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A Study of Japan's Energy Landscape in the Transition to Renewable Electricity

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ABSTRACT

The global shift towards renewable energy sources is driven by the desire for a sustainable energy future. Integrating intermittent renewable sources and maintaining grid stability are obstacles that must be overcome to achieve this goal, which is why grid stability and energy storage systems are being investigated in this study using Energy PLAN simulation. This study conducts a thorough analysis of energy storage solutions necessary to support Japan's energy landscape shift to renewable electricity. It offers a comprehensive analysis considering technological, environmental, and policy aspects to evaluate the applicability, difficulties, and potential of renewable electricity. Technical factors emphasize how critical it is to maintain grid balance and consider scalability and technology compatibility with Japan's distinct energy infrastructure. Economic analyses examine revenue streams, levelized storage prices, investment needs, and cost-benefit evaluations to shed light on the viability and appeal of technologies for storing energy from an economic standpoint. The goal of synthesizing these several characteristics is to provide policymakers, and energy stakeholders participating in Japan's ambitious journey towards renewable electricity with strategic insights, practical recommendations, and a roadmap. This study aims to steer Japan's energy landscape towards resilience, sustainability, and diversification by establishing links between imperatives, economic feasibility, and technical breakthroughs.

1. INTRODUCTION

The global imperative to combat climate change has spurred a transformative shift in the energy sector, propelling nations worldwide to pursue sustainable and renewable energy sources. Among these nations, Japan stands as a significant player navigating a complex energy landscape marked by challenges of energy security, sustainability, and technological innovation. Faced with a history of heavy reliance on imported fossil fuels and reeling from the aftermath of the Fukushima nuclear disaster in 2011, Japan embarked on a determined journey to recalibrate its energy policies and transition towards a more sustainable, diversified, and resilient energy future [1]. In 2021, the electricity generated from total renewable energy sources in Japan is approximately 211.5 thousand gigawatt hours. To reduce the dependency on fossil fuel and greenhouse gas emissions, the Japanese government currently aims to increase the renewable energy share [2]. Figure 1 represents the annual progress of the renewable transition in which the installed capacity of renewable energy plants is gradually increasing from 2012 to 2021 and Figure 2 represents the breakdown of renewable energy resources shares in the year 2022 which also describes the installed capacity and the annual electricity production from renewable resources in the year 2022 [3].

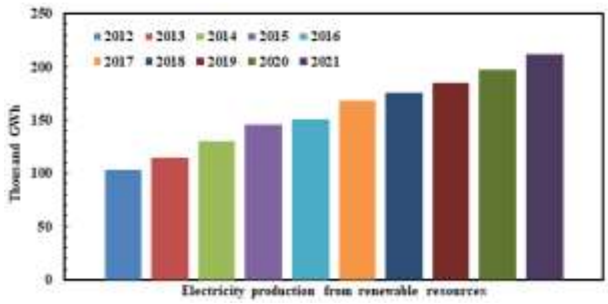

Figure 1. Annual progress of renewable energy transition adapted from [2]

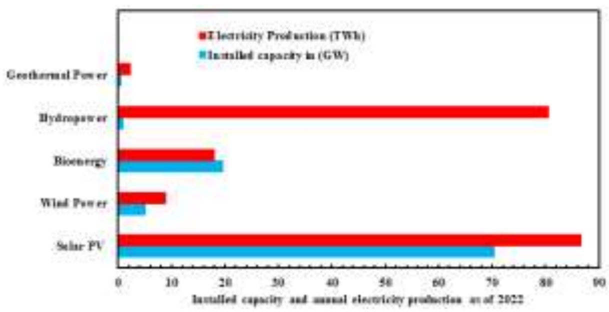

Figure 2. Electricity production from renewable resources in 2022 adapted from [3]

Japan's energy transition lies in the ambitious goal of achieving renewable electricity by harnessing the potential of wind, solar, hydro, and other clean energy sources. However, the integration of these intermittent renewable resources into the existing energy grid poses multifaceted challenges, particularly concerning grid stability, variability management, and the need for reliable energy storage solutions. As renewable energy sources are inherently variable and often unable to align their generation with demand, the role of energy storage systems becomes increasingly pivotal in ensuring a smooth, reliable, and resilient transition towards higher shares of renewable electricity [4].

This study embarks on a comprehensive investigation into the diverse array of storage options available to facilitate Japan's energy landscape transition to renewable electricity. It endeavors to dissect, analyze, and assess the technical, economic, environmental, and policy dimensions associated with various energy storage technologies. The primary aim is to delineate a strategic roadmap that maximizes the synergies between renewable energy integration and the deployment of efficient, cost-effective, and sustainable energy storage systems [1].

The significance of this research stems not only from its focus on Japan's energy landscape but also from its relevance to the broader global context of transitioning towards renewable-based energy systems. By scrutinizing the intricacies of energy storage technologies within the Japanese context, this study aims to offer insights, strategies, and policy recommendations that may resonate with other nations grappling with similar challenges in their pursuit of a sustainable energy transition [4].

This study will delve into the technological landscape of energy storage, analyzing a spectrum of storage options ranging from battery technologies (such as lithium-ion, and flow batteries) to more conventional methods like pumped hydroelectric storage, and compressed air energy storage. Each technology will be scrutinized based on its technical capabilities, scalability, efficiency, and potential challenges for integration within Japan's energy infrastructure [5]. Moreover, this study recognizes that the effectiveness of energy storage solutions is contingent not only on their technical prowess but also on their economic viability and environmental footprint. Thus, the techno-economic section will provide an in-depth analysis of the economic aspects, including cost-benefit analyses, investment requirements, and market dynamics influencing the deployment of energy storage technologies in Japan.

In summary, the novelty of this study endeavors to balance the demand and supply with suitable energy storage options due to the intermittent nature of renewable resources. By amalgamating technical insights, economic evaluations, environmental considerations, and policy perspectives, this research aspires to furnish stakeholders, policymakers, and researchers with a comprehensive roadmap to navigate the intricate terrain of integrating renewable energy and storage solutions, steering Japan towards a sustainable energy future [1].

2. LITERATURE REVIEW

Japan has begun a major endeavor to reconstruct its energy environment in the wake of the Fukushima nuclear accident in 2011. Before this disaster, Japan was largely dependent on nuclear power, which constituted a sizeable amount of its energy mix. However, the accident and worries about nuclear safety caused a significant change in the country's energy policies, which resulted in a reassessment of its energy plans and a strong move toward renewable energy sources [1].

Japan is firmly committed to diversifying its energy portfolio and lowering its reliance on conventional fossil fuels and nuclear power, which signaled a shift in the country's energy paradigm. At the vanguard of Japan's energy transition, this pivotal event in the country's energy history marked the beginning of the process of realizing the promise of renewable energy sources. Japan has set substantial targets for improving its capacity for renewable energy after an extensive reorientation. The primary goal put ahead by the government is to ensure that 36-38% of the electricity in its power grid comes from renewable sources [3]. This represents a big step that calls for a revolution in the way energy is produced, distributed, and used across the nation. The move towards the incorporation of energy from renewable sources has significant ramifications for both Japan's domestic energy market and its reputation as a leader in clean and sustainable energy worldwide. It is in complete harmony with the worldwide endeavor to tackle climate change, curtail carbon emissions, and establish a more robust and sustainable energy system.

A complex and diverse challenge lies in integrating renewable energy sources including geothermal, hydroelectric, solar, and wind power into Japan's energy grid. Even though these renewable energy sources are plentiful and environmentally beneficial, their energy production is inherently unpredictable, hence creative ways to integrate them into the current energy infrastructure are required. In addition, the switch to renewable energy sources increases the demand for advanced energy storage technologies. Because renewable energy sources are intermittent, storage solutions are vital for efficiently capturing, storing, and distributing energy during periods of high demand or decline in renewable supply [6].

In this setting, Japan is positioned to lead the way toward a more robust, sustainable, and diversified energy landscape by recalibrating policies, transforming infrastructure, and advancing technological innovation. Not only is the effective integration of renewable energy sources essential to meeting Japan's lofty energy ambitions, but it also establishes a strong example for other countries hoping to undertake similar energy transformations. The objective of this paper is to provide a thorough analysis of the complex dynamics, opportunities, and tactics related to incorporating renewable energy sources into Japan's energy mix. It aims to investigate the various aspects of integrating renewable energy, with a particular emphasis on how energy storage technologies might help Japan achieve its goal of 36-38% renewable electricity by the year 2030 [3]. By conducting a thorough examination of technological, economic, environmental, and regulatory aspects, this research endeavors to furnish significant perspectives and tactical counsel that are imperative for guiding Japan toward a sustainable and resilient energy future [6].

A key component to encourage the use of renewable energy is the introduction of a Feed-in Tariff (FiT) scheme. By ensuring set, above-market prices for renewable energy providers and encouraging investment in solar, wind, biomass, geothermal, and small hydroelectric power generation, the FiT mechanism made it easier to integrate renewable energy sources into the electrical grid. Using this policy instrument, Japan intends to increase private sector involvement, promote the growth of renewable energy sources, and quicken the adoption of clean energy technology nationwide. By offering favorable tariff rates, the FiT system attempted to lower entrance barriers for renewable energy projects and create an atmosphere that would encourage investments in renewable energy [7].

Japan established ambitious goals to increase its capacity for renewable energy in line with international agreements to fight climate change and move toward sustainable energy sources. Additionally, the Japanese government unveiled a bolder goal by a date in the future, to attain a carbon-neutral goal, indicating a commitment to significant long-term changes in the energy industry. This overarching goal demonstrates Japan's commitment to greatly increase its capacity for renewable energy sources and to lowering greenhouse gas emissions while promoting energy security and sustainability [6].

Japan's government frequently updates its Strategic Energy Plan, which acts as a guide for the country's energy policy goals and directions. To address environmental problems and achieve energy security, sustainability, and economic competitiveness, the plan outlines the overarching strategy, policy frameworks, and action plans. The Strategic Energy Plan highlights the importance of increasing energy efficiency, diversifying energy sources, and promoting renewable energy as the cornerstones of a strategy to lessen dependency on nuclear and fossil fuels. It also emphasizes how crucial innovation, R&D, and technology improvement are to boosting the effectiveness of renewable energy sources [4].

Even though Japan's renewable energy legislation has significantly increased the number of renewable energy installations, difficulties still exist. The attainment of the established goals will require overcoming notable obstacles such as legal frameworks, land limits for large-scale renewable projects, grid integration challenges, and intermittent management. Japan is still fully committed to increasing its capacity for renewable energy [1]. The country is still investigating market incentives, legislative changes, and technology advancements to break down obstacles and hasten the use of renewable energy sources. Japan's ambitions for renewable energy are expected to be realized in large part through the integration of energy storage systems and the development of smart grid technology.

In summary, Japan is taking a proactive approach to shifting to a more sustainable and varied energy mix, as evidenced by its renewable energy regulations and targets. Even if there has been progress, further policy innovations and tweaks are necessary to overcome obstacles and realize Japan's vision of a future powered by renewable energy. Strong energy storage technologies are required as Japan shifts to a more renewable-focused energy mix to handle the erratic and intermittent nature of renewable energy sources [2]. A thorough analysis of the state of energy storage technology identifies a variety of choices, each with special qualities, benefits, drawbacks, and applicability to Japan's energy system. Among the most widely used and economically feasible forms of energy storage are lithium-ion batteries. Lithium-ion batteries, which are well-known for their high energy density, scalability, and quick response time, have been widely used in a variety of applications, such as grid-scale applications, electric vehicles, and stationary storage systems. Enhancing energy density, longevity, and cost reduction are the main goals of ongoing research [8].

The second option is flow batteries that offer an alternate storage technology with built-in benefits in terms of scalability and energy and power decoupling, such as vanadium redox flow batteries. They are appropriate for grid-level applications where flexibility and duration are crucial elements because of their capacity to store significant amounts of energy for extended periods. Pumped hydroelectric storage is cost cost-effective option [7]. Utilizing the potential energy contained in raised reservoirs, pumped hydroelectric storage systems generate electricity. Water is pumped to the higher reservoir during times when there is an excess of electricity generated, and when the need for electricity increases, the stored water is released to power turbines. Although there are obstacles in the way of establishing new pumped hydro projects due to Japan's topography and spatial constraints, the country's current installations greatly enhance grid stability. The other option is the Compressed Air Energy Storage (CAES) system, compressed air is stored in underground reservoirs or caverns by CAES systems. The compressed air is released and heated when electricity is needed, which powers turbines to produce energy. Potential benefits in scalability and relatively long-duration storage are provided by CAES. Hydrogen-based storage is a recently popular storage method. With its versatility as an energy carrier, hydrogen is becoming more and more popular as a storage medium. Power-to-gas systems and similar technologies use electrolysis to turn surplus electricity into hydrogen, which may be stored and used as a feedstock for a variety of businesses or as a fuel for fuel cells to generate electricity. In line with its goals for a hydrogen society, Japan has been investigating hydrogen as a potential energy storage and transportation medium. Every energy storage system has a unique set of concerns and obstacles. The selection and application of energy storage technologies in Japan's energy landscape are heavily influenced by several critical aspects, including cost-effectiveness, round-trip efficiency, energy density, scalability, environmental impact, and geographic limitations. It will take careful planning, new technology, regulatory support, and system modernization to integrate these various energy storage solutions into Japan's electrical infrastructure. Advances in demand-side management, smart grid technology, and sophisticated control systems have the potential to improve the efficacy and efficiency of energy storage integration [9].

A mix of these storage technologies, adapted to Japan's geographic and economic context, will be essential to achieving the country's energy transition goals while maintaining system stability and dependability. There are many different approaches for energy storage available in the technical environment, each with unique benefits and drawbacks. The success of Japan's integration of renewable energy sources and its transition to a sustainable energy future will depend on its pursuit of the best combination of these technologies [4].

To ensure the efficient deployment and exploitation of these technologies, several technical factors and challenges related to the integration of energy storage systems into Japan's energy infrastructure must be addressed. Japan's growing reliance on intermittent renewable energy sources, such as wind and solar electricity, presents management issues. Energy storage devices are essential for reducing intermittent because they store excess energy during times of peak generation and release it when demand exceeds the production of renewable energy. Variations in voltage and frequency can result from the unstable nature of renewable energy sources, which can affect grid stability. Energy storage technologies can help preserve grid stability by controlling voltage and frequency. Careful consideration of compatibility and interoperability is necessary when integrating different energy storage technologies into the current grid architecture [7]. For deployment to be effective, it must be ensured that there are no conflicts or disturbances in the grid during the integration process. During charge and discharge cycles, the energy storage system's round-trip efficiency, which represents the ratio of energy output to input, must be considered. Improving the effectiveness of storage systems guarantees little energy loss, which optimizes the energy system.

To meet the sustainability and NetZero targets, energy storage technologies must be evaluated, and their effects reduced. This includes resource extraction and waste management. The integration of several studies, research articles, and scholarly works in this extensive literature review will offer a nuanced knowledge of the complex features of energy storage choices for the transition to a carbon-neutral goal. This study seeks to identify gaps, possibilities, and strategic routes to guide future empirical research and recommendations by critically examining the body of existing literature [5].

3. METHODS AND MODELLING

The Energy PLAN software package is utilized to balance the electricity demand and supply. It is open-source software intended to analyze the energy, environmental, and economic impact of various energy strategies [10]. In this section, the data collection of statistical data and estimation of projected renewable electricity capacity are determined to balance the demand and supply from renewable resources [10]. The annual electricity demand was calculated using Eq. (1) below where t represents time in hours, and P_d represents annual electricity consumption [11].

$$P_d = \sum_{t=1}^{8784} P_d\, t \tag{1}$$

The investment cost was determined by unit cost and number of units as per Eq. (2) below [11].

$$C_{Inv} = P_x \times C_{unit-x} \tag{2}$$

where,

C_{Inv} is an investment cost
P_x is the number of units
C_{unit-x} is the unit cost

A flow chart and sequence of work for simulation in Energy PLAN software is presented in Figure 3. This flow chart represents the sequence of modeling in Energy PLAN software. The electricity demand of 110 TWh/year was input in this scenario which is approximately 12.5% of the total electricity demand (870 TWh) in the year 2022 as shown in Figure 4 [3].

Based on Table 1, the generation mix of renewable energy power plants capacity is input in Energy PLAN and simulates the scenario as per Figure 5.

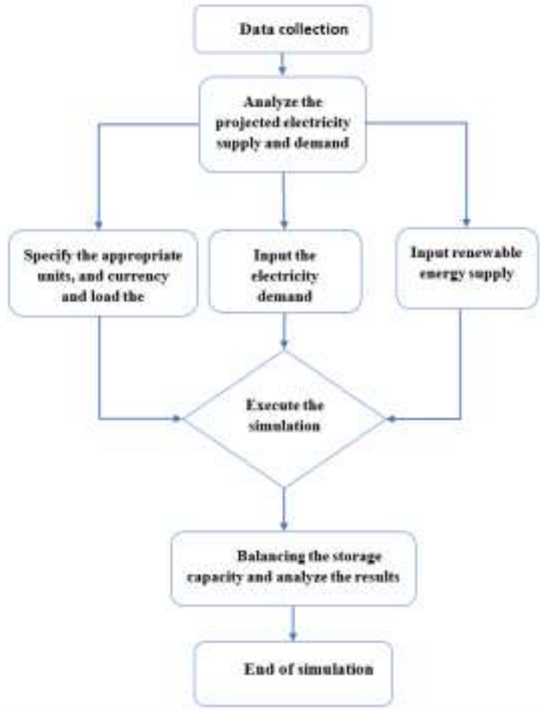

Figure 3. Flowchart of Energy PLAN simulation [10]

Figure 4. Electricity demand input in Energy PLAN [10]

The installed capacity of renewable power plants and target capacity by the year 2030 are summarized in Table 1.

Table 1. Summary of installed capacity and target capacity of renewable power plants

Type of Renewable Resources	Installed Capacity of Renewable Electricity (2022) (MW) [3]	Target Capacity of Renewable Electricity by 2030 (MW)
Wind	5,170	20,000
Solar Photovoltaics	70,400	
Geothermal Power	560	89,800
Hydropower	1,000	1,273
Bioenergy	19,600	
Total	96,730	111,073

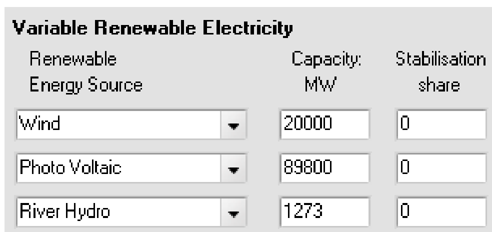

Figure 5. Renewable plants capacity input in Energy PLAN [10]

4. TECHNO-ECONOMIC ANALYSIS

The capital cost of the wind turbine power plant and solar PV plant, operating period, and O&M costs are determined based on the data from the Renewable Energy Institute [12-15] where the statical cost for the hydroelectric power plant was taken from the study [16], and input Energy PLAN simulation as per Figure 6 below.

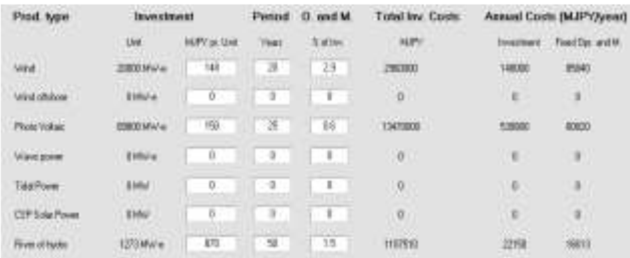

Figure 6. Results of total investment costs and annual operating costs from Energy PLAN [10]

To stabilize the grid, it is necessary to provide an energy storage system of 18,000 GWh capacity as per the simulation results shown in Figure 7 below.

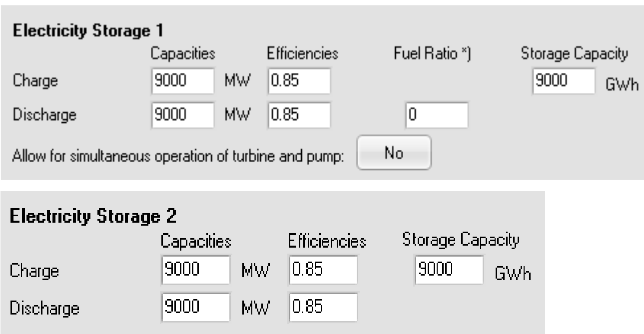

Figure 7. Energy storage capacity based on calculated scenario [10]

Suitable energy storage systems, applicable ranges, round trip efficiency, and costs are summarized in Table 2 as per the statistical data from the International Renewable Energy Agency and Renewable Energy Institute, Japan [3, 17-18]. Pump hydro and CAES storage options are suitable for larger capacity and the battery storage option is suitable for small and medium scale plants [19].

Table 2. Comparison of energy storage technologies adapted from IRENA [17] and REI [3]

Technology	Size Range (MW)	Capital Cost ($/kW)	Capital Cost ($/kWh)	Round Trip Efficiency (%)
Pum ped Hydro	280~3000	2000~3500	420~430	70~85
CAES	180~1000	960~1150	60~120	40~70
Li-ion battery	100	3100~3300	520~550	85~95
Flow batteries	100	1450~1750	290~350	60~85

5. RESULTS AND DISCUSSION

Please use the SI set of units as much as possible. The simulation was carried out based on the data shown in Figure 4 and Table 1 to generate annual electricity demand and supply whereas the results from Figure 8 indicate the annual electricity demand and production. The base load is approximately 7,000 MW.

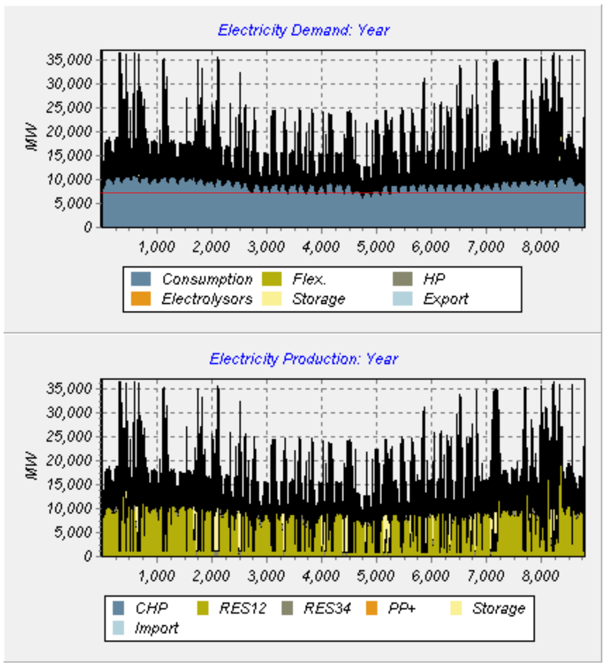

Figure 8. Annual electricity demand and production capacity [10]

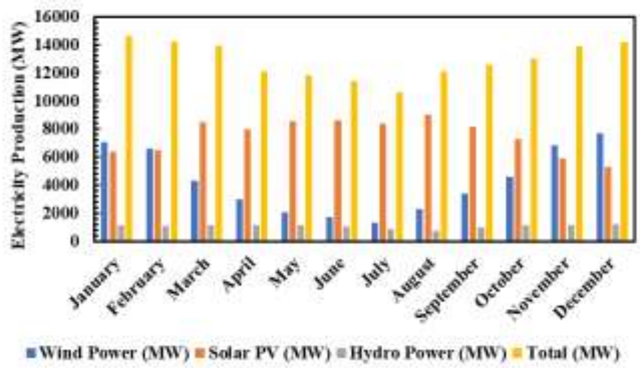

Figure 9. Monthly electricity production results from Energy PLAN simulation [10]

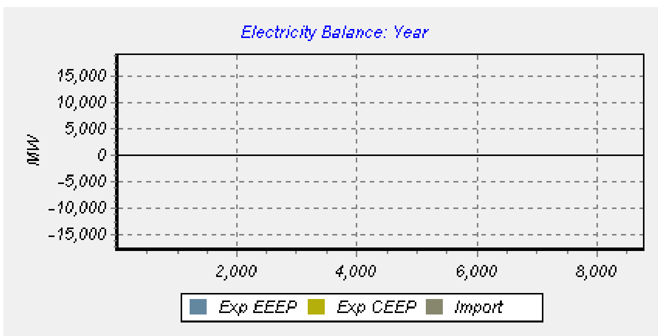

Figure 10. Electricity balance [10]

The simulation results shown in Figure 9 indicate monthly electricity production results where July is the lowest electricity production due to the summer season also known as typhoon season in which the electricity generation from hydropower and wind power is slightly reduced compared to other seasons. The results shown in Figure 10 prove that the grid's 100% stability is achieved which means no electricity import is needed. However, the energy storage capacity of 18,000 GWh (as shown in Figure 7) is needed to balance the intermittent nature (above and below the balance line).

Among suitable storage options summarized in Table 2, pumped hydro storage is the most economical and large-scale storage option [20]. However, it has some limitations such as geographical restrictions, and space requirements, especially in Japan, land prices are extremely expensive, and environmental impact assessments are in strict control. In this regard, the lithium-ion battery storage system is the most suitable energy storage system due to its flexibility and higher round-trip efficiency [21].

6. CONCLUSIONS

This investigation has rigorously analyzed to balance supply and demand, and grid stability with storage options using the Energy PLAN software package.

This study presents a roadmap that seeks to steer Japan's energy landscape toward resilience, sustainability, and diversification while promoting energy security, cutting emissions, and boosting economic competitiveness. In conclusion, this study is an invaluable resource for discussions on the integration and storage of renewable energy sources in addition to providing a thorough roadmap for Japan's energy transformation. Through the integration of economic viability, environmental requirements, regulatory requirements, and technological developments, this research aims to make a substantial contribution to the pursuit of sustainable energy futures. Further improvements in storage technologies and efforts to bring down the storage costs of hydrogen and power-to-gas technologies will enhance energy productivity.

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NOMENCLATURE

CAES	Compressed Air Energy Storage
CEEP	Critical Excess Electricity Production
EEEP	Exportable Excess Electricity Production
RES	Renewable Energy Source
VRES	Variable Renewable Energy Source