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Paradigm of Pumped Hydro Energy Storage: Comprehensive Review

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Abstract: At present, climate change and anthropogenic impacts have a significant impact on the availability of water resources, hydroelectric power generation and the use of renewable energy sources. Maximizing and improving power utilization and providing balanced power in the national grid and sustainable energy at grid level is very important. It is widely recognized to utilize renewable energy from various sources and improve water resources management and utilization practices by providing PHES. This review paper examines the implication of Pumped Hydro Energy Storage (PHES) systems in fulfilling the nature of variable energy system to meet peak load. The review considers the characteristics, status and various topologies of PHES systems. The review explores that the preferred sites or topologies that varies in practice can be implemented at different sites of PHES. The paper highlights the importance of PHES, the PHES topologies, features, development of PHES. Suggests future directions and gaps may provide good input for researchers specifically focusing on peak load control, optimization and control mechanisms, improving efficiency and performance: environmental impacts, integration of renewable energy sources and optimal PHES sizing.

Keywords: Hydro energy, Topologies, Pumped storage, Hydropower

1. Introduction

Global freshwater scarcity and the effects of climate change have led to the increasing use of renewable energy sources to meet sustainable energy demands. The increasing global energy demand can be met by providing renewable energy sources to mitigate climate change and ensure a clean environment for future generations [1-2]. Nowadays, renewable energy storage is considered as an important part of the energy system in the development of sustainable energy storage technologies to reduce the impact of variable energy production and the intermittency and uncertainty of renewable energy resources could pose a significant challenge to achieve reliable and sustainable supply [1].

Supply of global freshwater for different sectors become very scarce because of population growth and climate changes consequently, governments are increasing their interest to use of renewable sources energy to provide sustainable and balanced energy [3]. Using abundant renewable resources, dry regions can meet their pressing water needs, economic barriers, mitigate climate change and reduce their dependence on non-renewable energy sources. Innovative approach required to realize the potential of this and ensure a water-secure and environmentally responsible future [2].

The intermittency of renewable energy sources, such as geothermal, solar power and wind might generate high or low energy it might demand energy management techniques. Provision of such type of single renewable energy sources unable to meet sustainable energy supply that necessitates energy storage technologies and hybrid approach enables the optimization of energy supply and demand, in order to reduce the risks associated with intermittency of renewable energy sources [1].

Moreover, number of researches depicts the development of renewable resources currently growing and anticipated to fulfil a growing future energy demand [4, 5]. However, the loss of produced power is serious problem in our power system significant amount is expected to loss from produced energy this is serious problem in our power system in order to alleviate this problem PHES become prominent solution for countries like Ethiopia which is not yet experienced [6].

Small hydro has emerged as a promising alternative energy source, offering environmental benefits, technological advances and efficient electricity supply, and its integration into the existing grid infrastructure is essential to promote a sustainable and renewable energy future. It may bring befits of maximized reliability, efficiency and the renewable energy sources integration in order to bring solution for power cut and blackouts [7].

Storage technologies like PHES play an important part to alleviate the difficulties of intermittent or variable energy generation and unbalanced demand and supply situations therefore, PHES have been served in a way sustaining variable energy production and harmonizing of power generation [8]. Pumped Hydro Energy Storage (PHES) has been gaining great attention. Since the 1980s, PHES has been a proven and widely used technology for utility-scale electricity storage [9]. It is considered the most developed technology for sustaining energy grid level, out of 3% generated electric energy over 99% of global energy stored using PHES [10]. PHES provide good efficiency which serve 70% to 80% and expected to serves 50 - 100 years depending long service and also stable and relatively cost-effective as compared to other energy storages [11, 12].

A pumped hydro energy storage storages designed to use the energy that is not utilized by generating this energy when required and if functions by pumping from a lower reservoir to a higher reservoir moreover, when the energy demand is high, the stored water back to the lower reservoir and generates energy [12, 13]. Challenges associated with the adoption of renewable energy, these can be overcome through measures and policy recommendations that promote its adoption. To overcome these challenges, it is essential to adopt measures and policy recommendations that promote the adoption of renewable energy sources. This can be achieved through incentives, to encourage investment in renewable energy projects. Furthermore, research and development in renewable energy technologies can be accelerated to improve efficiency and reduce costs [14].

Addressing PHES planning, the sustainability question points to management initiatives with significant financial outlays and strict social and environmental standards. Furthermore, while developing PHES environmental impact is critical issue therefore it should be considered properly considering multidisciplinary approach for sustainable development and success of the projects in order to meet the current demand without affecting future utilization [15-17]. However, the cost of a PHES rely on specific condition of site. Nowadays extract to construct PHES has become big challenge and has raised uncertainties about contribution of this mature energy storage option to future energy systems [18], because of this, choosing a PHES plant location is a more difficult process that merits consideration as an important area for future research [19, 20].

Main objective of this review on pumped hydro energy storage systems (PHES) aims to provide a review of various aspects regarding significance, developments, topologies, comprehensive features and future recommendations.

2. Features of Pumped Hydro Energy Storage (PHES)

The purpose of pumped hydro energy storage (PHES) is to provide an efficient and reliable means of storing and releasing electricity on a large scale and it is a derived from amount of and total head the available water. It serves several important purposes in the energy sector. PHES is primarily utilized as a method of storing and releasing electrical energy on a large scale PHES is not typically used specifically for flood control purposes [21]. However, it's worth noting that the operation of existing hydropower facilities, including conventional hydroelectric power plants, can contribute to flood control efforts [22, 23].

2.1 Sustaining Energy and Peak Shaving

Important aspect PHES is sustaining energy at grid scale through provision of energy by providing water energy storage at higher elevation point when the energy load is low the then generate energy by releasing the water during periods of peak load. PHES combines two existing or proposed reservoirs installed at different elevations. Water storage will be conducted for the period of low electricity demand to store surplus energy from the lower to the upper reservoir in the form of water storage. It acts as energy storage battery, balance fluctuations in electricity provision and demand, and helps to manage intermittency of renewable energy sources like solar and wind [8, 22-24].

In order to determine the capacity of pumped energy storage important to know the size and elevation difference between the two existing or proposed reservoirs and furthermore higher elevation difference produces higher energy [25-27]. Meeting peak energy demand is critical issues when it is required. PHES is well known energy storage used to provide balanced energy for long period. PHES systems can provide both high power output and long-duration energy storage. When high demand required PHES can rapidly provide the stored energy to meet the high load. This minimize the congestion on power plants and helps avoid the necessity costly additional power generation capacity [24, 28].

2.2 Time-Shifting Energy and Standby Power Service

PHES easily provide time shifting protocol during generation of excess energy with low load and allows excess energy storage, this encourages the use of renewable energy sources more since it makes it possible to store excess energy during times of high production and use it during times of higher demand [8], [29].

PHES serve as consistent standby power source when grid failure happened or during any accidents. PHES easily provide electricity to prioritized demand, safeguarding provision of electricity in worst scenarios [22, 30].

2.3 Service for Longevity and Lifecycle and Supplementary Services

It provide supplementary services to energy grid, balancing variable energy production and maintain grid stability by ensuring instantaneous electricity generation utilization are balanced [19, 31]. Furthermore, provides grid operators with the flexibility to balance Energy production and storage of surplus electrical energy during times of base load and releasing it during periods of peak load. This enhance to balance the grid, optimize power generation resources and avoid overloading [8, 32].

PHES is well known for a long term operational service. The PHES components reservoirs, pumps, turbines and generators and other parts are long-lasting and serve efficiently for many years with appropriate attention maintenance and management. This long term service have positive impact on the economic feasibility and sustainability of PHES [17, 33].

2.4 Integration of Renewable Energy Sources

PHES attracted global attention for the reason of integrating renewable energy sources or intermittent energy sources, might lead us to consider pumped energy sources, to allow balanced energy production [17, 24, 34]. PHES might have a significant environmental impact during the construction phase when land and water resources are utilized. However, during operation stage has a minimum environmental impact. Regarding emission of greenhouse gases, do not release gases during operation and storage this make PHES a clean and environmentally friendly storage solution [35, 36].

2.5 Environmental benefits

In addition to their technical characteristics, pumped storage power plants offer several environmental benefits [8, 9]. They do not emit greenhouse gases or other pollutants during operation, making them a clean energy option. What's more, as they do not require large areas of land or significant consumption of resources, their environmental footprint is relatively small compared to other methods of power generation [11, 12].

Generally, the features of PHES include its high storage capacity, high power output, efficiency, grid flexibility, longevity, and favourable environmental conditions. The purpose of PHES is to increase the flexibility, reliability, and efficiency of the electricity grid. It plays a crucial role in allowing the penetration and optimization of renewable energy sources, while also ensuring grid stability and meeting fluctuating electricity demand.

3. Pumped Hydro Energy Storage Development

Global pumped storage capacity rose from around 100 gigawatts in 2010 to more than 139.9 gigawatts in 2023, an increase of more than 30% in ten years. With PHES capacity of almost 45 gigawatts in the latter year, China held the record for the highest capacity [37].

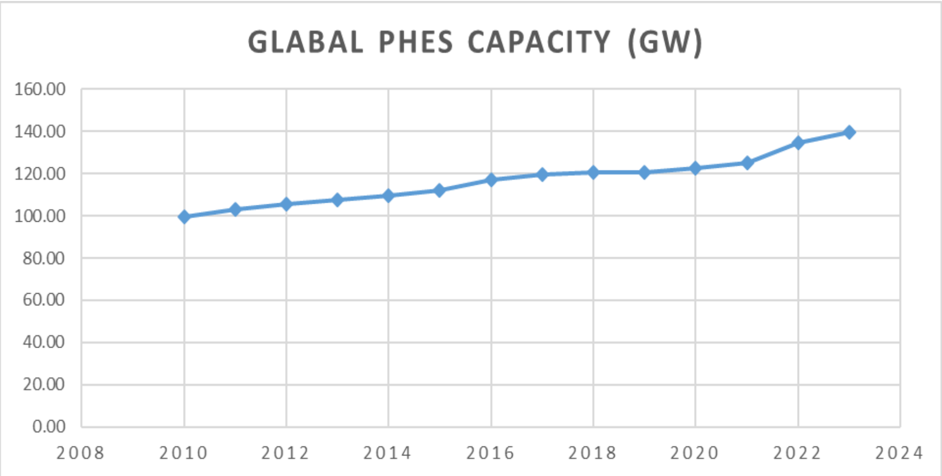

Figure 1. Capacity of PHES Globally [37].

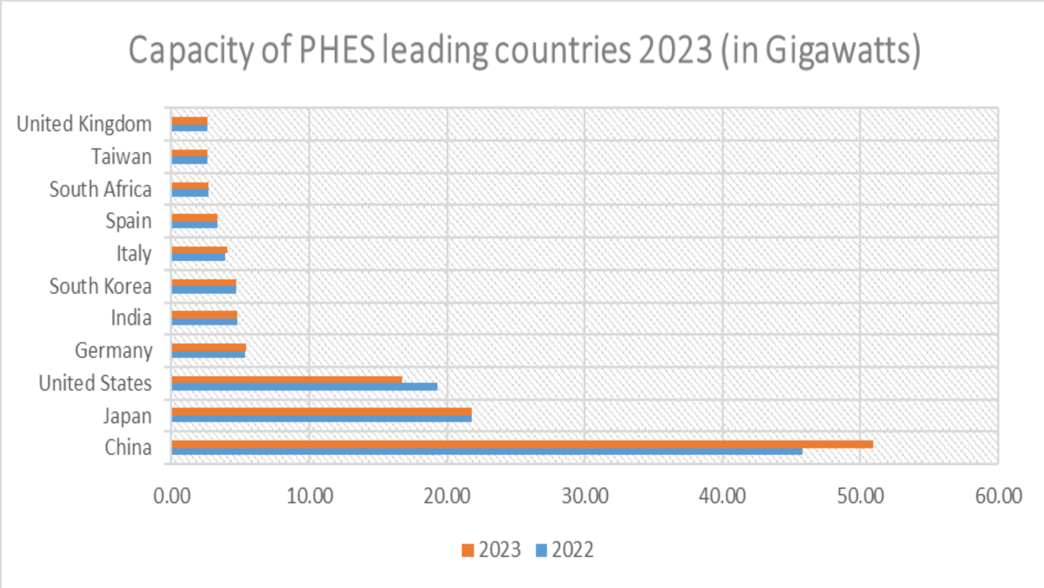

Figure 2. Capacity of PHES worldwide by countries [37].

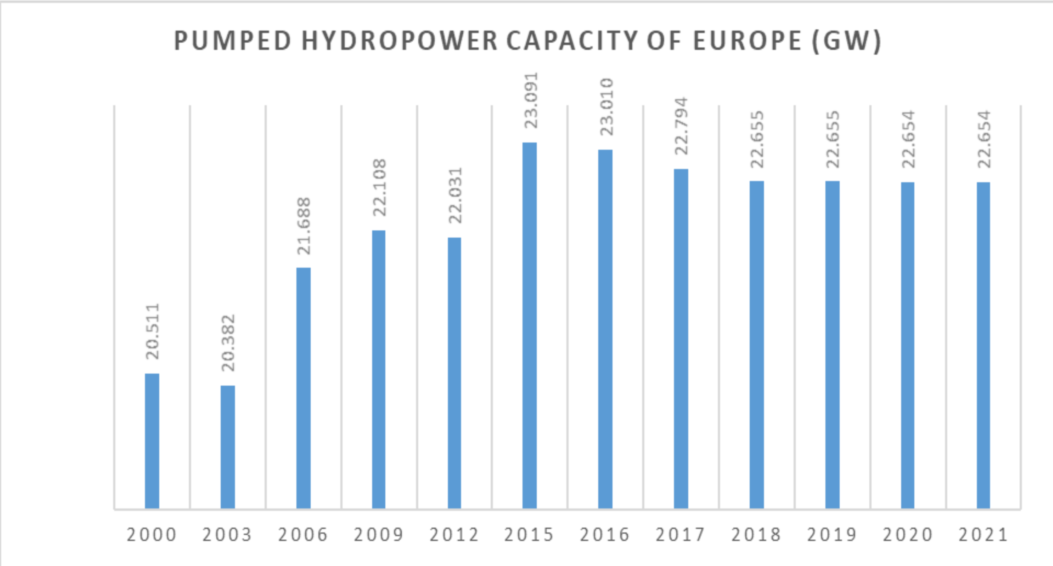

Figure 3. Growth of PHES capacity of Europe [41].

China ranks first with 50.9 GW of PHES capacity by 2023, with Japan and the US also in second and third place with around 21.8 GW and 16.7 GW of PHES capacity by the end of 2023 respectively [38]. Further studies show that in 2015 and 2017, new PHES with a capacity of 2.5 GW and 3.2 GW respectively will be commissioned worldwide [39].

The development of nuclear power in Europe in the 1960s and 1990s boosted the use of PHES, but countries such as Austria developed PHES without having nuclear power. Most of Europe's pumped storage capacity is installed in Austria, France, Germany, Italy, Spain and Switzerland. As shown below, the status of PHES shows a slight increase from 2008 due to increased energy demand and a change in perception towards wind generation. The 430 MW PHES of Reisseck II in Australia was installed in 2014, and the 852 MW expansion of the La Muela pumped storage plant in Spain was also completed [11, 40]. The status of recent advances in PHES of Europe is outlined here.

Japan is one of the country know in using PHES and the country has developed PHES since 1980s to 1990s directly related development of nuclear power, highly developed with nuclear energy and PHES power capacity of installed electrical generation capacity is 21.8GW [42]. Most PHES installed near to nuclear power plants for easily integration of with PHES as an example Imaichi one of largest PHES around 1050MW installed capacity located between Fukushima nuclear power plants and Tokyo. Furthermore, japan is blessed country for PHES development through integration of sea water sources which have low investment cost when there is connection to nearest nuclear or steam turbine power plants as compared conventional reservoirs and rivers [43].

Currently, China is known with high rate of economic growth due to this energy consumption has been growing and demanding efficient use of electricity, balanced grid, balancing intermittent energy generation and storage of surplus power. Government of China aims to reduce carbon emission and have increased the development of renewable energy sources, which will be supplemented by PHES to support energy fluctuation to have sustainable energy grid [44].

Although the first 11 MW PHES project was built in 1968 and the second pumped storage project was completed in 1975, further development was put on hold until the 1990s. While the development of pumped storage is relatively recent compared to Japan, the US and Europe, China ranks first with a PHES capacity of 50.9 GW by 2023 [37].

Pumped hydropower has been growing in China, largely due to the country's increasing electricity consumption, driven by its rapid economic expansion. As a result, pumped hydro has been recognized as a particularly useful technology for improving grid resilience by bridging the gap between periods of high and low electricity demand. Since the nuclear energy and energy crisis due to large increment in oil and gas price in 1970s, USA were constructed PHES from 1960s to 1990s. There are a number of feasible PHES sites studies depicted the USA has a PHES potential more than 1000 GW [11]. United States currently generating 22.9 GW from 43 PHES and the country is working on 67 new PHES with in different states to be completed near future [45, 46].

Nagarjunasagar PHES scheme the first in India history completed in 1981 & was intended to provide 770MW, furthermore up to 2008 742MW, 3500MW supplemented to the country electricity grid. Currently, India is ranked fifth with PHES capacity of 4.7 GW by 2023 [37]. Rapid population and economic growth enhanced provision of PHES in India due increasing energy demand and electric grid regulation issues. PHES was considered as one useful technology for sustainability grid balance and improve performance intermittent or renewable energy sources in order to fulfil high demand by generating stored energy during low demand period [47].

3.1 Africa

The status of pumped hydro energy storage (PHES) in Africa varies between countries and regions. Some African countries have embraced PHES as a key component of their energy infrastructure, while others have yet to develop significant PHES projects. Most of the projects are located in South Africa, Egypt, Morocco and Tunisia [37, 48]. When we compare with other Africa countries South Africa has dominated the developed PHES system in Africa. The Palmiet Pumped Storage Scheme and the Drakensberg Pumped Storage Scheme two of PHES has been in operation. The country has the capacity of 2832MW pumped energy storage [37, 49, 51]. Ataqa PHES is Egypt's proposed scheme to use seawater from the Mediterranean Sea as a lower reservoir. Ataqa PHES designed to regulate peak demand and improve grid stability [52, 53].

Morocco is known with Afourer PHES with capacity of 465 MW project developed for the purpose of to balance peak load and enhance grid stability [54]. While some countries, such as China, the US, Germany and Japan, have made progress in developing PHES, investment costs, technological readiness and suitable geographical locations for PHES implementation remain major challenges. The renewable energy landscape in Africa is diverse, with a growing focus on wind, solar and other forms of clean energy. As renewable energy continues to expand, the demand for energy storage solutions such as PHES could increase in the region.

3.2 Ethiopia

Ethiopia is one of the developing countries located in the Horn of Africa has the ambition to provide sustainable hydropower energy and the electricity generated large-scale hydropower schemes of the country and have various types of energy resources, especially renewable energy sources such as hydropower, wind energy, solar energy and geothermal energy as well as biomass resources. Like many of other African countries, Ethiopia has no history with PHES [55], however the country has abundant energy resources and the exploitable reserve of hydroelectric power is 45,000 MW and placed second in Africa one fifth of Africa's feasible hydroelectric power potential [6, 39, 56]. Ethiopia has seventeen (17) existing and under construction of large hydroelectric plants, including the Grand Ethiopian Renaissance Dam (GERD), Gilgel Gibe IV (Koysha), Gilgel Gibe III and Tekeze Dam and renewable energy developments from wind, solar and geothermal sources are expected to be increased significantly near future. The availability of existing hydropower plants and the potential of hydropower is a great boon for the future development of PHES and may create a good opportunity to integrate intermittent energy sources with conventional hydropower plants incorporating pumped hydro energy storage technology [17, 30, 55, 57, 58]. The researcher was shown how to implement PHES on Tana Beles existing hydropower scheme by integrating potential energy sources of wind and solar power systems by considering techno-economic details so as to indicate potential power generation sustainably throughout the year [59]. Assegie carried out the study, which aimed to investigate the provision of pumped PHES for the existing Koka hydropower stations in Ethiopia, proposing additional storage to improve the capacity and efficiency of the main reservoir by pumping water from the lower Koka reservoir to the upper new reservoir to generate during peak demand periods [60].

4. Review on Topologies of Hydro-Energy Storages

A number of topographical factors influence the selection of a suitable site for a pumped storage project. In determining the feasibility and efficiency of the project, the topography of the area plays an important role. Valleys, hollows, hilltops and areas close to dams and reservoirs are among the best locations for pump storage. The study evaluated potential sites of PHES using different topologies which was paired reservoirs 1km to 20 km height above150 m and 29 terawatt hours estimated for thirty one countries of Europe [61]. Additionally, other study was conducted to extract feasible PHES sites of Tibet using different topologies such as linking two existing reservoirs and transformation of existing lake or reservoir to PHES by searching feasible site for a second reservoir [62]. Jinyang et al assessed hybrid PHES using topology of abandoned coal mine sites which is integrated with wind and solar power. The estimated existing coal mine sites in China which are feasible PHES for daily and short period energy balancing [63]. A study of the surroundings of a water reservoir in the central part of Iran in order to identify suitable sites for the construction of an upper reservoir. In order to take into account the grid situation, road accessibility and detailed geological characteristics of the selected site, various data layers were used [64].

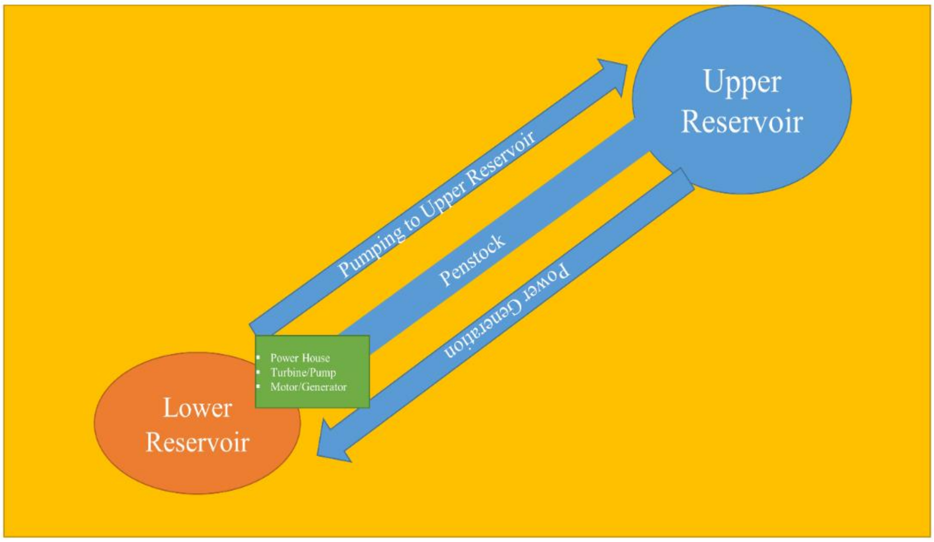

Figure 4. The schematic outline depicts PHES

Table 1. Topologies applied at different studies

Topology 1 (TP1):	Linking two existing reservoirs PHES facilities.
Topology 2 (TP2):	It depicts PHES sites obtained by extracting from highest part with respect to existing lake or reservoir.
Topology 3 (TP3):	PHES site which will be selected based of topographic condition or terrain it might be valleys, depressions, hill tops, near to dam or reservoir.
Topology 4 (TP4):	PHES sites which are situated at highest areas as new reservoir site which is near to sea as the lower reservoir.
Topology 5 (TP5):	PHES site situated near to conventional hydropower reservoir with a lake or an artificial reservoir to consider as new PHES.
Topology 6 (TP6):	PHES site based river water source.
Topology 7 (TP7):	Abandoned mine pit new PHES site which require nearest water source [63]
Source: [61], [65-68]	

Figure 5. Sample PHES site at existing Reservoir of Koka with New Proposed PHES site near to Koka reservoirs.

PHES systems offer a solution for regions lacking freshwater, such as those in Africa and the Middle East, to integrate PHES into their energy systems and benefit from this mature, utility-scale storage system, which is helping to increase the penetration of renewables [65].

Methodology was applied to extract PHES based on different topologies such as using transformation of existing reservoirs, permanent rivers, PHES from seawater [12]. Studies depicts that GIS with MCDM applied different topologies in some part of the world in order evaluate potential of capacity of PHES. Generally this review presents topologies for evaluation of the PHES capacity as it was utilized [9, 61, 65, 66].

5. Review on GIS Algorithm for Hydro potential

Over the last decade, a number of studies have been conducted to assess and evaluate PHES based on the application of MCDM through the integration of Geographic Information System (GIS) in different parts of the world various locations including: Ireland [69], Europe [17, 61], USA [67], Spain [36], Iran [12, 64], Turkey [33, 70], Australia [9], Brazil [71] and China [62, 72].

Feasible PHES sites have been extracted from a 20km by 40km area in the south-west of Ireland using a computer programme, and this programme has paved the way for further investigations to improve site selection [69]. Different GIS thematic layers applied with respect defined parameters to provide PHES on Zayanderud dam. The study utilized exiting reservoir, head, conveyance ratio of length to head, slope percentage, grid network, roads accessibility, geological condition and other data utilized to identify suitable sites [64]. Tool was developed to investigate PHES between Songavatn and Totak between both reservoirs and new Pumped Storage Plant was designed with a capacity of 1200 MW [20]. The existing seven hydropower reservoirs in Turkey assessed for provision of PHES by applying MCDM, the study further evaluated lower reservoirs of pumped-storage facilities with performance of PHES candidate sites [33]. In order to depict optimal location of the upper reservoir multicriteria analysis was applied by integrating so the methodology applied in this study can designed to be implemented to other geographic locations [36].

The various PHES topologies were implemented to evaluate the PHS potential in Tibet by using GIS and provided tow new models, Tibet was about 997.2 GW h, 946.2 GW h and 2552.0 GW h under different topology scenarios [62]. In previous study the authors evaluated GIS based MCDM techniques of different models for the area of 1324 km^2 [35]. The study estimated with 1590 MWh -1700 MWh PHES capacity for 15 upper reservoirs and mean reservoir surface area around 7.85 ha. Rogeau proposed investigated small-PHES potential in France with a capacity ranges 14 GWh- 33 GWh near to 8% and 18% of PHES capacity of the country. He considered parameters like interval with in lakes, the maximum elevation, and the distance to grid used to extract PHES sites at large area coverage [26]. This study by Wu *et al.,* [19] depicted selection feasible PHES site for the of case of Zhejiang province, China by applying MCDM tools such as triangular intuitionistic fuzzy numbers, crisp numerical values and 2-dimension uncertain linguistic variables are adopted and criteria weighting conducted using the analytic hierarchy process (AHP) with extended Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) for processing PHES site selection. The research was conducted in Northern Norway used 84 pairs of reservoirs used for analysis and selected 19 different potential PHES sites with estimated capacity of 25 GW. The result of the investigation includes parameters that optimizes the mode of the PHES with respect to economic feasibility and its effective operation [22]. A study by Hunt *et al.,* [73] depicts ways to connect seasonal PHES with hydropower reservoirs for the purpose of river flow regulation, control floods, reduce the spillage and increase power generation in the hydropower when geological condition does not allow the provision of new reservoirs and to store the electricity from intermittent renewable sources to use during peak load time. Furthermore reduce transmission cost and complications, minimize the cost of electricity transmission from hydroelectric plants in the Amazon [73]. Lu *et al.,* [9] developed GIS algorithms to identify feasible sites for off-river PHES for 168 dry-gully sites and 22 turkey's nest sites of PHES capacity of 441GW for South. Ghorbani *et al.,* [12] estimated feasible capacity of PHES in Iran by applying automatized GIS based methods considering different topologies with in maximum distance of 20 km and used TOPSIS method for feasible 250 sites selection up to 5108 GWh PHES capacity. Nzotcha and his co-workers [74] carefully applied MCDM method in Western Cameroon. MCDM techniques used to identify decision factors and criteria, and AHP as MCDM techniques, fuzzy logic-based and rating scales scoring systems and the Elimination and Choice Expressing Reality (ELECTRE) III. It was successfully tested on eleven PHES potential sites which are found in Western Cameroon. Hunt *et al.,* [23] developed methods to potential sites for conventional hydropower and seasonal PHES. The study further depicted that the conventional hydro-potential less expensive than SPHS, however the potential for Indus basin only 26 GW which costs below 50 USD/MWh and due high sedimentation reservoirs have significant impact on sustainable long term service however seasonal pumped hydropower storage is very interesting as an alternative scheme to support and sustaining hydropower generation.

6. Future Directions

It is known that PHES have a great impact in provision of sustainable and efficient energy supply due to the nature its efficiency, large-scale energy storage capacity, long term service and self-discharge. Now a days the policy changes of the electricity markets in some countries creates conducive environment for renewable energy sources become more favorable & turned public interest to PHES. However there are some obstacles are happening all over the world which are hindering the provision of new PHES. These barriers might be technological, policy and environmental challenges. The technological challenge arises from the renewable energy integration, controlling mechanism, impacts on environment, improving optimization, efficiency and [24, 69, 75, 76]. Mentioned below factors impacts how development of pumped hydro energy storages. The advancements on future research and development will emphasis on some of mentioned issues in order to improve the future the technology, overall effectiveness, adaptability, efficiency and others.

6.1 Optimization and controlling mechanism

Improving performance of pumped hydro energy storages highly depend on PHES system control and optimization. Managing effectively the Energy generation and PHES facilities highly enhance the performance of PHES in response to variable patterns of electricity demand and supply, research in this field depend on real-time monitoring, predictive modeling, and sophisticated algorithms [77-78].

6.2 Improving Efficiency and Performance

There are many studies, which is proposed to enhance the efficiency of PHES systems. Furthermore, improving conversion of electrical energy by pumping to stored potential energy and stored water used to generate electrical energy is an important future work. It involves improving the materials used in pumps, turbines, and hydraulic systems as well as PHES facility design and operation to assist boost overall performance and efficiency [47].

6.3 Impacts on Environment

PHES might have a significant environmental impact during the construction stage when land and water resources are utilized. Understanding and evaluating environmental impact of PHES is very important field of study. The challenges of developing new PHES vary from country to country environmental policies, permitting procedures assessed considering, the ecological implications of reservoir construction, operation, and water management and the possibility of disrupting fish and marine habitats. Furthermore, by taking in to consideration less environmentally harmful building techniques, usage of alternative materials and the possibility of closed-loop systems, researchers are attempting to increase the sustainability of PHES [33, 74].

6.4 Renewable Energy Integration Vs PHES Sizing

Avoiding the nature of variability and intermittency of renewable energy source outputs and maintain grid stability is critical study area. It this involves to identify the ideal ratio of generation capacity, storage capacity and flexibility. More studies are required to design the optimal PHES system dimension considering intermittent or renewable energy integration in order to increase the contribution of renewable energy sources are increasing [12, 66, 78].

Finding more feasible, easily integrated with renewable energy sources and environmentally friendly solutions to provide extra storage capacity is one of the PHES research gaps. Traditional PHES systems cannot be widely deployed since their construction can be capital demanding and requires particular geological conditions. In order to alleviate the gap studies might give attention or priority in developing novel methods and technologies for Hydro-energy storages, like underground PHES or hybrid systems.

7. Conclusions

The integration of intermittent energy sources with pumped storage is a promising approach to maintain a reliable and efficient energy supply in the balancing of the grid energy system. PHES as an important aspect in sustaining energy at grid scale by providing energy by providing water energy storage at higher elevation point when the energy load is low the then generate energy by releasing the water during periods of peak load. PHES easily provide time shifting protocol during generation of excess energy at low load and allows excess energy storage, this encourages the use of renewable energy sources more as it makes it possible to store excess energy during times of high production and use it during times of higher demand. PHES serve as a constant standby power source in case of grid failure or accidents. Ancillary services: They provide ancillary services to the power grid, balancing variable energy production and maintaining grid stability by ensuring that the instantaneous utilization of power generation is balanced. One of the main benefits of PHES attracted global attention for the reason of integrating renewable energy sources or intermittent energy sources, might lead us to consider pumped energy sources to allow balanced energy production.

This review paper shows the development of PHES around the world, taking into account the PHES capacity of countries. The review shows that China ranks first with PHES capacity of 50.9 GW by 2023. Japan and the USA also hold the second and third rank of PHES capacity of around 21.8 GW and 16.7 GW respectively by 2023. This review has addressed the future works focusing on the integration of renewable energy, control mechanism, impact on the environment, improvement of optimization, efficiency and performance that will be addressed by future researchers and stakeholders. This work has explained and discussed the aspects of PHES and the development of PHES in different nations by using literature collection and review. The review can benefit researchers, policy makers and postgraduate students to support further studies and investigations on the development and placement of PHES. It will be of great benefit to the scientific community, postgraduate students, decision makers and policy makers.

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Wendmagegn Girma: Conceptualization, methodology, formal analysis, investigation, resources, writing-original draft preparation, writing-review and editing. Admasu Gebeyehu Awoke: supervision, writing-review and editing. Both the authors have read and agreed to the published version of the manuscript.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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