. Need for high temperature materials b. Effective thermal integration c. Cold-start and intermittent operations d. Lifetime	5	Platinum Group Metals (PGM)
Alkaline Exchange Membrane	AEM	~ 60° - 80°C	polymer membrane OH- conducting	PGM-free (e.g., Ni-based)	a. Pilot demonstrations b. Low-cost materials c. Dynamic operation capability d. Differential pressure operation	a. Durability and performance of current membranes b. Trace PGM catalysts still needed c. Efficiency losses using pure water feed	3	
Proton Conducting Solid Oxide	P-SOE	~ 450° - 600°C	ceramic membrane H+ conducting	PGM-free	a. High electrical efficiency potential b. Thermal energy integration, e.g., with nuclear or solar c. Lower cost materials and operating temperature than O-SOE	a. Only demonstrated at the laboratory scale b. Lifetime c. Faradaic efficiency limitations d. Manufacturability/scale-up	5	

Source: (KESDM, 2023b; Rey et al., 2023; U.S. Department of Energy, 2024)

Consequently, GH₂, which is generated by employing REs for water electrolysis, is becoming the primary energy source to discuss this issue (Rey et al., 2023).

Based on (Accenture & China Hydrogen Alliance, 2023; KESDM, 2023; Rey et al., 2023; Jaeger & deBiasi, 2022; IRENA, 2020; U.S. Department of Energy, 2024) currently there are four main types of electrolyzers: AE, PEM, SOE and AEM. AE, PEM and AEM are low temperature electrolysis technologies while SOE is high temperature. AE has the lowest capital cost of any plant operating at a commercial scale (input exceeding 2 MW); it costs approximately \$800 to \$1,000 per kW and has an efficiency of about 55 kWh per kilogram of hydrogen produced. Because of their expensive catalysts, PEM units have a higher capital cost range of \$1,400 to \$1,700 per kW, but they also have greater load-following ability and a considerably higher efficiency of 52 kWh input per kilogram of H₂ produced. SOE, basically fuel-cells operating in reverse, utilize waste heat from external sources to reduce primary energy input and achieve higher efficiencies approaching 40 kWh input per kg of H₂ product. AEM electrolysis combines the advantages of alkaline with PEM electrolysis. Since operation takes place under slightly alkaline conditions, inexpensive, non-precious metal catalysts can be used for the electrodes. Details of electrolyzer comparison, as shown in Table 1 and Figure 5.

The growing consensus of the importance of green hydrogen in meeting long-term net-zero climate targets has placed sharp focus on the urgent need to reduce the high production costs using electrolyzers. According to (IRENA, 2020), improved electrolyzer design and construction, economies of scale, substituting abundant metals for scarce materials, increasing efficiency and flexibility of operations and high technology deployment in line with a 1.5 °C climate target can all help to lower investment costs for electrolyzer plants by 40% in the short term and 80% in the long term.

(Reksten et al., 2022) successfully developed CAPEX of AE and PEM electrolyzer through formulation as seen in Equation 2, where k_0 , k are constant, Q electrolyzer capacity, V plant installation year, V_0 reference year, α scaling factor, β learning factor. The formula explains the cost associated with electrolyser plants, which are determined by the plant's capacity and the rate of learning rate on technology development, production year used instead of rated current density to describe technology progress and economy of scale.

$$C = \left(k_0 + \frac{k}{Q} Q^\alpha\right) \left(\frac{V}{V_0}\right)^\beta \tag{2}$$

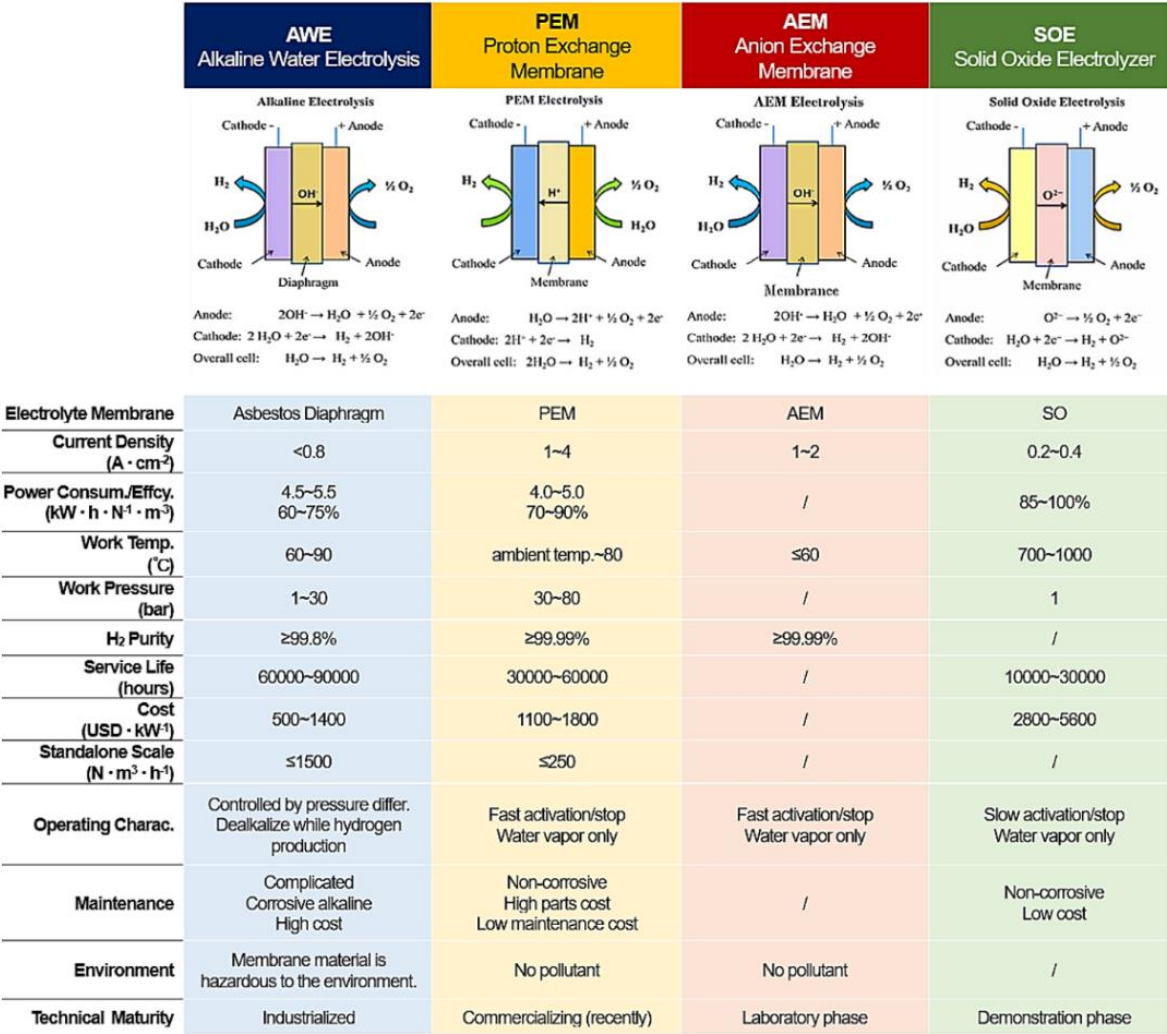


Fig 5. AE, PEM, SOE and AEM comparison (Source: Andy, 2021)

(Rey et al., 2023) described that the technological and regulatory framework for hydrogen remains underdeveloped, with significant disparities in green hydrogen legislation across various regions globally. However, electrolyzer manufacturers are in general agreement on the potential for rapidly reducing capital costs through economies of scale. The challenges to overcome, including reducing the cost of electrolyzers, improving their efficiency and developing a supportive regulatory framework.

2.6 Supporting Infrastructures and Location

In the site selection process, it is necessary to focus on the availability of existing RE sources (Zwickl-Bernhard & Auer, 2022) in Indonesia that ready to support the GH₂ production with optimization economic aspect (CAPEX and OPEX) and development time. Various factors determine the appropriateness of sites for harnessing RE for GH₂ production. These include access to a water source, the capacity of the RE source for annual production, the availability of an electricity grid and the presence of transportation infrastructure.

SHP will continue to be little from a macro standpoint, but it may still be crucial to future GH₂ development in Indonesia considering the location and its maturity of supporting infrastructure. From the techno economics analysis in the introduction, for the first development of GH₂ pilot project in

Indonesia feasibly considered started from SHP commenced during the Dutch Era.

3. Methodology

3.1 SHP Locations and Available Excess Energy

In this study, based on reference from Figure 6, two SHP are selected according to the shortest distance toward Tanjung Priok GT power plant. Compared to another SHP around West Java region, both Kracak and Ubrug are the nearest location with a maximum distance of 112 km, compared to others which are more than 150 km, including toll roads. Kracak SHP located in Bogor regency, has total capacity of 18.9 megawatts. Ubrug SHP located in Sukabumi regency has total capacity of 18.36 megawatts. Each SHP is examined for its average annual excess power, which will be utilized to generate GH₂. Both Kracak and Ubrug, has three generators on each site. After examined the historical realization of production at each location, we choose the lowest maximum capacity factor (CF) that each generating engine unit can reliably achieve as a reference for the optimistic scenario.

It was found that the lowest maximum average CF for 4 years (2020-2023) at Kracak and Ubrug was 64.62% and 59.57% consecutively. The maximum average CF achieved was 76.09% and 68.31% consecutively. By using multivariate analysis for



Fig 6. Location of the SHPs with the shortest relative distance

Table 2
Ubrug CF and Monthly Net Sales 2020-2023

Ubrug	Net Capacity (MW) a	Avg. CF (%) b	Avg. Monthly Net Sales (kWh) c
#1	5.94	30.95	
#2	5.94	36.23	4,318,551.35
#3	6.48	29.71	

Table 3
Kracak CF and Monthly Net Sales 2020-2023

Kracak	Net Capacity (MW) a	Avg. CF (%) b	Avg. Monthly Net Sales (kWh) c
#1	6.30	33.60	
#2	6.30	35.87	4,664,601.92
#3	6.30	31.97	

each generator’s CF, we can get amount of excess energy (kWh) can be utilized, as shown in Equation 3 using coefficients on Table 4.

Historical SHP operational data as secondary data sources, collected in range 2020-2023. Table 2 and 3 display summary of monthly 4 years CF and Net Sales both in Ubrug and Kracak. How often power plant is running at maximum power CF are considered independent variables, while monthly Net Sales are considered dependent variables.

$$c = intercept + \beta_1b_1 + \beta_2b_2 + \beta_3b_3 \tag{3}$$

We should choose the lowest maximum CF that each generating engine unit can reliably achieve as a reference for the optimistic scenario. For Ubrug and Kracak safely chosen maximum CF of 59.57% and 64.62% as shown in Figure 7. Table 5 shows monthly excess energy in kWh by put in CF value column f, to get value of variable c in column g by Equation 3. In this analysis, we utilised two distinct variable operating (utility) cost

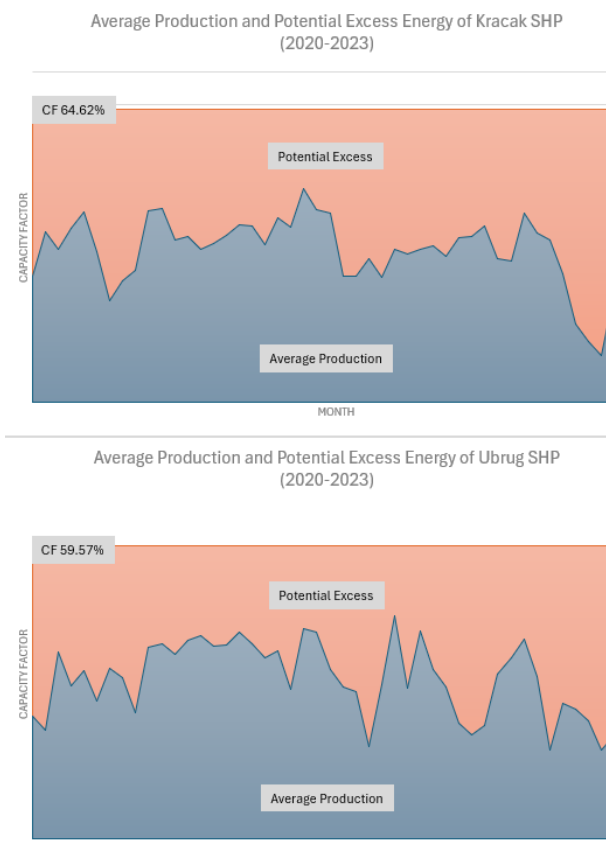


Fig 7. Potential excess energy from Kracak and Ubrug

Table 4
Coefficient result of multiple regression

Ubrug	Value	Kracak	Value
intercept	36066.765	intercept	41494.063
β_1	44778.528	β_1	45242.901
β_2	41714.642	β_2	46015.042
β_3	46628.382	β_3	45426.382

on electricity feed prices for excess power price derived from historical data in the industrial sector. The electricity feed prices used include a selling price to the grid of 0.041 USD/kWh and a basic production cost (BPC) of 0.022 USD/kWh. The value of 1 USD assumed in this study is equivalent to Rp 15,700.

3.2 GH₂ Electrolyzer Components and System Scaling

In this study, AE is selected on the basis of the highest TRL and lowest CAPEX. According to (Shin et al., 2023; Xu et al., 2023), the AE system, with its low CAPEX and scalability, enables large-scale hydrogen production. Meanwhile, China’s significant cost advantage in hydrogen production, particularly in AE systems, ensures market competitiveness and profitability, with prices projected to remain significantly lower than in the EU and US even after rapid innovation and cost reduction as estimated by Bloomberg.

The AE system necessitates an extra pump and a heat exchanger as seen in Figure 8. This is due to the fact that before entering the stack, electrolytes are combined to keep the

Table 5
Monthly Excess Energy Result for GH₂

Ubrug	Avg. CF (%)	Max. CF (%)	Lowest Max. CF (%)	CF for GH ₂ (%)	Monthly for GH ₂ (kWh)
	b	d	e = min(d)	f = e-b	g
#1	30.95	59.57	59.57	28.62	
#2	36.23	60.68	59.57	23.34	3,683,633.05
#3	29.71	68.31	59.57	29.86	

Kracak	Average CF (%)	Max. CF (%)	Lowest Max. CF (%)	CF for GH ₂ (%)	Monthly for GH ₂ (kWh)
	b	d	e = min(d)	f = e-b	g
#1	33.60	69.32	64.62	31.02	
#2	35.87	76.09	64.62	28.75	4,250,927.29
#3	31.97	64.62	64.62	32.65	

Potassium hydroxide (KOH) solution concentration steady. Moreover, to maintain the concentration of KOH stays 30% during the operation of the system, make-up water is added (Shin et al., 2023). For the assumption used in this study, based on (Zun & McLellan, 2023), the total capital cost of AE consist of three components: stack capital cost as 50%, 20% of mechanical capital cost and 30% of electrical capital cost. Mechanical and electrical components are collectively referred to as Balance of Plant (BoP) equipment. The mechanical BoP encompasses elements such as the circulating pump, cooling apparatus, dryer and equipment that support electrolyte functions. The electrical BoP, on the other hand, includes the power supply and various electronic supporting devices.

In the scaling assumption for the AE electrolyzer system, the energy consumption of the system is quantified as 4.80 kWh/Nm³. Furthermore, with respect to hydrogen storage technology, it is important to note that the volumetric density of hydrogen under standard conditions of pressure and temperature is relatively low, specifically 0.08988 g/L (Rey et

al., 2023). Additional variable operating cost material shown in Table 6. The system scaling simulated in this study can be seen in Table 7.

In order to ensure an ample supply of electrical energy for the GH₂ electrolyzer, this study used a power transformer to harness the excess power generated by SHP. During the simulation, we incorporated a 10 MVA step-down power transformer to accommodate the electricity use. According to a research conducted by (Indarto et al., 2017), the average total cost of ownership (TCO) per MVA was 19,384.29 USD/MVA, while the cumulative TCO for a 10 MVA system was 193,842.89 USD.

3.3 GH₂ Production Discounted Cash Flow Analysis

This study determined the LCOH by implementing SHP excess power as RE power source. Furthermore, apart from the two location of RE sources namely Kracak and Ubrug, AE technology of water electrolysis through forecourt model were taken into account on GH₂ production and discussed, the representation shown in Figure 9. DCF considers the time value of money and the risk associated with the investment, which results in a more precise estimation of the investment's inherent worth. When evaluating a financial situation, it's crucial to

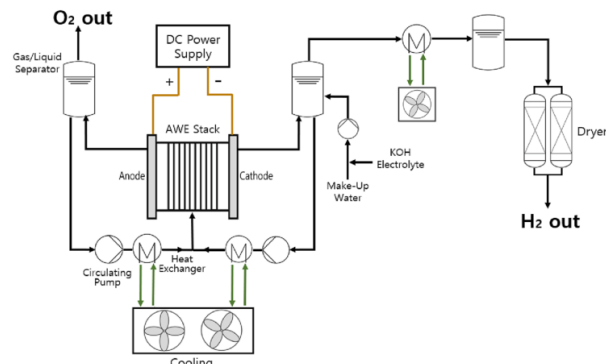


Fig 8. AE system (Source: Jang et al., 2022)

Table 6
Additional variable operating cost materials

Variable Operating Cost Material	USD/gal	Usage per kg H ₂ (gal)
Process Water	0.002374951	3.78
Cooling Water	0.00011335	0.108322325
Compressed Inert Gas	0.033086332	0.022934991

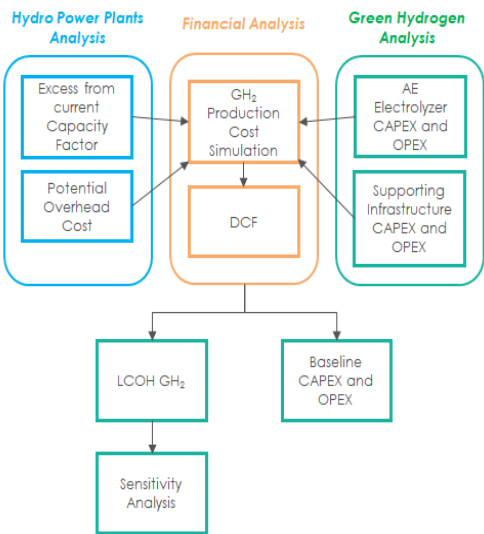


Fig 9. Flowchart of financial evaluation process

Table 7
AE System Scaling for GH₂

AE Capacity	Production (Nm ³ /h)	Production (kg/h)	Production Capacity (kg/day)	Energy Consumption (kWh per Nm ³)	Running hours daily (assumed plant outage 18 days/year)	Daily Production (kg)	Energy Consumption daily (kWh)	Energy Consumption monthly (kWh), 30 days each month	Energy Consumption (kWh/kg)
25 kW	5.00	0.45	10.79	4.80	22.80	10.25	547.20	16,416.00	53.4045
250 kW	50.00	4.49	107.86	4.80	22.80	102.46	5,472.00	164,160.00	53.4045
1 MW	200.00	17.98	431.42	4.80	22.80	409.85	21,888.00	656,640.00	53.4045
2 MW	400.00	35.95	862.85	4.80	22.80	819.71	43,776.00	1,313,280.00	53.4045
5 MW	1,000.00	89.88	2,157.12	4.80	22.80	2,049.26	109,440.00	3,283,200.00	53.4045

Table 8
Production model cost factor

Variables	Value	Remarks
Annual Unplanned Outage (hours)	14	
Annual Planned Outage (days)	18	
Start-up Year	2025	
Length of Construction Period (years)	1	
Plant life (years)	25	
Depreciation Schedule Length (years)	15	MACRS
Revenues during start-up (%)	50%	
Replacement (% direct capital cost)	15%	Year 10 th operation
Decommissioning costs (% of depreciable capital investment)	10%	Salvage value is assumed to equal decommissioning costs
Inflation rate (%)	2.6%	Indonesia, December 2023
Total Tax Rate (%)	22%	Indonesia, corporate tax rate December 2023
Working Capital (% of yearly change in operating costs)	15%	
After Tax Real IRR (%)	8%	

remember that monetary value declines over time. DCF assists investors in assessing the viability of a project or investment by factoring in anticipated future cash flows. LCOH calculated through DCF model yielding a predetermined IRR.

In this research, it is assumed that 100% of the financing comes from company equity. The sensitivity analysis was conducted to examine the degree of variation in the LCOH relative to the potential installation capacity of the electrolyzer within the SHP. Several other variables assumed for this GH₂ production model can be seen in Table 8.

Other indirect capital cost, fixed and variable operating cost are required to accurately calculate annual cash flow in the model. The indirect capital cost considered from site preparation, engineering & design, project contingency and up-front permitting. The fixed operating cost per year assumed includes labor cost, G&A rate, licensing, permits and fees, property tax and insurance, rent, production maintenance and repairs. Other annual variable operating costs include environmental surcharges, other materials, waste treatment, unplanned replacement capital, and operator profit.

4. Result and Discussion

Climate change has the potential to cause significant fluctuations in water availability, which can directly impact the

amount of excess power that power plants can generate. In Indonesia, two main types of droughts occur: meteorological droughts, caused by precipitation deficits, and hydrological droughts, resulting from deficits in surface and subsurface water flow, often associated with broader river basin conditions. These variations in water supply can, in turn, affect the potential for hydrogen production using this excess power. Droughts are expected to become more frequent and severe due to intensified El Niño events linked to rising global temperatures (The World Bank Group & Asian Development Bank, 2021). This weather phenomenon is likely influenced by climate change and seasonal variability, including the impact of El Niño and La Niña.

The advantages of SHPs in Indonesia lie in their smaller size, run-of-river systems with daily reservoir pools, and widespread distribution, making them well-suited for Indonesia's archipelagic nature. Leveraging these assets can enhance national energy security. This research focuses on an SHP in West Java as a potential site for co-firing with GH₂, given its proximity and long-standing operational status. According to data from the West Java Province Central Statistics Agency, the region has experienced an increase in the frequency and intensity of extreme rainfall over the past five years, as well as intermittent periods of drought. However, a challenge arises

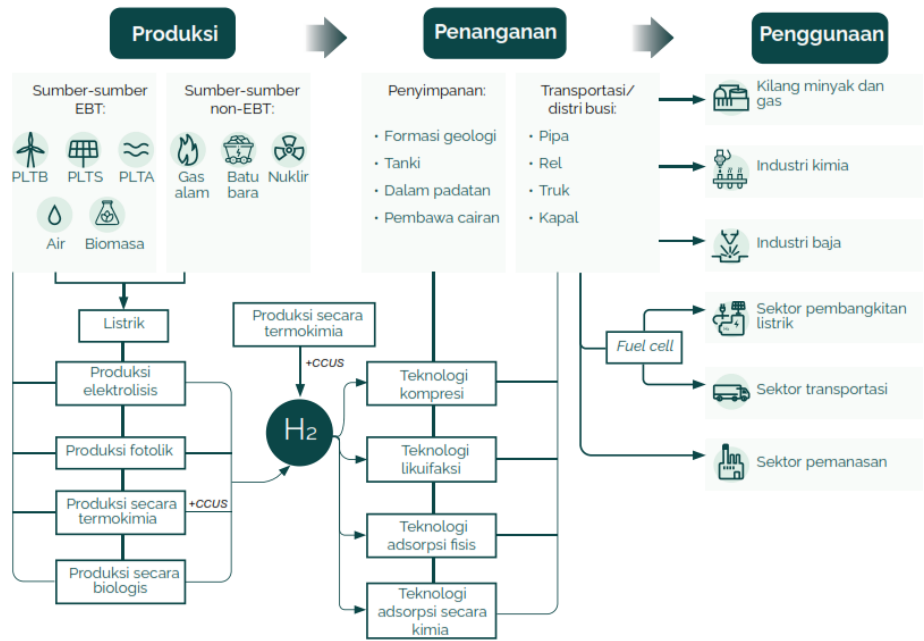


Fig 10. Hydrogen supply chain scheme in Indonesia (Source: KESDM, 2023b)

from the accumulation of river waste pollution, domestic garbage, and agricultural land-clearing waste in the upstream sections of major rivers in West Java, particularly the Cisadane and Citarum rivers, despite the abundant surface water availability.

Based on report by (ADB & The World Bank, 2013; Abidin, 2023), they analyzed that rivers in West Java reveals an alarming situation. Pollution has heavily damaged rivers and groundwater supplies in these areas. This contamination comes from a variety of sources, including household trash that isn't correctly disposed of industrial waste from factories of all sizes, and runoff from farms. Mitigating river pollution necessitates a comprehensive and collaborative approach engaging all stakeholders. This encompasses governmental entities, the private sector and active community involvement. In this research the author restricts the analysis of potential waste mitigation strategies to the GH₂ production model by preparing other annual variable operating costs including environmental surcharges, other materials and waste treatment.

According to the report of Indonesia national hydrogen strategy by (KESDM, 2023b), MEMR as regulator had outlined that the hydrogen supply chain encompasses the manufacturing, storage, conveyance and delivery of hydrogen to consumers. Hydrogen can be derived from different sources, stored using various methods and applied for diverse uses. Throughout the supply chain, numerous factors and stakeholders will play a role in different stages from initial production to final distribution. The adaptability of the hydrogen supply chain system will dictate the selection of technology, such as infrastructure, transportation and storage, as depicted in Figure 10.

MEMR has developed a plan for implementing GH₂ within industrial ecosystems, encompassing electricity and transportation ecosystems in Indonesia. MEMR has initiated the mapping of needs through engagement with relevant stakeholders from industrial and transportation to identify priority sectors with potential for utilizing hydrogen until 2060. The initial data gathered from various stakeholders provides a preliminary overview and further mapping will involve a wider

range of stakeholders for more accurate projections of future hydrogen needs. The projections will set targets for GH₂ development in Indonesia. A robust system of governance is crucial for establishing credibility and allocating responsibilities among different parties participating in the development of a hydrogen economy. This includes government entities, private sector organizations, educational institutions and civil society.

In this simulation, the H₂A production model is employed to ascertain the LCOH of GH₂ production and the LCOH associated with GH₂ compression, storage and dispensing (CSD). It should be noted, however, that the results pertaining to CSD's LCOH are not the primary focus of this research. As per the stipulations of Equation 1, the components contributing to the LCOH in this analytical model encompass: capital costs, decommissioning costs, fixed O&M costs, electricity feed costs, other raw materials costs, byproducts credits and other variable costs. It should be noted also that possible income from electrolysis process (byproducts credits) such as oxygen and pure water is not considered.

4.1 DCF and LCOH Analysis

The excess value in column g in Table 5 is the maximum monthly feed-in limit to the Input_Sheet_Template H₂A production model. We calculate three scenarios of AE capacity in production model (Table 7): 1, 2 and 5 MW that will produce 409.85, 819.71 and 2,049.26 kg/day GH₂ respectively by annual 95% CF of AE, include storage and refueling station, 24 hours operating with 4 shift groups (3 on duty, 1 off).

Considering the projection parameters on the Equation 2, we get total AE capital in USD/kW for each capacity scenario: 1,241.27 USD/kW for 1 MW capacity, 1,033.97 USD/kW for 2 MW and 826.99 USD/kW for 5 MW. This shows that capital costs per kW consistently fall as the installed capacity of the electrolyzer increases. Regarding cost per kW, resulted total installed GH₂ production system cost after additional 10% electrolyzer installation factor cost and 10 MVA auxiliary power transformer TCO are \$1,504,629.15, \$2,377,597.49 and \$4,560,351.32 consecutively. These values are then filled into

Table 9
DCF and LCOH Analysis Results

Variables	Krakak SHP			Ubrug SHP		
	1 MW System	2 MW System	5 MW System	1 MW System	2 MW System	5 MW System
	Selling Price	Selling Price	Selling Price	Selling Price	Selling Price	Selling Price
AE Design Capacity (kg H ₂ per day)	431.42	862.85	2,157.12	431.42	862.85	2,157.12
Average GH ₂ Daily Production (kg H ₂ per day)	409.85	819.71	2,049.26	409.85	819.71	2,049.26
AE CAPEX (USD/kW)	1,241.27	1,033.97	826.99	1,241.27	1,033.97	826.99
Stack System Cost	620.64	516.99	413.50	620.64	516.99	413.50
Mechanical BoP	248.25	206.79	165.40	248.25	206.79	165.40
Electrical BoP	372.38	310.19	248.10	372.38	310.19	248.10
10 MVA Auxiliary Transformer TCO (USD)	193,842.89	193,842.89	193,842.89	193,842.89	193,842.89	193,842.89
Total Installed GH ₂ Production System Cost (USD)	1,504,629.15	2,377,597.49	4,560,351.32	1,504,629.15	2,377,597.49	4,560,351.32
Total Direct & Indirect GH ₂ Production Capital Cost (USD)	2,093,946.12	3,262,414.24	6,184,030.24	2,093,946.12	3,262,414.24	6,184,030.24
Total Fixed Operating Cost (USD per year)	261,318.58	328,336.36	495,906.37	261,318.58	328,336.36	495,906.37
Variable Operating (Utility) Cost (USD per year)	330,816.90	661,633.81	1,653,416.67	330,816.90	661,633.81	1,653,416.67
Other Variable Operating Cost (USD per year)		51,695.96			65,111.96	
LCOH Production GH ₂ (USD per kg H ₂)	6.11	4.89	4.02	6.20	4.94	4.04
Deliverable GH ₂ (kg per year)	149,084.08	298,168.15	745,420.38	149,084.08	298,168.15	745,420.38
After-tax Income Cumulative Value 25 years Plant Life (USD)	9,733,926.14	15,179,583.51	28,899,003.22	9,742,302.84	15,187,960.21	28,907,379.92
						28,433,249.94

the model of each scenario for DCF analysis, to obtain LCOH GH₂ production, as shown in Table 9. Then by adding indirect capital cost figures such as site establishment, engineering & design, project eventuality and up-front licensing costs, the total direct and indirect capital costs will be respectively: \$2,093,946.12, \$3,262,414.24 and \$6,184,030.24.

Table 10
Comparison with current estimated LCOH

RE sources	Type of EL	LCOE (ctUSD/kWh)	LCOH production (USD/kg)	Notes
Solar PV	AE	59.6	7 – 34 *	Current global LCOH 2023 (Brilian et al., 2022)
Geothermal	AE	8.02	3.86	
Hydropower	AE	2.02	2.18	This research

Annual variable cost allocated for river waste treatment and handling in Ubrug and Kracak is equal to 45,864 USD/year and 32,448 USD/year consecutively. This different local river situation brings the annual total other variable operating cost differently (Table 9). The results of the analysis, derived from the H2A production model applied to two SHPs across three AE capacity scenarios, indicate that the most cost-effective LCOH production is achieved at the Kracak SHP with a 5 MW system. This scenario yields an LCOH of \$2.98/kg, utilizing the BPC electricity feed price. This 5 MW system has the capacity to annually deliver 745,420.38 kg of GH₂. Furthermore, the after-tax income generated by this system over a 25-year plant life culminates in a cumulative value totaling \$28,424,873 with NPV equal to zero.

4.2 Sensitivity Analysis

On each three scenario simulation, we calculate each different price of feed in electricity, based on selling price and BPC as well, sensitivity result shown in Figure 11. The maximum AE capacity dependent on excess power availability allowed is 6.47 MW in Kracak and 5.61 MW in Ubrug. The lowest possible LCOH is \$2.18/kg from Kracak SHP utilizing BPC electricity feed price, meanwhile \$2.59/kg from Ubrug SHP. From the formulation result of our project optimization strategy, we have to implement megawatt scale market ready technology AE, to get lower USD/kW capital cost and lower USD/kg production cost.

Figure 11 presents the outcomes of a sensitivity analysis conducted for three distinct scenarios at two locations of GH₂ production. This analysis illustrates the variation in the LCOH when the cost or value of a particular component deviates by ±5% from the baseline value, while all other variables remain constant. This approach provides a comprehensive understanding of how changes in individual components can impact the overall cost-effectiveness of hydrogen production. In essence, the magnitude of the change in the LCOH indicates a particular component's sensitivity to the LCOH. Among all components, the utilities (electricity) consumption was identified as the most sensitive in all three scenarios. This is due to its direct correlation with the volume of electricity fed to AE

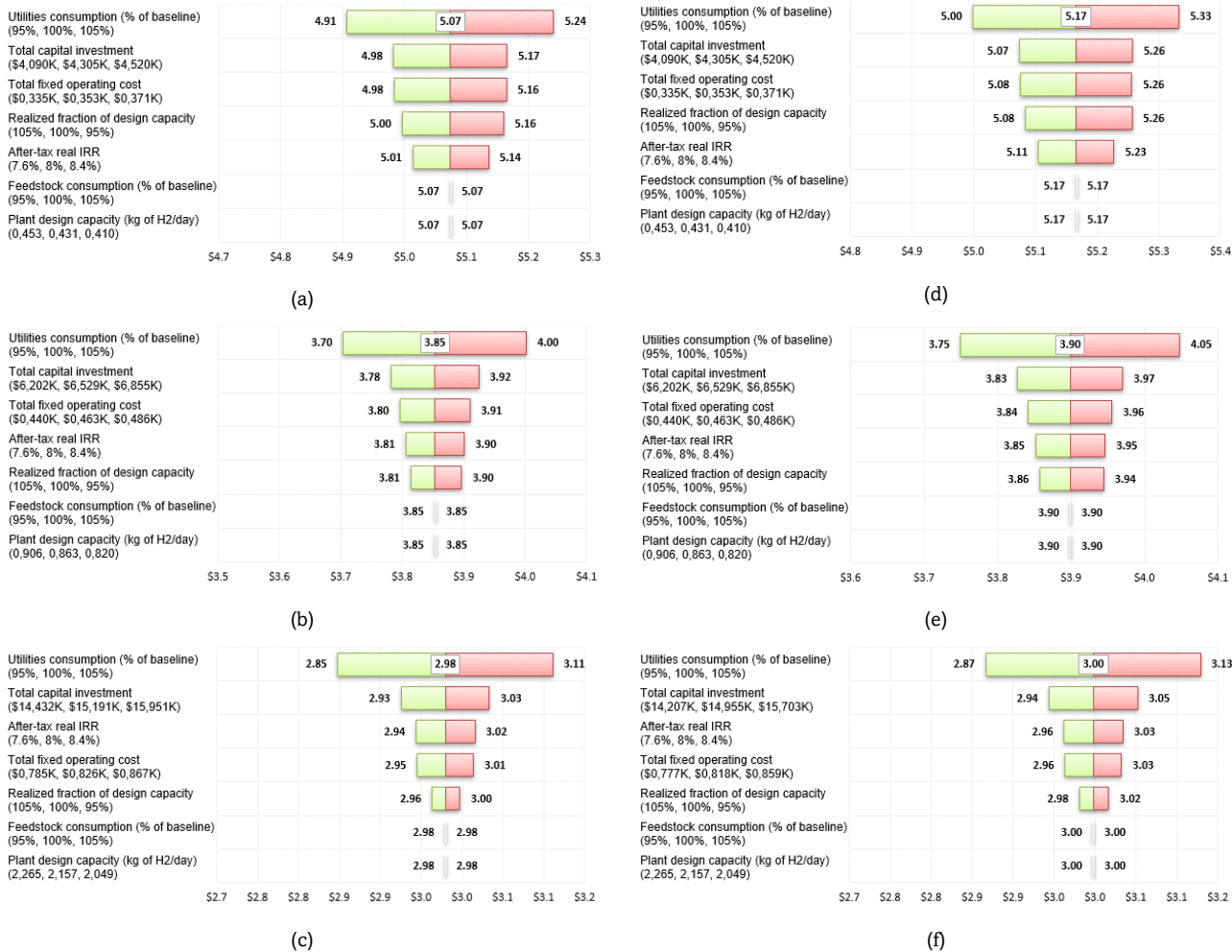


Fig 11. Sensitivity analysis of LCOH for each SHP and AE of (a) 1 MW AE Kracak (b) 2 MW AE Kracak (c) 5 MW AE Kracak (d) 1 MW AE Ubrug (e) 2 MW AE Ubrug (f) 5 MW AE Ubrug

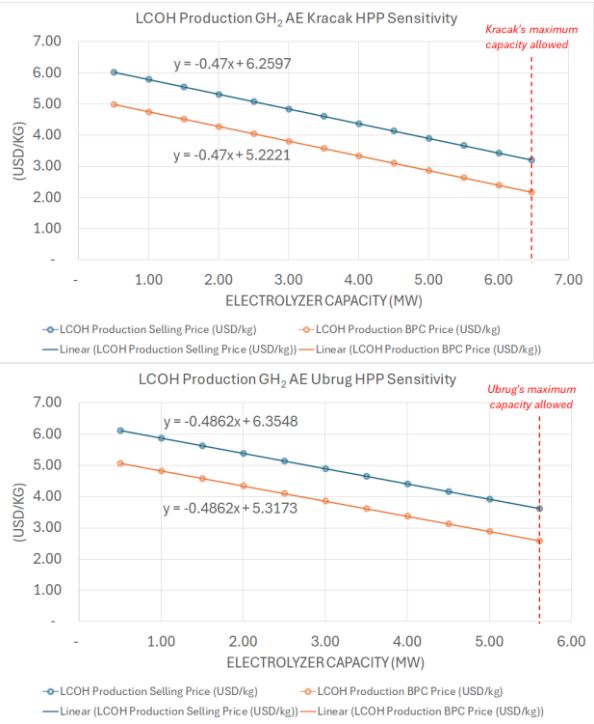


Fig 12. LCOH GH₂ production sensitivity on AE capacity

directly rely on CF, which in turn influences hydrogen production. Consequently, a decrease in the volume of electricity consumed results in a substantial increase in the LCOH.

5. Conclusion

Our research optimizes GH₂ production opportunities using excess electricity from SHPs across Indonesia. The lowest LCOH production achieved using linear regression in Figure 12, was as low as 2.18 USD/kg from 6.47 MW AE in Kracak SHP, resulting in an annual production of 745.42 tons GH₂. The method supports decarbonization and is economically feasible for Indonesia. Analysis reveals LCOH result remain below market price levels as shown in Table 10, with the lowest costs associated with specific installed electrolyzer capacities, considering SHP characteristics also CAPEX & OPEX.

This proof of concept indicates potential scalability of GH₂ in Indonesia, suggesting gas engine co-firing with GH₂ as a viable option, starting from optimization of retroactively operated HPP with a small capacity, where other SHPs dispersed in so many locations in Indonesia’s islands will unlock the potential GH₂ cluster in the emerging Indonesian market. Indonesia’s geography favors combined energy production using hydro, wind and solar energy, will reduce fossil fuel dependency, decarbonizing and promoting a green circular economy.

The global interest in GH₂ extends to Indonesia, where there are expectations for new market entrants. However, Indonesia’s technological development in GH₂ generation is behind leading countries such as Europe, the US, Japan, Korea and China. This presents a challenge that requires significant investment and technological advancements. It is stressed that collaborative efforts, both domestically and internationally, are needed to accelerate GH₂ technology projects in Indonesia. Government

regulations and incentives play a vital role in promoting capacity development.

As part of Indonesia's path toward achieving NZE and energy independence, the country's unique geographical characteristics, including water, wind and solar resources, support integrated energy production. PLN, whom responsible for operating SHPs, HPPs, thermal power plants and electricity infrastructure, plays a crucial role in this energy transition. With increasing electricity consumption because of economic growth, the Indonesian government's commitment to NZE becomes essential. It is crucial to increase electricity generation, particularly from RE sources, to meet the growing demand while balancing economic growth and sustainability.

Indonesia's equatorial position, solar intensity, rainy seasons and wind resources create a conducive environment for renewable energy. An optimized combination of solar PV and wind turbines, along with GH₂ integration, can drive sustainable electricity generation. Electrolyzers are pivotal in GH₂ production and suppliers have significant control over technology access and pricing. Building partnerships with electrolyzer manufacturers is crucial and government policies supporting electrolyzer adoption, incentives within the GH₂ ecosystem, tax relaxation and collaborative research and development efforts will enhance GH₂ production. This integrated approach, combined with solar PV and wind turbines, can support sustainable electricity generation and ensure national energy security in line with the NZE program.

The initial phase of GH₂ generation is an innovative business achieved by optimizing excess production from SHPs. This underscores the critical role of government regulations and policies in enhancing and promoting GH₂ generation. Furthermore, potential subsequent steps in developing the GH₂ production ecosystem have been explored. When integrated with solar PV and wind turbines, this comprehensive approach can drive sustainable electricity generation and ensure national energy security in correlation with the NZE program, particularly suited to Indonesia's unique characteristics.

Acknowledgments

The author would like to acknowledge the support of the School of Business and Management ITB for the opportunity to research in this topic.

Author Contributions: Hendy Eka Hardana: conceptualization, methodology, conceptual framework, financial analysis, writing and editing original draft, review, Pupung Adiwibowo: conceptualization, conceptual framework, power plant project assessment, validation, Yos Sunitiyoso; supervision, resources, review, validation, Tri Edi Kurniawan; writing, excess power review. All authors have read and agreed to the published version of the manuscript.

Funding: The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflicts of Interest: The authors declare no conflict of interest.

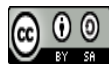
References

Abdin, Z. (2024). Bridging the energy future: The role and potential of hydrogen co-firing with natural gas. *Journal of Cleaner Production*, 436, 140724. <https://doi.org/10.1016/j.jclepro.2024.140724>
Abidin, J. Z. (2023). Challenges in dealing with water pollution issues in the West Java island. *Journal of Sustainability, Society, and Eco-Welfare*, 1(1). <https://doi.org/10.61511/jssew.v1i1.2023.137>

- Accenture, & China Hydrogen Alliance. (2023). *Green Hydrogen in China: A Roadmap for Progress*. <https://www.weforum.org/publications/green-hydrogen-in-china-a-roadmap-for-progress/>
- ADB, & The World Bank. (2013). *Downstream Impacts of Water Pollution in the Upper Citarum River, West Java, Indonesia: Economic Assessment of Interventions to Improve Water Quality*. <https://www.adb.org/publications/downstream-impacts-water-pollution-upper-citarum-river-west-java-indonesia>
- Agora Industry and Umlaut. (2023). *Levelised cost of hydrogen*. https://static.agora-energiawende.de/fileadmin/Projekte/2022/2022-12-10_Trans4Real/A-EW_301_LCOH_WEB.pdf
- Alhuyi Nazari, M., Fahim Alavi, M., Salem, M., & Assad, M. E. H. (2022). Utilization of hydrogen in gas turbines: a comprehensive review. *International Journal of Low-Carbon Technologies*, 17, 513–519. <https://doi.org/10.1093/ijlct/ctac025>
- Andy. (2021). *Fuel Cell Topics: Renewable Energy & Hydrogen Making*. <https://www.kewelltest.com/Fuel-Cell-Topics-Renewable-Energy-Hydrogen-Making-Kewell-Offers-Water-Electrolytic-Tank-Testing-id3926818.html>
- Bamisile, O., Li, J., Huang, Q., Obiora, S., Ayambire, P., Zhang, Z., & Hu, W. (2020). Environmental impact of hydrogen production from Southwest China's hydro power water abandonment control. *International Journal of Hydrogen Energy*, 45(46), 25587–25598. <https://doi.org/10.1016/j.ijhydene.2020.06.289>
- Blohm, M., & Dettner, F. (2023). Green hydrogen production: Integrating environmental and social criteria to ensure sustainability. *Smart Energy*, 11, 100112. <https://doi.org/10.1016/j.segy.2023.100112>
- Brilian, V., Jaelani, K., Mubarak, M., Ruliandi, D., & Firmansyah, W. (2022). Techno-Economic Study of Green Hydrogen Production Using Integrated Bottoming Organic Rankine Cycle and Electrolysis Systems in Ulubelu Geothermal Power Plant. *8th Indonesia International Geothermal Conference & Exhibition (IIGCE) 2022*. Jakarta.
- Buana, Y., Mursitama, T. N., Abdinagoro, S. B., & Pradipto, Y. D. (2023). Stakeholder engagement by power system experts of Indonesia electricity sector for sustainable energy transition. *International Journal of Energy Sector Management*, 17(3), 474–488. <https://doi.org/10.1108/IJESM-05-2021-0021>
- Buechler, E., Powell, S., Sun, T., Astier, N., Zanocco, C., Bolorinos, J., Flora, J., Boudet, H., & Rajagopal, R. (2022). Global changes in electricity consumption during COVID-19. *IScience*, 25(1), 103568. <https://doi.org/10.1016/j.isci.2021.103568>
- Cheng, W., & Lee, S. (2022). How Green Are the National Hydrogen Strategies? *Sustainability*, 14(3), 1930. <https://doi.org/10.3390/su14031930>
- Das, S., De, S., Dutta, R., & De, S. (2024). Multi-criteria decision-making for techno-economic and environmentally sustainable decentralized hybrid power and green hydrogen cogeneration system. *Renewable and Sustainable Energy Reviews*, 191, 114135. <https://doi.org/10.1016/j.rser.2023.114135>
- Enerdata. (2023). *Electricity domestic consumption*. World Energy & Climate Statistics. <https://yearbook.enerdata.net/electricity/electricity-domestic-consumption-data.html>
- Energy Sector Management Assistance Program (ESMAP), Organisation for Economic Co-operation and Development (OECD), Global Infrastructure Facility, & Hydrogen Council. (2024). *Scaling Hydrogen Financing for Development*. <https://read.oecd.org/10.1787/0287b22e-en?format=pdf>
- ESMAP, & The World Bank. (2017). *Small hydro resource mapping in Indonesia: Small hydropower potential report*. <http://documents.worldbank.org/curated/en/315901506072186354/Small-hydropower-potential-report>
- Fokeer, S., Bianco, E., Strohmaier, R., Sievernich, J., Melnikov, Y., Stamm, A., Heredia, A., & Nunez, A. (2024). *Green Hydrogen For Sustainable Industrial Development: A Policy Toolkit For Developing Countries*. <https://doi.org/10.13140/RG.2.2.21621.14568>
- Friedl, G., Reichelstein, S., Bach, A., Blaschke, M., & Kemmer, L. (2023). Applications of the levelized cost concept. *Journal of Business Economics*, 93(6), 1125–1148. <https://doi.org/10.1007/s11573-023-01171-7>
- GE Vernova. (2023, September). *Hydrogen fueled gas turbines*. GE Vernova. <https://www.gevernova.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines>
- Hafner, M., & Luciani, G. (Eds.). (2022). *The Palgrave Handbook of International Energy Economics*. Springer International Publishing. <https://doi.org/10.1007/978-3-030-86884-0>
- Handayani, K., Filatova, T., & Krozer, Y. (2019). The Vulnerability of the Power Sector to Climate Variability and Change: Evidence from Indonesia. *Energies*, 12(19), 3640. <https://doi.org/10.3390/en12193640>
- IEA. (2022). *An Energy Sector Roadmap to Net Zero Emissions in Indonesia*. <https://www.iea.org/reports/an-energy-sector-roadmap-to-net-zero-emissions-in-indonesia>
- IESR. (2023). *Delivering Indonesia's Power Sector Transition: Costs, Benefits, and Implications of Intervening the 13.8 GW Coal-fired Power Plants Project Pipeline of Indonesia's State-owned Utility*. <https://iesr.or.id/en/pustaka/delivering-indonesias-power-sector-transition>
- Indarto, A., Garniwa, I., Setiabudy, R., & Hudaya, C. (2017). Total cost of ownership analysis of 60 MVA 150/120 kV power transformer. *2017 15th International Conference on Quality in Research (QIR): International Symposium on Electrical and Computer Engineering*, 291–295. <https://doi.org/10.1109/QIR.2017.8168499>
- IRENA. (2020). *Green hydrogen cost reduction: scaling up electrolyzers to meet the 1.5° C climate goal*. International Renewable Energy Agency.
- IRENA. (2022). *Geopolitics of the energy transformation: the hydrogen factor*. International Renewable Energy Agency. <https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen>
- Islam, P. A., & Febrian, R. (2020, October 27). *What Is The History Of The First Time There Was Electricity In Indonesia?* <https://voi.id/en/memori/18081/>
- Jaeger, H., & deBiasi, V. (2022, November 2). *Needed: Electrolyzers Producing Cheap, Green, Hydrogen*. Pequot Publishing Inc. <https://gasturbineworld.com/electrolyzers-green-hydrogen/>
- Jang, D., Kim, J., Kim, D., Han, W.-B., & Kang, S. (2022). Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies. *Energy Conversion and Management*, 258, 115499. <https://doi.org/10.1016/j.enconman.2022.115499>
- Jovan, D. J., Dolanc, G., & Pregelj, B. (2021). Cogeneration of green hydrogen in a cascade hydropower plant. *Energy Conversion and Management*: X. <https://api.semanticscholar.org/CorpusID:234891896>
- Kawasaki. (2022, September 7). *Hydrogen gas turbine offers promise of clean electricity*. Nature Research Custom. <https://www.nature.com/articles/d42473-022-00211-0>
- KESDM. (2023a). *Handbook of Energy & Economic Statistics of Indonesia 2023*. <https://www.esdm.go.id/id/publikasi/handbook-of-energy-economic-statistics-of-indonesia>
- KESDM. (2023b). *Strategi Hidrogen Nasional*. <https://ebtke.esdm.go.id/post/2023/12/15/3680/strategi-hidrogen-nasional>
- Krishnan, S., Koning, V., Theodorus de Groot, M., de Groot, A., Mendoza, P. G., Junginger, M., & Kramer, G. J. (2023). Present and future cost of alkaline and PEM electrolyser stacks. *International Journal of Hydrogen Energy*, 48(83), 32313–32330. <https://doi.org/10.1016/j.ijhydene.2023.05.031>
- Laget, H., Griebel, P., Gooren, L., Hampp, F., Jouret, N., & Lammel, O. (2022). Demonstration of Natural Gas and Hydrogen Cocombustion in an Industrial Gas Turbine. *Journal of Engineering for Gas Turbines and Power*, 145(4), 41007. <https://doi.org/10.1115/1.4056046>
- Langer, J., Quist, J., & Blok, K. (2021). Review of Renewable Energy Potentials in Indonesia and Their Contribution to a 100% Renewable Electricity System. *Energies*, 14(21), 7033. <https://doi.org/10.3390/en14217033>
- Li, L., Feng, L., Manier, H., & Manier, M.-A. (2024). Life cycle optimization for hydrogen supply chain network design. *International Journal of Hydrogen Energy*, 52, 491–520. <https://doi.org/10.1016/j.ijhydene.2022.03.219>

- Maka, A. O. M., & Mehmood, M. (2024). Green hydrogen energy production: current status and potential. *Clean Energy*, 8(2), 1–7. <https://doi.org/10.1093/ce/zkae012>
- Manullang, E., & Sinaga, N. (2022). Potential and Challenges of Hydrogen Development as New Renewable Energy in Indonesia. *R.E.M. (Rekayasa Energi Manufaktur) Jurnal*. <https://doi.org/10.21070/r.e.m.v7i2.1647>
- Martin-Ortega, J. L., Chornet, J., Sebos, I., Akkermans, S., & López Blanco, M. J. (2024). Enhancing Transparency of Climate Efforts: MITICA's Integrated Approach to Greenhouse Gas Mitigation. *Sustainability*, 16(10), 4219. <https://doi.org/10.3390/su16104219>
- Miyamoto, K., Mhi, K. I., Kawakami, T., Nakamura, S., Tanimura, S., & Masada, J. (2018). *Development Of Hydrogen And Natural Gas Co-Firing Gas Turbine*. <https://api.semanticscholar.org/CorpusID:263783210>
- Murti, B., & Pratomo, S. A. (2022). Pemodelan Infrastruktur Hidrogen Untuk Aplikasi Fuel Cell Dan Dampaknya Terhadap Era Ekonomi Hidrogen Studi Kasus Di Kota Semarang. *Jurnal Universal Technic*, 1(1), 25–51. <https://journal.unimar-amni.ac.id/index.php/UNITECH/article/download/19/20>
- Novianto, D., Koerniawan, M. D., Munawir, M., & Sekartaji, D. (2022). Impact of lifestyle changes on home energy consumption during pandemic COVID-19 in Indonesia. *Sustainable Cities and Society*, 83, 103930. <https://doi.org/10.1016/j.scs.2022.103930>
- Pambudi, N. A., Firdaus, R. A., Rizkiana, R., Ulfa, D. K., Salsabila, M. S., Suharno, & Sukatiman. (2023). Renewable Energy in Indonesia: Current Status, Potential, and Future Development. *Sustainability*, 15(3), 2342. <https://doi.org/10.3390/su15032342>
- Penev, M., Saur, G., Hunter, C., & Zuboy, J. (2018). H2A: Hydrogen production model: Version 3.2018 user guide (draft). *User Guide i, US Department of Energy, United States of America*.
- PLN. (2022). *2022 Annual Report: Leading The Way to Empower The Nation*. https://web.pln.co.id/statics/uploads/2023/06/Laporan-Tahunan-2022_Final_3005_Med-Res.pdf
- PLN. (2023). *2022 Sustainability Report: Strengthening the Determination Towards a Sustainable Company*. https://web.pln.co.id/statics/uploads/2023/09/SR-PLN-2022_High.pdf
- PLN Indonesia Power. (2021). *Virtual Museum Hydropower Plant*. CSR Hero. <https://csrhero.co.id/virtual-museum>
- Prawitasari, A., Nurliyanti, V., Putri Utami, D. M., Nurdiana, E., Akhmad, K., Aji, P., Syaifei, S., Ifanda, I., & Mulyana, I. G. (2024). A systematic decision-making approach to optimizing microgrid energy sources in rural areas through diesel generator operation and techno-economic analysis: A case study of Baron Technopark in Indonesia. *International Journal of Renewable Energy Development*, 13(2), 315–328. <https://doi.org/10.61435/ijred.2024.59560>
- Rahman, A., Richards, R., Dargusch, P., & Wadley, D. (2023). Pathways to reduce Indonesia's dependence on oil and achieve longer-term decarbonization. *Renewable Energy*, 202, 1305–1323. <https://doi.org/10.1016/j.renene.2022.11.051>
- Rakhmindyarto, R. (2020). Climate Policies in Indonesia's Development Agenda: Why a Carbon Tax is Marginalised. *Proceeding of LPPM UPN "VETERAN" Yogyakarta Conference Series 2020- Political and Social Science Series*, 1–8. <https://doi.org/10.31098/pss.v1i1.83>
- Ratnaningsih, D., Nasution, E. L., Wardhani, N. T., Pitalokasari, O. D., & Fauzi, R. (2019). Water pollution trends in Ciliwung River based on water quality parameters. *IOP Conference Series: Earth and Environmental Science*, 407(1), 012006. <https://doi.org/10.1088/1755-1315/407/1/012006>
- Reksten, A. H., Thomassen, M. S., Møller-Holst, S., & Sundseth, K. (2022). Projecting the future cost of PEM and alkaline water electrolyzers; a CAPEX model including electrolyser plant size and technology development. *International Journal of Hydrogen Energy*, 47(90), 38106–38113. <https://doi.org/10.1016/j.ijhydene.2022.08.306>
- Rey, J., Segura, F., & Andújar, J. M. (2023). Green Hydrogen: Resources Consumption, Technological Maturity, and Regulatory Framework. *Energies*, 16(17), 6222. <https://doi.org/10.3390/en16176222>
- Rospriandana, N., Burke, P. J., Suryani, A., Mubarak, M. H., & Pangestu, M. A. (2023). Over a century of small hydropower projects in Indonesia: a historical review. *Energy, Sustainability and Society*, 13(1), 30. <https://doi.org/10.1186/s13705-023-00408-1>
- Sari, D. P., & Pinassang, J. L. (2023). Examining the Impact of COVID-19 in Indonesia through Household Electricity Consumption and Modern Lifestyle. *Civil Engineering and Architecture*, 11(2), 1032–1047. <https://doi.org/10.13189/cea.2023.110236>
- Sebos, I., Nydrioti, I., Katsiardi, P., & Assimakopoulos, D. (2023). Stakeholder perceptions on climate change impacts and adaptation actions in Greece. *Euro-Mediterranean Journal for Environmental Integration*, 8(4), 777–793. <https://doi.org/10.1007/s41207-023-00396-w>
- Shahabuddin, M., Rhamdhani, M. A., & Brooks, G. A. (2023). Technoeconomic Analysis for Green Hydrogen in Terms of Production, Compression, Transportation and Storage Considering the Australian Perspective. *Processes*, 11(7), 2196. <https://doi.org/10.3390/pr11072196>
- Shin, H., Jang, D., Lee, S., Cho, H.-S., Kim, K.-H., & Kang, S. (2023). Techno-economic evaluation of green hydrogen production with low-temperature water electrolysis technologies directly coupled with renewable power sources. *Energy Conversion and Management*, 286, 117083. <https://doi.org/10.1016/j.enconman.2023.117083>
- Sukmara, R. B., A., & Bachtiar, R. (2024). Understanding the stakeholders' interests and role toward climate change adaptation (case study of Indonesia). *International Journal of Disaster Resilience in the Built Environment, ahead-of-print(ahead-of-print)*. <https://doi.org/10.1108/IJDRBE-02-2023-0036>
- Sulistyo, H. D. D., Setiawan, E. A., Purwanto, W. W., & Kaharudin, D. (2023). Power to Gas-Hydrogen Industry Development Based on Floating PV in Indonesia. *2023 13th International Conference on Power, Energy and Electrical Engineering (CPEEE)*, 515–520. <https://doi.org/10.1109/CPEEE56777.2023.10217578>
- Sunitiyoso, Y., Mahardi, J. P., Anggoro, Y., & Wicaksono, A. (2020). New and renewable energy resources in the Indonesian electricity sector: a systems thinking approach. *International Journal of Energy Sector Management*, 14(6), 1381–1403. <https://doi.org/10.1108/IJESM-11-2019-0019>
- Tambunan, H. B., Hakam, D. F., Prahastono, I., Phramtrisanti, A., Purnomoadi, A. P., Aisyah, S., Wicaksono, Y., & Sandy, I. G. R. (2020). The Challenges and Opportunities of Renewable Energy Source (RES) Penetration in Indonesia: Case Study of Java-Bali Power System. *Energies*, 13(22). <https://doi.org/10.3390/en13225903>
- The World Bank Group. (2023). *Indonesia Country Climate and Development Report*. <https://www.worldbank.org/en/country/indonesia/publication/indonesia-country-climate-and-development-report>
- The World Bank Group, & Asian Development Bank. (2021). *Climate Risk Profile: Indonesia*. <https://www.adb.org/publications/climate-risk-country-profile-indonesia>
- U.S. Department of Energy. (2024). *Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan*. <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-multi-year-program-plan>
- Wade, F., Chailan, A., Roche, R., Bertrand, V., & Paire, D. (2023). Sizing of an Integrated Power Supply System with an Electrolyzer and a Hydrogen-Fueled Gas Turbine. *2023 IEEE Belgrade PowerTech*, 1–6. <https://doi.org/10.1109/PowerTech55446.2023.10202861>
- Xu, D., Liu, Z., Shan, R., Weng, H., & Zhang, H. (2023). How a Grid Company Could Enter the Hydrogen Industry through a New Business Model: A Case Study in China. *Sustainability*, 15(5). <https://doi.org/10.3390/su15054417>
- Zahra, N. A. (2022). Green Hydrogen Energy Technology for Zero Carbon Emission Realization in Indonesia. *The International Journal of Business Management and Technology*, 6(1). <https://theijbmt.com/archive/0943/2079601627.pdf>
- Zun, M. T., & McLellan, B. C. (2023). Cost Projection of Global Green Hydrogen Production Scenarios. *Hydrogen*, 4(4), 932–960. <https://doi.org/10.3390/hydrogen4040055>
- Zwickl-Bernhard, S., & Auer, H. (2022). Green hydrogen from hydropower: A non-cooperative modeling approach assessing

the profitability gap and future business cases. *Energy Strategy Reviews*, 43, 100912. <https://doi.org/10.1016/j.esr.2022.100912>



© 2024. The Author(s). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution-ShareAlike 4.0 (CC BY-SA) International License (<http://creativecommons.org/licenses/by-sa/4.0/>)