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Green Hydrogen as a Catalyst for Indonesia's Energy Transition: Challenges, Opportunities, and Policy Frameworks

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ABSTRACT

Global climate change necessitates deep decarbonization of all economic sectors due to significant greenhouse gas emissions. Indonesia has committed to reduce emissions by adding the share of renewable energy contribution to the nation's energy mix. Green Hydrogen (GH_2) emerged as a key element in the energy transition due to its environmentally friendly and diverse applications in energy and industry sectors. This study provides comprehensive analysis of the GH_2 adoption in Indonesia. By leveraging the renewable energy potential, Indonesia is economically viable to produce GH_2 in 2031, aligning with the National Hydrogen Strategy. The study highlights the potential benefits of GH_2 including reduction of greenhouse gas emissions, supporting net zero targets, creating green jobs, and increasing renewable energy integration. Additionally, the analysis emphasizes the importance of government support in the development of regulatory framework, including establishing a clear national hydrogen strategy, implementing targeted fiscal policies, and developing GH_2 production, safety, and certification standards. The proposed regulatory framework emphasizes the importance of carbon taxation, public awareness campaigns, and fostering a skilled workforce. By addressing existing regulatory gaps and enhancing stakeholder collaboration, Indonesia can effectively integrate GH_2 into its energy mix, paving the way for a competitive green hydrogen economy.

Keywords: Decarbonization, Energy Transition, Green Hydrogen, Regulatory Framework, Renewable Energy
JEL Classifications: O13, Q42, Q48

1. INTRODUCTION

Global climate change is a major international focus due to its severe consequences including significant economic losses, depletion of natural resources, and damage to social and cultural environments (Zhu and Fan, 2021). The Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment Report (AR6) (IPCC, 2022) highlights that the negative impacts and associated damages worsen with every increase in global temperature. Electricity and heat production are key sectors influencing greenhouse gas emissions, accounting for approximately 25-30% of emissions (IPCC, 2022; Khadra et al., 2024). Electricity generation in Indonesia has relied mainly on fossil fuels, the coal dominated about 61% and natural gas contributed around 17% of the electricity (IEA, 2023; Kanugrahan et al., 2022). Limiting global warming requires deep decarbonization of the whole nation's economy (Copley, 2023; Nagaj et al., 2024; Wang et al., 2021). Indonesia should decommission existing fossil fuel power plants and construct more renewable energy power plants and energy storage to achieve the net-zero emissions target (Kanugrahan and Hakam, 2023). Studies indicate that decreased in carbon emissions directly influence by the increase consumption of renewable energy, such in the USA and China, where renewable energy initiatives have been implemented (Feng and Zhao, 2022; Mohamad et al., 2023).

Indonesia aims to modifying its primary energy mix by diminishing the proportions of coal and oil and augmenting the proportion of renewable energy sources (Hakam et al., 2022; The World Bank Group, 2023). Indonesia committed to achieve 31.89% reduction in GHG emissions by 2030 (MEMR, 2023b). The government set targets for the country's energy transition under Government Regulation 79/2014 on National Energy Policy. The aim is to decrease the coal contribution from 43% to 30% by 2025 and 25% by 2050, oil to less than 25% by 2025 and under 20% by 2050, and gas to 22% of the energy mix by 2025 and 24% by 2050 (Indonesian Regulation, 2014). Additionally, the renewables energy should reach a minimum of 23% of the total primary energy sources in 2025 and 31% in 2050 according to Presidential Regulation No. 22/2017 on National Energy Planning (Presidential Regulation, 2017; Tambunan et al., 2020).

Energy transition is an effort to achieve sustainability, energy resilience, and independence (Regufe et al., 2021). A key factor in driving energy transition is the use of zero-carbon emissions energy (Kolmasiak, 2024). Hydrogen (H_2) emerges as a promising element to support clean energy transition due to its renewability, storability, and adaptability (Zhu and Wei, 2022). H_2 is a clean energy carrier that can be used for power generation, heating, transportation, and industry (Tarhan and Çil, 2021). Green hydrogen (GH_2), which result in no carbon emissions, is considered the most preferred option for energy transition (MEMR, 2023a; Risco-Bravo et al., 2024a). (Zahra, 2023) and (Sulistyo et al., 2023) explained that GH_2 is vital in the energy transition and could decarbonize difficult-to-abate sectors significantly. The integration of hydrogen production with renewable energy projects could provide a sustainable pathway for energy transition (Budhijanto and Pancasakti, 2024a).

Green hydrogen energy transition in Indonesia is faced with challenges, including uncertainty of supply-demand, unformed hydrogen policy and market, infrastructure barriers, and limited Investment (MEMR, 2023b). Despite the challenges, some studies reveal that GH_2 production from hydropower, solar energy, and biomass seems promising in Indonesia (Budhijanto and Pancasakti, 2024a; Fransiscus et al., 2022; Hardana et al., 2024a; Prakoso et al., 2024a; Susilaningsih et al., 2014; Widarningtyas et al., 2019). The existing literature of GH_2 in Indonesia mostly focused on techno-economic viability of the GH_2 production. In order to assess the potential of GH_2 energy transition in Indonesia, comprehensive analysis from various point of view was needed. As highlighted by (Tudor, 2023), the dynamic nature of the GH_2 market necessitates comprehensive policy frameworks that can adapt to technological advancements and global sustainability demands. A clear regulatory climate provides certainty and stability for industry players and investors, ensuring fairness and equality for all players in the market (Cheng and Lee, 2022; MEMR, 2023b; Renewable Energy Agency, 2024; Rey et al., 2023a).

There is a lack of comprehensive research addressing the knowledge gaps related to GH_2 energy transition in Indonesia. Therefore, this research fills research gap by providing a comprehensive analysis of the challenges, opportunities, and regulatory framework for GH_2 adoption in Indonesia. This research offers strategic insights to overcoming market, production, and policy barriers, while exploring the Indonesia's potential for leveraging renewable energy sources to support GH_2 development. Section 2 provides the literature review for the GH_2 energy and Section 3 highlights the GH_2 development in Indonesia. Section 4 presents the regulatory framework to support GH_2 energy transition in Indonesia. Section 5 summarizes key conclusions and recommendations.

2. LITERATURE REVIEW

Hydrogen energy can be categorized based on how it is produced. Currently, half of the hydrogen comes from natural gas, 30% from oil, and 15% from coal, which are not always considered environmentally friendly (Karayel and Dincer, 2024). Gray Hydrogen produced from natural gas through steam reforming and releases significant CO_2 emissions, which are unsuitable for climate change mitigation (Howarth and Jacobson, 2021). Blue Hydrogen is produced from natural gas, then the carbon emissions are captured and stored using Carbon Capture and Storage technologies. This reduces CO_2 emissions but requires substantial investment and infrastructure development (Bauer et al., 2022). Green hydrogen is a promising technology that has been gaining attention recently as a possible answer to the difficulties of moving toward a sustainable energy future (Zahra, 2023). The concept of GH_2 refers to the process of producing hydrogen gas through electrolysis, using renewable energy sources like solar or wind power, resulting in no carbon emissions. It is considered environmentally friendly and supports the transition to clean energy (Hassan et al., 2024a; Risco-Bravo et al., 2024b).

The importance of GH_2 in the global energy mix can be attributed to its potential to address some of the most pressing challenges faced by the world today, including climate change, energy security, economic growth, and sustainable development (Hassan et al., 2024b; MEMR, 2023b; Rey et al., 2023a). As a clean and versatile energy carrier, GH_2 offers a range of benefits that make it a vital component in our quest to decarbonize the global economy (MEMR, 2023b). Table 1 summarizes global GH_2 projects across various countries, highlighting the different stages of GH_2 development. Leading countries like the European Union, United States, Australia, and China have established strong regulatory frameworks and are expanding GH_2 infrastructure, with some targeting export markets. Leading countries aim to reduce GH_2 production costs to \$1-\$4/kg by 2030. While some countries are at advance development, others are in the early stages of exploration. Developing nations, such as the Philippines, Malaysia, India, Vietnam, and Pakistan, are focusing on integrating hydrogen into sectors like transportation and industry, supported by emerging regulatory policies. Overall, the global landscape reflects a diverse approach to GH_2 development, driven by each country's levels of infrastructure, policy support, and market readiness.

3. INDONESIA'S GREEN HYDROGEN DEVELOPMENT

Green hydrogen is being harnessed as a clean alternative across various sectors, including electricity generation, public transportation, maritime, and aviation industries (Ueckerdt et al., 2021). Its adoption is crucial in advancing environmental

Table 1: Literature review

Author	Country	Stage of Development	Utilization	Regulation	RE	Outcome	Price (USD/kg)
(Shin, 2022)	South Korea	Large-scale GH_2 production, storage, and application, the commercialization is being developed on Jeju Island	Fuel Cell and Power generation	Introduce Hydrogen Economy Activation Roadmap in Jan 2019, the first hydrogen economy blueprint was announced in November 2021	Solar and Wind, import necessities	Expand hydrogen production from 130,000 tons in 2018 to 5.26 million tons in 2040	2 in 2050
(Furfari and Clerici, 2021; Muhsen et al., 2023)	European Union	Advanced development, with several GH_2 pilot projects, research initiatives, and production hubs across Europe, especially Germany and Spain	Primarily decarbonization Industries (steel and chemical production), Heavy Transportation (trucks, ships), and Energy Storage for grid stability	Introduce Hydrogen Strategy for a Climate-Neutral Europe in July 2020 and 2050 Hydrogen Roadmap	Solar and Wind using PEM and AE	40 GW in 2030	3-6
(Bade et al., 2024a)	United States	Develop several projects and pilot plants for GH_2 production, particularly in regions with abundant renewable energy resources like California and the Gulf Coast	Construction, Transportation, Industrial feedstock, and Power generation.	Introduce Road Map to a US Hydrogen Economy through the Fuel Cell and Hydrogen Energy Association in March 2020, DOE has established the Hydrogen Program Plan and Hydrogen strategy documents	Solar, Wind, and Hydro	By 2030 plans to develop up to 10 GW	1 by 2030
(Marouani et al., 2023a)	Japan	Advanced R and D focus on hydrogen economy	Power generation, Transportation (hydrogen-based automobiles, ships, trains, and forklifts), and Industry	Introduce The First Strategic Energy Plan, The Strategic Road Map for Hydrogen and Fuel Cells, and Hydrogen Energy Utilization Schedule	Exploring imports	Plans to achieve 3 million tons of hydrogen production annually by 2030	5-6
(Li et al., 2022)	China	Rapidly expanding	Fuel cells and Transportation	In 2016 published China's first roadmap on the development of hydrogen energy infrastructure, related technologies, and a corresponding policy framework.	NA	NA	3-7.5
(Agaton et al., 2022)	Philippines	Exploratory phase focusing on hydrogen as part of energy transition.	Transportation, Industry, Electricity, Heat, Energy Storage	5-year Philippine Fuel Cell and Electrolyzer Research and Development Roadmap and Hydrogen Energy Release Optimizer (HERO)	Solar, Wind, Hydro, Geothermal, Biomass, Ocean	NA	6
(Jumaat and Khalid, 2024)	Malaysia	Early stages of exploring and developing the hydrogen industry and economy.	Fuel cells as a priority R and D area	Hydrogen Economy Technology Roadmap in Oct 2023.	Solar, Palm Oil Mill Effluent (POME), and Hydro	NA	NA

(Contd...)

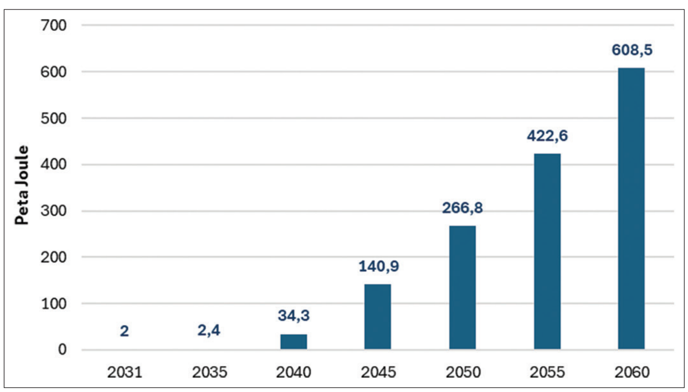
Table 1: ***(Continued)***

Author	Country	Stage of Development	Utilization	Regulation	RE	Outcome	Price (USD/kg)
(Rezaei et al., 2020)	Afghanistan	Initial stage of development	NA	NA	Wind using AEC	260,610 kWh/year	2.1-2.3
(Khan et al., 2022; Yin et al., 2024)	Australia	Advanced development stage over 113 hydrogen projects registered across the country	Export to Asian markets	National Hydrogen Strategy, focus on becoming a leading GH_2 exporter.	Solar and Wind using PEM and AE	Targeting 8 GW of electrolyzer capacity by 2030	2
(Gallardo et al., 2021)	Chile	Early-stage, developing export routes	Export to global markets (Asia, Europe)	Chilean National Long Term Energy Policy which was launched in 2018	Solar using PEM and AE		1.67 in 2025.
(Benalcazar and Komorowska, 2024)	Morocco	Developing export infrastructure	Export to Europe	Hydrogen roadmap focused on Europe	Solar and Wind using PEM	13.9-30.1 TWh demand by 2030	3.2-3.5 in 2030
(Harichandan et al., 2023)	India	Early stage, but progressing with multiple projects and investments	Decarbonizing industries (steel, ammonia, transport, refineries)	National Green Hydrogen Mission	Solar, Wind, Biomass, and Offshore Wind using PEM and AE	5 MMT by 2030	\$3.2-\$7.0
(Hoang et al., 2023)	Vietnam	Initial stage, with small-scale projects in pilot phases	Decarbonize industries (steel, cement, transport, electricity) and Export	National Energy Development Plan 2020, targeting hydrogen by 2030 and beyond	Offshore Wind, Solar, Hydropower, and Biomass using PEM and AE	22 million tons/year by 2050	3-6 in 2050
(Moura et al., 2020)	Brazil	Rapidly expanding	Transportation	Brazil has a clear hydrogen strategy, with strong governmental support for renewable energy development	Solar, Wind, and Biogas using AEC		0.110 and 0.963 US\$/kWh
(Mohsin et al., 2018)	Pakistan	Early-stage	Fuel cell	Currently not introducing any Hydrogen economy map or a policy for the introduction of Hydrogen	Wind using PEM	10,545 kg/day, in summer optimized up to 51,917,390 kg/day of hydrogen	5.30-5.80

sustainability and mitigating carbon emissions, marking a significant step towards a greener future. Hydrogen demand in Indonesia is currently around 1.75 million tons per year in 2021, almost entirely for the chemical and refining subsector, dominated by use for urea (88%), ammonia (4%), and oil refineries (2%) (MEMR, 2023b). Most of the hydrogen currently used in Indonesia comes from natural gas (Hassan et al., 2024b). In electricity, GH_2 play roles including co-firing in fossil power plants to reduce emissions, energy storage for remote areas to support full electrification, and help mitigate the intermittency of renewable energy in the national grid (MEMR, 2023b; Susilaningsih et al., 2014).

The GH_2 demand expected steadily grows as the increase of electricity and electromobility demand in Indonesia (MEMR, 2023b). This is also supported by the nation's policies in promoting net zero emissions and strategic initiatives to develop hydrogen economy. Per capita electricity consumption is projected to increase from less than 1,000 kilowatt-hours (kWh) in 2021 to over 1,500 kWh in 2030, and around 4,400 kWh by 2060 (National Energy Board, 2024). By 2060, transportation will be the second-largest consumer of electricity. (Siregar and Möller, 2023) shown that transport electrification can only effectively reduce CO_2 emissions if its electricity demand is generated from renewable energy sources. Transport electrification with large scale integration of renewables could lower the annual costs by decreasing fossil fuel costs in the transport and electricity sectors.

Figure 1: Hydrogen demand projection in NZE model (MEMR, 2023b)



Based on the Ministry of Energy and Mineral Resources' Net Zero Emission modeling, demand for low-carbon hydrogen from various sectors is projected to grow in 2031-2060. The low-carbon hydrogen demand growing from around 0.2 PJ (equivalent to 26,000 barrels of oil) in 2031, up to 34.3 PJ in 2040, and peaking to reach 609 PJ in 2060 as can be seen in Figure 1. The use of low-carbon hydrogen for transportation begins in 2031 equivalent to 26,000 barrels of oil or 0.04 TWh (truck transportation) growing 52.5 million barrels of oil or 89 TWh (shipping and truck transportation) in 2060. In the industrial sector, the use of low-carbon hydrogen will begin in 2041, equivalent to 2.8 TWh to 79 TWh in 2060 (MEMR, 2023b).

Indonesia's geographical features support energy production from its abundant renewable energy resources. According to the National Energy Council Republic of Indonesia, Indonesia has a 3,687 GW renewable energy potential, made up of 63 GW of ocean power, 23 GW of geothermal energy, 57 GW of biopower, 155 GW of wind power, 95 GW of hydropower, and 3,294 GW of solar power (Table 2). Most areas of Indonesia have an annual solar irradiation intensity of around 1,600 kWh/m^2-1,800 kWh/m^2. Wind resources in Indonesia have a speed of 4 m/s-7 m/s, and technically, the potential reaches 60 GW (onshore) and 188 GW (offshore). Additionally, Indonesia is an archipelagic country with huge hydro resource potential (National Energy Board, 2024). The use of renewable energy sources for GH_2 production must be further optimized to increase the overall utilization of renewable energy in Indonesia, which is currently only 0.3% (National Energy Board, 2024).

The generated electricity from renewable resources powers an electrolyzer, which splits water (H_2O) into hydrogen (H_2) and oxygen (O_2). The resulting hydrogen gas from electrolysis is collected and stored in a specialized H_2 tank, which is transported to an H_2 pipeline for distribution to end-users (Marouani et al., 2023b). The Indonesian Ministry of Energy and Mineral Resources analyzed the potential location of GH_2 production in Indonesia,

Figure 2: Map of announced low-emission hydrogen production projects (IEA, 2023)

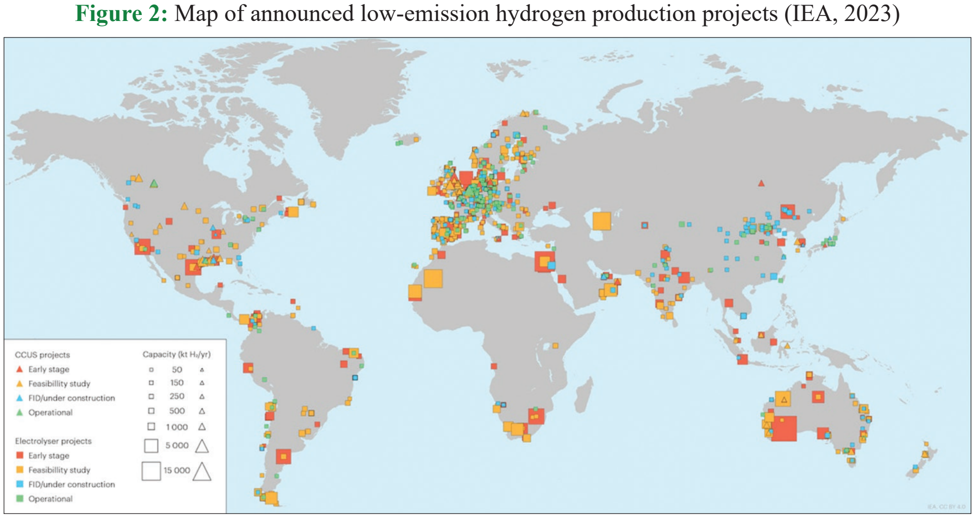
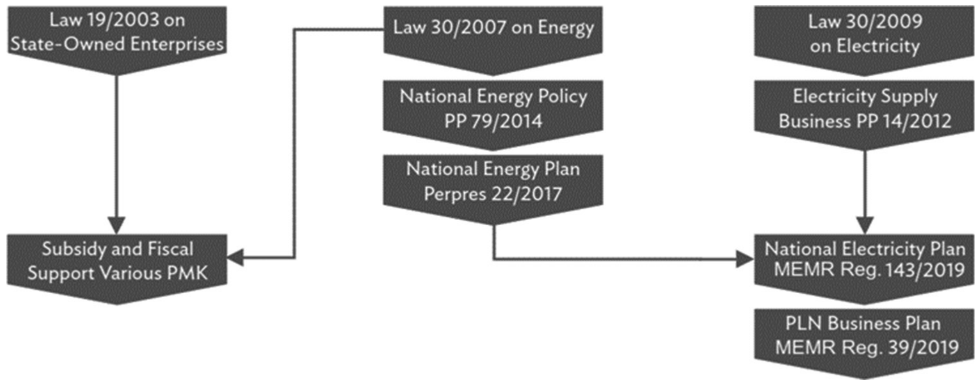


Figure 3: Indonesia's energy policy and planning framework (Asian Development Bank, 2020)



as shown in Table 3. Nusa Tenggara has the most significant potential, several provinces are also predicted to be able to produce GH_2 far above the national average, such as West Java, Central Java, East Java, Papua, Riau, and South Sumatra. The nation's total GH_2 production capacity is expected to grow over the years as the development of the regulatory framework, enhancement of technology, and infrastructure of hydrogen energy (MEMR, 2023b). International Energy Agency (IEA, 2023) announced projects on GH_2 production which classified by technology route and status, from concept to operation (Figure 2). Based on the figure, status of GH_2 production in Indonesia mostly on early stages. The first GH_2 Plant in Indonesia was inaugurated in 2023 by PT PLN (Perusahaan Listrik Negara) as the government-owned corporation. The first GH_2 plant is powered entirely by solar energy and can produce 51 tons of hydrogen annually, of this, 43 tons can fuel 147 cars to travel 100 km daily (National Energy Board, 2024).

Green hydrogen production depends on factors like yield production of renewable power plants, electrolyzer technology, and GH_2 infrastructure readiness. The increase in renewable power plant yield production may drive down the cost of electricity production and in turn, reduce the cost of the GH_2 production. (MEMR, 2023b) mention that 70 % of GH_2 price is determined by electricity price from renewable sources besides the initial investment of electrolyzer technology. The average selling price of electricity per kWh in 2022 is IDR 1,137/kWh (7 cents, exchange rate Rp 16,251.47). In order to achieve price competitiveness in GH_2 energy, Indonesia must pay attention to the pricing policy for renewable energy power plants. The determination of electricity tariffs by the government is regulated in MEMR Regulation No. 3 of 2020 concerning the Fourth Amendment to MEMR Regulation No. 28 of 2016 concerning Electricity Tariffs provided by PT PLN (Persero).

Indonesia's Hydrogen Strategy mentioned the GH_2 production aims to start in 2031. The electrolyzer cost prediction was reported by previous studies considering factors like scale-up, manufacturing volumes, and technology improvements. (Reksten et al., 2022), predicts that the gap in CAPEX between Alkaline Electrolyzer (AE) and Proton Exchange Membrane Electrolyzer (PEM) technologies is expected to narrow significantly as plant sizes increase. For very large plants (greater than 100 MW), the costs for both technologies will approach 320-400 USD/kW by 2030. The electrolyzer capital costs will be estimated to

Table 2: Indonesia's renewable energy power plant potential and utilization in 2022 (National Energy Board, 2024)

Type of Renewable Energy	Total Potential (GW)	Utilization (GW)	Utilization (%)
Ocean	63	0	0.0
Geothermal	23	2.4	10.4
Bioenergy	57	3.1	5.4
Wind	155	0.2	0.1
Hydro	95	6.7	7.1
Solar	3.294	0.3	0.0
Total	3.687	12.7	0.3

Table 3: GH_2 production potential in the NZE model (MEMR, 2023b)

Location	GH_2 Potential (GWh)
Riau	14,402
North Sumatera	14,384
West Java	10,622
Central Java	10,597
East Java	10,348
Central Kalimantan	8,975
Nusa Tenggara Timur	16,572
Papua	11,681

drop to 88 USD/kW for AE and 60 USD/kW for PEM under an optimistic scenario by 2050, or 388 USD/kW and 286 USD/kW, respectively, under a pessimistic scenario (Zun and McLellan, 2023). According to (IEA, 2022), the initial investment of AE may cost 500-1,400 USD/kW, 1,100-1,800 USD/kW for PEM, and 2,800-5,600 USD/kW for SOE. Electrolyzer manufacturers generally agree on the potential for rapidly reducing capital costs through economies of scale (Rey et al., 2023b).

The average cost of GH_2 production consists of investment and operational costs, which are defined using the Levelized Cost of Hydrogen (LCOH). LCOH accounts for all capital and operating production costs in a levelized manner over a unit of produced hydrogen and its derivative (USD/kg) (Zulfhazli et al., 2024). 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 (Zun and McLellan, 2023). Based on (MEMR, 2023b) calculations by taking three PLN case studies, the price of hydrogen production is around 4.61-5.45 USD/

kg in 2030, assuming the cost of a PEM electrolyzer is between 450 and 1700 USD. In comparison, the projected hydrogen price in Japan is around 5.7-7.7 USD/kg in 2025 (Roos, 2021), around 5.5-7.7 USD/kg in South Korea (Chu et al., 2022), and around 4.9-6.5 USD/kg in Singapore (KBR and Argus, 2020). Despite that, the projected price of GH_2 in Indonesia is not yet competitive because it is three times the current average cost of production. Therefore, the government needs to help the growth of this sector by making policies, creating an investment climate, and developing competitive business models. Regarding energy pricing, (Pratikto et al., 2023) found that more than 95% of non-subsidized residential consumers in Indonesia are willing to pay up to 40% higher than the current price for greener electricity. This willingness to pay increases with the share of renewable energy in the energy mix. These findings highlight the strong potential market for greener energy solutions in Indonesia, indicating that consumers are ready to support and invest in cleaner energy alternatives.

Benefits of GH_2 production outweigh the challenges, including reducing dependence on fossil fuels, being environmentally friendly, and providing an efficient energy carrier (MEMR, 2023b). (Marchenko and Solomin, 2015) shows that the use of hydrogen proves beneficial for long-term storage, whereas the electricity economy is preferable in the case of short-term energy storage. In the electricity generation sector, GH_2 serve as an energy transport medium, becoming an option to meet domestic needs and expand energy connectivity that is geographically unreachable. Additionally, GH_2 can be used as fuel for co-firing, which has the potential to reduce greenhouse gas emissions by 10,588,235 tons of CO_2-eq (MEMR, 2023b). GH_2 as a raw material in the fertilizer supports Indonesia's potential as the 3rd-largest ammonia exporter in the world.

The economic viability of GH_2 production in Indonesia seems a promising opportunity. (Hardana et al., 2024b) mentioned that GH_2 production from small hydropower plants in Indonesia is economically feasible and offers scalability for future energy production in Indonesia. (Prakoso et al., 2024b) also reports the economic and technical feasibility of constructing a GH_2 facility in Jambi, Indonesia. The finding highlighted Jambi's projected selling price for GH_2 demonstrates competitiveness within the market. These findings offer valuable insights into the potential profitability and market prospects of GH_2. Additionally, (Budhijanto and Pancasakti, 2024b) results indicate that the establishment of hydrogen production in Indonesia using fermentation technology and agricultural waste is economically viable. Integrating GH_2 into Indonesia's energy mix represents a transformative opportunity to decarbonize the energy sector and advance sustainability goals. By critically evaluating various aspects, including scalability, technological challenges, and socioeconomic implications, stakeholders can gain a holistic understanding of the potential benefits and challenges associated with GH_2. This information will aid in making informed decisions and formulating effective strategies to drive the successful integration of GH_2 into the energy landscape (Stöckl et al., 2021). The government support through clearer policy, incentives, and infrastructure readiness is essential to shape market competitiveness of GH_2.

4. REGULATORY FOR GREEN HYDROGEN DEVELOPMENT

Governments play a critical role in providing policy and regulatory certainty, ensuring better planning, and supporting effective market development and business models. Uncertainty in policies results in adverse risks for public and private sector project development and can make the costs of providing clean energy prohibitively high (Barradale, 2010). Government could accelerate the transition toward GH_2 energy by developing national strategies, coordinating local efforts, and accelerating regulatory changes and development. Those pathways are necessary to facilitate the adoption of hydrogen as a competitive energy source (Scita et al., 2020). The national strategies and efforts may include funding and investment, establishing a clear national H_2 roadmap, fostering collaboration and partnerships, promoting regional H_2 clusters, supporting pilot and demonstration projects, and developing skilled workforces. Regulatory changes should focus on standards and certifications, permitting and licensing processes, market mechanisms, research and development (R and D) support, and infrastructure development. H_2 networks should be planned and developed, with opportunities to integrate with existing infrastructure to maximize efficiency and minimize costs (Renewable Energy Agency, 2021).

4.1. Existing Regulation

The Government of the Republic of Indonesia has issued several regulations to enhanced energy security, availability, and sustainability especially for the development and utilization of renewable energy. In principle, the development of GH_2 has been addressed within the framework of renewable energy policies (Table 4). Law 30/2007 on Energy lays out a cascading framework of energy policy formulation and planning. Figure 3 shows the linkages with subsidy, fiscal incentive policies, and other direct government support as administered by the Ministry of Finance (MoF) (Asian Development Bank, 2020). Subsidies for State-Owned Enterprises (SOEs) regulate under the Law 19/2003, which obliges the government to compensate an SOE for the execution of any government assignment for the public good that is not profitable (Indonesian Regulation, 2019). For example, Minister of Finance Regulation (PMK) 116/2016 regulate for LPG Subsidy (Minister of Finance Regulation, 2016) and PMK No. 44/2017regulate for Electricity Subsidy (Minister of Finance Regulation, 2017).

Law 30/2007 authorizes the government to provide facilities and incentives to companies for renewable energy supply (Indonesian Regulation, 2007). Law No. 78/2019 regulate tax allowance to encourage and increase direct investment activities (Presidential Regulation, 2019). Tax holidays regulate in PMK No. 150/2018, facilitate corporate income tax reduction, and provides tax holidays for investment in pioneer industries including economic infrastructure(Minister of Finance Regulation, 2018), as stipulated in Investment Coordinating Board Regulation 1/2019 as amended by 6/2019 (Investment Coordinating Board Regulation, 2019). Exemption of import duty on machinery, equipment, and raw materials regulates in PMK No. 176/PMK.011/2009 in junction with PMK no. 76/PMK.011/2012 in junction with PMK No. 188/PMK.010/2015 (Minister of Finance Regulation, 2015).

Table 4: Indonesia's Renewable Energy Regulations (Indonesian Regulation, 2007; Indonesian Regulation, 2009; Indonesian Regulation, 2014; MEMR Regulation, 2017a; MEMR Regulation, 2017b; MEMR Regulation, 2020; Presidential Regulation, 2006; Presidential Regulation, 2017; Presidential Regulation, 2022; MEMR, 2023b)

Indonesian Regulation	Description
Presidential Regulation No. 5/2006	National Energy Policy, direct efforts to the creation of sufficiency of domestic energy supply.
Law No. 30/2007	Energy concern, emphasizes energy security, sustainable development, energy resilience, and environmental preservation.
Law No. 30/2009	Regulates planning and governance in the electricity sector, prioritizing the development of new and RE sources.
Government Regulation No. 79/2014	National Energy Policy, promotes the use of RE and curbs the use of fossil energy sources. It sets RE mix targets from 2020 to 2050.
MEMR Regulation No. 12/2017	Guideline for State Electricity Company (PT PLN) in purchasing electricity from a power plant that utilizes RE sources.
Presidential Regulation No. 22/2017	National Energy General Plan, plan for RE development up to 2050, including a general action plan for hydrogen development, such as regulatory framework preparation, technology and manufacturing capacity development, and provision of incentives.
MEMR Regulation No. 50/2017 amended by No. 53/2018	Utilization of RE sources for the provision of electricity was passed to accelerate the development of RE for the benefit of national electricity. It is necessary to rearrange the provisions regarding the mechanism and purchase price of electricity by PT PLN which utilizes RE sources.
Draft Bill on New and Renewable Energy	Regulates RE development, including pricing, incentives, etc., In the latest draft, hydrogen is recognized as a new energy source.
MEMR Regulation No. 9/2020	Improve efficiency in the electricity supply business of PT PLN, it is necessary to regulate a target-setting mechanism and realize electricity supply efficiency in the form of electricity generation efficiency and electricity network efficiency.
Presidential Regulation No. 112/2022	Increasing investment and accelerating the achievement of RE mix targets in the appropriate national energy mix with the national energy policy and reduction of greenhouse gas emissions, it is necessary to regulate the accelerated development of power plants from RE sources.
National Hydrogen Strategy 2023	Indonesian government aims to implement three key measures covering diversification on energy supply sources, expansion of domestic demand, and creation of export market for hydrogen.

Additionally, Indonesia's government may directly fund renewable energy development with Special Allocation Fund from the State Budget (APBN) or implement public-private partnership (PPP) (Asian Development Bank, 2020).

Although Indonesian government has introduced various policies and regulations to promote renewable energy, further concrete actions are needed, particularly in implementing and providing clearer incentives to stimulate the growth of the GH_2 energy sector. Effective GH_2 development policies should include setting clear targets, offering incentives, establishing detailed implementation policies for GH_2 deployment procedures, encouraging international cooperation for technology and knowledge transfer, providing funding for hydrogen R and D, streamlining the permitting process for hydrogen projects, and encouraging private investment in hydrogen infrastructure through international partnerships (Dewi et al., 2023). The legal framework governing GH_2 in Indonesia is indeed complex, involving commitment and dynamic interplay between multisectoral stakeholders.

4.2. GH_2 Regulatory Framework

The Green Hydrogen policy approach should have four central pillars, including a National Hydrogen Strategy to define ambitions and pathways for hydrogen development, Policy Priorities that focus on high-value applications of GH_2, Guarantees of Origin to ensure transparent carbon emissions labeling across the hydrogen lifecycle, and Governance system and enabling policies that integrates GH_2 into the broader energy system with involvement from civil society and industry (International Renewable Energy Agency, 2022). Indonesia's National Hydrogen Strategy highlights the current condition of hydrogen utilization in Indonesia, as well as the direction and objectives of hydrogen development. Indonesia planned to introduce GH_2 across four key economic sectors including transportation, industrial feedstock, power generation, and commodity (MEMR, 2023b). Policy priorities of GH_2 deployment in Indonesia should be focused on incentives and fiscal policies that support capital flows and encourage innovation and competition. The incentive strategy includes tariff discounts and tax exemptions, investment frameworks for capital grants and ongoing subsidies, and innovation competitions with progress monitoring programs (Bade et al., 2024b). Additionally, to increase the competitiveness of GH_2 prices, an emissions trading scheme and a carbon tax can be implemented (MEMR, 2023b).

Hydrogen business permits and licenses are currently in the initial stages of identification for the permits required in the Standard Classification of Indonesian Business Fields code to encourage a GH_2 ecosystem (Nyoman Ary Whyudi, 2024). Indonesian Ministry of Energy and Mineral Resources (MEMR) also preparing regulations on the incentives and tax breaks to step up the development of GH_2 in 2024. This policy will later be included in the Draft Law on New Energy Renewable Energy, which is still in the evaluation stage. The draft policy also will cover standards for tax holidays, tax allowances, taxes, and the fundamental regulations for carbon trading (Indonesia Business Post, 2024). Indonesia may adopt GH_2 policies and regulations from leading international countries like Australia. After releasing the National Hydrogen Strategy in 2019, which spans 57 collaborative actions in seven key areas, Australia augmented its regulation with Technology Roadmap 2020. The broader national energy plan intends to accelerate the development of new emerging technologies by making them economically competitive.

Australia also accelerates GH_2 development by providing funds and lending to hydrogen R and D projects. Australian Renewable Energy Agency (ARENA) offers financial assistance for clean energy projects and research to accelerate the transition of technologies from the R and D stage to pre-commercial deployment activities. As Australia's green bank, the Clean Energy Finance Corporation (CEFC) catalyzes the increased finance flows in Australia's clean energy sector. Australia has implemented a Carbon Pricing Scheme and designed the guarantees of origin scheme for GH_2 (Pingkuo and Xue, 2022). Providing grants for GH_2-related R and D projects is essential to accelerate the adoption of domestic hydrogen technology in Indonesia (International Renewable Energy Agency, 2022). Inter-ministry collaboration such as with the National Research and Innovation Agency (BRIN), Ministry of Finance, Ministry of State-Owned Enterprises, Ministry of Industry, and Ministry of Transportation must be optimized. Additionally, financial assistance for developing hydrogen infrastructure, is needed to overcome initial barriers and encourage a comprehensive hydrogen network. The country must foster collaboration between the public and private sectors and international organizations to share best practices and access funding, leveraging global expertise in promoting GH_2 adoption (Renewable Energy Agency, 2024). Educational campaigns are also essential to raise awareness about the GH_2's environmental and health benefits, since the consumer perspectives matters (Pramana et al., 2024).

Indonesia's carbon tax policy has been established in Law No 7/2021 on the Harmonization of Tax Regulation. The tax mandates the government to implement the carbon tax of USD 2 per ton of CO_2 on April 1, 2022, applied to coal-fired power plants. It is a disincentive for fossil energy and an incentive for renewable energy (Indonesian Regulation, 2021). Carbon pricing and emissions reduction incentives create a market advantage for low-carbon or zero-emission technologies (International Renewable Energy Agency, 2022; Paradongan et al., 2024). The carbon tax should be increased and expanded to other polluting sectors. Governments also can impose air pollution taxes to reduce fossil energy dependence and encourage businesses to switch to renewable energy (Eko Eddya Supriyanto, 2023).

Reducing renewable energy costs directly impacts the cost competitiveness of GH_2 production. The widespread deployment of electrolyzers and affordable renewable electricity make GH_2 more cost-effective (Renewable Energy Agency, 2021). MEMR is responsible for energy sector tariff regulation, including procurement and contracting renewable energy generation by the State Electricity Company (PLN). The key regulation governing renewable energy pricing is MEMR Regulation No. 50/2017 on Utilization of Renewable Energy Resources for Electricity Supply, as amended by No. 53/2018 (MEMR Regulation, 2017b). The application of efficient pricing in the power system affects decision making in investment planning and mitigates market power. (Hakam et al., 2019) highlights nodal pricing implementation will be beneficial for electricity market designers and stakeholders in Indonesia. The most feasible option for closing the gap between renewable energy costs and PLN's purchase price in Indonesia is some form of subsidy funded from the state budget (Asian Development Bank, 2020). MEMR may issue a new regulation to amend the existing renewable energy pricing regulations; if existing pricing regulations are retained, a new Minister of Finance regulation will need to be issued covering the budget subsidy mechanism.

Indonesia's long-term strategy is targeting GH_2 as an export commodity (MEMR, 2023b). To support this goal, Indonesia needs to create comprehensive regulations that align with international frameworks, especially regarding emission standards for GH_2 production, certification schemes for GH_2 production, safety standards for production, distribution, and utilization schemes. Indonesia needs to strengthen its carbon pricing scheme to accelerate the implementation of GH_2 energy on a large scale. Utilizing the current energy regulatory landscape's framework, Indonesia can strategically design clear regulations and policies for GH_2 deployment. Based on the discussion that has been explained, the regulatory framework for GH_2 development is shown in Table 5. The comprehensive regulatory landscape will maximize the GH_2 energy transition and contribute to achieving sustainable development goals. Successful design and implementation of the regulatory framework are critical to the establishment, growth, and competitiveness of the GH_2 market in Indonesia. By creating a multisectoral approach, Indonesia's regulator can ensure comprehensive and coordinated governance to implement efficient regulations and encourage a sustainable GH_2 industry.

Table 5: Suggestions of policy roadmap to deploy green hydrogen economy in Indonesia

Time Frame	Regulatory Roadmap
November-2030	▪ Establish an effective and coordinated governance structure between ministries and agencies overseeing the GH_2 sector ▪ Accelerate incentives and subsidies on GH_2 R and D and project ▪ Accelerate fiscal policies, such as tariff discounts, tax exemptions, and tax holidays ▪ Investment frameworks for capital grants regulation ▪ Supporting on finance and loan program for GH_2 development ▪ Strengthen Carbon Tax regulation ▪ Raising social awareness of GH_2 creates a skilled-workforce
2031-2040	▪ Amendment on renewable energy tariff regulation ▪ Supporting regulation in GH_2 infrastructure development ▪ GH_2 licensing and certification regulation, including guarantee of origin ▪ Regulation on standards and technical production of GH_2 ▪ Regulation on GH_2 storage and transport pipeline ▪ Supporting regulation on fuel cell vehicle and refilling station development
2041-2060	▪ GH_2 Export Regulation ▪ Policy on Green Shipping Corridor ▪ Establishing GH_2 Hubs to integrate supply chain ▪ Integration hydrogen economy across multisectoral industry

5. CONCLUSION AND RECOMMENDATION

The green hydrogen (GH_2) energy transition presents a critical opportunity for Indonesia to align its energy sector with global sustainability goals and national decarbonization targets. GH_2 offer significant long-term benefits, including supporting net-zero emissions targets, achieving universal energy access in line with SDG 7 (clean energy), creating potential for green jobs, increasing the penetration of renewable energy into the national energy mix, and strengthening the country's position in GH_2 and ammonia exports. Indonesia's abundant renewable energy resources provide substantial potential for GH_2 development, which is expected to begin by 2031, according to the National Hydrogen Strategy. The use of hydrogen in the electricity sector can serve as a long-term goal while infrastructure and technological readiness are being prepared. Government support is needed to accelerate the readiness of market players to conduct pilot projects and participate in the GH_2 energy transition.

This study underscores the necessity of a comprehensive regulatory framework to facilitate the growth of GH_2 deployment in Indonesia. While the current regulatory environment is generally supportive of renewable energy, it requires significant enhancement to address the specific needs of GH_2. A well-designed regulatory framework is essential to achieving GH_2 competitiveness in both domestic and global hydrogen markets. The proposed regulatory framework focuses on establishing a clear national strategy with specific targets, accelerating research and development through grants policy, leading investment through targeted incentives and fiscal policies, and creating standards for safety, certification, and emission of GH_2 production and utilization in Indonesia. This study also emphasizes the importance of carbon taxation, public awareness, and building a skilled workforce in GH_2 energy adoption. Additionally, multisectoral collaborative efforts are needed to address existing physical and regulatory infrastructure challenges, paving the way for establishing a GH_2 economy in Indonesia.

To accelerate GH_2 development in Indonesia and ensure a sustainable energy transition, future research must focus on strengthening an adaptive regulatory framework aligned with global hydrogen policies. Further studies should evaluate the integration of local renewable energy sources, such as solar and hydropower, to reduce GH_2 production costs, while assessing GH_2's role in decarbonizing heavy industries and transportation sectors. Research on GH_2 storage, distribution, and its synergy with carbon capture and storage technologies also will be crucial, alongside efforts to raise public awareness and develop a skilled workforce to support GH_2 adoption. Long-term environmental impact studies are necessary to monitor GH_2's contribution to emission reduction targets and sustainability in Indonesia.

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