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CHALLENGES AND PROSPECTS OF RENEWABLE ENERGY PENETRATION AND ENERGY STORAGE TECHNOLOGIES IN INDONESIA: A REVIEW

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Abstract
Indonesia has significant renewable energy potential, but it is underutilized due to technical, economic, and integration constraints. This study looks at the challenges to solar and wind energy adoption and assesses the role of energy storage technologies in overcoming them. Photovoltaic (PV) and wind systems have fluctuation, grid instability, and reactive power control issues, whilst geothermal and hydro sources, while more reliable, still require additional grid services. This paper summarizes the technical and grid integration challenges of PV systems, emphasizing issues such as harmonic distortion, voltage instability, and high upfront costs. Potential options for energy storage include lithium-ion batteries, pumped hydropower, and compressed air. Each technology's distinguishing features, such as energy density, price, and operating restrictions, are thoroughly evaluated. Despite their promise, hefty investment costs and limited deployment prevent widespread adoption. This article provides techniques for increasing renewable energy integration, such as hybrid power systems, better grid management, and sophisticated energy storage options. Future research should concentrate on microgrid optimization, cost-benefit modeling, and case study comparisons to help drive policy and infrastructure development. This comprehensive research emphasizes the importance of innovative ideas to help Indonesia achieve its energy transition and sustainable development goals.

1. INTRODUCTION

Energy storage plays a critical role in integrating renewable energy sources into modern energy grids, addressing variability and reliability issues. As Indonesia strives to reduce its dependency on fossil fuels and increase renewable energy penetration, challenges such as grid stability, energy access, and efficiency have come to the forefront. The nation faces unique geographic, economic, and infrastructural constraints requiring tailored energy storage solutions. Among various energy storage technologies, pumped hydro, lithium-ion batteries, compressed air, liquid air, and hydrogen systems present distinct advantages and limitations. For instance, pumped hydro is highly efficient but limited by site availability and high upfront costs. Lithium-ion batteries, widely used for small-scale applications, struggle with scalability and waste disposal concerns. Compressed air energy storage (CAES) and liquid air energy storage (LAES) are promising but remain constrained by site requirements and technological immaturity. Meanwhile, hydrogen energy storage offers significant potential for long-term storage but suffers from low efficiency and high investment costs. Table 1 outlines Indonesia's key barriers to renewable energy development, highlighting financial, regulatory, and infrastructural constraints. High investment costs and limited incentives deter the expansion of renewable technologies, while low electricity selling prices reduce the economic attractiveness of such projects

This paper explores the prospects of these energy storage technologies in the Indonesian context, examining their technical, economic, and environmental implications. Furthermore, it identifies potential solutions and avenues for future research to overcome integration challenges, thereby fostering the growth of renewable energy and advancing energy sustainability in Indonesia.

2. Methodology

This study takes a holistic approach to assessing energy storage technologies and their potential integration into Indonesia's energy environment. It starts with a thorough literature assessment, which analyzes existing studies on various energy storage technologies such as pumped hydro, lithium-ion batteries, compressed air, liquid air, and hydrogen systems, as well as global best practices and pertinent case studies. The technical and economic evaluation entails examining each technology's technical specifications, operating limits, and scalability, as well as identifying site-specific difficulties such as geographical suitability and infrastructure availability.

Table 1. Challenges to renewable energy development in Indonesia

No.	Identified Barriers	References
1	High investment costs for new and renewable technologies and low incentives for renewable energy	(Arafah et al., 2018; Dwipayana et al., 2021; Hidayatno et al., 2020; Martosaputro & Murti, 2014; Maulidia et al., 2019; Nugroho et al., 2017; Pristiandaru & Pambudi, 2019; Setiawan, 2014; Setyawati, 2020; Sukarso Pradityo, 2018; Udin, 2020; Umam et al., 2018)
2	The selling price of electricity from renewable energy is too low	(Burke et al., 2019; Martosaputro & Murti, 2014; Sukarso Pradityo, 2018; Umam et al., 2018)
3	Most investors and financial institutions view renewable energy projects as too risky investments.	(John Kimani Kirari et al., 2018; Pristiandaru & Pambudi, 2019)
4	High dependence on fossil fuels and subsidy imbalance cause cheap fossil energy prices, while renewable energy is expensive.	(Burke et al., 2019; Maulidia et al., 2019; Sukarso Pradityo, 2018; Udin, 2020)
5	Single buyer of electricity and monopoly in the electricity sector	(Budi et al., 2020; Hidayatno et al., 2020; John Kimani Kirari et al., 2018; Maulidia et al., 2019; Setyawati, 2020)
6	Limited investment in research and development of renewable technology, lack of data, and uncertain resource availability	(Budi et al., 2020; Dwipayana et al., 2021; Tarigan et al., 2015; Udin, 2020; Umam et al., 2018; Widya Yudha & Tjahjono, 2019)
7	Poor coordination between central and local government, ministries, and agencies creates legal uncertainty.	(Aidy Halimanjaya, 2019; Marquardt, 2014; Martosaputro & Murti, 2014; Sharvini et al., 2018; Sukarso Pradityo, 2018; Udin, 2020; Umam et al., 2018)
8	Limited open land for the use of renewable energy development	(Dwipayana et al., 2021; Udin, 2020)
9	Renewable energy areas in Indonesia are usually located in remote areas or have limited infrastructure.	(Arafah et al., 2018; Martosaputro & Murti, 2014; Pristiandaru & Pambudi, 2019; Umam et al., 2018)
10	Lack of expert capacity and weak local human resources	(Arafah et al., 2018; Marquardt, 2014; Nugroho et al., 2017; Pristiandaru & Pambudi, 2019; Umam et al., 2018; Widya Yudha & Tjahjono, 2019)
11	Lack of public awareness of renewable energy and community resistance	(Arafah et al., 2018; Martosaputro & Murti, 2014; Setiawan, 2014; Setyawati, 2020; Sharvini et al., 2018; Umam et al., 2018)
12	The lack of effective after-sales service has left many renewable energy projects neglected.	(Dwipayana et al., 2021; Nugroho et al., 2017)
13	The majority of technologies for the development and utilization of renewable energy cannot be made domestically.	(Sukarso Pradityo, 2018; Widya Yudha & Tjahjono, 2019)
14	The introduction of intermittent renewable energy disrupts the existing system.	(Burke et al., 2019)

Scenario development entails generating simulations that integrate renewable energy sources with various storage devices in Indonesia's grid and employing energy systems analytic techniques to assess the influence on grid stability, energy access, and overall efficiency. The social and environmental impact assessment investigates the potential environmental and socioeconomic consequences of deploying energy storage systems, such as land use, resource consumption, and waste management. It includes stakeholder consultation to gain insight into public acceptance and regulatory challenges. Finally, the paper synthesizes these findings to provide practical suggestions for policymakers, investors, and energy sector stakeholders, as well as a roadmap for increasing energy storage systems in Indonesia, considering technical, economic, and environmental considerations.

3. Result and Discussion

3.1 Renewable Energy Technologies

3.1.1 Hydropower

Hydropower is a sustainable and environmentally friendly energy source, delivering reliable electricity for over 50 years through conventional utilization. In line with this, the Indonesian government has set an ambitious target to add 7,529 MW of hydropower capacity by 2028 (PLN, 2019). Despite its vast potential, the development of large-capacity hydropower remains underutilized, mainly due to high upfront investment costs, environmental concerns, and socio-economic challenges (Paish, 2002). On the other hand, mini- and micro-hydropower systems present a more accessible and viable alternative, especially for on-grid and off-grid applications (Didik et al., 2018; Erinofiardi et al., 2017). In remote areas with adequate resources, micro-hydropower installations offer an effective solution to improve the nation’s electricity ratio and bring energy access to underserved regions (PLN, 2019).

Integration of hydropower into the grid is straightforward due to its ability to synchronize with other power producers and maintain stable frequency levels (Heimisson, 2014). As a consistent and reliable energy source, hydropower is well-suited to serve as a baseload power plant (Peters & Burda, 2007). Furthermore, hydropower offers energy storage solutions through pumped hydro systems, utilizing upper and lower reservoirs to store and generate electricity. Excess grid energy is used to pump water to an upper reservoir, while during demand peaks, water released from this reservoir generates power by driving turbines (Cheng et al., 2019). Hydropower's adaptability also extends to hybrid systems, where it complements intermittent renewables like solar and wind (Hiendro et al., 2013; Hülsmann et al., 2015; Muhida et al., 2001; Shezan et al., 2018; Syahputra & Soesanti, 2021). Existing hydroelectric facilities can be upgraded to support pumped hydro energy storage (PHES) for enhanced grid stability (Hussain et al., 2019).

3.1.2 Geothermal Energy

With an installed capacity of 2,130.7 MW, geothermal energy is critical in Indonesia's renewable energy landscape (MEMR, 2021). The country boasts an estimated geothermal potential of 75 GW—equivalent to 40% of the world’s total (Asian Development Bank & The World Bank, 2015). From 2016 to 2018, geothermal capacity experienced significant growth, recording increases of 14.29%, 10.04%, and 12.99%, respectively (MEMR, 2020a). However, post-2019, growth slowed to just 4.27%, with no capacity additions in 2020 (PabumNews, 2020).

As the second-largest geothermal resource holder after the United States, Indonesia has identified geothermal energy as a cornerstone of its energy transition strategy. Development initiatives are focused on high-demand areas such as Sumatra, Java, Sulawesi, Nusa Tenggara, and Maluku (PLN, 2019). Backed by government policies and financial support from international institutions like the World Bank and the Asian Development Bank, geothermal expansion is expected to accelerate.

Geothermal energy is a reliable year-round baseload power source, offering stability unaffected by seasonal variations like rainfall (Nasruddin et al., 2016). Its integration into the energy grid is seamless, as geothermal plants employ steam-based systems similar to gas or coal-fired plants. Additionally, geothermal energy can complement wind and solar power in hybrid systems, enhancing renewable grid reliability (Godson et al., 2013; Naseh & Behdani, 2020). As a result, geothermal energy is poised to play a pivotal role in stabilizing Indonesia’s renewable energy network.

3.1.3 Wind Energy

Indonesia has used wind energy for basic applications like water pumping and lighting for over three decades. With wind speeds averaging 2-6 m/s, the country possesses an estimated wind power potential of 9,286.61 MW (Widodo Wahyu Purwanto et al., 2006). However, as of 2020, only 154.3 MW—about 1.66% of the total potential—had been harnessed, primarily from medium-capacity projects like the 75 MW Sidrap plant (2018) and the 72 MW Jeneponto facility (2019) (PLN, 2019).

Indonesia’s extensive coastline, the second longest globally at 95,181 km, presents significant opportunities for offshore wind development (KKP, n.d.). Coastal and offshore sites benefit from higher wind speeds, reduced land acquisition conflicts, and minimal disruption to local landscapes (Sahin,

2004). Recent studies highlight the feasibility of both onshore and offshore wind installations, demonstrating robust seasonal energy potential in various locations (Erwin et al., 2018; Said et al., 2019; Satwika et al., 2019).
Advances in wind turbine technology offer new deployment opportunities. While horizontal-axis wind turbines (HAWTs) dominate the market, vertical-axis wind turbines (VAWTs) have emerged as a viable alternative, delivering up to ten times more energy per unit size (Islam et al., 2013). Wind turbine capacities have significantly increased over the decades, from 20 kW in the 1980s to current designs exceeding 15 MW (Department of Energy, 2020; GE Renewable Energy, n.d.).

3.1.4 Solar Energy

Indonesia's journey with solar energy began in the 1970s by introducing solar home systems (SHS) (Outhred & Retnanestri, 2015). The first on-grid centralized solar power facility, a 1 MWp plant, was launched in Bali in 2013 (MEMR, 2013). As a tropical nation, Indonesia receives ample sunlight, averaging 4.8 kWh/m²/day and offering a theoretical solar energy potential of 207,898 MW (Rumbayan et al., 2012). Despite this, only 153.5 MW, or 0.07% of the potential, has been developed, emphasizing the untapped opportunity (MEMR, 2021).
To meet its 2025 renewable energy goals, Indonesia plans to expand rooftop and floating solar facilities, including the 145 MW Cirata Floating PV Project (MEMR, 2021). Solar power is particularly suitable for hybrid applications in remote areas, where it can be combined with diesel systems to improve electrification (Pristiandaru & Pambudi, 2019). In urban regions, rooftop PV installations and SHS programs are prioritized.
Photovoltaic (PV) and concentrated solar power (CSP) systems dominate solar technologies, with PV leading adoption due to its shorter payback period of five years compared to CSP’s 17.5 years (Ahmad et al., 2020). According to IRENA, accelerated solar PV deployment could reduce global CO_2 emissions by 21%, with Asia emerging as a leader in solar utilization. Innovations in the value chain are expected to drive cost reductions and increase adoption, with solar PV playing a central role in future energy systems (IRENA, 2019a).

3.2. Energy Storage Technologies

Intermittent renewable energy utilization requires energy storage (ES) as a backup when energy sources are unavailable, especially for isolated grids. Hence, ES is crucial for renewable energy growth (Ibrahim et al., 2008). ES might not be required if wind or PV systems are connected to a grid that is still primarily supplied by fossil generators. However, ES installation is unavoidable if most generators are from intermittent sources. The combination of renewable energy sources with ES helps eliminate renewable sources' uncertainty (Breeze, 2018a). Moreover, ES can act as a peaker generator, voltage regulator, and frequency regulation, making it profitable for the energy generation, transmission, and distribution sectors (Hussain et al., 2019).
ES technology is commonly classified into mechanical energy storage, electrical energy storage, thermal energy storage, and chemical energy storage. The author presents several types of energy storage technology that have been tested and have large capacities as the best candidates ready for application in Indonesia.

3.2.1 Pumped Hydro Storage

This storage system works by moving water between two reservoirs with different elevations. Water is pumped to the upper reservoir to store energy when there is a surplus in the energy supply. Then, water flows into the lower reservoir, turning the turbines and producing electrical power when needed. The pumped hydro energy storage (PHES) has the largest capacity, most mature, and most widely used ES compared to other ES systems (Hussain et al., 2019; Ibrahim et al., 2008; Mahlia et al., 2014). Figure 1 shows the layout of the Upper Cisokan PHES project, a 1,040 MW facility currently under construction in Indonesia. This diagram highlights the system's key components, including the upper and lower reservoirs, the pump-turbine units, and connecting waterways
Indonesia has great potential for the development of this type of storage. Indonesia is estimated to have 26,000 potential sites for PHES with a storage capacity of 821,000 GWh in its mountainous areas. The state-owned electricity company PLN is currently in the construction stage of the Cisokan pumped storage plant with 1,040 MW capacity and in the planning stage of Matenggeng PHES (943MW) and Grindulu PHES (1,000 MW) (Bappenas, 2019). The development of Cisokan pumped storage is to reduce the supply cost during peak loads, improve load factors, increase the capacity factor of coal plants, and use flexible generators to anticipate the entry of intermittent renewable energy plants (PLN, 2019).
Other potential types of PHES technology for Indonesia are seawater PHES and microgrid PHES. A seawater PHES project was proposed to meet peak demand in East Java in 2007 (Japan External Trade Organization, 2008). This type of PHES has the advantage of readily available lower reservoirs and utilizes seawater as its working fluid.

Furthermore, the PHES, on a smaller scale, such as micro-hydro, is also very likely developed for Indonesia's remote areas. A study on the microgrid design of a PHS hybrid generator with a photovoltaic found that the daily cost of such a system is 71.3% lower compared to a hybrid diesel generator with a photovoltaic (Mousavi et al., 2020)

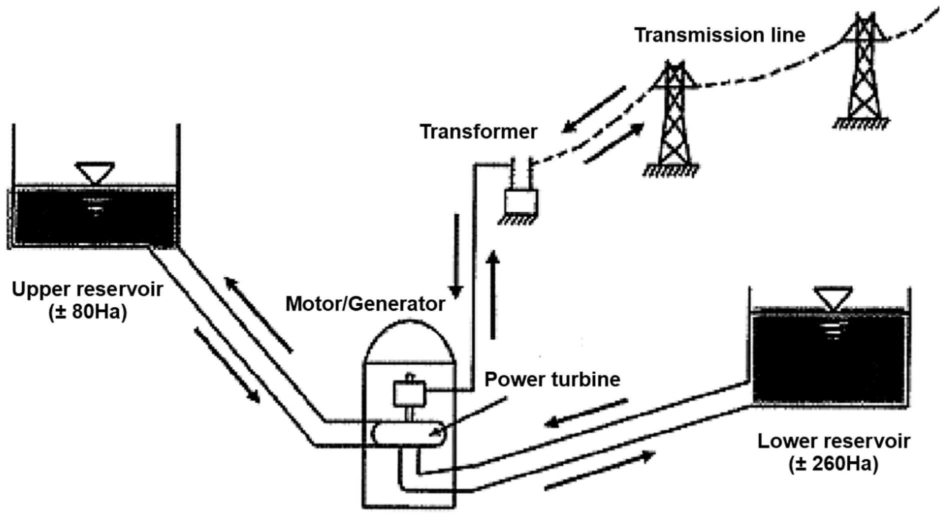

Figure 1. Layout draft of Upper Cisokan Pumped Hydro 1040 MW project (modified from (Buletin KNI-BB, 2010))

PHES has the lowest levelized cost of storage (LCOS) among large-scale storage options, ranging from \$50 to \$200 per MWh. While the initial investment is significant, operational costs are low. For example, the 1,040 MW Upper Cisokan project costs around \$800 million. PHES is particularly well suited for peak demand management and grid stability in Java and Sumatra, where hydropower resources are plentiful.

3.2.2 Lithium-ion Battery

Lithium-ion (Li-ion) batteries store and release energy electrochemically, i.e., moving lithium ions between the positive and negative electrodes. When there is excess electrical energy in the grid, the battery stores electricity by releasing lithium ions from the positive electrode to the negative electrode through the electrolyte medium. Meanwhile, when the source's supply is unfavorable, the electricity is returned by sending lithium ions from the negative electrode to the positive electrode.

Accumulator technologies for batteries vary from a typical known battery like lithium-ion, nickel-cadmium, and sodium-sulfur, lead-acid, nickel-metal hydride, nickel-iron, zinc-air, iron-air, and lithium-polymer. The Li-ion battery is the most widely used technology because of its maturity and energy density (Breeze, 2018c; Ibrahim et al., 2008). The advantages of battery storage are high energy density, high power, charge rate, duration of use, lifetime, high round-trip efficiency, safety, and competitive cost (World Nuclear Association, 2020).

Li-ion batteries were first studied in the 1970s and became popular in the 2000s, mainly used in small electronic applications. Subsequently, lithium batteries are now being tested and demonstrated in microgrid applications and grid and utility systems with capacities up to 30 MW (Breeze, 2018c; Hussain et al., 2019). Utility-scale Li-ion battery storage systems continue to experience increasing demand due to their low costs (IRENA, 2019b). Figure 2 presents a Tesla Powerpack, an example of a utility-scale Li-ion battery storage system. The system consists of 16 battery pods housed in a modular unit, designed to provide scalable energy storage for grid applications. IRENA (IRENA, 2017) projected that the total cost of installing Li-ion batteries for stationary electricity storage could fall 54-61% by 2030.

The potential use of lithium-ion batteries to assist renewable generation in Indonesia is vast, especially for remote area electrification paired with solar panels (PLN, 2019). Moreover, Indonesia has abundant electrode material for lithium-ion batteries, i.e., nickel ore, with resources of 11,887 million tons (MEMR, 2020b). Hence, Li-ion battery production and utilization could be the key to future renewable growth in this country.

The cost of Li-ion batteries has significantly decreased, from approximately \$1,100 per kilowatt hour in 2010 to \$130 per kWh in 2023, with further reductions expected to \$60-80 per kWh by 2030. Indonesia's abundant nickel resources make it a potential domestic lithium-ion battery production hub. These batteries are ideal for remote microgrids, solar-storage hybrid systems, and short-term backup storage.

Figure 2. A typical Tesla Powerpack with 16 battery pods (Tesla Australia & New Zealand, 2025)

3.2.3 Compressed Air Energy Storage

Compressed air energy storage (CAES) works by storing compressed air into the cavern when there is an excess of electrical energy in the grid. Conversely, compressed air is released from underground storage as an air supply for gas turbine engines to generate electricity. This system has two advantages when compared to conventional gas turbines. Firstly, CAES offers higher air pressure up to 40-70 bar (Ibrahim et al., 2008). Secondly, CAES makes the use of expensive gas fuel is more efficient because there is no need to rotate the compressor to produce compressed air (Mahlia et al., 2014). Converting high-pressure air into electricity has an efficiency of up to 70%, while overall electricity storage efficiency for recharge and discharge cycle reaches 50% (Ibrahim et al., 2008). CAES can be used as a backup power supply from several hours to days (Budt et al., 2016), even up to 26 hours (Gür, 2018). CAES can also become peak shaving and demand-side management, assisting the renewable power generation integration, support smart-grids applications, and provide working fluid in compressed air engines (Wang et al., 2017).

The cavern's storage provides a large storage capacity of compressed air to supply electricity for several hours. This storage also saves on the installation costs of building surface facilities for air storage (Gür, 2018). Air storage in underground caverns can also take advantage of ancient salt mines or underground natural gas reservoirs to benefit from geostatic pressure (Ibrahim et al., 2008). Indonesia has the opportunity to exploit depleted gas fields for this purpose. For example, the use of carbonate reservoir of the Arun gas field that has not been operating since 2014 (Atmadibrata et al., 2019). Many studies on compressed gas storage, such as CO2 in carbonate reservoirs, have shown promising results (Raza et al., 2017).

The latest development of CAES is adiabatic CAES (ACAES) with integrated thermal storage. This additional adiabatic thermal storage is used to capture compression heat during the filling cycle. Furthermore, the heat is then reused to preheat the compressed air before the gas turbine's expansion stage. The CAES combination system's efficiency with thermal storage can reach 86% (Gür, 2018). Examples of the ACAES project are the 5 MW Angas ACAES project in South Australia and the 50 MW Zhongyan Jintan CAES project in Jiangsu, China (King et al., 2021).

CAES has a medium capital cost (~\$1,000-\$1,200/kW) and low operational costs. Repurposing depleted gas fields in Indonesia may reduce infrastructure costs. CAES is appropriate for large-scale applications, but less so for small-scale or distributed storage.

3.2.4 Liquid Air Energy Storage

Air as an energy storage medium is further developed to liquid air energy storage (LAES) as part of cryogenic energy storage (CES) technology. LAES uses electricity to cool the air until it turns into liquid and stores the liquid air in the cryo storage tank. Conversely, the liquid air is converted back to a gas state and then mixes with fuel in the combustion chamber to turn a gas turbine engine and generate electricity. Compared to CAES, LAES has several advantages, including satisfactory efficiency, no geographical constraints, reliability, mature technology (Guizzi et al., 2015), safe for the environment (Peng et al., 2018), low specific investment costs (Morgan et al., 2015), and low fuel consumption due to its high energy density (Budt et al., 2016). Liquid air energy density could reach six times greater than the CAES system, while fuel consumption for the LAES cycle is only half of single storage in CAES (Krawczyk et al., 2018).

The LAES can be integrated with other thermal systems for higher overall process efficiency. A LAES with an original and conservative design has alternating efficiency of about 54% to 55% due to the liquid air storage and recovery process (Guizzi et al., 2015). An increase in energy storage efficiency of more than two times can be obtained when the cold heat of liquid air is reused to produce new liquid air (Chino & Araki, 2000). The utilization of waste heat from external sources for air liquefaction and energy recovery units of LAES, such as gas turbine-based peaking plants (Ding et al., 2016)or nuclear power plants (Peng et al., 2018), can also increase fuel efficiency and isentropic efficiency is more than 80% for round trips (Antonelli et al., 2017; Damak et al., 2020; Guizzi et al., 2015). Furthermore, for the air liquefaction process, LAES can be integrated with a liquefied natural gas (LNG) regasification plant (Ding et al., 2016). LAES can take advantage of cold waste for the LNG regasification process rather than seawater. Indonesia, as the top 10 gas-producing countries in the world, has several LNG processing plants. Hence, integrating the LAES system with the LNG plant can be assessed further as an electricity generation and energy storage in this country. Figure 3 illustrates a CAES system, showing its major components: the compression unit, the underground cavern for air storage, and the expansion turbine used for electricity generation. The system provides large-scale energy storage with the ability to supply power for several hours to days.

The LAES system presents potential storage technology options for integrating intermittent power plants, such as wind and solar power, and utilizing heat sources from existing plants. A study by Morgan (Morgan et al., 2015)of a 20 MW LAES plant with 80 MWh storage and a recharge time of 12 hours found that LAES technology's cost is very competitive with other storage solutions. Therefore, future development of this technology with several pilot plants' success stories is anticipated to grow along with renewable energy growth.

LAES has a higher initial investment than batteries (~$2,000/kW) but lower lifecycle costs. Integration with Indonesia's LNG terminals like Bontang and Tangguh may increase its feasibility. LAES is ideal for grid-scale storage and industrial energy applications.

Figure 3. Liquid Air Energy Storage design called CRYOBattery (Sumitomo SHI FW, 2025)

3.2.5 Hydrogen Storage

The energy storage system with hydrogen works with three main stages: hydrogen production when there is an excess supply of electricity in the network, storage, and hydrogen release to generate electricity when needed (Zhang et al., 2016). Hydrogen as an energy storage medium is a different solution because, so far, hydrogen is commonly produced and used for the metal industry or automotive needs. About 95% of hydrogen production is extracted from natural gas through a high-temperature endothermic process with fossil fuels, producing CO2 as much as 2.5 times the hydrogen made (Amirante et al., 2017). Apart from fossil fuels, several ways to produce hydrogen could use nuclear power, biomass, or a renewable electricity source. Production methods with an established technology that is energy-intensive and high emissions can be replaced by water electrolysis using renewable electricity (Zhang et al., 2016). As a proponent of intermittent energy sources, a hybrid between solar generation, wind turbines, and hydrogen production is the right approach. The integration of hydrogen production with solar energy generation can involve four different techniques: photovoltaic panels, photo-electrolysis, solar thermal, and photobiological generation (Amirante et al., 2017). The hydrogen produced can be stored as a compressed gas or kept as a liquid in cryogenic ecosystems such as LAES. Storage under pressure in composite tanks with 350-700 bar pressure might be a cheaper option for hybrid applications with renewable power generation. On the other hand, cryogenic storage at temperatures below 10°K, where hydrogen gas will liquefy, is an answer for space shortage but increases operational costs (Breeze, 2018b).

Lastly, a fuel cell is a standard method to generate electricity from hydrogen. The fuel cell is an oxidation-reduction process of hydrogen with oxygen in the electrochemical cell with two electrodes separated by an electrolyte. The fuel cell is distinguished based on the electrolyte used, the operating temperature, the design, and the areas of application (Ibrahim et al., 2008; Zhang et al., 2016), namely:

- Alkaline Fuel Cell (AFC)
- Polymer Exchange Membrane Fuel Cell (PEMFC)
- Direct Methanol Fuel Cell (DMFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

The process of generating electricity with this fuel cell has the advantage of zero emissions with water by-products. However, with greater efficiency and can take advantage of existing plants, adapting a combustion engine with hydrogen fuel is easy. Hydrogen can be used like natural gas fuel, such as fuel for internal combustion engines such as gas turbines, piston engines, and boiler (Breeze, 2018b).

The cost of producing green hydrogen is currently high (~$4-$6/kg), but the benefits outweigh the risks. Indonesia's abundant nickel resources help fuel cell development, and hydrogen could be used in industrial sectors like ammonia production. Hydrogen storage is ideal for long-term storage, export markets, and hard-to-electrify sectors.

3.3 Challenges in Renewable Energy and Energy Storage

3.3.1 Challenges of Renewable Energy Penetration

The high potential of renewable energy resources in Indonesia contrasts with the current capacity of this green energy. Several distinguished challenges for renewable energy development in Indonesia are summarized in Table 2. However, only limited literature discusses the technological constraints and the grid integration challenges of renewable energy generators. Noting some examples of challenges faced by PV systems in Bali Island (Muhammad Saladin, 2019) and Parang Island (Naimah et al., n.d.) and wind turbines in Sidrap and Jeneponto (Arief et al., 2020; Barus & Dalimi, 2020; Widyaningsih et al., 2020), addressing these issues is essential ahead of the development.

Most of the issues in integrating renewable energy are the variability of the RE resources and its struggle to serve ancillary services (IRENA, 2020). This inadequacy will affect grid services such as scheduling and dispatch, voltage regulation, reactive power, frequency control, and system protection. Several identified challenges in the generation and integration of PV systems into the grid are presented in Table 2 and Table 3. Variable renewable energy sources like solar and wind are the main contributors of harmonic distortion and disturbance to frequency stability in recent years due to decreased overall inertia (Bajaj & Singh, 2020).

Geothermal, hydro, and biomass power plants also face the challenge of providing these ancillary services, but with a smaller severity level (Ali et al., 2018). These generators have lower variability, and the changes are slowly over the months or years timescale. Moreover, they use synchronous generators to convert the mechanical energy of turbine rotation into electrical energy so that it is easier to adjust to the grid requirement (Bajaj & Singh, 2020)

Like PV, the high variability of wind resources creates significant challenges in its integration into the grid. Power quality and power system planning are influenced by the wind's stochastic nature, resulting in very unpredictable power generated by wind turbines (Islam et al., 2013). Wind speed often fluctuates from minute to minute, making it hard to forecast accurately during daily periods (Georgilakis, 2008). However, wind power generators have the advantage of their ability to provide reactive power as needed even when the wind turbine does not generate power (Ahmed et al., 2020). Furthermore, wind turbines are also better at stabilizing the frequency and maintaining the output voltage (Ahmed et al., 2020)

3.3.2 Challenges of Energy Storage Technologies

Energy storage systems are becoming a necessity with the increasing penetration of wind power and solar generation. Table 4 shows the technical characteristics of the selected storage technologies. However, several factors hampered the application of this energy storage. Each technology has unavoided challenges due to its unique features, location constraints, or economic barriers.

Pumps hydro have three main drawbacks: the scarcity of available locations for two large reservoirs, long development times of more than ten years at high costs, and related environmental and social challenges that are impacted by the construction of reservoirs and supporting infrastructure (Chen et al., 2009). Several technical improvements of pumped hydro technology are also needed for the flexibility of operations, business models, and network connections (Hülsmann et al., 2015).

Table 2. Technical challenges of electricity generation from PV systems

Challenges	Remark	References
The fluctuation of PV power	The natural drawback of solar PV is its dependence on sun exposure, so the power fluctuates due to variations in radiation levels and temperatures.	(Dwipayana et al., 2021; Lupangu & Bansal, 2017; Shah et al., 2015; Tarigan et al., 2015)
Voltage Regulation	Irradiation instabilities in PV systems create fluctuations and unbalance in the voltage profile.	(Al-Shetwi et al., 2020; Alshahrani et al., 2019; Lupangu & Bansal, 2017)
Active Power Regulation	The inverter of the PV system provides maximum active power, which varies according to solar radiation. Using the controller to adjust the sun angle causes a delay in response time and a delay in the maximum active power.	(Al-Shetwi et al., 2020; Alshahrani et al., 2019)
Reactive Power Regulation	Most PV system inverters do not have nonactive/reactive power (PQ) controls, so they do not provide sufficient reactive power to meet grid requirements.	(Al-Shetwi et al., 2020; Alshahrani et al., 2019)
High installation costs	Although the price per kWh of electricity from solar PV has continued to decline from year to year, PV technology's capital cost is very high as almost all expenditure is upfront.	(Lupangu & Bansal, 2017)
Depending on tracking devices	The PV angle must always adjust to achieve maximum power point tracking (MPPT) using mechanical and electronic tracking systems.	(Lupangu & Bansal, 2017)
Partial Uncertainty	Uncertainty to predict the energy production from intermittent solar power plants precisely on a time scale remains a constraint for PV.	(Alshahrani et al., 2019)
Uncontrollable Variability	The solar power source has a discontinuous and non-constant character, so it is difficult to control even though it has been predicted correctly.	(Alshahrani et al., 2019)

Moreover, Li-ion batteries have proven to be ideal and are widely used in small electronic applications. Simultaneously, large capacity batteries are being developed in several locations along with wind and solar generators. The high initial cost issue is also a challenge for Li-ion batteries due to their unique packaging and internal overcharge protection circuits (Chen et al., 2009; Hussain et al., 2019). Besides, an increase in Li-ion batteries' temperature due to internal short circuits or overcharging can cause safety problems (Hussain et al., 2019). The safety concern is also a significant challenge for its waste disposal.

Like pumped hydro, compressed air also has significant challenges for its dependency on the availability of a specific location, and it is even more challenging to find an ideal place for CAES (Antonelli et al., 2017; Chen et al., 2009; King et al., 2021). CAES need specific locations such as salt caves, aquifers, or gas fields, so it is economically viable. CAES requires a large storage area because of its low energy density so that artificial surface storage will be costly (Antonelli et al., 2017). Another weakness is that CAES works with gas plants using fossil fuels, so it is not completely clean and still produces emissions (Chen et al., 2009). The issue of lower cycle efficiency than PHES or battery is also a challenge to consider (Ibrahim et al., 2008; King et al., 2021). On the other hand, LAES is proposed to answer CAES's storage problem using liquid air stored in smaller tanks for months thanks to its high density (Antonelli et al., 2017). However, LAES technology is still at the demonstration phase, with only one facility in the UK with an efficiency of around 8% (Krawczyk et al., 2018). Thus, more experiments are needed to validate LAES performance and to reduce system uncertainty. Extensive investment and uncertain return duration adds to the weight of LAES development (Damak et al., 2020).

Table 3. The challenges of integration of PV systems into the grid

Challenges	Remark	References
Power Quality and reliability	Integration of large-scale PV systems, which consists of electronic devices into the grid, will cause injection of harmonics and voltage flicker into the grid can degrade power quality	(Al-Shetwi et al., 2020; Alshahrani et al., 2019; Lupangu & Bansal, 2017)
Harmonics Distortion	Harmonic distortion resulting from direct current conversion to alternating current can increase the distribution grid's losses through heat generation.	(Al-Shetwi et al., 2020; Alshahrani et al., 2019; Jamal et al., 2017; Shah et al., 2015)
Protection Challenges	The penetration of a PV system in the grid will cause a bidirectional power flow that creates significant shifts in protection schemes.	(Alshahrani et al., 2019)
Voltage Stability	The power system's inability to maintain its voltage levels at acceptable levels can result in voltage instability and even collapses the entire system.	(Al-Shetwi et al., 2020; Alshahrani et al., 2019; Jamal et al., 2017; Lupangu & Bansal, 2017; Shah et al., 2015)
Rotor Angle Stability	The PV system's static source element does not contribute to the power system's angular oscillation, causing a significant reduction of the grid's equivalent inertia.	(Alshahrani et al., 2019)
Frequency Stability	PV technology has no rotating mechanism to control the frequency and provide inertia support into the grid. This disadvantage, along with power variability, can cause frequency stability problems in the grid.	(Al-Shetwi et al., 2020; Alshahrani et al., 2019; Jamal et al., 2017; Shah et al., 2015)
Ramp up and ramp down	Severe and rapid power fluctuations due to increased penetration of large-scale PV installations to the grid require quick compensation from other generators or storage.	(Jamal et al., 2017)
Power flow back from PV	Because there is no power setting to adjust the load as in conventional generators, if the power generated by PV exceeds the load demand, the current will return to the PV and even impact other generators.	(Jamal et al., 2017; Lupangu & Bansal, 2017; Shah et al., 2015)
Fast transients	Rapid bursts of energy in the system caused by sudden solar irradiation changes can cause short bursts of oscillation.	(Jamal et al., 2017; Lupangu & Bansal, 2017)
Accidental islanding	The PV system will continue to supply electricity if there is sufficient irradiation even though there is a blackout in the grid. This event creates an islanding phenomenon.	(Jamal et al., 2017; Lupangu & Bansal, 2017)
Over or under loading	A high current that spikes at start-up due to connected loads can temporarily overload the power system. PV systems are not designed to tackle this kind of problem.	(Jamal et al., 2017; Shah et al., 2015)
Depending on backup storage	PV systems find it challenging to match intermittent energy production with dynamic power demand. Energy storage is used to meet load demands on time and add flexibility in load management.	(Lupangu & Bansal, 2017)

Table 4. The characteristics of selected energy storage technology [70]

Storage	Energy	Power Rating	Storage	Lifetime	Discharge	Maturity

Technology	Density (Wh/L)	(MW)	Duration	(years)	Time	
Pumped Hydro	0.5–2	30 to 5000	Up to Months	40–60	Days	Mature
Compressed Air	2–6	More than 300	Up to Months	20–40	Days	Mature
Hydrogen fuel cell	500–3000	Up to 50	Up to Months	5–20	Days	Developing
Li-ion Battery	150–500	Up to 100	Up to Days	5–15	Hours	Demo
Liquid Air*	60–120	More than 200	Up to Months	20–60	Days	Demo

*additional data (Ding et al., 2016)

Lastly, hydrogen extraction from the water using an electrolyzer is a promising technology with abundant raw water. However, the best electrolyzer's efficiency is only 70%, while the fuel cell's highest efficiency for converting hydrogen back into electricity is only 50%, so the combination results in low efficiency of only 35% (Chen et al., 2009; Ibrahim et al., 2008). Like other new technologies, high investment costs and relatively short component life for grid applications make this technology still not widely available (Chen et al., 2009; Zhang et al., 2016).

3.4 Potential Solutions and Future Research Directions

3.4.1 Solutions for Renewable Energy Penetration Challenges

Renewable energy represents the future of Indonesia and the world in response to the ever-increasing energy needs and reducing GHG emissions at the same time. However, integrating this energy source into the existing grid faces significant technical challenges, especially in variable sources such as wind and solar. These technical challenges relate to variability, uncertainty, and asynchronous operations. These problems have been widely discussed in the literature, with several approaches but not limited to generation diversity, flexible conventional generation, load control, curtailment for over-generation, better weather forecasting, and energy storage (Kroposki, 2017).

Indonesia's two electrical energy problems are no electricity access and unequal access to electricity, especially in remote areas and islands where most of the existing power plants are powered by fossil fuels. Developing only one type of generator for the primary energy source is a risky step because there can be a prolonged blackout if there is a delay in fuel supply. Hybrid generation of renewable and conventional power plants can be applied to solve this problem with or without energy storage. As a result, there is always backup power when a generator fails to deliver electricity. Moreover, the government is committed to developing 20 hybrid power plants in microgrid settings based on the maritime economy's local potential in the next few years (MEMR, 2019). Hence, hybrid schemes provide time-shifting advantages with energy storage and increased reliability and power quality (Bajaj & Singh, 2020).

Furthermore, in an extensive grid with a diversity of generators, excess production in an area can be sent to the less productive site simultaneously (Bajaj & Singh, 2020). However, if the current electricity demand is low, power limitation or curtailment should be applied. Several conventional techniques can be used for curtailment, such as braking a wind turbine to cut off the power supply. However, this curtailment itself is a disadvantage because we cannot use this free energy source when it is available. Power limitation can be avoided by integrating power plants into the electricity network with innovative and effective generation and transmission planning techniques that are reliable, flexible, safe, efficient, and economical (Liang et al., 2017). The curtailment can also be avoided with demand-side management or load control. Electricity consumers, especially those in the industry, are advised to shift their electricity consumption to periods of excessive availability (Bajaj & Singh, 2020).

For energy storage, Sinsel (Sinsel et al., 2020) reviewed the problems and solutions for integrating intermittent grid generators. Two types of approaches can be taken to overcome problems arising from the penetration of variable generators, namely distributed and centralized technology. In both methods, energy storage is used to balance the power supply and peak load power control. However, in distributed technology, small-scale storage such as Li-ion batteries can be managed from the demand side, namely optimization of consumption and peak shaving. Whereas in centralized technology, larger energy storage capacity is needed to perform a similar task.

3.4.2 Solutions for Energy Storage Challenges

Adding storage technology to the grid with renewable energy sources has many advantages for both suppliers and consumers. Suppliers can guarantee their power supply to the grid at all times without significant disruption from the weather. Simultaneously, consumers do not need to think about when electricity is available and are more flexible in using electricity.

However, several challenges must be faced in its development, as described in 3.2. In general, one of the reasons for not applying this technology is because the investment is quite expensive, especially if the power plant's capacity is quite large (Kroposki, 2017). This costly investment applies to all energy storage types and might be solved by spreading energy storage to a small size. For example, developing solar power plants in small capacities but spread out to get closer to the load. The installation of energy storage on consumers' houses is another alternative to keep spending at a minimum. However, this certainly does not match the characteristics and goals of renewable energy development for remote areas and islands whose people are mostly underprivileged.

Further, of the many types of prospective storage for renewable energy development in Indonesia, only Li-ion batteries have been implemented to help overcome solar generation's variability effects on small scales. Other energy storages like compressed air and pumped hydro technology that has been in operation for decades in other parts of the world are not yet available. Only one pumped hydro project that still under construction, while two other projects are in planning.

The economic challenges and the scarcity of energy storage in this country provide ample opportunity for future research on applying this technology to help integrate renewable energy into the future. First, an in-depth evaluation of the effects of combining two large wind farms in Jeneponto and Sidrap, selecting energy storage types, and analyzing the robustness of overall energy production and transmission could be a starting point for research. Furthermore, we need to examine a complete system analysis in energy storage to assist renewable energy includes cost optimization, efficiency, reliability, maintenance, social and environmental impacts as a guide for its application. Finally, research on combining various energy storage methods with renewable energy sources by maximizing domestic potential can be used as the basis for the policymaker to create supportive policies.

3.4.3 Policies and Strategies for Scaling Renewable Energy in Indonesia

A strong regulatory framework and incentives are needed to accelerate renewable energy adoption in Indonesia. A Renewable Energy Portfolio Standard would require utility companies to generate a minimum percentage of electricity from renewable sources, encouraging adoption. Feed-in Tariffs (FiT) and competitive auctions can attract private investment in renewable energy projects with favorable pricing. Distributed generation can be encouraged by improving net metering policies to compensate small-scale producers. Reduced import duties on solar panels, wind turbines, and battery storage systems can lower costs. To reduce delays and accelerate project deployment, permit and licence processes must be streamlined.

Grid integration and infrastructure development are also important. Smart grid technologies like advanced grid management systems and digital monitoring tools can improve energy grid reliability. Expanding transmission networks to connect renewable energy-rich regions to high-demand cities optimizes energy distribution. Investing in grid-forming inverters, demand response systems, and virtual power plants will also help manage renewable energy variability.

Energy storage is essential for electricity stability. Financial incentives for Li-ion and other battery technologies can boost BESS adoption. Promote hybrid renewable energy systems that combine solar and wind with storage to improve reliability. Supporting large-scale storage projects like pumped hydro, CAES, and hydrogen storage pilot projects will boost energy resilience. Investing in domestic production and recycling facilities will reduce energy storage system costs and imports.

Long-term success requires fostering research, innovation, and workforce development. Increasing R&D funding for high-efficiency PV, next-generation batteries, and hydrogen fuel cells will spur innovation. Technical training and renewable energy courses in university and vocational curricula will train workers. Establishing renewable energy innovation hubs as government-funded test beds for new technologies will accelerate innovation and deployment.

Scaling renewable energy requires financing and investment. Public-private partnerships can boost government, private sector, and international investor collaboration. Green bonds and low-interest loans will attract renewable energy investment. Risk mitigation mechanisms like government-backed guarantees reduce project risks and boost investor confidence.

Promote decentralized and community-based renewable energy solutions to increase clean energy access. Off-grid and hybrid mini-grids will electrify rural areas. Community empowerment comes from incentivizing cooperatives and local businesses to own renewable projects. Expanding Energy-as-a-Service models like solar PV and storage leasing and subscription will help households and businesses adopt renewable energy without upfront costs.

Finally, a just energy transition requires environmental and social sustainability. Project approvals with sustainable land use planning and environmental impact assessments reduce ecological damage. Promoting circular economy practices like solar panel and battery recycling reduces environmental impact. National campaigns will promote renewable energy adoption and raise awareness.

3.4.4 Future Research Opportunities

Although the renewable energy industry is mostly mature and has been implemented in many countries, Indonesia is still new in adopting this technology, with evidence of its low energy mix share. With advantages in resources varying from geothermal, hydro, biomass, wind, solar, and other new sources, much needs to be done to optimize their potential, not just assessing their resources and economies. Future research should focus more on identifying the overall potential of one microgrid (for remote areas or islands) to create a scenario for developing a reliable power generation system from many challenges and solutions that have been identified. Furthermore, a model to measure the relationship between each design's challenges and solutions by comparing the estimated costs should be carried out with suitable software. Finally, relevant case studies compared with the comprehensive analysis of the modeling results are also vital to research in order to produce a detailed solution for further development and policy recommendations.

4. Conclusion

Renewable energy development in Indonesia is still prolonged compared to other countries, so more serious efforts are needed to achieve the government's ambitious targets. Especially in eastern Indonesia, renewable energy sources have great promise for replacing traditional fossil-based power plants and increasing electricity access in far-off areas. However, the intermittent character of renewables presents a major obstacle that calls for creative ideas for reliable grid integration.

With pumped hydro, lithium-ion batteries, compressed air, liquid air, and hydrogen fuel cells found to be the most appropriate solutions for Indonesia, energy storage technologies play a central role in addressing these challenges. Every technology has different advantages and drawbacks; their acceptance will rely on-site availability, investment expenses, and efficiency. Like the generation of renewable energy, though, the deployment of energy storage is hampered by financial, technical, and legal limitations requiring specific solutions.

Future studies should concentrate on optimizing hybrid energy systems combining several renewable sources to improve dependability, thus accelerating the change. Comprehensive feasibility studies are also required to assess energy storage integration's technical, financial, and legal facets. To help the significant adoption of renewable energy, policymakers must also prioritize incentives, infrastructure development, and capacity-building programs. Ensuring Indonesia's sustainable and strong energy future will depend on addressing these issues through multidisciplinary research and coordinated policy initiatives.

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