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Exploring the Role of Pumped Hydro Energy Storage in Nepal's Renewable Energy Transition: Technical, Economic, and Environmental Perspectives - A Review

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Abstract

The global transition to renewable energy is crucial for mitigating climate change and achieving sustainable development goals. Nepal, with its abundant hydropower potential and immense potential for solar and wind energy is well-positioned to lead this shift. However, the variability of solar and wind energy, along with seasonal fluctuations in rivers, necessitates robust energy storage solutions to ensure grid stability. Nepal's vulnerability to natural disasters such as earthquakes, landslides, and floods further exacerbates the challenges, often damaging hydropower infrastructure and disrupting energy production. Pumped Hydro Energy Storage (PHES) emerges as a key solution—technically feasible across more than 2,800 identified sites with combined potential of 50TWh. It can be integrated with existing infrastructure to improve grid flexibility and reliability. Economically, PHES offers a lower lifecycle cost, with reduced environmental mitigation costs, especially in off-river configurations. Environmentally, PHES has a relatively low carbon footprint and, when carefully located, minimizes impacts on biodiversity and water quality. PHES can stabilize the grid, support renewable integration, and reduce import dependency, paving the way for a resilient, low-carbon energy future in Nepal. This review explores the technical feasibility, economic viability, and environmental implications of PHES implementation, while also identifying key areas for future research and policy development to optimize its adoption within Nepal's unique geographic and socio-economic context. By adopting this technology, Nepal can diversify its energy mix, enhance disaster resilience, and move toward a more sustainable and self-reliant energy future.

Keywords: Pumped Hydro Energy Storage (PHES), Grid Stability, Smart Grid Management, Solar and Wind Energy Integration, Energy Portfolio Optimization, Sustainable Development

1. Introduction

The global energy system is quickly shifting away from fossil fuel power systems to renewable power systems (Blakers, et al., 2019). The UN secretary-general launched the sustainable energy for all multistakeholder partnership between government, the private sector, and civil society in 2011, with the goal of achieving universal access tomodern energy, doubling energy efficiency and renewable energy by 2030, thereby promoting the UN sustainable goal of affordable, reliable, sustainable, and modern energy for all (Karlsson-Vinkhuyzen, 2016). Furthermore, the world is committed to the Paris agreement, which aims for zero carbon emissions by 2050 and limits global warming to 1.5 degrees Celsius (Teske, 2019). Since the energy sector emits 3/4 of greenhouse gases globally, primarily fromfossil fuels, this pattern should change, and renewable energy should rise. The assessment done by International Energy Agency shows to meet this goal in 2050, 90% global energy should come from Renewable sources, with solar PV and wind together nearly 70% share (IEA, 2021). From the last decades there seemed a huge rise in renewable energy primarily in wind and solar photovoltaic (PV) technologies globally. This is due to a considerable decline in their cost, and efficient unlimited resources. However, hydropower energy seems declining due to competition with wind and solar as shown in Figure-1 (IEA, 2024). Solar and wind energy are subject to variability due to their reliance on natural phenomena that can be unpredictable, such as daytime hours and wind patterns. Thus, there will be large energy variation in world due to rapid deployment of this variable energy and these cannot be balanced by battery, coal, or thermal plants, necessitating a massive potential battery system, and a natural battery-pumped hydro storage plant is the solution (Blakers, et al., 2021).

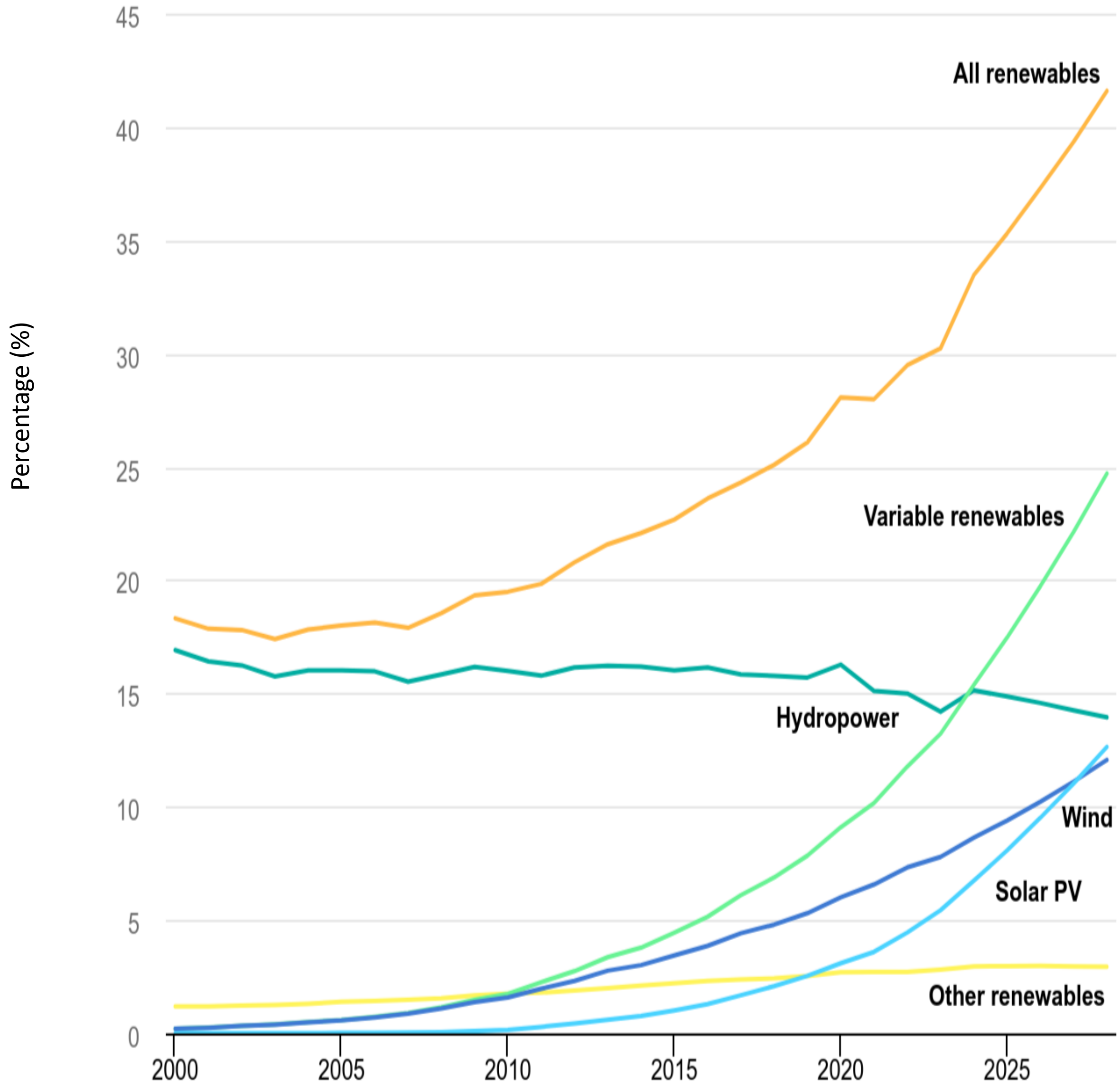

Figure 1. Share of renewable electricity generation by technology, 2000-2028 *(IEA, 2024)*.

In Nepal, for the fiscal year 78/79, traditional biomass accounted for 64.17% of total consumption, a decrease of 4.13% from FY 75/76. Positively, in FY 78/79, the share of renewable energy, including hydropower, increased to 7.48%. However, for imported energy, there hasn't been much of a shift in the previous five years, the amount of energy imported, including coal, petroleum, and electricity—remains at 28.35% in FY 78/79 (Figure-2). This calls for better energy management methods and a rise in hydropower and renewable energy sources inside the nation (WECS, 2023).

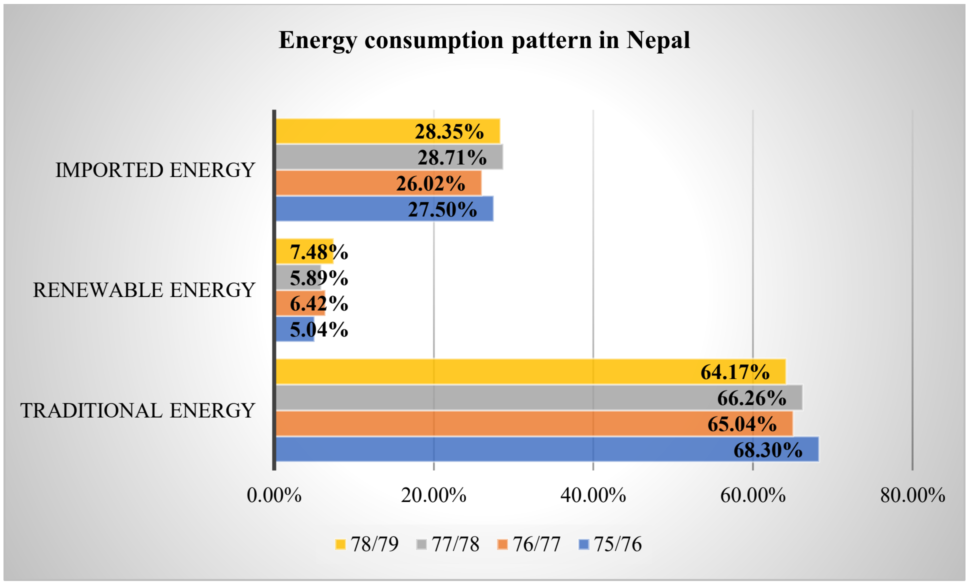

Figure 2. Energy consumption pattern in Nepal- energy synopsis report *(WECS, 2023)*.

Nepal possesses a vast hydropower potential because of its unique geography, which includes numerous rivers, snow-capped mountains, and a large elevation fluctuation in a short distance (Adhikari, 2006). Theoretically, Nepal has the potential to produce 83 gigawatts of hydropower energy in which 43 gigawatts of hydropower is technically and economically feasible (Alam, et al., 2017; Shrestha, 2017). However, a recent report by Water and Energy Commission Secretariat 2019 shows 72.5 GW of gross potential, 32.7 GW of economically feasible with a total install capacity of 48.1 GW for reservoir projects (Aryal, et al., 2024). But, over the past century, Nepal has harnessed only about 5% of its economically viable hydropower potential, indicating a sluggish pace of development (Bhatt & Joshi, 2024). Most of the electricity is generated by run-of-river (ROR) type hydropower, with a little amount coming from peaking run-of-river (PROR) and storage plants and no pumped hydropower facilities (NEA, 2024; DOED, 2024). Due to abundant ROR projects in Nepal, there will be a surplus in electricity, and thereby export in the wet season however, in the dry season only 1/3 of electricity is produced and has to be imported (Gurung & Tiwari, 2016).

The electricity demand in the dry season is mostly balanced by importing electricity from India and utilizing the thermal plant in Hetauda, the only operational thermal plant in Nepal (Gurung & Tiwari, 2016; NEA, 2024). The power summit 2023 held in Nepal by Independent Power Producer Association Nepal conclude with the goal of importing no electricity by 2025 in Nepal, promoting renewable resources (Himalayan News Service, 2023). Even though Nepal cut imports by 40% in 2022 compared to 2018, to achieve the target Nepal should invest in sustainable renewable resources like Hydropower, solar and wind (NEA, 2022).

Nepal is ranked 10th globally among nations most at risk from climate change (Eckstein, et al., 2021). While hydropower remains the primary source of energy and is expected to maintain this status for several decades, it is also vulnerable to the impacts of climate change. These risks include variations in precipitation, prolonged drought, intense rainfall events, floods, landslides, and the potential for glacial lake outburst floods (GLOFs). Such hazards can damage critical hydropower infrastructure, reduce water availability during dry seasons, and disrupt electricity generation Therefore, it is crucial to invest in other renewable energy sources, such as solar and wind, to enhance climate resilience (Malla & Dhananjayan, 2023; Suman, 2021).

According to the 2008 report entitled “Solar and wind energy resources assessment in Nepal” by APEC, Nepal has a potential of 2100 MW for grid integrated PV systems and 3000 MW of wind (APEC, 2008). Another study by Neupane et al shows Nepal has significant potential of 47,628 MW of solar energy and 1686 MW of wind energy with a co-location potential of about 890 and 267 MW of solar and wind energy (Neupane, et al., 2022). As of May 2025, 23 solar projects with a total grid-connected capacity of 116.74 MW are operational, while the Nepal Electricity Authority awarded contracts for an additional 960 MW of solar power projects in its latest auction round held in November 2024 (DOED, 2025). With the Significant decrease in price in PV and Nepal commitment to net zero carbon emissions, these sectors going to boost (Blakers, et al., 2019). A recent study by: Dr. Sven Teske, Dr. Sarah Niklas, and Dr. Saori Miyake on the Nepal energy pathway until 2050, analyzing in 3 different scenarios of – with reference scene, with existing method scene and Nepal 1.5°C scene implies that Nepal hydropower will be dominant with in decade then solar energy going to accelerate till 2050 with introduction to hydrogen energy (Figure-3). This may result in power variation demanding for pumped storage hydropower. This study also suggests the need for smart grid management from 2025 onwards to increase the power system's flexibility for grid integration, load balancing, and a secure supply of electricity (Teske, et al., 2023).

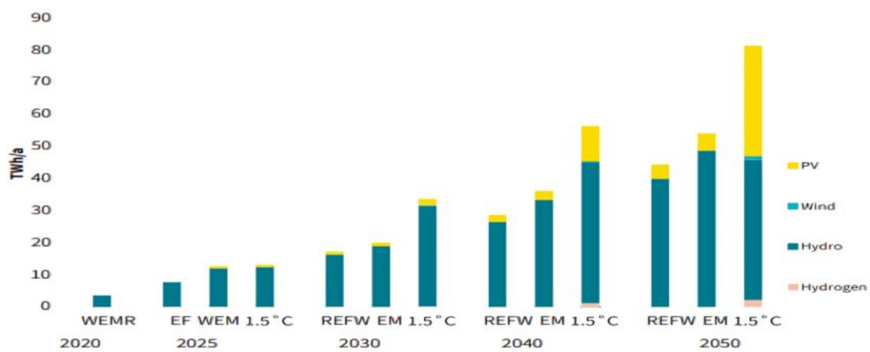

Figure 3. Nepal Predicted Renewable share by 2050 *(Teske, et al., 2023)*.

Nepal has also established cross-border electricity trade with India and Bangladesh (Sharma, et al., 2024; Bhattarai, et al., 2024). Both nations have an increasing share of variable energy, mostly solar PV and committed to Paris agreement in Figure 4 and 5 (IEA, 2021; Das, et al., 2020). Thus, more energy is needed to balance upcoming fluctuation, and Nepal can be established as power market to export energy in this neighboring country, thus emphasize should be given to hydropower like dam or pumped hydro energy (Vaidya, et al., 2021).

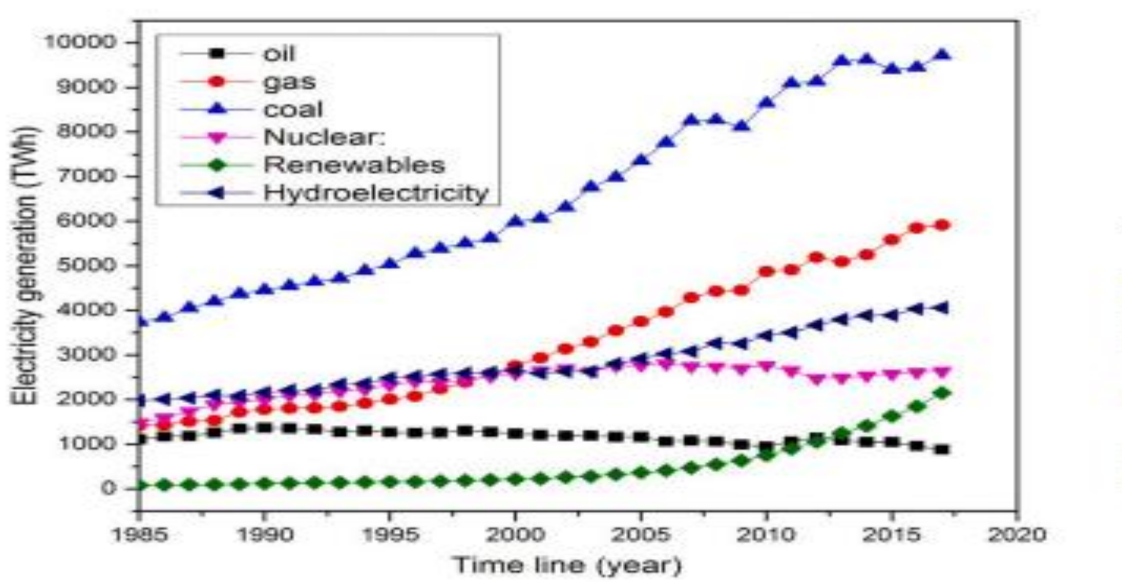

Figure 4. Electricity generation Pattern in Bangladesh (Das, et al., 2020)

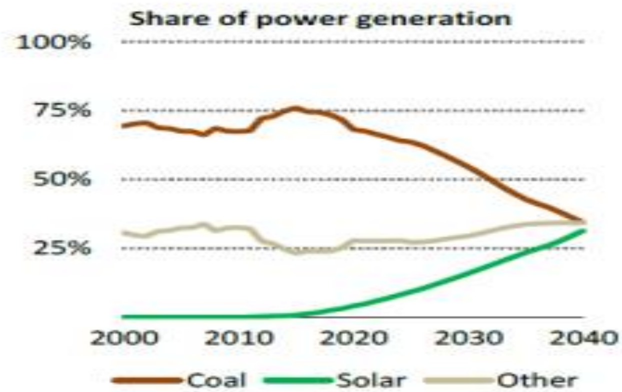

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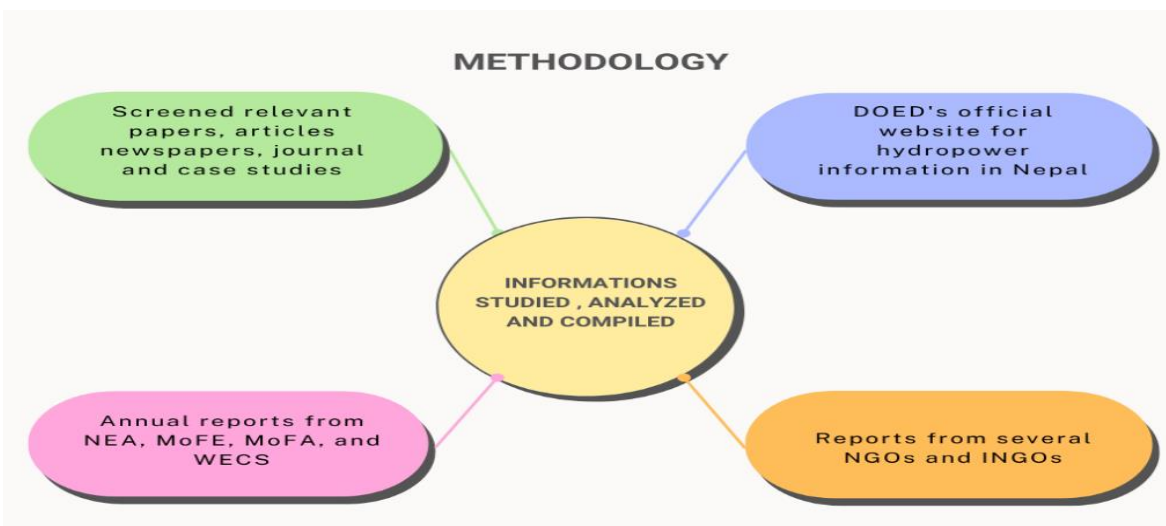
Figure 5. Share of energy generation in India (IEA, 2021).

Investing in pumped hydropower storage is essential to balance these fluctuations, stabilize the grid, and enhance energy security (Rehman, et al., 2015). By harnessing its hydropower resources like PHES more effectively, Nepal can reduce dependency on imports, support its carbon reduction goals, and strengthen its role as a reliable power exporter to neighboring countries like India and Bangladesh. A Study of Jirel et al has conducted under the hypothesis that integrating Solar PV with pumped hydropower plants are profitable to country like Nepal (Jirel, et al., 2022).

2. Methodology

A comprehensive literature review was conducted, encompassing geological, hydrological, and economic aspects. This involved analyzing numerous journals, government reports, technical documents from NGOs and INGOs, as well as case study reports from Nepal and other countries with similar geographical characteristics. Additionally, various government official reports and websites were studied, analyzed, and compiled to inform the development of this review paper.



3. Pumped Hydroelectricity Storage

Pumped Hydro Energy Storage (PHES) functions as a large-scale energy storage solution, absorbing surplus electricity during periods of low demand and releasing it to the grid during peak demand, like a battery. Discharge and recharge are the two phases of operation for this kind of hydropower (Harby, et al., 2013). It sets up two water reservoirs at different elevations, and during the discharge phase, when there is a power shortage, electricity is produced as water flows from the upper reservoir to the lower reservoir through a turbine. But when there is an excess of energy, then the water is pumped back to the top reservoir, which is the recharge phase as shown in Figure-5 (Novak, 2020). The Turbine can also function as a pump in this arrangement. The generator receives electricity from sources rather than making its own. The generator and turbine then start pumping water in the opposite direction during recharge phase. Sometimes the pump and turbine can be configured separately. The pumped hydroelectricity storage has an efficiency of 80% as 20% is lost during the pumping and generation cycle (Antal, 2014).

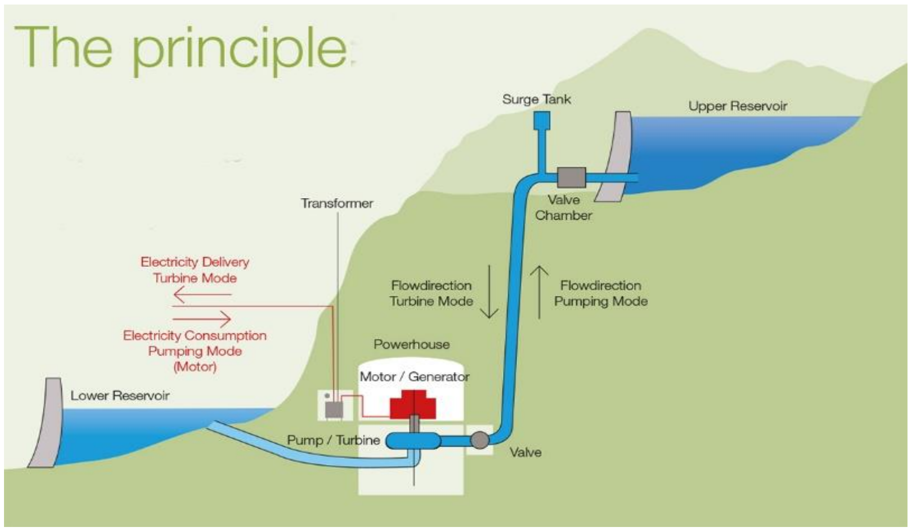


Figure 6. Principle of Pumped-up hydroelectricity storage *(Novak, 2020)*

Pumped hydroelectricity storage can be on-river and off-river (Lohani & Blakers, 2021). If any reservoir is located in a river that is on-river, otherwise off-river. Both an open loop and a closed loop version of this are possible (Blakers, et al., 2021; Saulsbury, 2020). PHES can be configured in 7 different topologies: connecting two reservoirs (L2L), Building one reservoir in flat land proximately to existing reservoir (F2L), Conventional green field where both reservoirs are constructed in flat lands (F2F), seawater and green fields where one reservoir in sea and another in flat land (F2S), add reservoir close to abandon pit (F2A), add reservoir close to river (F2R) and Lake to River (L2R) (Gimeno-Gutiérrez & Lacal-Arántegui, 2015).

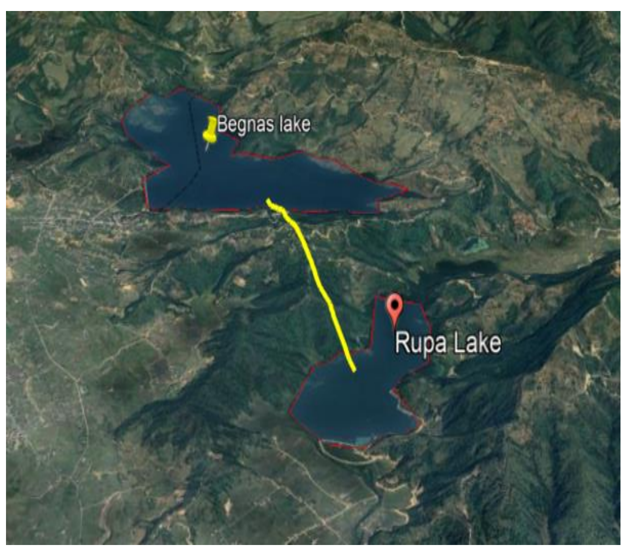


Figure 7. Lake to Lake Topology (L2L)

Figure 8. Flat Land to Lake Topography (F2L)

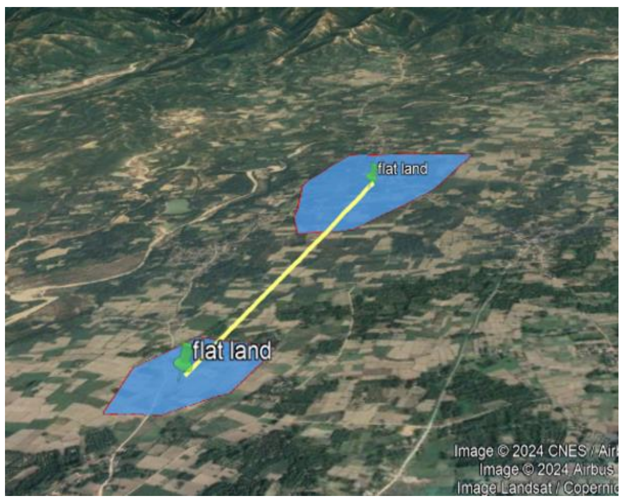


Figure 9. Conventional Green Field Topology (F2F)

Figure 10. Flat Land to Sea Topology (F2S)

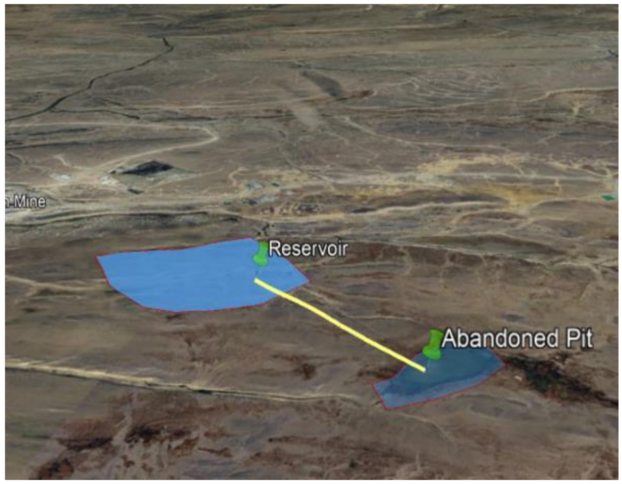


Figure 11. Reservoir to Abandoned Pit Topology (F2A)

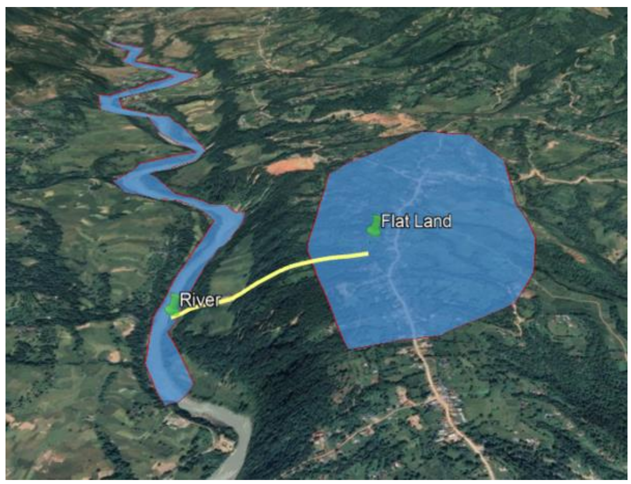


Figure 12. Flat Land to River Topology (F2R)

Figure 13. Lake to River Topology (L2R)

4. PHES Atlas

Pumped Hydroelectricity storage comprises 96% of global storage power capacity and 99% of global energy storage volume (Lohani & Blakers, 2021). The amount of energy produced by PHES is proportional to the head between the reservoir and the total utilizable volume of water as given in expression below (IEA, 2021).

$$E = \frac{n \rho V g H}{360*10^{9}} \qquad \text{(Equation 1)}$$

The global survey of greenfield off-river PHES conducted by Australian National University found 616000 excellent sites in latitude between 60 ^{0}N and 56 ^{0} S with a combined potential of 23 million GWh as shown in the figure. These Sites are categorized from A to E, based on Cost per energy storage volume (Stocks, et al., 2021). Atlas of off-river PHES in Nepal is shown in the figure as global green field 500GWh 50h (Stocks, et al., 2021).

Figure 14. Global Atlas of PHES *(Stocks, et al., 2021)*.

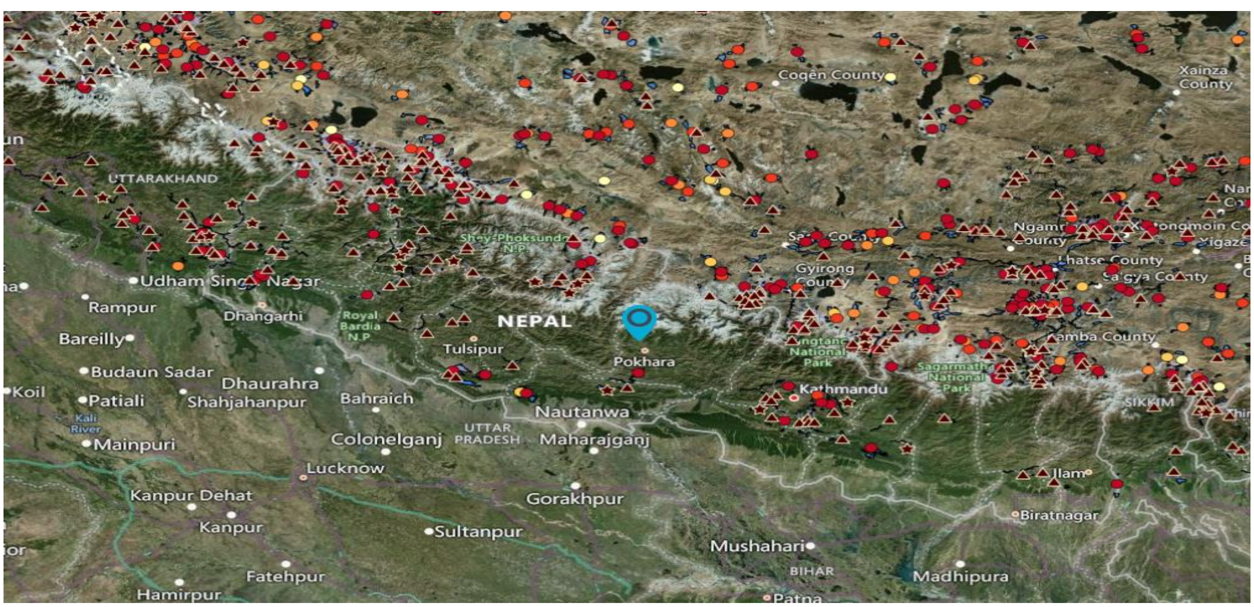


Figure 15. Nepal PHES as in global green field 500 GWh 50h *(Stocks, et al., 2021)*.

5. Discussions

5.1 Site Identification Assessment and Feasibility

For any Site identification of PHES, the geo-data from water bodies and the elevations are required. Then the analysis of topography and multi-criteria filter using GIS any potential sites are identified (Ghorbani, et al., 2019; Ahmed, et al., 2021; Lu & Wang, 2017). For example, to identified off-river L2L topology sites, 2 reservoirs within certain radius and elevation difference are mandatory likewise for on-river F2R configurations, Selections of perennial river, selection of suitable flat land area and slopes with height of reservoir to meet targeted volume (Haas, et al., 2022).

The global atlas of Greenfield study by ANU had identified good 2800 PHES sites in Nepal with combined capacity 50TWh (Lohani & Blakers, 2021). This study is guided on locating 2 reservoirs with head between 100m to 800m, minimum water to rock ratio (W/R) of 3, minimum Reservoir volume of 1GL, Minimum slope between reservoir of 1:20 and assume earth and rock wall with maximum height range of 5 to 100m (ANU, 2025; Lu, et al., 2018). However, the study done by R Baniya et al shows theoretical capacity of 3012 GWh and only 42% of it, 1269 GWh are technically feasible by various topology as shown in table below. Most of them are concentrated in mid hills and southern plains (Baniya, et al., 2023).

Table 1: Theoretical and technical feasibility of PHES in Nepal (Baniya, et al., 2023)

Topology	Number of Site (Theoretically Feasible)	Number of Site (Technically Feasible)	Theoretical Power (GWh)	Technically Feasible Power (GWh)
L2L	89	29	11.3	4.1
F2L	37	2	7.9	0.9
L2R	205	88	276.5	65.1
F2R	6134	1739	2716	1198.8

A recent report by NEA has identified 42000MW of pumped hydroelectricity storage plants in Nepal. The latest study in 3 different river basins by NEA had identified 50 potential sites in Koshi River, 58 in Gandaki and 46 in Karnali River Basin. Most's of PHES projects are in study phase while one is announced. The Begnas-Rupa Pumped up hydroelectricity project of capacity 150 MW in Pokhara has already been announced and expected to start soon. Similarly, Syapru Lake PHES of 332 MW is understudy phase whereas PHES site like Hulingtar-Dumpim project of 1712 MW in Chitwan and Dhading and Karnali-Chisapani project of 5375 MW in Surkhet are under prefeasibility phase (NEA, 2024).

5.2 Economic Feasibility

There are 4 types of cost for construction of any hydropower project. Among them Associate costs, which is the major cost that arises due to the cost of engineering structures and equipment along with operation and maintenance costs. Generally, the greater the number and complexity of structures and equipment, the higher the overall cost. The capital cost of dam hydropower is comparatively higher than ROR and PHES. Second cost is Induced cost that mitigates adverse impact produced by project on nature and people like Resettlement, Rehabilitation, and Relocation etc. The lower environmental impact of Pumped Hydro Energy Storage (PHES) contributes to its capital cost ranking below Dam and Run-of-River (ROR) hydropower: Dam > ROR > PHES. Third Cost is external cost which arises for smooth construction and operation processes like upgrade of transport facility and communication, local electrification etc. This cost varies according to site conditions. Final cost is opportunity cost, which hydropower producers had to pay for government for using natural resources like water. Since the dam Hydropower uses more resources and produce more electricity, they had to pay more royalty to government compared to PHES (Jalsrot Vikas Sanstha, 2004; Mishra, et al., 2012; Deane, et al., 2010; Zohbi, 2021).

The cost of PHES mainly arises for planning and approval, construction of reservoir, Water conveyance like tunnel, pipe costs, Costs of powerhouse, switchyard, generator etc., Cost of access road, Electricity and transmission line and operation and maintenance costs (Blakers, et al., 2021; Nikolaos, et al., 2023). Construction costs of different types and topologies of PHES are different. The topology which includes water sources to flat land (F2L, F2S, F2R) or flat lands to flat lands(F2F) are more costly than other due to construction of completely new reservoirs with no water leakage and evaporations (Haas, et al., 2022). Similarly, on-river PHES construction cost is high and unpredictable because of river geomorphology and hydrology. The cost increases due to difficult transmission distance, environmental consideration and river training works like diversion of river during constructions (Görtz, et al., 2022). However, off-river PHES costs are relatively predictable, and the same design may be copied and pasted all around the world (Lohani & Blakers, 2021). Off-river is well suited to low-cost, short-term storage, avoid community conflict, reduce transmission costs and increase PPA value. Thus, sites like L2L are ideal sites for construction (Stocks, et al., 2018).

For operation and maintenance cost of PHES, different tariff systems are needed compared to conventional hydropower as it works differently i.e. generation and consumption (Zhang, et al., 2018; Jacob, et al., 2021) . Its selling price should be higher than purchase price to cover capital cost over system lifetime and roundtrip storage energy loss (Sivakumar, et al., 2014).

5.3 Environment and Social Consideration

The environmental impact associated with Pumped Hydro Energy Storage (PHES) projects primarily arises from the flooding of large areas of land required for reservoir construction, along with extensive infrastructural developments such as roads, pipelines, tunnels, powerhouses, switchyards, and high-voltage transmission lines. These interventions not only alter the physical landscape but also disrupt ecological integrity and initiate a cascade of environmental changes that can extend well beyond the immediate project area (Plant, 2008; Zhang, et al., 2023). The resulting outcomes include disturbances to the environment, such as the loss of vegetation, the construction of access roads, the disposal of spoils, increased human presence, transmission line infrastructure and altered water quality in reservoir or catchment areas. In a similar vein, this also has an influence on biodiversity, leading to the spread of alien plants, the loss of habitat from vegetation clearing, and changes in the hydrology of the terrain (Normyle & Pittock, 2020; Patocka, 2014). For more information go through study by Anna Normyle and Jammie Pittock on impacts of PHES construction on subalpine and alpine biodiversity (Normyle & Pittock, 2020).

This impact also varies according to type of PHES. Off-river PHES have a lower environmental impact than on-river PHES (Blakers, et al., 2021). On-river PHES requires additional procedures such as flood mitigation arrangements, silt management, and diversion arrangements during dam building (Silalahi, et al., 2022). Fish ladders, longitudinal connectivity, and environmental flow are provided in the river as a result of effects on river flows and habitat, as well as territorial biodiversity. This provision is not used in off-river PHES due to the lower environmental impact on these aspects (Hunt, et al., 2021) .

The development of Pumped Hydro Energy Storage (PHES) projects contributes not only to energy infrastructure but also to significant socio-economic improvements in nearby communities. The construction or upgrading of roads and bridges enhances regional connectivity, facilitating greater access to markets, education, and healthcare services. Furthermore, the construction phase generates employment opportunities for local residents, which directly contributes to increased household incomes and improved living standards. These projects also support skill development and capacity-building initiatives, thereby promoting long-term socio-economic resilience and reducing the need for outward migration from rural areas (Aung, et al., 2021; Smith, 2024).

6. Conclusion

Pumped Hydro Energy Storage (PHES) stands out as a strategic solution to the evolving energy challenges in Nepal. As the global transition to renewable energy intensifies, PHES emerges as a critical solution for balancing the intermittency of solar and wind power, enabling grid stability and energy optimization. Technically, Nepal is well positioned to deploy PHES across its varied topography, with thousands of viable sites identified. Economically, PHES presents a competitive lifecycle cost, especially in off-river configurations, and environmentally, it offers a sustainable pathway with minimal carbon emissions and biodiversity impacts when developed with proper safeguards.

This review concludes that PHES can significantly improve Nepal's energy security by mitigating seasonal supply-demand imbalances, integrating variable renewables, and reducing dependence on energy imports. Moreover, its implementation also aligns with national and international climate commitments and enhances the country's potential as a regional energy exporter.

Future research should focus on advancing modeling techniques, evaluating socio-economic impacts, and exploring innovations in energy storage to further refine PHES strategies. By prioritizing these efforts, Nepal can maximize the utility of its hydropower assets, contributing to its domestic energy security while playing a pivotal role in the region's transition to renewable energy systems.

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