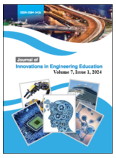

Journal of Innovations in Engineering Education
JIEE 2024, Vol. 7, Issue 1.

https://doi.org/10.3126/jiee.v7i1.73334

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Energy storage systems in the context of Nepal

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ARTICLE INFO

Article history:

Received 23 September 2024
Revised in 6 November 2024
Accepted 25 November 2024

Keywords:

Energy storage system
Renewable energy
Pumped hydro energy storage
Battery
Energy security

Abstract

Energy storage is essential for managing the reliability of renewable energy by responding to fluctuations of energy systems. With the dominance of hydropower, constituting 95% of Nepal's generation capacity, mostly by run-of-river, energy storage systems (ESS) are vital not only during dry seasons but also to address vulnerabilities of hydropower stations during the rainy season. Moreover, Nepal's inadequate commitment to diversifying the energy mix, particularly with a focus on modern renewables along with effective energy storage solutions pose a severe threat to energy security of the country. This paper aims to analyze the distinctive characteristics of numerous ESS and their applicability in Nepal in terms of size, operation, cost and lifetime. Based on a comprehensive literature review, it's evident that Pumped Hydro Energy Storage (PHES), would be promising ESS for large-scale (MWh to GWh) and diurnal to seasonal use. This is due to higher round-trip efficiency (above 80%), lower capital cost per unit energy storage, and matured technology having strong competence in Nepal. Nepal's long experience in hydropower and having several on-river and over 2800 potential off-river PHES sites make PHES promising technology for energy independence and reliable energy system in Nepal.

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1. Introduction

Nepal's energy consumption is heavily dominated by traditional biomass (63.87%) and commercial fossil fuel (25.80%), with a smaller share of electricity (7.23%) and modern renewables (3.10%) in 2024 [1]. Despite the relatively low share of electricity in Nepal's energy mix, nearly all electricity is generated from hydropower sources. Currently, installed power plants capacity is 3157 MW of which 2990 MW hydropower, 106.9 MW solar, 53.4 MW thermal, and 6 MW biomass, all is managed by Nepal Electricity Authority (NEA) [2]. Because of hydropower dominance in electricity generation and no adequate source diversification for electricity mix in Nepal, seasonal variation of hydro electricity production caused to import electricity from India. In the fiscal year (FY) 2022/2023, around 16% Nepal's electricity demand is met through imported electricity from India [3] highlighting a pressing need for substantial generation within the country. This underscores that Nepal needs to diversify its electricity generation sources. In line with this, Lohani and Blakers research indicates that covering just 1% of the total land surface with solar photovoltaic (PV), Nepal can generate 100 times the electricity needed to meet for high per-capita energy consumption [4]. Moreover, there is another GIS-based study which highlights that Nepal has significant solar PV potential, estimating that the annual generation could reach up to 552 TWh, further emphasizing vast potential of solar PV [5]. Furthermore, integration with pumped hydro energy storage (PHES) projects, seasonal and diurnal electricity production fluctuation could be managed within the country eliminating the need of imports [4], [6].

Nepal's electricity market is largely dominated by hydropower based with over 9600 MW of hydropower plant (HPP) currently under construction [7] indicating a lack of diversification in national energy generation mix as evidenced by the issuance of construction license for only 89 MW of solar projects [8]. Most of the HPP prevalent are run-of river (RoR) systems (more than 90%), reliant on various climatic conditions which poses a severe threat to the energy security of the country

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[9]. Source diversification for electricity generation and energy storage systems can mitigate the impact of such hazards. As per the NEA report, NEA's hydropower experienced around 10% decrease in generation in the FY 2022/23 compared to the highest recorded annual energy of FY 2021/22, primarily due to reduction in river discharge during the dry season months [3]. This underscores the necessity for diversifying energy sources to balance the increasing energy demand, especially considering the diurnal and seasonal variations. Electricity is imported during the dry season, as generation from hydropower doesn't adequately meet dry season demands, causing an imbalance in the supply-demand chain [10]. On the other hand, surplus energy generated during wet season is exported to India and Bangladesh. However, the lack of an effective Energy Storage System (ESS) exacerbates this situation, necessitating increased imports from India and contributing to persistent power cut issues within Nepal.

Addressing these challenges requires strategic solutions to enhance energy security. Firstly, source diversification of electricity generation by increasing the share of modern renewables including solar PV (ground mounted, agrivoltaic, rooftop) and biogas to national electricity mix [11], [12] and secondly, by installing sufficient energy storage systems (ESS). The primary function of ESS is to manage system fluctuations due to seasonal variation of hydropower electricity generation and intermittent output of modern renewables, and ensure 24 hour, 7 days of electricity by balancing surplus and deficit electricity especially during peak load time [13]. According to global energy storage database, Pumped Hydro Energy Storage (PHES) constituted a significant portion around 89% and remaining storage capacity is distributed among other energy storage technologies like Li-ion batteries, flywheels, Compressed Air Energy Storage (CAES), lead-acid batteries, etc [14]. In the energy storage sector in Nepal, very few studies have been conducted. Global PHES Atlas identifies 2800 off-river PHES sites in Nepal [15]. Further, the feasibility analysis of two sites have been conducted by NEA and its subsidiaries. A preliminary study on 150 MW pumped storage project for Rupa and Begnas Lakes in Pokhara, along with another 104 MW pumped storage project at the Lower Seti hydropower project have been conducted [16]. Additionally, Lohani and Blakers have identified PHES as one of the key components in a pathway to achieve 100% renewable energy in Nepal [4].

Nevertheless, earlier studies have not explored other potential storage systems and the competitive benefits of these systems to select a best storage system in the context of Nepal. This study aims to bridge this gap by conducting a thorough comparison of ESS based on parameters such as cost, efficiency, storage capacity, duration, environmental impact, maturity, lifetime, operational and maintenance (O&M) cost etc., The final aim is to select the most suitable storage technology ensuring energy security and maintaining the supply demand chain in Nepal. This study could provide valuable insights and can guide the strategic planning of effective ESS feasible to the country's energy landscape.

The structure of this paper is as follows: Section 2 provides a comparative analysis of various energy storage systems, focusing on key parameters such as energy density, efficiency, and cost and other. Section 3 identifies the most suitable energy storage system for Nepal, considering the country's specific energy needs and resources. Section 4 discusses the significance and potential impact of the selected energy storage system within the Nepalese context. Finally, Section 5 concludes the paper by summarizing the findings and suggesting directions for future research.

2. Comparison of various energy storage system

Table 1 illustrates some of the most utilized and feasible Energy Storage Systems (ESS) among available technologies by considering all the parameters that play a significant role in determining storage systems. Comparing various energy storage systems reveals distinct characteristics crucial for understanding their suitability across diverse applications. PHES emerges as a mature and versatile option with an efficiency of 80%. Its rapid response time of 20 seconds to 12 minutes and medium to long-term storage duration make it ideal for grid-level energy storage, with a medium to low environmental impact. Moreover, PHES offers a more environmentally friendly solution in particularly in the case of off-river PHES, which has low environmental impact [17]. Following PHES, Lithium-ion batteries, commercially established, boast efficiency rates of 85-90% and quick response times ranging from milliseconds to second. Their moderate energy density and relatively low environmental impact render them suitable for short to medium-term storage needs. Further, Lead-acid batteries, also mature and versatile, offer efficiencies of 70-90% with rapid response times of 5-10 milliseconds, but they are best suited for short-term storage, however they have high environmental impact and limited lifespan. CAES, another mature technology, holds a significant capacity with a lower cost per kW but faces limited preference due to its complex design.

Table 1: Comparison of Energy Storage Systems

Type	Maturity	Efficiency (%)	Response Time	Energy Density (Wh/L)	Power Cap. Cost ($/kW)	Energy Cap. Cost ($/kWh)	Charge Time	Discharge Time	Env. Impact	Energy Storage	Duration	O&M Cost ($/kWh)	Lifetime (years/cycles)
PHES	Mature & versatile [18]	80 [17]	20sec–12min [18]	0.49–1.49 [19]	2000–43000 [20]	5–100 [20]	hr–months [20]	hr–days [21]	Medium/Low [17], [22]	High [23]	L [24]	0.005 [25]	50–1000(>13000) [26]
Li-ion Battery	Commercialized [18]	85–90 [20]	20ms–s [20]	200–400 [27]	900–4000 [20]	600–3800 [20]	min–days [20]	min–hr [26]	Low/Medium [13]	High [23]	S/M [13]	-	5–15(100–10,000) [26]
Lead Acid Battery	Mature & versatile [18]	70–90 [28]	5–10ms [20]	-	300–600 [20]	200–400 [20]	min–days [18]	sec–hr [18]	High [22]	Medium [29]	S [24]	50 [30]	5–15(500–1800) [26]
CAES	R&D phase [18]	70–80 [31]	1–15min [18]	2–6 (large) [25]	400–1000 [20]	2–120 [20]	hr–months [20]	hr–days [20]	Medium/Low [20]	Medium [29]	M [24]	0.004 [32]	48–72 (>13,000) [33]
Hydrogen Fuel Cells	R&D/marketed [34]	25–58 [31]	sec–hr [21]	-	500–10,000 [20]	15 [24]	hr–months [20]	sec–24hr+ [20]	Low [29]	Medium [29]	Seasonal [24]	-	5–20(1000–20,000) [26]
Flywheel	R&D [35]	80–95 [18]	ms–12min [18]	20–85 [36]	250–350 [20]	1000–14000 [20]	sec–min [20]	sec–<15min [20]	Low [33]	Low [26]	S [33]	0.004 [36]	15–20(20,000–100,000) [26]
SMES	Early commercial [37]	95 [18]	ms–8sec [18]	0.2–0.25 [25]	200–489 [20]	1000–72,000 [20]	min–hr [20]	ms–8sec [20]	Very Low [22]	Low [26]	S [18]	0.001 [38]	15–20(upto 100,000) [26]

Technologies Hydrogen Fuel Cells, Flywheels, and Superconducting Magnetic Energy Storage (SMES) present varying efficiencies, response times, and environmental impacts, catering to specific use cases from grid-scale to portable applications. Each system's capital costs, charge/discharge times, and operational lifetimes further influence their applicability, highlighting the importance of tailored solutions based on energy demands, environmental considerations, and economic feasibility.

3. Suitable energy storage system for Nepal

PHES is a mature and versatile technology that offers large energy storage capacity, cost-effectiveness in terms of energy per kW, extended storage duration, higher life expectancy, lower operating costs, infinite cycle stability, and permanent storage [16]. Additionally, PHES possesses other advantages such as flexible start/stop capabilities, rapid response speeds, adaptability to load changes, and the ability to regulate frequency, keep voltage stability, and maintain grid stability through network connection application, which helps to maintain load supply and demand pattern [39], [40]. Compared to other ESS systems mentioned in Table 1, the environmental impact of PHES is low, which can be further reduced significantly in Nepal by choosing an appropriate site from the 2800 available off-river sites identified by Global PHES Atlas [15]. Nepal needs seasonal energy storage due to significantly reduced generation from RoR hydropower in dry season and urgent need of energy source diversification in Nepal's energy mix could result an increased share of solar PV. This underscores the necessity for long-term, higher-capacity storage solutions with enhanced higher energy efficiency and can be fulfilled by integrating PHES. Moreover, Nepal has a geographical feasibility for the installation of PHES due to its diverse terrain and environmental conditions [16]. When considering larger capacity systems, PHES stands out as a more cost-effective option compared to other technologies mentioned in Table 1. This positions PHES as the optimal energy storage technology within the context of Nepal.

Lead acid and Li-ion batteries meet the technical requirements for storage capacity as both are mature and commercialized technologies. They possess higher efficiency and fast response time. However, lead acid has a higher environmental impact, lower discharge time, lower life expectancy, and smaller number of cycles [41], [42], [43]. Nepal needs seasonal storage technology with higher discharge and efficiency to store the surplus energy from the wet season. Given the requirement for long-duration energy storage, battery energy storage systems may not be cost-effective for substantial energy storage needs over longer durations [44]. While batteries, such as lithium-ion or lead-acid, provide high efficiency and rapid response times, they may not be as cost-effective or practical for storing energy over longer durations, particularly for a country like Nepal with limited industrial capacity for battery production. Therefore, while battery technologies are viable options, PHES may be more suitable for grid-scale storage applications.

CAES, another form of medium duration and higher capacity storage technology, has a higher efficiency and can be implemented for storage purposes. However, it faces self-discharge and air storage challenges in Nepal's context due to the absence of underground salt mines [20]. Various forms of hydrogen storage for long-term energy storage are emerging worldwide. Specifically, green hydrogen has gained attention due to its lower environmental impact and potential long-term cost benefits [45] . However, despite being in R&D phases, the efficiency of hydrogen storage systems is significantly low and has a high cost of operation as compared to PHES and battery storage systems [24]. Moreover, though promising, green hydrogen remains a relatively new technology [24], [33]. Research activities related to hydrogen storage require a new level of operation, infrastructure, and expertise compared to the well-established and technically informed personnel involved in matured PHES [46],[47].

4. Discussion

This paper comprises a comparison of different energy storage technologies (such as PHES, CAES, Li-ion battery, Lead acid battery, hydrogen fuel cell, flywheel, and SMES) against key parameters such as environmental impact, cost, energy density, technology maturity, storage capacity, lifetime, operation, and maintenance (O&M) cost etc. The study underscores the crucial role of energy storage systems (ESS) in addressing Nepal's energy supply-demand imbalance. Among all analyzed technologies, PHES aligns perfectly with Nepal's energy storage needs. It offers high energy efficiency, lower maintenance costs, high power storage capacity, quicker response times for grid stability, minimal environmental impact, extended lifespans, and infinite lifecycle stability throughout its lifetime. Moreover, the availability of infrastructure and sites is abundant in Nepal which makes PHES installation more feasible. This study contributes valuable insights into the selection and implementation of energy storage systems based on based on cost, efficiency, storage capacity duration, and availability of infrastructures, and environmental factors.

Although PHES demonstrates significant potential for

Nepal's energy landscape, barriers such as limited data and research, inadequate energy systems planning, and policy gaps are the major hindrance of its development in Nepal. Additionally, the lack of knowledge regarding the sensitivity of energy security, need of energy storage and its role in ensuring uninterrupted power supply, and energy independence within the country further hinder the timely implementation of PHES. Moreover, prevailing unawareness on the lower expected cost over its lifetime represents another key factor impeding the adoption and integration of PHES into Nepal's energy infrastructure.

By implementing PHES, the most suitable form of ESS for Nepal, can significantly contribute to achieving net-zero carbon emissions. Moreover, prioritizing ESS aligns not only with Sustainable Development Goal (SDG) 7 - access to affordable, reliable, sustainable, and modern energy for all but also with SDG 13 - addressing climate change and its impacts. Within SDG -7, the proposed actions include reaching 99% of households for access to electricity, reducing fossil fuels dependency to 30%, limiting the use of LPG to less than 40% of households, installing 15 GW worth of capacity and increasing the per capita consumption to 1500 kWh [48]. To meet these targets enormous generation from both hydroelectricity and modern renewable energy sources is imperative. However, to mitigate the impact of erratic electricity generation from the sources, integration of ESS technology is crucial. The advantages of ESS in this context become more evident as it addresses the specific targets outlined in SDG-7 and SDG-13. Thus, to facilitate a smoother transition to cleaner energy, enhance energy security through efficient storage and distribution, and support the broader national goals of energy security and independence, Nepal has to invest in the available 2800 off-river PHES sites.

5. Conclusion

Nepal faces significant challenges and opportunities in its energy landscape. To mitigate the use of unsustainable energy sources more diverse energy sources along with ESS should be introduced. The energy mix in generation and storage system not only helps to reduce the challenges faced by RoR hydropower plant such as climatic vulnerabilities, seasonal variations, and insufficient rainfall, it also ensures the grid reliability and stability. The study emphasizes the importance of ESS in mitigating these challenges and ensuring a resilient and stable power supply and compares various energy storage in the context of Nepal through comprehensive literature review. On evaluating parameters like cost, energy efficiency, storage capacity, availability, time duration, maturity levels, among others, it reveals that PHES is the most suitable form of ESS for peak levelling, diurnal and seasonal storage in Nepal.

Acknowledgement

The authors acknowledge the "Energizing Higher Education for Economic Transition (e-REET)" supported by the German Academic Exchange Program (DAAD) and "Sustainable Engineer Engineering Doctoral (SEED) Program" funded by Swedish Research Council for partial support of researchers.

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