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Overview of Pumped Storage Hydropower Systems and Their Potential Utilization in Indonesia

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***Abstract*—The increasing demand of sustainable energy sources as well as intermitten of power generation from renewable energy sources, energy storage system will become the most important system to ensure grid stability and reliability. Indonesia has abundant of renewable energy sources, i.e solar energy, wind energy, geothermal energy and hydro energy. Recently renewable energy harnessing in Indonesia is encouraged to meet energy mix target 23% in 2025 and replace fossil energy. Based on Indonesia Outlook Energy Book, in 2023 the total capacity of power generation in Indonesia is about 83,8 GW, almost 50% still use coal energy meanwhile RES in energy mix around 15%. Indonesia has commited on paris agreement which is related to climate change problem solving in order to reduce green house gas emission. Indonesia also has target towards net zero emission in 2050. Therefore, renewable energy harnessing must be boosted. The abundance of renewable energy sources made Indonesia use renewable energy for the future energy particularly in power generation. One of the problems in renewable energy sources (RES) for power generation is intermittent, hence the energy storage systems are needed to secure the electricity supply as well as grid stability and reliability. Indonesia has potential to develop pumped storage hydropower because of Indonesian location in the mountain and hill. Nowdays Indonesia first pumped storage hydropower system still builds in Upper Cisokan. Therefore, the study of energy storage systems is needed for sustainable energy sources in the future. This paper aims to analyze the principle and technology of Pumped Storage Hydropower (PSH), evaluate the potential as well as the simple simulation of harnessing PSH system in Indonesia.**

***Index Terms*—power generation, renewable energy, storage system, intermittent, PSH**

I. Introduction

The use of RES to replace fossil energy in power generation will be the future trend of the power industry. Nowdays, power generation installed capacity in Indonesia is dominated by fossil energy as shown in Fig. 1 power generation installed capacity in Indonesia 2013 - 2022. Power generation installed capacity in Indonesia is about 83,8 GW, almost 50% still uses coal energy, 25% uses gas meanwhile only 15% uses renewable energy sources.

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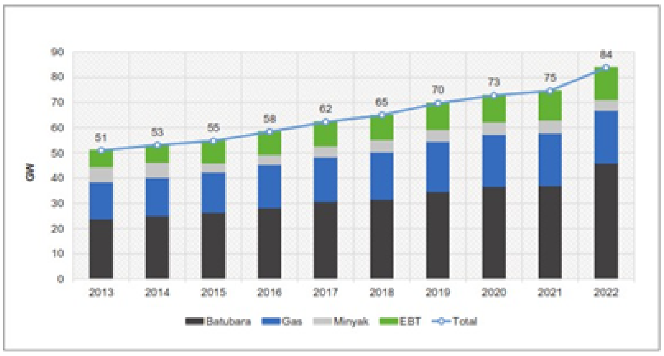

Fig. 1. Overview of the measurement device setup.

Practically Indonesia has abundant solar energy potential based on Indonesia Energy Outlook Report 2023 [1]. The potentiaal of RES in Indonesia is shown in Table 1 below.

The worldwide energy sector is undergoing substantial changes as societies shift to more sustainable and low emission energy systems.The change is driven by growing awareness of increasing climate change mitigation, reducing fossil energy and energy security [2]. The growth of renewable energy such as solar and wind becomes the center of transition energy. However, these energy sources are intermittent because of dependence on nature. Therefore, providing sustainable in electricity energy and stability grid electricity become more challenging, hence energy storage system development is needed particulary for large scale capacity in power generation [3], [4]. In public transportation, it can be used battery for energy storage system, but for power generation needed large scale capacity energy storage system. PSH system will become the best choice since the mature technology of PSH system compared to other energy storage technologies.

TABLE I
RES POTENTIAL IN INDONESIA AND POWER GENERATION INSTALLED CAPACITY FROM RES

RES	Potential Total (GW)	Installed Capacity (GW)	% of Installed Capacity
Ocean	63	-	-
Geothermal	23	2.4	10.3%
Bioenergy	57	3.1	5.4%
Wind	155	0.2	0.1%
Hydro	95	6.7	7%
Solar	3.294	0.3	0.01%
Total	**3.687**	**12.6**	**0.3%**

This paper proposes PSH system harnessing as well as its development in Indonesia. Meanwhile this paper reviews literature study of the technology of pumped storage hydropower, the detail study about comparisons with other storage technologies such as battery or hydrogen will be discussed later. The following diagram for literature study can be shown in Fig. 2 below. From Fig.2 below, it can be explained how the literature study method in this research.

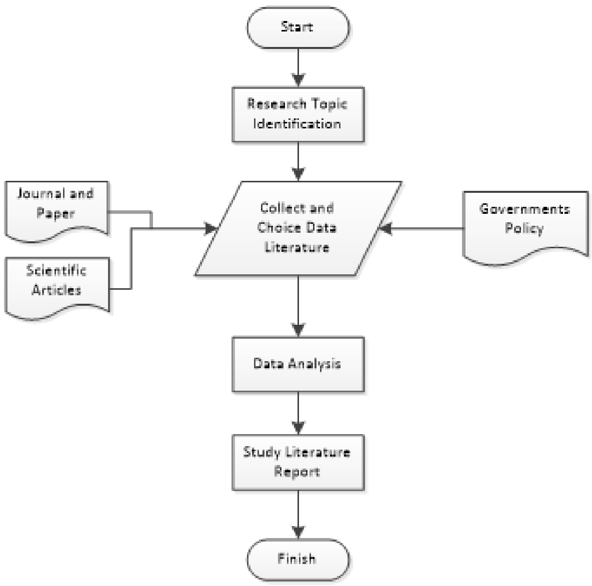

Fig. 2. Literature Study Flow Diagram.

In the future study will be focused on economic analysis of pumped storage hydropower especially in Indonesia and also detailed simulation about the operation of the system is needed.

Based on the paper which will be discussed below, there are describe about worldwide hydropower growth in over the world, type of energy storage system and how the integration of pumped storage hydropower incorporate with other RES, meanwhile the simulation for dynamic system will need to be detailed in future study.

II. Worldwide Hydropower Growth

In 2022, global hydropower capacity reached 1.330 GW and generate a total of 4.370 TWh of electricity energy. However, hydropower install capacity in Indonesia is relatively small, just only 6,7 GW. Fig. 3 Worldwide Hydropower Installed Capacity describes that China have a biggest hydropower install capacity in the world with 370,2 GW.

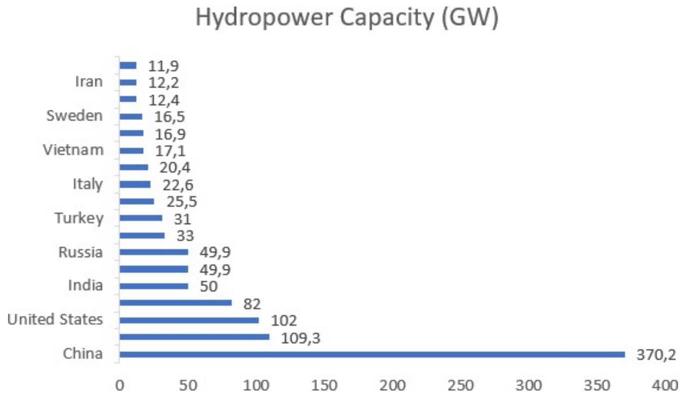

Fig. 3. Worldwide Hydropower Installed Capacity

In the end of 2020, several countries have finished hydropower construction project with the biggest hydropower installed capacity in China 12,7 GW, meanwhile Indonesia succeeded increasing hydropower installed capacity 236 MW.

Indonesia has a small hydropower installed capacity of 6,7 GW. For comparison, the global hydropower installed capacity reached 1.330 GW. From Table 1 above, Indonesia has relatively small renewable energy potential from ocean, geothermal, bioenergy, wind and hydro, however Indonesia has vast solar energy potential of 3.294 GW [5]. In the future Indonesia will rely mostly on solar energy for its sustainable energy needs. Therefore, Indonesia will need substantial energy storage systems for overnight and longer periods [6], [7].

Pumped storage hydropower system (PSH), in recent years, have represented 99% of the electricity storage capacity in the world, which makes them the most used mechanical energy storage systems. This paper also presents that Indonesia has huge potential for low cost off river PSH with low environmental and social impact, furthermore as a future renewable energy power generation from solar energy Indonesia need them to ensure the stability of electricity grid [8], [9].

III. Energy Storage System Technologies

Energy storage systems can be classified into five major categories : mechanical systems, thermal system, chemical, electrochemical system and electrical storage technologies. Fig. 4 describes Energy Storage System Classification [10].

From Fig. 4, the PSH system was classified into mechanical storage systems. PSH stores excess electrical energy by harnessing the potential energy store in water. The growing need for energy storage systems globally will become a trend in the future since the power production from renewable energy is intermitten thus it needs reliable and mature energy storage systems. Hence, currently many countries focus on energy storage research and how a comparison of batteries and PSH system as energy storage systems with the integration of

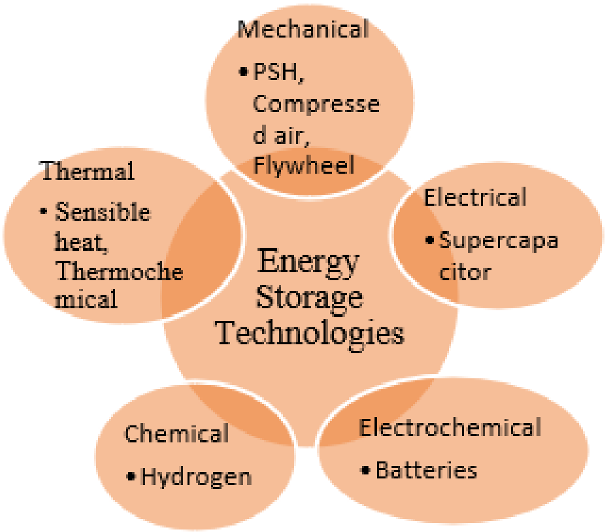

Fig. 4. Energy Storage Systems Classification

wind and solar PV energy sources, which are the major trend technologies in the renewable energy sector [11].

In recent years, there are ten countries which have constructed energy storage systems on pumped storage hydropower is the largest constructed as described in Fig. 5 Ten Countries with Large Energy Storage System. China was the country which have either the largest energy storage system capacity in the world or pumped storage hydropower system. Fig. 6 describes worldwide pumped storage hydropower installed capacity 2016 – 2023 [12].

Hydropower has the largest contribution among all RES. The increasing demand of energy and the transition toward clean energy have proposed new challenges, such as increased energy efficiency and storage. Energy storage systems are a critical area of research, which is required for integration of renewable energies [13].

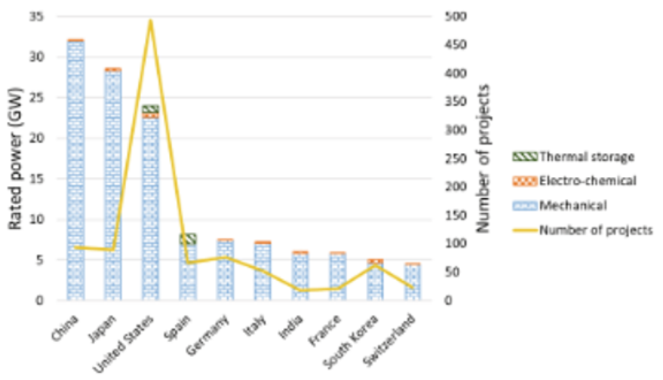

Fig. 5. Ten Countries with Large Energy Storage System

IV. Pumped Storage Hydropower

Pumped storage hydropower system (PSH) stock surplus electrical energy by utilizing the potential energy stored in

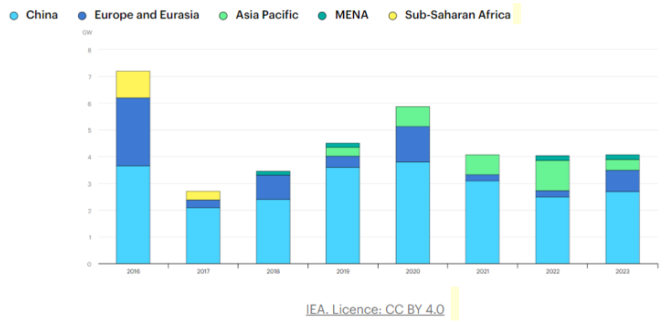

Fig. 6. Worldwide Pumped Storage Hydropower Installed Capacity 2016 - 2023

water. Fig. 7 describes principle of pumped storage Pumped storage hydropower system (PSH) stock surplus electrical energy by utilizing the potential energy stored in water. Fig. 7 describes principle of pumped storage hydropower system, energy surplus from the system stored in water, in which excess energy is utilized to transfer water from lower artificial lakes to higher ones. Meanwhile, when electricity demand rises, water from higher artificial lakes is pumped through turbines connected to generators to generate electricity, effectively operating as a hydropower plant. Energy stored in Pumped Storage Hydropower (PSH) can be quickly released during periods of high demand, converting it into electrical energy [14]. PSH has the potential for balancing demand and supply from renewable energy power generation, levelling other generating units and ensuring security and reliability electricity grid.

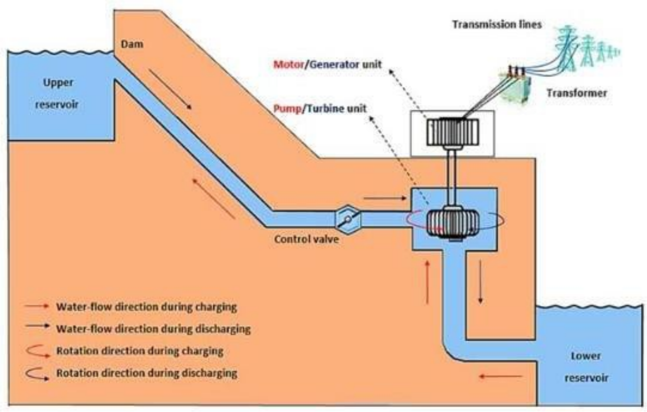

Fig. 7. Principle of Pumped Storage Hydropower

A. *Characteristic of PSH Systems and Used of PSH*

In recent years, numerous detailed studies have been conducted on energy storage systems, most of them concludes that PSH systems have seen wide opportunity for implementation because PSH systems have some advantages characteristics, including large scale capacity on storage systems and power capabilities, long term energy storage systems potential as well as operational efficiency [15].

PSH systems highlight technical characteristics which make them appropriate for the huge storage energy systems when there is surplus from renewable energy sources (RES). Nowdays PSH systems contribute to peak electricity generation, grid stability and ancillary services. They also aid in integrating variable renewable energy (VRE) by storing surplus energy produced during periods of low demand [16]. PSH systems have power capacity ranges from 10 to 4000 MW, level of technology readiness of 11/11 based on the International Energy Agency (IEA) guides as well as providing flexibility in system design. The duration of discharge for PSH system at rated power ranges between 1 to over 24 hours, with storage durations spanning hours to days. PSH systems have an efficiency of 70 – 85% and maintain effective energy storage. With the minimal reaction time, PSH systems adapt to fluctuating energy demands.

The technical characteristics of PSH systems listed below:

- Energy Storage
- Grid Stability
- Integration of VRE (Variable Renewable Energy)
- Load Balancing
- Low Environmental Impact and Long Lifespan

B. Integrated PSH systems with RES

Although renewable energy sources environmentally friendly but there are intermittent. This feature becomes a challenge for ensuring reliable power supply and grid stability, crucial aspects for delivering energy storage systems to end users [17].

Solar energy exhibits lower intermittency than wind energy due to fluctuations wind velocity as meteorological factors. This variability will impact directly on renewable energy power generation and consequently also impact the stability of the power grid [18]. Grid stability is crucial problem as growing rapidly renewable energy power generation. Fig.8 describes Curtailment Energy from Solar PV Energy.

The curtailment energy of solar PV caused by no integration with energy storage system, over supply and limited transmission grid on the dispatch electricity energy to other location which have peak load at the same time. As the more renewable energy connected on grid, the more over supply risk if there are no compatible energy storage systems. Consequently, the risk in curtailment on PV and wind energy actually no need but it will happen. Fig. 9 describes an example on curtailment PV and wind energy [19], [20].

V. Pumped Storage Hydropower Potential in Indonesia

Indonesia has set target net zero emission (NZE) by 2050 as Paris agreement related with climate change. If Indonesia depend on fossil energy continuously to supply electricity energy, it is difficult to reach the target NZE in 2050. Currently, the largest renewable energy power generation uses in Indonesia is solar PV energy.

In recent years, the Indonesian government has revised its estimates for renewable energy potential to 3.687 GW, with 3.294 GW from solar PV energy and 394 GW from wind, hydro, geothermal, ocean energy and bioenergy combined.

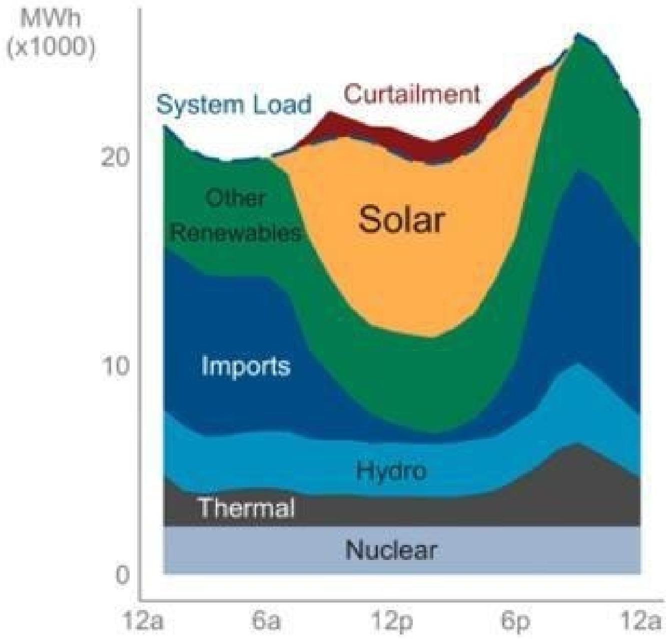

Fig. 8. Solar PV Energy Curtailment

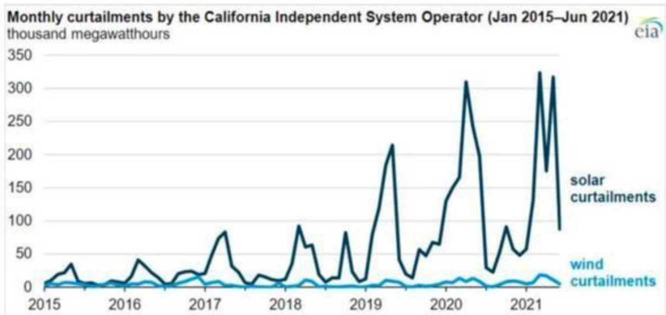

Fig. 9. Solar PV Energy Curtailment

Power generation installed capacity in Indonesia is 75 GW, whereas potential solar PV energy total 3.294 GW. Thus, in the future renewable energy power generation will supply electricity energy needs. Indonesia, as the sole large tropical archipelago, has weather data indicating that it could potentially generate 180.000 TWh per year of solar electricity from its maritime regions over a period of 40 years. Therefore, Indonesia will need large scale energy storage systems for overnight and longer period to store excess energy from RES and integration VRE into energy storage systems. Nowdays Indonesia starts construct PSH system project in Upper Ciocan for the pilot energy storage systems project. In recent years underlining PSH systems and batteries is the leading technology of energy storage system for electrical energy. Pumped Storage Hydropower (PSH) makes up approximately 95% of global storage capacity and 99% of global storage energy. It is a well-established and widely deployed technology known for its cost-effectiveness. The working fluid used in PSH, water, is much more abundant compared to the chemicals used in batteries.

Battery storage encompasses applications for homes, utilities and electric vehicles (EVs). The future deployment of EV batteries is expected to exceed that of home and utility batteries. Presently, the Pumped Storage Hydropower (PSH) system is more cost-effective than batteries for applications requiring overnight and longer-term storage. In the future, the cost of battery storage is expected to decrease, although there is significant uncertainty regarding future prices. If V2G (Vehicle to Grid) technology gains prominence, EV batteries could play a significant role in meeting future storage needs.

This is due to the scale of battery storage potential within an EV fleet is considerable and the cost of these batteries is largely offset by their primary purpose, which is mobility.

Indonesia has potential off river PSH system based on pumped hydro energy storage atlas was undertaken by The University of National Australian. Fig. 10 describes potential 150 GWh Greenfield off river pumped storage hydropower (PSH) sites in Indonesia.

Potential of PSH in Indonesia Based on Greenfield Data According to the global greenfield atlas, Indonesia has identified a total of 26.000 off-river PSH sites, with a combined energy storage capacity of 800 TWh. Currently, Indonesia has no PSH system caused by fossil energy still dominate in the harnessing of power generation. However, this is about changing. Indonesia has included 4000 MW off river PSH system in RUPTL or National Electricity Development Plan document. Table 2 below describes planning of PSH system in Indonesia.

Fig. 10. Potential of PSH in Indonesia Based on Greenfield Data

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The electricity company state Indonesia (Perusahaan Listrik Negara) / PLN plan to develop 4 x 250 MW PSH systems in Sumatera, which are expected connect to grid PLN in 2029 – 2032.

TABLE II
PLANNING OF PSH SYSTEM IN INDONESIA

Location of PSH	Capacity (MW)	Operation Target
PSH Upper Cisokan, West Java	1,000	2025
PSH Avengeing, West Java	943	2028
PSH Grindle, East Java	1,000	2030

In the next chapter, it will estimate how many energies storage system which are required in 2050 as net zero emission (NZE) program from government. Underlining, in 2050 power generation in Indonesia will be covered by renewable energy from solar PV energy and wind energy. Indonesia located in Khalistan area so Indonesia has tropes season, the sun will radiate continuously over the year. Thus, seasonal energy storage system is not really needed because Indonesia don't have summer and winter season. This paper proposes PSH system should be used for weekly energy storage system for balancing over night and day period. It is estimated energy storage system requirement to sustain 100% renewable energy power generation in the country which have low latitudes as Indonesia also located, is shown in Table III estimation energy storage system in some country and Annual Demand (TWh).

TABLE III
ESTIMATION ENERGY STORAGE SYSTEM IN SOME COUNTRY

Author	Blakers et) al., (2017)	Lu et al., (2021)	Lu et al., (2021)	Cheng et al., (2021)
Studied country	Australia	Australia	Southeast Asia	Japan
Scope of Study	Electricity	Energy	Electricity	Electricity
Annual Demand (TWh)	205	393	7524	896

Country	Energy Storage (GWh)-min/max	Estimated required storage (day)
Australia	407 - 574	0.7 - 1.0
Australia	321 - 2049	0.9 - 1.3
Southeast Asia	15,506 - 44,707	0.8 - 2.2
Japan	2069 - 13,750	0.8 - 5.6

By following the rule of thumb of this one-day storage system, Indonesia, which is carbon-free, prosperous and has a developed industry, by 2050 will consume 9,000 TWh of renewable electricity per year. This amount was obtained with the assumption that currently electrical energy consumption in Indonesia is 300 TWh per year. If it is assumed that the annual increase in electrical energy consumption is 300 TWh, then in 2050 or 30 years from now, the estimated electrical energy consumption will increase 30 times greater. from this year or around 9000 TWh. This assumption is based on the upper limit calculation and assumes population growth of 335 million. Assuming this data, energy storage of 25 TWh (75 kWh per person) and a power storage capacity of 1000 GW are needed.

A. PSH System Operation Mode

1) Open Loop Pumped Storage Hydropower: According to the Department of Energy in USA, Open Loop PSH is defined as a system that is continuously connected to natural water flow. Open loop PHS systems involve the movement of significant volumes of water between upper and lower reservoirs. This primary advantage lies in leveraging existing water resources and infrastructure, minimizing the requirement for extensive land use and construction. However, these systems can pose environmental challenges, affecting water quality, aquatic habitats and local ecosystems. Moreover, their operation depends on water availability and may be impacted by seasonal fluctuations and droughts. When the lower artificial lakes are an existing dam, the power plant can be situated downstream, eliminating the need for excavation.

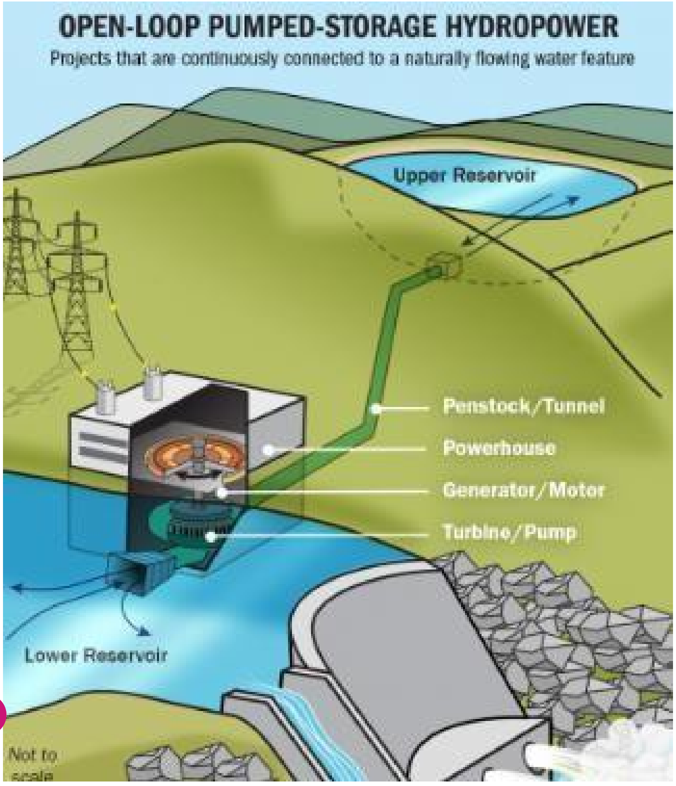

Fig. 11. Open Loop Pumped Storage Hydropower

2) Closed Loop Pumped Storage Hydropower: According to the USA's Department of Energy definition, a closed-loop PSH "is not constantly linked to a naturally flowing water feature. Thus, typically, a closed-loop PHS system includes upper and lower reservoirs located away from major water sources, with limited water input. However, the term continuous is crucial in this definition since some PSH projects are classified as closed systems despite initially using water from natural flowing surface water features to fill their reservoirs and periodically replace losses from evaporation and seepage. Closed-loop systems cause less environmental disruption than open-loop systems by reducing water consumption and avoiding disruption to natural water bodies. Additionally, these systems can also be situated in regions where open loop systems may not be viable due to limited water resources. However, closed-loop systems necessitate significant upfront investment in reservoir construction and water supply, potentially reducing their cost- effectiveness compared to open-loop systems. This system can be utilized in small artificial lakes filled by rainfall or water transported from various locations.

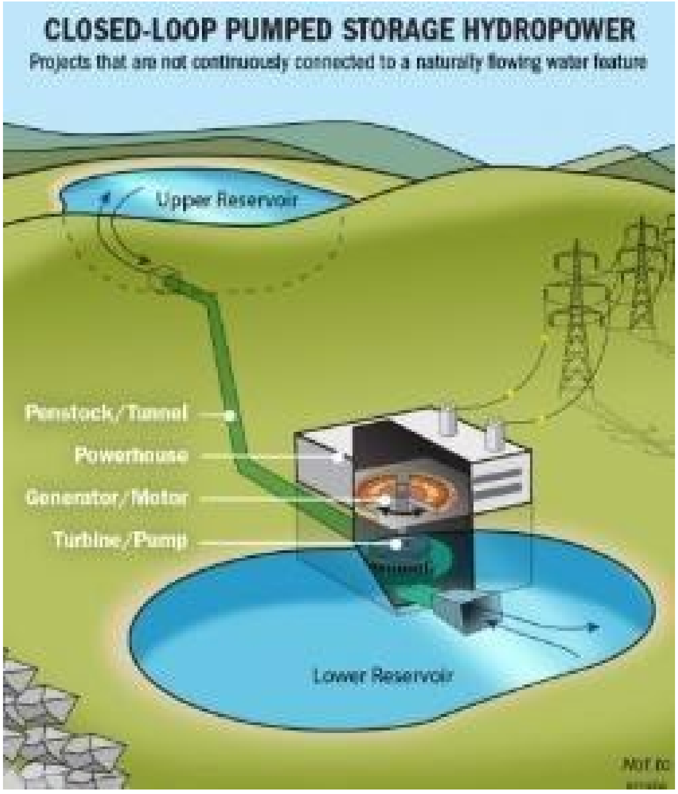

Fig. 12. Closed Loop Pumped Storage Hydropower

VI. CONCLUSIONS

The temporary conclusion that can be obtained from this literature review is that in short, PSH (Pumped Storage Hydropower) systems provide a range of distinct benefits that gain importance a renewable energy sources are adopted more widely. Through offering essential services such as frequency regulation, voltage support, load shifting and enhancing system resilience, PSH systems bolster the stability and dependability of today's electrical grid. Its fast response time, flexibility and ability to seamlessly integrate with renewable energy sources make it a critical part in the energy system of the future. Meanwhile, the future study is needed for more detail simulation with actual data in Indonesia, how the harnessing and efficiency of this system must be clarified with the actual condition in Indonesia.

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