GREEN HYDROGEN IN INDONESIA: AN OVERVIEW OF PRESENT STATUS, CHALLENGES, AND FUTURE POTENTIAL

HIDROGEN VERDE ÎN INDONEZIA: O TRECERE ÎN REVISTĂ A SITUAȚIEI ACTUALE, PROVOCĂRILOR ȘI POTENȚIALULUI VIITOR

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Abstract: *Indonesia targets a clean energy mix of 31% by 2050 and net zero emissions by 2060. Green hydrogen is seen as a key strategy. This study examines the current state, challenges, and future potential of green hydrogen development in Indonesia. Despite high potential, technical, economic, social, and regulatory hurdles exist. The government is initiating pilot projects, regulations, and collaborations to accelerate the transition to a green hydrogen economy. This study aims to inform and recommend strategies for optimizing this development.*

Keywords: Low carbon hydrogen, Green hydrogen, Indonesia, Hydrogen challenges, Hydrogen strategy.

Rezumat: *Indonezia vizează un mix de energie curată de 31% până în 2050 și zero emisii nete până în 2060. Hidrogenul verde este văzut ca o strategie cheie. Acest studiu examinează starea actuală, provocările și potențialul viitor al dezvoltării hidrogenului verde în Indonezia. În ciuda potențialului ridicat, există obstacole tehnice, economice, sociale și de reglementare. Guvernul inițiază proiecte pilot, reglementări și colaborări pentru a accelera tranziția către o economie verde a hidrogenului. Acest studiu își propune să informeze și să recomande strategii pentru optimizarea acestei dezvoltări.*

Cuvinte cheie: *Hidrogen cu emisii scăzute de carbon, Hidrogen verde, Indonezia, Provocări cu hidrogen, Strategia hidrogenului.*

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1. Introduction

The Paris Agreement stands as the key pillars in the worldwide effort to mitigate climate change and establish a sustainable future. Adopted at the United Nations (UN) Climate Change Conference in 2015, it set an ambitious goal to restrain the global average temperature increase to below 2° Celsius or, with rigorous efforts, to 1.5° Celsius, above pre-industrial levels [1,2]. The agreement also sets goals to increase adaptive capacity and resilience, reduce vulnerability to climate hazards, and contribute to sustainable development [3,4]. It has been signed by 195 countries, including Indonesia, on December 12, 2015. Indonesia, in its the Nationally Determined Contributions (NDC), committed to reducing greenhouse gas (GHG) emissions by 31.89% from the Business as Usual (BAU) scenario with national efforts by 2030, or 43.20% with international support [5-7].

The Paris Agreement is closely related to the Indonesian government's endeavors to reduce greenhouse gas emissions, by encouraging an increase in the energy mix from New and Renewable Energy (NRE) sources. Based on Presidential Regulation No. 22/2017 as outlined in the National Energy General Plan (RUEN), the Indonesian government has set a target of an NRE mix of 23% in 2025 and 31% in 2050 to achieve Net Zero Emissions (NZE) by 2060 [8,9]. Currently, green hydrogen has been recognized as a potential energy vector, even projected to be one of the contributors to the energy transition and has an important role in decarbonization [10,11]. The Ministry of Energy and Mineral Resources (MEMR) has encouraged low carbon hydrogen to become one of the energy sources that can be used to meet the needs for energy in various sectors [12].

The utilization of low carbon hydrogen in Indonesia holds great potential that can have positive impacts across various sectors. Energy diversification, supply security, and carbon emission reduction are key benefits of integrating green hydrogen into the national energy portfolio [13,14]. The plan to widely utilize green hydrogen certainly goes hand in hand with the great potential of renewable energy. With abundant resource, Indonesia has an opportunity to advance towards self-sufficiency in meeting domestic needs and exports [15].

As green hydrogen serves as one of the important solutions for decarbonization, understanding its present development is crucial. At the global level, there has been a significant increase in investment and research related to green hydrogen. Many developed countries have announced their national strategies to encourage the production and utilization of green hydrogen, reflecting awareness of the key role of it in reducing carbon emissions and supporting energy security [16,17]. At the national level, Indonesia has also shown serious interest in the development of green hydrogen. The Indonesian government has embarked on initial steps to design policies and regulations that support the growth of the green hydrogen industry. This initiative also includes research and development support, as well as collaboration with the private sector to build supporting infrastructure [18]. Even in the 2021-2030 Electricity Supply Business Plan (RUPTL), PT Perusahaan Listrik Negara (PLN) has proposed the application of fuel cell technology collaboration, green hydrogen production, and NRE-based power plants as alternative models for sustainable NRE development for isolated areas [19].

A deep understanding of up-to-date information can be an important cornerstone in strategic decision-making, accelerating innovation, and achieving common goals. The study reported in this article focuses on the present status and potential for green hydrogen development in Indonesia. The discussion will be divided into several sections, starting with discussing the development and utilization of NRE in Indonesia as an energy driving for green hydrogen production, positioning green hydrogen in achieving the NZE target in 2060, existing policy and regulatory framework, research and development of green hydrogen by national research institutions, national hydrogen strategy by MEMR, existing green hydrogen pilot project, and challenges and future potential for green hydrogen. This study is expected to provide comprehensive information on the development of green hydrogen, including several recommendations related to steps to optimize the development of green hydrogen as one of Indonesia's future clean energy sources.

2. Methods

The method employed in this study is based on the research conducted by Pambudi et al., (2023) [20], ensuring that the process of preparing review articles should involve a series of systematic steps to ensure the analysis comprehensiveness and informativeness. In Figure 1, information is presented about the steps of working on this study.

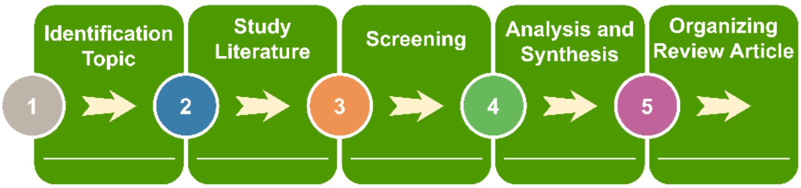

Figure 1. Structure of proposed method.

Figure 1 illustrates the five-stage process of working on this review article. The steps are described as follows:

1. Identifying the Research Topic: This first step involves selecting a topic to review. In this regard, the focus is on "Green Hydrogen in Indonesia," with the aim of providing an inclusive understanding of its present status, challenges, and future potential.
2. Conducting a Comprehensive Literature Review: The researchers then proceed to find appropriate and relevant articles related to green hydrogen according to the context of the chosen topic. This step involves a thorough review of academic manuscripts, government reports, industry publications, and other reliable sources to gather multiple perspectives on the subject.
3. Screening Process: Following the literature review, a selection process is undertaken to identify the most relevant and good quality sources of information. This step aims to ensure that the selected articles make a significant contribution in supporting an in-depth understanding of the topic to be researched.
4. Analysis and Synthesis: Afterwards, the collected articles are analyzed and synthesized. This step involves a thorough examination of the various perspectives, findings, and insights presented in the literature. The aim is to identify patterns, trends, and common themes related to the present status, challenges, and future potential of green hydrogen in Indonesia.
5. Compiling the Article Review: The insights gained from the previous steps are structured to create a review article. This synthesis is designed to provide a comprehensive picture of green hydrogen in Indonesia.

Such approach is employed to generate an article that can meet the desired objectives: to present an in-depth and informative analysis, assist in understanding the latest conditions, and detail the challenges and potential that may be faced and found in the future development of green hydrogen in Indonesia.

3. Green Hydrogen Development Status in Indonesia

3.1. Renewable energy potential for energy driving green hydrogen production in Indonesia

Indonesia as a country that has abundant energy resources with a very large, scattered, and diverse potential in NRE [21]. Based on data from MEMR, it has a potential of 3,766 GW of NRE, with details as presented in Table 1. This great potential is the main capital for Indonesia to realize the energy transition to clean energy through, among others, the green hydrogen scheme [22].

Table 1. **Potential and utilization of renewable energy in Indonesia [23]**

Types of Renewable Energy	Total Potential (GW)	Total Installed (MW)	% Utilization
Solar	3,294	271.6	0.008
Wind	155	154.3	0.100
Marine current power	142	0	0.000
Hydro energy	95	6,688.9	7.041
Bioenergy	57	3,086.6	5.415
Goethermal	23	2,355.4	10.241
Total	**3,766**	**12,556.8**	**0.333**

Table 1 reflects the great potential and utilization of NRE in Indonesia. However, its utilization is still very low, only reached 0.333% in 2022. Further efforts are needed to improve the utilization of other resources. The large opportunities for the utilization of NRE illustrate how great the potential for the development of green hydrogen production in Indonesia is.

Analysis of the potential production of green hydrogen from NRE in various regions in Indonesia, as presented in the NZE model by MEMR, is presented in Figure 2. Eight provinces show the most potential and are supported by the abundant diversity of NRE resources. The total green hydrogen production potential of the eight provinces in the NZE target for 2060 is 96,617 GWh, with details of each potential as presented in Figure 2.

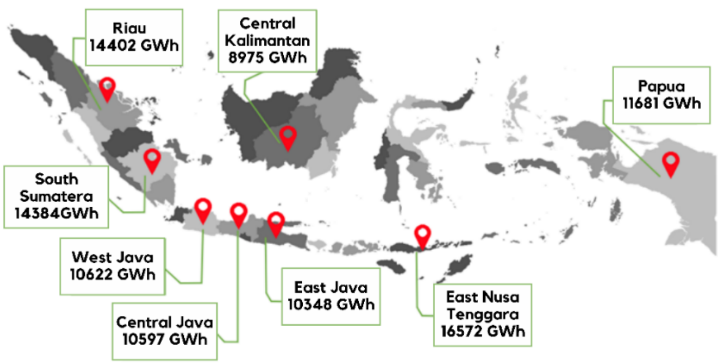

Figure 2. Map of the distribution of the most potential green H_2 production potential in 8 provinces in Indonesia.

Other than these eight provinces, 26 other provinces also have the potential to produce green hydrogen in the NZE target of 2060, albeit not to the same extent as the eight provinces. The combined potential of green hydrogen production by 26 provinces amounts to 87,517 GWh, bringing the total potential of 34 provinces in Indonesia to 185,134 GWh [24].

3.2. Green Hydrogen Policies and Regulation Overview in Indonesia

Comprehensive policies and regulations related to green hydrogen in Indonesia are currently still in the development stage and have not been fully defined in detail. However, the government has actually mentioned the importance of the role of green hydrogen as future energy in the net zero road map prepared by MEMR [25]. In Figure 3, information on policies and regulations that serve as a basic framework for green hydrogen development in Indonesia is presented.

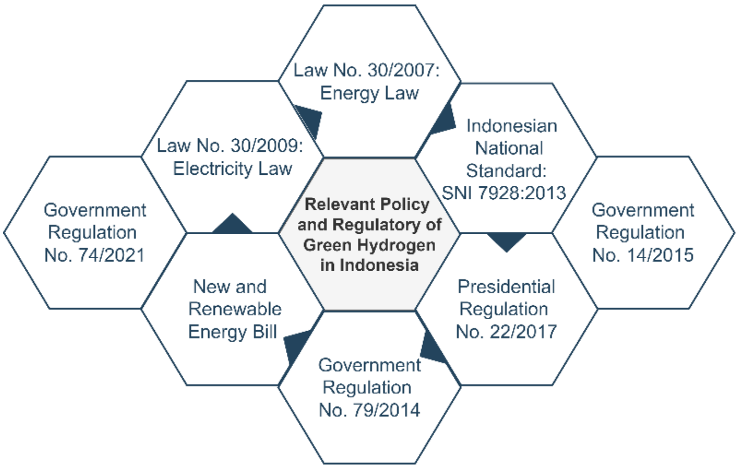

Figure 3. Summary of relevant base policy and regulatory framework on green hydrogen development.

Based on information from Figure 3, there are around eight policies and regulations that support the development of green hydrogen in Indonesia and supporting documents in the form of a national green hydrogen strategy. Supporting policies and regulations that already exist today can actually be used as the initial basis for development. However, these policies and regulations must of course be dynamic, thus requiring adjustment to technological developments and changes in energy needs. In general, the National Hydrogen Strategy (NHS) contains information regarding:

- Development of NRE resources for green hydrogen production.
- Development of efficient and affordable low carbon hydrogen production technology.
- Development of low carbon hydrogen transportation and storage infrastructure.
- Increasing the public and government awareness regarding the importance of developing low carbon hydrogen.

NHS is an important document that can be a guideline for the government, private sector, and community in developing low carbon hydrogen as a new and renewable energy source that is sustainable in Indonesia [24].

3.3. Green hydrogen Positioning in Indonesia NRE Development to achieve NZE 2060

The Government of Indonesia has identified the importance of green hydrogen in the energy transition process to achieve the NZE target by 2060 [26,27]. Despite the absence of target related to the composition of green hydrogen in the national energy mix target plan, explicitly, in the RUEN in Presidential Regulation (PERPRES) Number 22 of 2017, the government has mentioned the role of hydrogen as one of the new types of energy used to meet national energy needs. Based on the matrix of the RUEN program, the planned strategy in hydrogen utilization is the utilization of fossil-based hydrogen fuel in the transportation sector. The proposed programs and activities include the development of production technology and utilization of hydrogen fuel for transportation (2016-2050), preparation of regulations for hydrogen-fueled cars for public transportation and private vehicles (2016-2019), development of hydrogen-fueled motor vehicle industry (fuel cell) (2025-2050), provision of fiscal incentives for hydrogen-fueled vehicles in accordance with applicable tax and customs laws and regulations (2016-2050), and prototyping of commercial-ready hydrogen-fueled vehicles.

In the draft update of the National Energy Policy (KEN), in the energy transition scenario in Indonesia, low carbon hydrogen, including blue hydrogen and green hydrogen, is identified as a key strategy to achieve NZE conditions. In the national hydrogen development roadmap, hydrogen will be utilized in the transportation sector, especially for small truck vehicles using fuel cell technology, and will be utilized as a fuel for power plants for industries with low-temperature processes. In the draft update of KEN, the target of hydrogen utilization in 2035 for industry in the energy transition scenario (hydrogen power plants replacing fossil-powered plants) is around 1 MTOE and for the transportation sector (small trucks with fuel cell technology) is 2-3 MTOE [28].

The energy-producing industrial sector is the largest contributor to greenhouse gas emissions (46.35%) in Indonesia [29], since the electricity supply system is still dominated by conventional fossil fuel-powered plants. Therefore, in the energy supply scheme to achieve the NZE target, the government proposes the utilization of NRE, targeting hydrogen utilization of 52 GW by 2060. The following Figure 4 presents information provided by MEMR on the energy transition roadmap to achieve the NZE target in 2060.

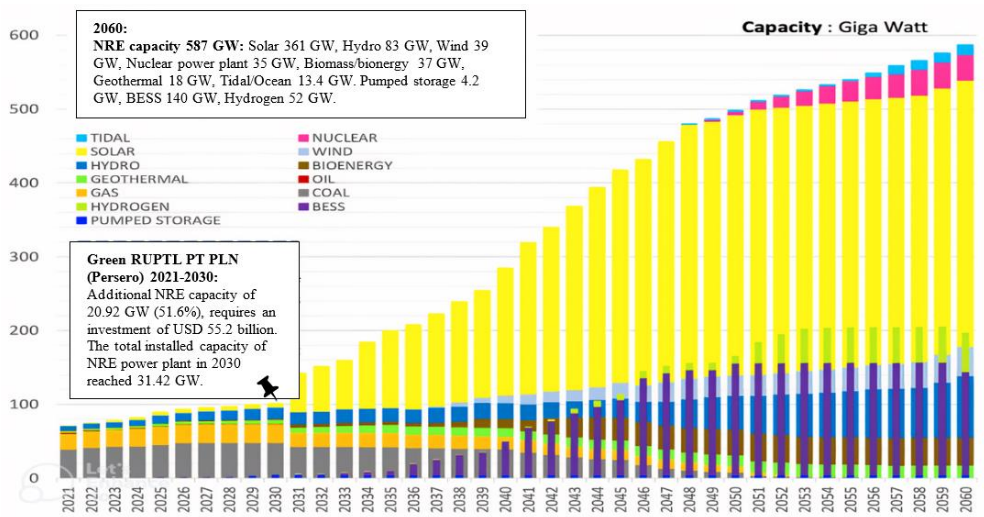

Figure 4. Roadmap of energy transition towards NZE target by 2060 [30].

Hydrogen utilization in the energy sector for the electricity sector proposed by the Ministry of Energy and Mineral Resources further strengthens the position of low carbon hydrogen in meeting the needs for clean energy in Indonesia. Based on these data, hydrogen utilization will begin in 2031. For the first phase (2031-2035), the second phase (2036-2040), the third phase (2041-2050), and the fourth phase (2051-2060), the hydrogen generation capacities targeted are 328 MW, 332 MW, 9 GW, and 52 GW, respectively. The estimated amount of investment needed is USD 0.8 – 25.2 billion (cumulative from 2031-2060) [31].

Indonesia's National Energy Council (DEN) has also drawn up a separate net-zero roadmap with different hydrogen targets. The DEN roadmap estimates that the demand for hydrogen will be around 8 TWh in the transportation sector by 2026. The figure will increase to 27 TWh in 2031, 76 TWh in 2041, and 103 TWh in 2051. This draft roadmap is still under discussion and will be included in the update of the National Energy Policy (KEN). Although the government has set long-term hydrogen projections, some consider the figure to be conservative. IESR even projects the annual final demand for green hydrogen in the energy sector will surpass 100 TWh by 2040 and 400 TWh by 2050 (excluding hydrogen used for synthetic fuel production). To achieve the target of net zero emissions by 2050, roughly half of this demand will come from the transport sector and the other half from industrial heat needs. Electrolyzer capacity is expected to reach 229 GW by 2050 to meet that demand, with most new capacity built after 2030 [31].

3.4. Green Hydrogen Technology Research and Development in Indonesia

The development of green hydrogen in Indonesia has actually started since around 2004, initiated by several research-based institutions including the Agency for the Assessment and Application of Technology (BPPT), the Indonesian Institute of Sciences (LIPI), the National Nuclear Energy Agency (BATAN), and several university-owned research institutions. In 2009 the development of a PEM-based green hydrogen prototype with a capacity of 500 mL/min and fuel cells with a capacity of 50 W. The development of green hydrogen has been continuing until now with its main driving institution, the National Research and Innovation Agency (BRIN). Currently, Indonesia has been able to make prototypes of hydrogen-fueled vehicles in the form of golf cars with a capacity of up to 2.5 kW [18,32]. However, to reach a higher stage, namely the green hydrogen society, there are still many challenges that need to be faced and require even greater resources. The following Figure 2 presents the timeline for the development of green hydrogen technology research in Indonesia initiated by BRIN.

The timeline in Figure 5 exhibits that BRIN has conducted numerous research and development of green hydrogen technology since 2006. The research covered various aspects, ranging from fuel cell components, hydrogen production, to fuel cell applications. The development of green hydrogen technology in Indonesia is important to support the energy transition to clean energy, bringing Indonesia to independently produce technology without having to rely on other countries' technology. To achieve technological independence, the government needs to focus on local research, technical education, and collaboration with universities and industry.

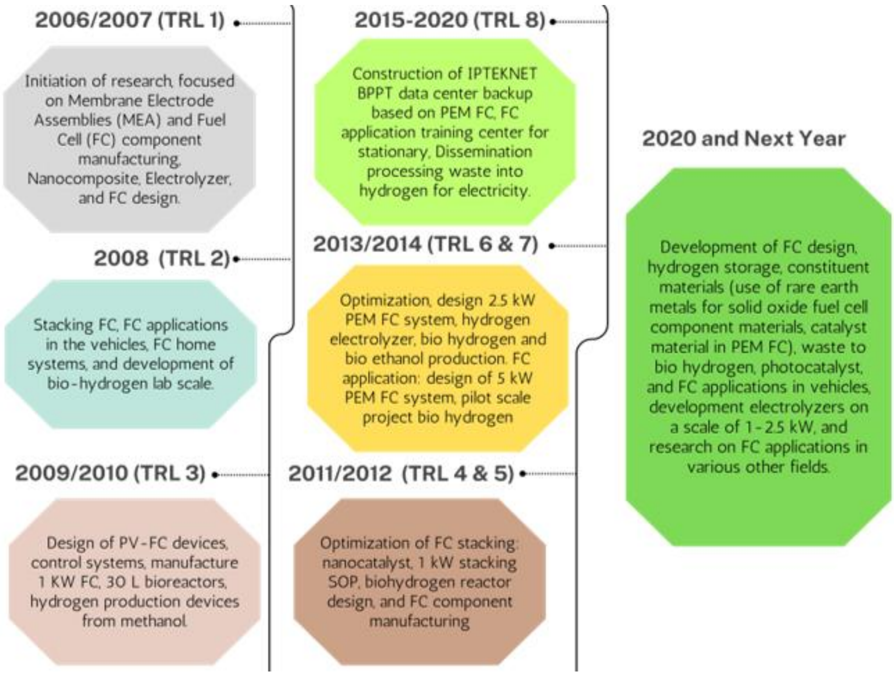

Figure 5. Timeline for the development of green hydrogen technology research in Indonesia initiated by BRIN.

3.5. Green Hydrogen Stakeholder Mapping in Indonesia

In developing green hydrogen in Indonesia, stakeholders play their significant role, especially in create a green hydrogen ecosystem that is technically, economically, socially, and environmentally sustainable [31]. Involving and coordinating all relevant parties, such as governments, energy companies, research institutions, communities, non-governmental organizations, private parties, and international partners, has a significant impact in realizing the development of green hydrogen as the clean energy of the future [33,34]. Figure 6 presents information on stakeholders who act as regulators representing the government and have a key role in the development of green hydrogen in Indonesia. They include the Ministry of Energy and Mineral Resources, Ministry of Industry, Ministry of Investment/Investment Coordinating Board, Ministry of Finance, Ministry of State-Owned Enterprises (BUMN), National Research and Innovation Agency, Ministry of Transportation, Ministry of Environment and Forestry, Ministry of Education, Culture, Research and Technology, Coordinating Ministry for Economic Affairs, Ministry of National Development Planning/National Development Planning Agency, Coordinating Ministry for Maritime Affairs and Investment, National Standardization Agency, National Energy Council. The regulators responsibilities include formulating energy and environmental policies that support green hydrogen development, providing incentives, regulating other supporting regulations, and implementing green hydrogen development programs.

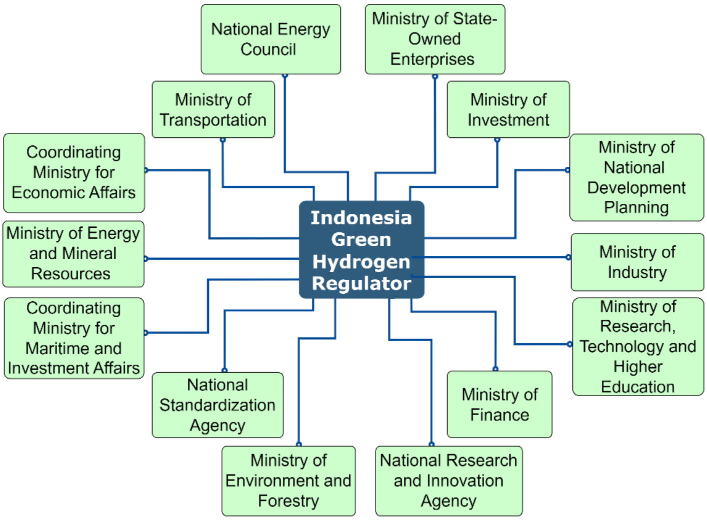

Figure 6. Stakeholder regulator green hydrogen development in Indonesia

Stakeholders in the context of green hydrogen development in Indonesia are not limited to regulators. Independent research institutions, university research institutions, non-governmental organizations, companies, and community groups also play an equally important role. Some private institutions that can be partners in green hydrogen development in Indonesia include The Institute for Essential Services Reform, International Energy Agency, International Renewable Energy Agency, ASEAN Center for Energy, Indonesia Fuel Cell and Hydrogen Energy, as well as research institutions affiliated with independent universities and research institutions such as the Center for Energy Studies of Universitas Gadjah Mada, Antasena-Surabaya Institute of Technology's hydrogen car research team, Fuel Cell and Hydrogen Research Center of Excellence of Universitas Sriwijaya, among others.

The companies that play a role as key players in the development of green hydrogen can be divided into several categories: PT PLN acts as a producer-demand entity, PT Pertamina is involved in distribution-production-demand, PT Krakatau Steel, PT Chandra Asri Petrochemical Tbk, and PT Pupuk Indonesia act as demand entities. PT Samator Indo Gas plays a role in production-distribution. PT Toyota Motor Manufacturing Indonesia and PT Yogya Presisi Tehnikatama Industri are involved in research development-manufacturing of technology devices. PT Air Products Indonesia is involved in production-distribution. Fortescue Future Industries, Hydrogene De France Energy, and Countrywide Hydrogen are involved in production, while PT Kereta Api Indonesia can play a role in research development-manufacturing of technology devices-demand. Overall, the presence of these companies indicates that Indonesia has great potential as key market players and in terms of green hydrogen technology development.

3.6. Hydrogen Utilization in Indonesia

Optimizing the utilization of low carbon hydrogen has great potential in supporting Indonesia's transition to clean energy sources. Low carbon hydrogen can be applied in various sectors. It can be used as an alternative fuel in transportation, industry, and the energy sector [35]. At present, in Indonesia, hydrogen has become part of the industrial sector, mainly used as a raw material in fertilizer production. Hydrogen utilized in Indonesia based on 2021 data reached around 1.75 million tons per year, dominated by the fertilizer sector, especially for urea production (88%), then ammonia (4%), and oil refineries (2%) [36], presented in Figure 7.

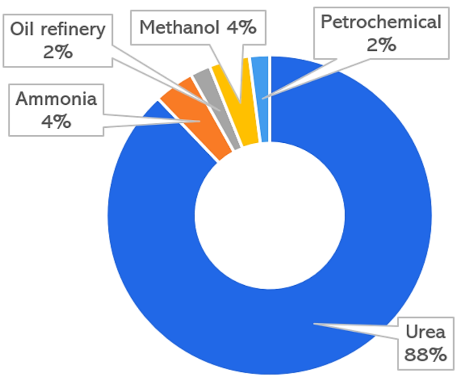

Figure 7. Hydrogen utilization existing in Indonesia

Most of the hydrogen used today in the industrial sector is sourced from natural gas. Of the total national gas production allocated to the industrial sector, about 11.2% is used as raw materials in the fertilizer industry to produce hydrogen and ammonia. According to Pertamina Power, it is estimated that the domestic hydrogen market currently reaches 1.3 MTPA, with more than 95% being captive demand, the details are around 1.1 MTPA for the fertilizer industry, 0.1 MTPA for oil refineries, and 0.1 MTPA for methanol. According to APOLIN, hydrogen is also needed in the oleochemical industry, especially to produce Fatty Alcohol and Saturate Fatty Acid [24]. In general, hydrogen in Indonesia is today sourced from fossil fuel and only used for the industrial sector. In fact, according to the NZE roadmap issued by the Ministry of Energy and Mineral Resources, hydrogen is projected to have a role in meeting energy needs in Indonesia. An overview of the plan of low carbon hydrogen utilization in Indonesia in the future is presented in Figure 8.

Figure 8. Plan of low carbon hydrogen utilization in Indonesia

A more detailed explanation or description of the plan of low carbon hydrogen utilize in Indonesia is as follows:

- **Industrial and feedstock**

Hydrogen utilization in the Indonesian industrial sector is directed to the fertilizer industry (ammonia), oil and gas refineries, steel, methanol, oleochemicals, refinery processes, and several other industries. Projections of demand for hydrogen as a raw material in the industrial sector are presented in Table 2.

Table 2. **Projections of the need for low carbon hydrogen as a raw material in the industrial sector [24]**

Type of Industry	Demand Projection (TWh/year)	Demand Projection (kilo ton/ year)	Estimated Time Utilization
Fertilizer	39.11	1185	2028
	43.99	1333	2029
	47.92	1452	2030
	48.31	1464	2032
	48.31	1464	2035
	48,31	1464	2040
	52.24	1583	2050
	76.73	2325	2060
Oil and Gas	75	2250	2022
Oleochemical	2.4	72	2022

Table 2 provides information on projections of demand for hydrogen in several industrial sectors. The fertilizer industry shows a significant increase in demand from 39.11 TWh in 2028 to 76.73 TWh in 2060. Given the low efficiency of hydrogen utilization, the application of hydrogen should indeed be suitable for sectors that can directly have a broad impact, such as the oil and gas industry sector [37], which initially demanded 75 TWh in 2022. The oleochemical industry is projected to demand 2.4 TWh. This projection analysis reflects a significant upward trend in hydrogen demand, particularly in the fertilizer industry, and highlights the need to develop hydrogen production capacity to support industry growth and the transition to clean energy.

- Transportation

Decarbonization of the transportation sector is a key focus in efforts to reduce greenhouse gas emissions. Low carbon hydrogen utilization is a promising solution in achieving this goal. Projections of hydrogen demand in the transportation sector are presented in Table 3.

Based on Table 3, the need for hydrogen to decarbonize the transportation sector in Indonesia will increase significantly in the future. Types of hydrogen-based transportation that are suitable for application are public transportation or industrial vehicles. According to the ASEAN Center for Energy (ACE), hydrogen for transportation has several advantages compared to battery-based electric vehicles [38]. The Ministry of

Transportation's planning states that a portion of the bus fleet is planned to switch to hydrogen by 2040, with an initial hydrogen requirement of around 6 GWh or equivalent to 0.21 kilo tons. This use will be sustainable and increase to reach 1.18 kilo tons by 2060. Furthermore, hydrogen demand for heavy transport vehicles is expected to reach 161 GWh (equivalent to 4.88 kilo tons of H2) by 2040, and will increase to 930.6 GWh (equivalent to 28.2 kilo tons of H2) by 2060. Meanwhile, for rail transportation, PT KAI has a development strategy to replace locomotives with electric rail trains that incorporate Fuel cell and/or battery technology in their system [24]. Total hydrogen demand for transportation in 2060 is expected to approach 1.6 million tons per year, with freight transport as the largest consumer (70%).

Table 3. **Hydrogen demand projected in the transportation sector [24]**

Type of Transportation	**Demand Projection (TWh/year)**	**Demand Projection (kilo ton/ year)**	**Estimated Time Utilization**
Shipping (for ammonia)	57.8	1536	2060
Shipping	12.8	384	2060
Freight transportation	0.16	4.8	2040
	0.93	28,2	2060
Bus	0.006	0.21	2040
	0.038	1.2	2060

- Power Plant

In the power generation sector, low-carbon hydrogen and ammonia derived from renewable energy sources can be used as co-firing fuel in Gas Power Plants (PLTG), Steam Gas Power Plants (PLTGU), and Gas Engine Power Plants (PLTMG). Hydrogen in co-firing can reduce natural gas consumption by 397,764.84 MMSCF/year, and reduce greenhouse gas emissions by 10,588,235-tons CO2-eq. Hydrogen can also be utilized to support dedieselization initiatives by utilizing fuel cells to replace Diesel Power Plants (PLTD). PT PLN projects the potential of hydrogen for dedieselization of around 3,100 GWh/year or around 93,939 tons of hydrogen/year. PLN has initiated several projects for hydrogen and ammonia co-firing, as well as fuel cell utilization [24]. In addition to the program to meet the electricity needs of the community, the utilization of hydrogen fuel cells in Indonesia is also used to meet the electricity needs of the Base Transceiver Station (BTS) telecommunications system [39]. Table 4 presents information on the projected demand for hydrogen in the power generation sector, especially in the scheme as a co-firing fuel.

Table 4. **Hydrogen demand projected in the power generation sector [24]**

Type of Power Plant	Demand Projection (TWh/year)	Demand Projection (kilo ton/ year)	Estimated Time Utilization
Gas-fired power plant	118.4	3552	2060
Co-firing steam power plant	102.2	3066	2060

- Heating

The need for hydrogen for high-temperature heating in the industrial sector plays a key role in the transformation towards cleaner and more sustainable production [40]. In the metal industry, hydrogen is utilized for smelting and forming metals at high temperatures, while in the ceramic industry, it is utilized for combustion and hardening. The paper industry utilizes it at high temperatures in the bleaching process and processing of wood fibers for papermaking. Projections of hydrogen demand in the high-temperature heating sector for industry are presented in Table 5.

Table 5. **Hydrogen demand projected in the industrial high-temperature heating sector [24]**

Type of Industry	Demand Projection (TWh/year)	Demand Projection (kilo ton/ year)	Estimated Time Utilization
Metal	11	330	2060
Ceramics	5.6	168	2060
Paper	12.7	381	2060

Table 5 shows that hydrogen for high temperatures will begin to undergo significant changes in 2060. The total need for hydrogen for high-temperature heating processes in 2060 is around 29.4 TWh or about 879 kilo tons. Furthermore, Figure 9 presents information on the projected total demand for low carbon hydrogen in Indonesia based on modeling in achieving the NZE target by MEMR.

Demand for low-carbon hydrogen is expected to experience significant growth, starting at around 0.2 PJ (equivalent to 26,000 barrels of oil) in 2031, rising to 34.3 PJ in 2040, and peaking at 609 PJ in 2060.

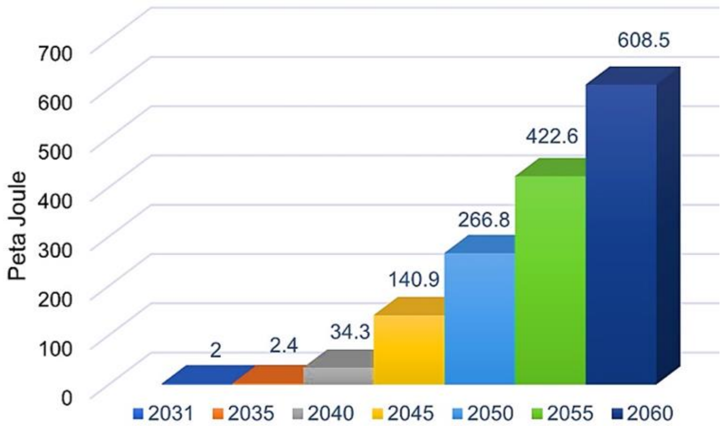

Figure 9. Hydrogen demand projection for 2031-2060 in the NZE model of MEMR [24]

3.7. Development Plan and Project for Green Hydrogen Utilization in Indonesia

The advancement of green hydrogen in Indonesia is presently in its early stages, with development efforts just underway. However, the government has initiated pilot projects for green hydrogen construction in various Indonesian regions, either through state-owned enterprises (SOEs) independently or in partnership with private entities [41]. Table 6 presents several pilot project plans for green hydrogen development in Indonesia.

Table 6. **Green hydrogen development plan in Indonesia**

Project Name	Location	Description
Hydrogen de France SA (HDF Energy) dan PT PLN	Sumba Island, Nusa Tenggara Timur (NTT) Province	Combination of Solar PV/Wind, battery, and hydrogen system (electrolysis and fuel cell). Current status: still being tested for its feasibility and is expected to be operational in 2024. Daytime power generation capacity: 7-8 mW; night power capacity: 1-2 mW [12,42].
PT Pertamina NRE dan TEPCO HD	Ulubelu, Tenggamus Regency, Lampung Province	Combination of hydrogen system and geothermal power plant (PLTP), with a production capacity of 100 kg /day. 20% of the production is sent to Pertamina's Refinery in Plaju. The project will be jointly developed with Tokyo Electric Power Company Holdings (TEPCO HD) [12,43].

Project Name	**Location**	**Description**
Indonesia Fortescue Future Industries (FFI) dan Pemprov KALTARA	Kalimantan Utara (KALTARA) Province	Combining green hydrogen and green ammonia production systems. The electricity used, with a projected capacity of 9000 MW, is sourced from the Kayan River Hydropower Plant. Ammonia production capacity is 300 tons per day or about 100 thousand tons per year [44,45].
Ibu Kota Negara (IKN)	Kalimantan Timur Province	BEV and FCEV are projected to be public transportation in IKN. Hydrogen is also set as an alternative to energy storage and as city gas [46,47].
PLN co-firing hidrogen dan amonia	Tanjung Priok, Pesanggaran, Keramasan, and Gresik	PT PLN together with Mitsubishi Heavy Industries (MHI), is conducting a technical and economic feasibility study on co-firing hydrogen and ammonia with biomass at power plants in Indonesia [24,48,49].
PT Pupuk Indonesia dan ACWA Power	n.a	The scope of the cooperation, namely Pupuk Indonesia will examine green hydrogen projects including downstream production of green chemicals such as methane, methanol, and ammonia, as well as the scope of power plants [50].
PT Pupuk Indonesia dan Japan Bank for International Cooperation (JBIC)	n. a	Pupuk Indonesia and JBIC agreed to exchange information related to the potential cooperation between Pupuk Indonesia and a number of Japanese companies in the field of ammonia, hydrogen, and renewable energy supply chains. JBIC will also provide financing support for potential projects [51,52].
PT Bakrie & Brothers Tbk and Envision Group	n.a	In the initial stage, a net zero industrial park will be established in the Sulawesi Tengah area, followed by the development of EBT projects, including green hydrogen projects [53].
Global Green Growth Institute (GGGI) bekerja sama dengan Samsung dan Hyundai	Sei Mangkei Special Economic Zone, Sumatra Utara	GGGI collaborates with Samsung and Hyundai plans to participate in green hydrogen development projects in Indonesia. This project will use geothermal and hydro power plants to produce green hydrogen [54]. Hydrogen from geothermal sources in the Sarulla Block will be supplied to the nearby Sei Mangkei Industrial Estate as fuel for steelmaking and cement [24].
Go Green Fuel Cell BTS Telkomsel	BTS in North Sumatra	Go Green Fuel Cell on BTS is one of Telkomsel's commitments in using NRE in the Telecommunications industry. 2021 data informs that there are already around 216 Go Green Fuel Cell BTSs throughout Indonesia, with 95 BTSs spread across the Northern Sumatra region. Go Green Fuel Cell technology utilizes Hydro Plus fuel (Methanol &; Water Mixture) to produce energy [55,56].

Project Name	Location	Description
PT PLN "Green Hydrogen Plant"	21 generating units owned by PT PLN (scattered)	PT PLN (Persero) has developed 21 units of Green Hydrogen Plant (GHP) spread throughout Indonesia;12 units are from PLN Indonesia Power, 8 units are from PLN Nusantara Power, and 1-unit is from the Main Plant (UIK) of Tanjung Jati B. The combined production capacity of the 21 units is expected to reach 199 tons per year, with an excess production of 124 tons per year [57,58].

Besides pilot projects, various low-carbon hydrogen development initiatives in Indonesia take the form of studies, collaborations, and investment plans like collaborations between BRIN and Toshiba EES for an autonomous off-grid hydrogen energy system project in 2018 and the contracted agreement between Indonesia Railway Company (PT. KAI) and ALSTOM for the delivery of a hydrogen-powered train project in 2019-2020 [59].

4. Green Hydrogen Development Challenges

In recent years, Indonesia has initiated several pilot projects for the production and utilization of low carbon hydrogen. The abundant potential of NRE is one of the main drivers of the development of the green hydrogen industry. Below are some explanations of the challenges faced in the development of green hydrogen in Indonesia.

From the technical side, the first challenge lies in production efficiency and utilization. In the power-to-power application scheme, currently, the overall round-trip efficiency falls within the range of 30-40%, with utilization limited to off-grid conditions only. Of course, this efficiency is affected by the losses of several factors, including electrolyzer efficiency, conversion process, transportation, and afuel cell or combustion efficiency, among others [60,61].

Another technical problem is related to the process of storing and distributing hydrogen, especially for the territory of Indonesia which has characteristics of archipelagic countries. In general, hydrogen can usually be stored in gaseous and liquid form or converted into the form of other chemical compounds such as ammonia. Storage of hydrogen in gaseous form requires a high-pressure tank; if stored in liquid form, it requires cryogenic temperatures due to its very low boiling point. Meanwhile, if stored in the form of ammonia, a longer chemical process is needed for the decomposition process [62,63].

Another challenge relates to the provision of feedwater. To maintain the lifetime and efficiency of electrolyzer production, it is recommended to use ultrapure water type (ASTM I and II) [64]. In terms of utilization, technical challenges include ensuring the provision of hydrogen with ultra-high purity levels, especially when using fuel cells, where recommended purity hydrogen levels reach 99.999%. In addition, the provision of fuel cell technology with high efficiency will be quite challenging, as current fuel cell efficiency levels fall within the range of 40-60% [65].

In the processes of production, storage, distribution, and utilization of green hydrogen, supporting infrastructure plays the key role in realizing the green hydrogen economy [66] Establishing such infrastructure requires significant investment funds, posing an economic challenge for Indonesia. The primary economic challenge remains the high cost of producing low carbon hydrogen. Currently, the most significant component of production costs is the expense of electricity generated from renewable energy sources, accounting for approximately 70% of the total [24].

In addition to technical problems, in the application of green hydrogen economy, Indonesia faces problems related to the limited production and utilization of hydrogen. In general, hydrogen is currently mostly only utilized as a non-fuel chemical, despite its potential to be used in various industries. In terms of production, currently, Indonesa has only a small number of large-scale hydrogen production companies. Only 4 large companies have been supporting hydrogen needs in Indonesia [67].

In the social sphere, the most significant challenge in the commercialization of green hydrogen worldwide, including in Indonesia, is concern about the matter of safety. Although hydrogen has a number of advantages as a clean fuel, the potential for fires and explosions resulting from leaks or misuse can create mistrust and concern among the public [68]. One specific indicator that can be used to see social tendencies related to public acceptance of new energy systems is the Human Development Index Pool Index (HPI). With an HPI value of 0.0567, Indonesia ranks second lowest after Vietnam among 10 other countries in the Asia Pacific region. This shows that, compared to other countries in the group, the general public in Indonesia is unlikely to have a significant interest in hydrogen energy system initiatives [13].

In addition to the technical, economic, and social aspects, regulations also play a crucial role in the development of green hydrogen. Clear regulations and supportive policies can create a conducive environment for investment in green hydrogen projects [69][70]. In Indonesia, no comprehensive technical regulatory framework governing green hydrogen in terms of production, storage, transportation, and utilization of hydrogen is available. The lack of national standards for hydrogen infrastructure and the absence of detailed regulations on fiscal or non-fiscal support from governments are also challenging.

5. Conclusions and Recommendations

In general, the Indonesian government has taken concrete steps to overcome various barriers to develop renewable energy in Indonesia, including regarding low carbon hydrogen. However, grappling with intricate challenges, particularly in the nascent stage of green hydrogen in Indonesia, requires additional efforts from relevant stakeholders. The following proposed recommendations aim to help stakeholders to achieve and bolster the development of the green hydrogen economy in the energy transition:

- Setting coherent targets related to the production, utilization, and penetration of low carbon hydrogen across various sectors. The targets must be measurable, realistic, and closely related to the achievement of NZE in 2060. The government shall immediately make updates to KEN and RUEN, so that the position and role of low carbon hydrogen appears clearer, especially related to special policies on its utilization in the transportation sector. The development of a clear and integrated set of procedures to accelerate the licensing and development of hydrogen projects also needs to be performed by the government to maintain the green hydrogen investment climate.
- In-depth research and development to address efficiency issues need to be performed. The focus on improving efficiency can be applied to electrolyzers through the development of electrode materials, catalysts, cell design, and identification of the latest technologies. Research addressing the reliable and fast performance of hydrogen sensors is imperative. In the context of utilization, research needs to focus on improving the efficiency of fuel cell technology or hydrogen combustion methods. Furthermore, innovations in the process of carrier energy conversion during production and distribution are also necessary. Under coordination of BRIN involving various research institutions, a national research roadmap can be formulated to support the development of green hydrogen technology.
- From the point of view of green hydrogen utilization and commercialization, at an early stage, the government should

prioritize investigating the role of green hydrogen in integrating various energy systems and its application in sectors with the highest economic value, with public transportation taking precedence. To create a sustainable hydrogen economy ecosystem, it is necessary to increase commercial demand for green hydrogen through the development of a robust domestic market and enhance export competitiveness.

- In terms of increasing networking and collaboration, the provision of collaborative platforms and strategic partnerships that serve as a medium for regular meetings, knowledge exchange, and coordination between parties involved in the development of green hydrogen is crucial. Network development and collaboration can also be carried out at both national and international levels. Cooperation can be done by establishing formal agreements with partner countries through the exchange of knowledge, experience, and technology with countries that have achieved significant progress.
- Establishing a supportive financial environment is a recommended strategy. In this phase, the government under the coordination of the Ministry of Investment and Finance and several related institutions can design efficient and targeted subsidy policies. Subsidies can be provided at an early stage to stimulate investment and reduce financial risks. In addition, fiscal incentives such as tax breaks or import duty reductions for production equipment and infrastructure and the provision of competitive electricity tariffs can also be implemented. The government additionally can foster the provision of special investment funds for green hydrogen projects through innovative funding schemes involving public and private sector partnerships.
- Infrastructure is a critical element in the development of green hydrogen. Immediate arrangement of a comprehensive and targeted infrastructure development masterplan by prioritizing green hydrogen development is imperative. Integrated Infrastructure Development, covering production, storage, and distribution infrastructure, is one form of initiative that needs attention. The government can also encourage the acceleration of the construction of renewable energy electricity production facilities and public hydrogen charging stations to support the adoption of hydrogen-powered vehicles.
- Concerns related to the acceptance of green hydrogen economy development in Indonesia are important social issues to consider,

requiring adopting a comprehensive approach in order to grow the level of public acceptance. Initiating an intensive education campaign and government cooperation with other parties to provide accurate information so that information dissemination can be carried out in various sources massively is recommended to overcome such issues. In addition, the government can also promote direct community involvement in the development of green hydrogen projects, establish partnership programs with local communities, support job training and skills development to empower local communities, and provide support for the establishment of independent monitoring agencies tasked with monitoring the impact of green hydrogen projects on communities and the environment.

These recommendations are of course inseparable from the projection of green hydrogen which will be one of the contributors to the energy transition and has an important role in decarbonizing the energy system in Indonesia. The Government of Indonesia through the Ministry of Energy and Mineral Resources (MEMR) has published a National Hydrogen Strategy document that can be used as based guidelines for the development of low carbon hydrogen in meeting energy needs in various sectors, such as industry, transportation, and power plants to support the achievement of the NZE 2060 target. Indonesia is one of the countries that has great potential to become a major player in the global green hydrogen market. The total potential of green hydrogen production from 34 provinces in Indonesia reaches 185,134 GWh. Furthermore, when viewed in terms of policies and regulations, currently there are no comprehensive policies and regulations related to green hydrogen as Indonesia in this case is still in the development stage, so policies and regulations cannot be fully defined in detail. At present, the utilization of existing hydrogen is still dominated by the industrial sector and most of the hydrogen is obtained from natural gas. The use of hydrogen in Indonesia based on 2021 data has only reached around 1.75 million tons per year, most of which is utilized in the fertilizer sector, especially for urea production. The government has planned to diversify hydrogen utilization and replace hydrogen derived from fossil fuels with low carbon hydrogen. Demand for low carbon hydrogen is expected to experience significant growth from 2031 to 2060. However, there are several complex obstacles that need to be faced and overcome in the realization of green hydrogen utilization. These challenges can come from technical, economic, social, and regulatory domains, necessitating collaborative efforts between the Government and related stakeholders. Through close cooperation, it is anticipated that the development of the green hydrogen industry in Indonesia can run smoothly and achieve the predefined targets.

REFERENCES

[1] *S. Gota, C. Huizenga, K. Peet, N. Medimorec, and S. Bakker*, "Decarbonising transport to achieve Paris Agreement targets," Energy Effic., vol. 12, no. 2, pp. 363–386, Feb. 2019, doi: 10.1007/s12053-018-9671-3.

[2] *M. Meinshausen et al.*, "Realization of Paris Agreement pledges may limit warming just below 2 °C," Nature, vol. 604, no. 7905, pp. 304–309, Apr. 2022, doi: 10.1038/s41586-022-04553-z.

[3] *E. A. Morgan, J. Nalau, and B. Mackey*, "Assessing the alignment of national-level adaptation plans to the Paris Agreement," Environ. Sci. Policy, vol. 93, no. June 2018, pp. 208–220, 2019, doi: 10.1016/j.envsci.2018.10.012.

[4] *W. S. A. Saunders, S. Kelly, S. Paisley, and L. B. Clarke*, "Progress Toward Implementing the Sendai Framework, the Paris Agreement, and the Sustainable Development Goals: Policy from Aotearoa New Zealand," Int. J. Disaster Risk Sci., vol. 11, no. 2, pp. 190–205, Apr. 2020, doi: 10.1007/s13753-020-00269-8.

[5] *A. A. Akaev and O. I. Davydova*, "A Mathematical Description of Selected Energy Transition Scenarios in the 21st Century, Intended to Realize the Main Goals of the Paris Climate Agreement," Energies, vol. 14, no. 9, p. 2558, Apr. 2021, doi: 10.3390/en14092558.

[6] *UNFCCC*, "Enhanced Nationally Determined Contribution Republic of Indonesia," 2022. [2024-02-02]. https://unfccc.int/sites/default/files/NDC/2022-09/23.09.2022_Enhanced%20NDC%20Indonesia.pdf.

[7] *Cierra Group and PT Hatfield Indonesia (PTHI)*, "Final SESA Scoping Report: Strategic Environmental and Social Assessment (SESA) of the Energy Transition Mechanism (ETM) in Indonesia," 2023. [2024-02-02]. https://fiskal.kemenkeu.go.id/docs/SESA_Scoping_Report_EN.pdf.

[8] *Arief Heru Kuncoro et al.*, "Fuel Demand Analysis on the Optimization of Sustainable Electricity System Expansion Planning 2021-2050 in West Kalimantan," Evergreen, vol. 10, no. 3, pp. 1683–1694, Sep. 2023, doi: 10.5109/7151717.

[9] *A. Rahman, R. Richards, P. Dargusch, and D. Wadley*, "Pathways to reduce Indonesia's dependence on oil and achieve longer-term decarbonization," Renew. Energy, vol. 202, no. November 2022, pp. 1305–1323, Jan. 2023, doi: 10.1016/j.renene.2022.11.051.

[10] *A. Kovač, M. Paranos, and D. Marciuš*, "Hydrogen in energy transition: A review," Int. J. Hydrogen Energy, vol. 46, no. 16, pp. 10016–10035, Mar. 2021, doi: 10.1016/j.ijhydene.2020.11.256.

[11] *Y. Zhang, D. Davis, and M. J. Brear*, "The role of hydrogen in decarbonizing a coupled energy system," J. Clean. Prod., vol. 346, no. March, p. 131082, Apr. 2022, doi: 10.1016/j.jclepro.2022.131082.

[12] *IESR*, "Indonesia Energy Transition Outlook 2023: Tracking Progress of Energy Transition in Indonesia: Pursuing Energy Security in the Time of Transition," Jakarta, 2022. [2024-02-02]. https://iesr.or.id/wp-content/uploads/2022/12/Indonesia-Energy-Transition-Outlook_2023.pdf.

[13] *H. B. Aditiya and M. Aziz*, "Prospect of hydrogen energy in Asia-Pacific: A perspective review on techno-socio-economy nexus," Int. J. Hydrogen Energy, vol. 46, no. 71, pp. 35027–35056, Oct. 2021, doi: 10.1016/j.ijhydene.2021.08.070.

[14] *B. E. Lebrouhi, J. J. Djoupo, B. Lamrani, K. Benabdelaziz, and T. Kousksou*, "Global hydrogen development - A technological and geopolitical overview," Int. J. Hydrogen Energy, vol. 47, no. 11, pp. 7016–7048, Feb. 2022, doi: 10.1016/j.ijhydene.2021.12.076.

[15] *D. Gunawan*, "Unlocking the Potential of Hydrogen in Indonesia," in Indonesia Post-Pandemic Outlook: Strategy towards Net-Zero Emissions by 2060 from the Renewables and Carbon-Neutral Energy Perspectives, Penerbit BRIN, 2022, pp. 209–235.

[16] *T. Capurso, M. Stefanizzi, M. Torresi, and S. M. Camporeale*, "Perspective of the role of hydrogen in the 21st century energy transition," Energy Convers. Manag., vol. 251, no. September 2021, p. 114898, Jan. 2022, doi: 10.1016/j.enconman.2021.114898.

[17] *C. Kim, S. H. Cho, S. M. Cho, Y. Na, S. Kim, and D. K. Kim*, "Review of hydrogen infrastructure: The current status and roll-out strategy," Int. J. Hydrogen Energy, vol. 48, no. 5, pp. 1701–1716, Jan. 2023, doi: 10.1016/j.ijhydene.2022.10.053.

[18] *Indonesia Fuel Cell and Hydrogen Energy (IFHE) and Badan Riset dan Inovasi Nasional (BRIN)*, Indonesia Hidrogen Roadmap. IFHE Press, 2023. https://ifhe.or.id/wp-content/uploads/2023/06/indonesia%20hidrogen%20roadmap.pdf.

[19] *PT. Perusahaan Listrik Negara*, "Rencana Usaha Penyediaan Tenaga Listrik 2021-2030," 2021. [2024-02-02]. https://web.pln.co.id/statics/uploads/2021/10/ruptl-2021-2030.pdf.

[20] *N. A. Pambudi et al.*, "Renewable Energy in Indonesia: Current Status, Potential, and Future Development," Sustainability, vol. 15, no. 3, p. 2342, Jan. 2023, doi: 10.3390/su15032342.

[21] *J. Langer, J. Quist, and K. Blok*, "Review of Renewable Energy Potentials in Indonesia and Their Contribution to a 100% Renewable Electricity System," Energies, vol. 14, no. 21, p. 7033, Oct. 2021, doi: 10.3390/en14217033.

[22] *N. A. Zahra*, "Green Hydrogen Energy Technology for Zero Carbon Emission Realization in Indonesia," Int. J. Bus. Manag. Technol., vol. 6, no. 1, pp. 148–151, 2022.

[23] *DITJEN EBTKE*, "Laporan Kinerja DITJEN EBTKE KESDM 2022," 2023. [2023-12-10]. https://ebtke.esdm.go.id/post/2023/05/05/3473/laporan.kinerja.ditjen.ebtke.tahun.2022.

[24] *Kementerian Energi Dan Sumber Daya Mineral Republik Indonesia*, "Strategi Hidrogen Nasional," 2023. [2024-02-02]. https://ebtke.esdm.go.id/flippdf/elibrary.html#pdfflip-PDFF-41.

[25] *EBTKE Press*, "Hidrogen Didorong Jadi Kontributor Transisi Energi Indonesia," Direktorat Jenderal EBTKE, 2022. https://ebtke.esdm.go.id/post/2022/02/23/3094/hidrogen.didorong.jadi.kontributor.transisi.energi.indonesia (accessed Nov. 13, 2023).

[26] *BAPPENAS*, "A Green Economy for A Net-Zero Future: How Indonesia can build back better after COVID-19 with the Low Carbon Development Initiative (LCDI)," Minist. Natl. Dev. Plan., vol. 12, no. 4, pp. 1–108, 2021.

[27] *Z. Arifin*, "The Feasibility of Green Hydrogen for Power Generation in Indonesia," 2022, no. April, doi: http://dx.doi.org/10.13140/RG.2.2.15250.32963.

[28] *Dewan Energi Nasional*, "Arah Perkembangan Pemanfaatan Energi Hidrogen di Indonesia," 2023. [2024-02-02]. https://den.go.id/berita/arah-perkembangan-pemanfaatan-energi-hidrogen-di-indonesia.

[29] *S. D. B. Fadhilah, A. Ghozali, and R. Yorika*, "Analysis of Household Primary CO2 Emissions Gas in Muara Rapak, Balikpapan City in 2020," Ruang, vol. 8, no. 1, pp. 47–57, 2022.
[30] *ERIA Study Team*, "By-Country Situation and Perspectives : Study on Enhanced Flexibilisation of Coal-fired Power Plants for Optimal Grid Stabilisation in the ASEAN Region," Jakarta, 2022. (Vol. FY2022, Issue 02). [2024-02-02]. https://www.eria.org/uploads/media/Research-Project-Report/2022-02-Enhanced-Flexibilisation-Coal-fired-Power-/7_Ch.3-By-Country-Situation-and-Perspective.pdf.
[31] *IESR*, "Green Hydrogen in Indonesia Stakeholders, Regulations and Business Prospects," 2022. [2023-11-02]. https://ekonidid.sharepoint.com/:b:/g/EZI9srw4CkRMgpKSvs04wp0Bsk5hsVzkWKKxv-I0e6EGZw?e=fpbEnC.
[32] *Media Indonesia*, "BRIN: Era Mobil Bertenaga Hidrogen Mulai di 2030," Media Indonesia, pp. 1–6, 2023. [2024-02-02]. https://mediaindonesia.com/ekonomi/600132/brin-era-mobil-bertenaga-hidrogen-mulai-di-2030.
[33] *I. Marouani et al.*, "Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future," Processes, vol. 11, no. 9, p. 2685, Sep. 2023, doi: 10.3390/pr11092685.
[34] *Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur*, "Green hydrogen: A pathway to a sustainable energy future," Int. J. Hydrogen Energy, vol. 50, pp. 310–333, Jan. 2024, doi: 10.1016/j.ijhydene.2023.08.321.
[35] *E. S. Hanley, J. Deane, and B. Ó. Gallachóir*, "The role of hydrogen in low carbon energy futures–A review of existing perspectives," Renew. Sustain. Energy Rev., vol. 82, no. January 2017, pp. 3027–3045, Feb. 2018, doi: 10.1016/j.rser.2017.10.034.
[36] *International Energy Agency (IEA)*, "An Energy Sector Roadmap to Net Zero Emissions in Indonesia," 2022. doi: 10.1787/4a9e9439-en.
[37] *N. A. C. Lestari, W. A. Nugroho, and H. Nugroho*, "Analisis Komparasi Jenis Teknologi Elektrolisis Hidrogen Sebagai Alternatif Energi Bersih di Indonesia," Energi dan Kelistrikan J. Ilm., vol. 14, no. 2, pp. 196–206, 2022, doi: https://doi.org/10.33322/energi.v14i2.1646.
[38] *ASEAN Centre for Energy*, "Hydrogen in ASEAN: Economic Prospects, Development, and Applications," Jakarta, 2021. [2024-02-02]. https://accept.aseanenergy.org/hydrogen-in-asean-economic-prospects-development-and-applications/.
[39] *World Bank*, "Green Hydrogen in Developing Countries," Washington DC, 2020. [2024-02-02]. https://documents1.worldbank.org/curated/en/953571597951239276/pdf/Green-Hydrogen-in-Developing-Countries.pdf.
[40] *IESR, Agora Energiewende, and LUT University*, "Deep decarbonization of Indonesia's energy system : A pathway to zero emissions," 2021. [2024-02-02]. https://iesr.or.id/wp-content/uploads/2021/05/IESR-Deep-Decarbonization-Final.pdf.
[41] *Dewan Energi Nasional*, Outlook Energi Indonesia 2022. Sekretariat Jenderal Dewan Energi Nasional, 2022. [2023-12-10]. https://den.go.id/publikasi/indonesia-energy-outlook#.
[42] *Gigih Udi Atmo*, "Emerging Technologies Untuk Mencapai Net Zero Emission Di Indonesia 2060," 2023. https://caseforsea.org/wp-content/uploads/2023/03/PENGGANTI-GIGIH-060323-Emerging-Technologie-NZE-CASE_Bappenas.pdf (accessed Feb. 02, 2024).
[43] *C. A. Filemon Patra*, "Pengembangan Energi Terbarukan Dalam Upaya Mewujudkan Pembangunan Berkelanjutan di PT. PERTAMINA," J. Green Growth dan Manaj. Lingkung., vol. 11, no. 2, pp. 113–122, Aug. 2022, doi: 10.21009/jgg.v11i2.28358.

[44] *I. M. S. Sayekti*, “Pembangunan Konstruksi Bendungan PLTA Kayan Cascade Ditargetkan Mulai Tahun Depan,” 2023. https://pressrelease.kontan.co.id/news/pembangunan-konstruksi-bendungan-plta-kayan-cascade-ditargetkan-mulai-tahun-depan (accessed Feb. 02, 2024).

[45] *R. Sayuti*, “PT KHE Target Pembangunan Konstruksi Bendungan PLTA Sungai Kayan Dimulai Tahun Depan,” 2023. https://www.rri.co.id/daerah/476207/pt-khe-target-pembangunan-konstruksi-bendungan-plta-sungai-kayan-dimulai-tahun-depan (accessed Feb. 02, 2024).

[46] *CNN Indonesia*, “OIKN: Kendaraan BBM Dilarang Masuk IKN,” CNN Indonesia, Sep. 27, 2023. https://www.cnnindonesia.com/otomotif/20230927201625-603-1004605/oikn-kendaraan-bbm-dilarang-masuk-ikn.

[47] *Z. Nadya*, “Kejar Target Net Zero , IKN akan Pakai Hidrogen Hijau pada 2038,” Katadata.co.id, no. September, Sep. 12, 2023. [2024-02-02]. https://katadata.co.id/happyfajrian/ekonomi-hijau/650050f576d30/kejar-target-net-zero-ikn-akan-pakai-hidrogen-hijau-pada-2038.

[48] *Harmanta*, “PLN Uji Coba Co-Firing Amonia dan Hidrogen pada Pembangkit Listrik,” Radio Republik Indonesia, Nov. 03, 2022. [2024-02-02]. https://www.rri.co.id/ daerah/78058/pln-uji-coba-co-firing-amonia-dan-hidrogen-pada-pembangkit-listrik.

[49] *Tim Publikasi Katadata*, “PLN - Mitsubishi Uji Coba Co - firing Amonia dan Hidrogen pada Pembangkit,” Katadata.co.id, no. November, Nov. 03, 2022. [2024-02-02]. https://katadata.co.id/dinihariyanti/info/6363689bda249/pln-mitsubishi-uji-coba-co-firing-amonia-dan-hidrogen-pada-pembangkit.

[50] *Humas Petrokimia Gresik*, “Petrokimia Gresik Komitmen Dukung Pengembangan Energi Bersih Tanah Air Lewat Green Hydrogen & Green Ammonia,” Pupuk Indonesia, p. 2023. [2024-02-02]. https://petrokimia-gresik.com/news/petrokimia-gresik-komitmen-dukung-pengembangan-energi-bersih-tanah-air-lewat-green-hydrogen-green-ammonia?hl=en.

[51] *Pupuk Indonesia*, “Pupuk Indonesia Collaborates with Japan to Explore Funding for Clean Energy Development,” Pupuk Indonesia, May 24, 2023. [2024-02-02]. https://www.pupuk-indonesia.com/media-info/222/detail.

[52] *P. Gumilar*, “Pupuk Indonesia Gandeng Japan Bank (JBIC) Kembangkan Bisnis Ammonia,” market.bisnis.com, May 23, 2023. [2024-02-02]. https://market.bisnis.com/read/20230523/192/1658530/pupuk-indonesia-gandeng-japan-bank-jbic-kembangkan-bisnis-ammonia.

[53] *Bakrie & Brothers*, “Bakrie initiated the first Net Zero Industrial Park in Indonesia with Envision,” bakrie-brothers.com, Nov. 13, 2022. [2024-02-02]. https://bakrie-brothers.com/id/news-and-media/bakrie-initiated-the-first-net-zero-industrial-park-in-indonesia-with-envision/.

[54] *Energy Voice*, “GGGI, Samsung, Hyundai to join $1.2bn green hydrogen scheme in Indonesia,” Energy Voice, Mar. 28, 2022. [2023-12-10]. https://www.energyvoice.com/renewables-energy-transition/398144/gggi-samsung-hyundai-to-join-1-2bn-green-hydrogen-scheme-in-indonesia/.

[55] *I. Gunawan*, “Telkomsel Terapkan 216 BTS Go Green di Seluruh Indonesia,” bumninc.com, Feb. 10, 2021. [2024-02-02]. https://bumninc.com/telkomsel-terapkan-216-bts-go-green-di-seluruh-indonesia/.

[56] *M. Husna*, "Telkomsel Hadirkan BTS Berteknologi Go Green Fuel Cell," Serambinews.com, 2021. [2024-02-02]. https://aceh.tribunnews.com/2021/02/09/teknologi-hadirkan-bts-berteknologi-go-green-fuel-cell?page=1.

[57] *PT PLN (Persero)*, "Pertama Di Indonesia, PLN Produksi Green Hydrogen 100 Persen Dari EBT Kapasitas 51 Ton Per Tahun," Press Release No. 559.PR/STH.00.01/X/2023, Oct. 10, 2023. [2024-02-02]. https://web.pln.co.id/media/siaran-pers/2023/10/pertama-di-indonesia-pln-produksi-green-hydrogen-100-persen-dari-ebt-kapasitas-51-ton-per-tahun.

[58] *Humas EBTKE*, "Ekosistem Hidrogen Hijau Mulai Tumbuh , 21 Pembangkit PLN Resmi Beroperasi," ebtke.esdm.go.id, pp. 9–12, Nov. 20, 2023. [2024-02-02]. https://ebtke.esdm.go.id/post/2023/11/20/3655/ekosistem.hidrogen.hijau.mulai.tumbuh.21.pembangkit.pln.resmi.beroperasi.

[59] *Y. Fransiscus, F. Kartikasari, E. Savitri, and E. Tarigand*, "Solar Hydrogen Option to Reach Renewable and Climate Change Targets of Indonesia," SSRN Electron. J., 2022, doi: 10.2139/ssrn.4036003.

[60] *G. Maggio, A. Nicita, and G. Squadrito*, "How the hydrogen production from RES could change energy and fuel markets: A review of recent literature," Int. J. Hydrogen Energy, vol. 44, no. 23, pp. 11371–11384, May 2019, doi: 10.1016/j.ijhydene.2019.03.121.

[61] *C. B. Agaton, K. I. T. Batac, and E. M. Reyes*, "Prospects and challenges for green hydrogen production and utilization in the Philippines," Int. J. Hydrogen Energy, vol. 47, no. 41, pp. 17859–17870, 2022, doi: 10.1016/j.ijhydene.2022.04.101.

[62] *H. Barthélémy*, "Hydrogen storage – Industrial prospectives," Int. J. Hydrogen Energy, vol. 37, no. 22, pp. 17364–17372, Nov. 2012, doi: 10.1016/j.ijhydene.2012.04.121.

[63] *M. Aziz, A. T. Wijayanta, and A. B. D. Nandiyanto*, "Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization," Energies, vol. 13, no. 12, p. 3062, Jun. 2020, doi: 10.3390/en13123062.

[64] *R. d'Amore-Domenech, I. Carrillo, E. Navarro, and T. J. Leo*, "Alkaline Electrolysis for Hydrogen Production at Sea: Perspectives on Economic Performance," Energies, vol. 16, no. 10, pp. 1–13, 2023, doi: 10.3390/en16104033.

[65] *Y. Luo, Y. Shi, and N. Cai*, "Bridging a bi-directional connection between electricity and fuels in hybrid multienergy systems," Hybrid Syst. Multi-energy Networks Futur. Energy Internet, pp. 41–84, Jan. 2021, doi: 10.1016/B978-0-12-819184-2.00003-1.

[66] W. W. Clark and J. Rifkin, "A green hydrogen economy," Energy Policy, vol. 34, no. 17, pp. 2630–2639, Nov. 2006, doi: 10.1016/j.enpol.2005.06.024.

[67] *E. Manullang and N. Sinaga*, "Potential and Challenges of Hydrogen Development as New Renewable Energy in Indonesia," R.E.M. (Rekayasa Energi Manufaktur) J., vol. 7, no. 2, pp. 55–62, Sep. 2022, doi: 10.21070/r.e.m.v7i2.1647.

[68] *N. V. Emodi, H. Lovell, C. Levitt, and E. Franklin*, "A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies," Int. J. Hydrogen Energy, vol. 46, no. 60, pp. 30669–30697, 2021, doi: 10.1016/j.ijhydene.2021.06.212.

[69] *A. Ballo et al.*, "Law and Policy Review on Green Hydrogen Potential in ECOWAS Countries," Energies, vol. 15, no. 7, p. 2304, Mar. 2022, doi: 10.3390/en15072304.

[70] *N. Ma, W. Zhao, W. Wang, X. Li, and H. Zhou*, "Large scale of green hydrogen storage: Opportunities and challenges," Int. J. Hydrogen Energy, vol. 50, pp. 379–396, Jan. 2024, doi: 10.1016/j.ijhydene.2023.09.021.

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