Kathmandu University Journal of Science, Engineering and Technology, Vol. 18, No. 2, December 2024

Kathmandu University
Journal of Science, Engineering and Technology

Pumped storage vs. hydrogen fuel for Nepal's excess hydroelectricity

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Abstract

Nepal's significant hydropower potential is hindered by seasonal variations in electricity generation, resulting in surplus power during the monsoon season and deficits in the winter months. This study addresses the need for efficient energy storage solutions to mitigate reliance on expensive electricity imports. We investigate the economic viability of two storage techniques: pumped hydro energy storage (PHES) and hydrogen storage. By conducting a cost comparison analysis, we assessed the levelized cost of electricity (LCOE) for each method under varying input electricity costs. Our results show that PHES is currently the more cost-effective option, with an LCOE of USD 22.43/MWh in an ideal scenario with free electricity, compared to hydrogen storage's USD 100/MWh. Even with a paid electricity cost of USD 50/MWh, PHES maintains a lower LCOE of USD 77.99/MWh, whereas hydrogen storage's LCOE increases significantly. Future advancements in hydrogen technology could reduce its LCOE to around USD 31.25/MWh, making it competitive for low energy storage needs. Our findings highlight PHES as the most practical solution for Nepal's immediate energy storage needs, while underscoring the potential of hydrogen storage for long-term clean energy integration.

Keywords: Hydropower; Hydrogen fuel; Pumped storage.

1. Introduction

Energy is a vital aspect of the world's infrastructure, industries, household, and transportation systems. It encompasses various sources such as fossil fuels, renewable energy, and nuclear power, each with its own environmental, economic, and geopolitical implications. Meeting the global demand for energy while addressing sustainability and climate concerns remains a complex challenge.

Our energy needs are constantly rising while the primary source of energy, fossil fuel, has limited reserves. It is forecasted that we will have an energy shortage in the near future (by 2042) if we don't develop alternatives [1]. While fossil fuels are the most widely used energy source, their limited reserves will likely drive up costs in the future. Hence, many sectors are now switching to other energy sources. With a plethora of options out there, renewable energy sources like hydro, solar, and wind power are gaining popularity due to their versatility, low carbon emissions, and diverse applications. This presents a great opportunity for countries like Nepal, since it holds an economically fit mode of producing electricity: Hydropower. The country's abundance of suitable locations, combined with the topographical advantage of valleys that offer natural storage potential, paves the way for cost-effective development of Pumped Hydro Energy Storage (PHES). Additionally, it benefits from its proximity to a well-established global energy market.

However, a major challenge remains. Most of its Hydropower are Run-of-River (RoR)-based plants which aren't reliable sources and Nepal lacks a good electricity storage system. As a result, there is a surplus of electricity during monsoon months [May-October] and a deficit during the dry season [Nov-April] [2, 3]. So no matter how large the capacity is, lack of efficient storage hinders consistent power supply.

The most common methods for storing hydroelectricity include pumped-storage plant, Compressed Hydrogen fuel, and lithium-ion voltaic cells. This paper focuses on two options: pumped-storage plant and compressed hydrogen fuel. We compare them in the context of Nepal, evaluating whether it would be viable to store excess electricity generated during the monsoon season for domestic use during the dry season rather than selling it to neighboring countries. While numerous studies have compared pumped hydroelectric storage (PHES) and hydrogen storage, their applicability to countries with abundant hydropower like Nepal remains under-explored. This research uniquely examines the economic viability of these storage options under the specific condition of nearly free surplus electricity, a characteris-

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*Corresponding author. Email: sapan.pokharel@gmail.com tic often overlooked in previous studies. By factoring in this unique advantage, we provide a comprehensive analysis that challenges conventional perceptions of hydrogen storage's competitiveness and offers valuable insights for policymakers in hydropower-rich nations.

PHES has been in practice for more than a century to aid with load balancing in the electricity industry. PHES entails pumping water from a lower reservoir to a nearby upper reservoir when there is spare power generation capacity and allowing the water to return to the lower reservoir through a turbine to generate electricity when there is high demand. It serves as a major storage solution for renewable energy generated from hydropower, solar, wind, etc [4]. Understanding the cost structure of PHES is crucial, especially when evaluating its suitability alongside other storage methods. Cost of a hydroelectric system comprises of six elements: (i) planning and approvals, (ii) construction of reservoirs, (iii) the water conveyance: tunnels, pipes, aqueducts, (iv) the power- house including pump/turbine, generator, switchyard and control, (v) access: roads, electricity transmission and water (for off-river systems) & (vi) operations and maintenance over the life of the system.

Hydrogen fuel refers to the use of hydrogen gas as a fuel source for applications like electricity generation , industrial use, and transportation. It can be a clean energy carrier when produced using renewable energy sources like hydro or solar power through electrolysis. When used in fuel cells or combustion engines, hydrogen produces only water vapor as a byproduct. Hydrogen fuel as a green energy source is slowly gaining traction in the industrial era. Global production stands at around 75 MtH_2/yr as pure hydrogen and an additional 45 MtH_2/yr as part of a mix of gasses. This is equivalent to 3% of global final energy demand, with only 4% of the total production coming from electrolysis [5].

2. Literature review

This review explores various storage technologies, focusing on pumped storage and hydrogen storage. Recent findings indicate that pumped storage plants exhibit superior performance for short to medium-term energy storage compared to other technologies. For long-term storage, however, compressed air storage and hydrogen storage emerge as more advantageous options [2].

A comprehensive techno-economic analysis reveals that hybrid renewable energy systems incorporating battery and pumped hydro storage demonstrate superior performance relative to those utilizing hydrogen-based storage [6].

The levelized cost of energy (LCOE) for hydrogen production varies significantly, with estimates ranging from €3.8 to €4.5 per kg [7]. These figures differ notably from other studies, which report a cost of 2 USD/kg [8]. Projections suggest that the levelized cost of hydrogen (LCOH) for hydrogen production will fall between 1.59-1.91 USD/kg by 2030 [9]. In terms of production efficiency, the ideal energy requirement for producing 1 kg of hydrogen is between 32-40 kWh, though real-world values are higher due to inefficiencies, with manufacturer reports indicating 42.2 to 65.6 kWh/kg [10, 11, 12]. Future projections suggest that surplus hydrogen production could reach up to 834,664 tons under ideal conditions, highlighting the need to transition from steam methane reforming (SMR) to more sustainable electrolysis methods [7, 10].

In the context of Nepal, the feasibility of pumped hydro energy storage (PHES) is being actively explored. Research by Rupesh et al. [13] identified over 1776 technically feasible PHES sites across the country, primarily river-to-flatland configurations.

Cost estimates for PHES in Nepal vary significantly; Deane [14] estimates capital costs ranging from USD 1000 to USD 4000/kW, influenced by site-specific factors and storage reservoir costs, which can range from USD 10/kWh to USD 169/kWh [15].

The Nepal Electricity Authority (NEA) and Japan International Co-operation Agency estimate the cost for Begnas-Rupa PHS at approximately USD 700/kW [16], while Jirel et al. [17] report costs around USD 1570/kW for Kulekhani PHES.

For hydrogen storage, transportation within Nepal will likely occur by road, impacting the overall cost. The LCOH is considered from multiple sources to provide a realistic estimate for Nepal, with a particular focus on the economic implications of local transportation and storage solutions [8, 15].

While global research provides valuable insights into the economic and performance aspects of storage technologies, there is a notable absence of studies that integrate these insights with localized data specific to Nepal's energy needs, particularly in comparing pumped hydro storage and hydrogen fuel.

3. Methodology

We analyzed Nepal's hydropower storage options by examining scholarly articles, reports, NEA publications, and online news sources. Relevant keywords like "Nepal hydropower storage," "pumped storage economics," and "hydrogen storage costs" guided the search.

We compared findings from multiple credible journals within the field to identify the most suitable and cost-effective storage solution for Nepal's hydroelectricity, considering self- sufficiency. The analysis focused on pumped hydro and hydrogen storage, evaluating whether investing in storage surpassed the economic benefit of selling surplus energy to India. To assess economic feasibility, the LCOE was calculated for both pumped hydro and hydrogen storage. The LCOE calculation considered initial capital expenditure, operational and maintenance costs, and other related costs. For pumped hydro storage, this included costs for constructing reservoirs, tunnels, pipes, and powerhouses, along with ongoing operational expenses. For hydrogen storage, we assessed costs related to hydrogen production via electrolysis, storage infrastructure, transportation, and conversion back to electricity.

Data on electricity rates, import/export volumes, and other relevant factors were obtained from recent Nepal Electricity Authority (NEA) reports and journals [18, 3]. Capital cost estimates for PHES and hydrogen storage, including construction, installation, and storage reservoir costs, were analyzed [14, 15, 16, 17]. The study evaluates various storage technologies based on LCOE and LCOH, considering local costs and transportation impact [8, 7]. Future projections for hydrogen production and technological advances were adopted from relevant studies [9].

We analyzed the LCOE graph from the ADB report [8], which presents price versus discharge duration curves for different storage options on a logarithmic scale. The report incorporates factors such as capital expenditure, maintenance costs, storage, transportation, and conversion, and adopts approximate values specific to Nepal.

For our study, we selected the price that best fits our criteria in Nepal,specifically focusing on a scenario with a 0$ input cost and a discharge duration exceeding 100 hours for the compressed hydrogen storage method.

We assumed that around 55kwh is needed to produce 1 kg of hydrogen [10, 11, 12] and in return it only produces 20kWh [8], which makes LCOH of 2$/kg for 0$ input price and 4.75$/kg for 50$ input price. LCOH for \$50/MWh input price is calculated as follows:

$$\text{LCOH} = \$2/\text{kg} + \$50/\text{MWh} \times \left(\frac{55}{1000}\right) \text{MWh/kg} = \$4.75/\text{kg} \tag{1}$$

The LCOH and LCOE are calculated similarly throughout the analysis. In the future, we assume a significant efficiency improvement from the current 0.36 to 0.9 in fuel cell electrolyzers. With this increased efficiency, 36 kWh will be sufficient to produce 1 kg of hydrogen, which will then yield 32 kWh of energy, keeping it within the typical range for fuel cells [10, 11].

To assess the economic feasibility of pumped hydro storage, a comparative analysis was conducted between PHES and hydrogen storage. The study focused on identifying suitable PHES sites with storage capacities below 5 Terawatt-hour(TWh). A dataset of potential PHES projects was compiled based on [19].

LCOE for PHES is calculated using the formula:

$$\text{LCOE} = \frac{\text{Capital cost} \times (P/A) + \text{Other annual costs}}{\text{Annual energy (MWh)}} + \text{Pumping cost (per MWh)}$$

To account for the time value of money, a discount rate of 8% was applied, reflecting Nepal's economic conditions. The present value factor (P/A) was calculated using the formula:

$$P/A = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \tag{2}$$

Where:

P: present value
A: annual value
i: interest rate (8%)
n: time (40 years)

This calculation resulted in a discount factor of 11.92 for a 40-year project lifespan. This differs from the discount factor of 18.2 used by [19]. To align cost estimates, calculated costs were adjusted by multiplying them by the ratio of 18.2 to 11.92.

Subsequently, the cost of pumping (per MWh) was incorporated into the LCOE calculation. The overall efficiency of the PHES system, assumed to be 90%, was then applied to account for storage losses, mechanical losses, and other inefficiencies. The final LCOE was adjusted as follows:

$$\text{LCOE} = \frac{\text{Cost per MWh}}{0.9} \tag{3}$$

Finally, we compared the LCOE of both storage options under different scenarios: USD0/MWh and USD50/MWh electricity costs for the present and future. The future comparison was done with the understanding that hydrogen storage is a new technology, with expected improvements in efficiency and cost-effectiveness over time. Comparing these LCOEs against the costs of importing electricity during the dry season helped choose the most economical option for Nepal to store excess energy from hydropower.

4. Discussion

Nepal has immense potential for renewable energy generation, especially hydropower. However, its abundant hydropower resources face a crucial challenge: seasonality. During the monsoon season, rivers overflow, generating excess electricity that often goes unused due to limited storage capacity. Conversely, dry seasons witness a significant drop in water levels, leading to power shortages. Since most of the power plants are RoR based, electricity demands are met by importing from the international market. This imbalance results in substantial losses for Nepal. RoR based power plants, the dominant type in Nepal, can't meet dry season demands, forcing the country to import electricity at a higher price (Rs. 10.74/unit) than it exports (Rs. 7.83/unit) [20, 21]. Overall, Nepal bore the loss of Rs. 8.99 billion on importing electricity in FY 2022/023 [20].

The summary of electricity imports and export data shows that Nepal conclusively needs a reliable storage unit or system if it is to be an energy hub which dreams to sell electricity primarily in South-Asia and with time in whole Asia. In addition to this unreliable production system, an economic factor is hindering Nepal's energy security: the rising cost of imported electricity. India, a major source of Nepal's electricity imports, increased its export tariff by 11.18% in the previous fiscal year and is expected to continue raising prices in the coming years [20]. The price has been fluctuating throughout the year but after the agreement of the 14th meeting of the bilateral Power Exchange Committee held in New Delhi on Friday decided it to be Rs.11.54/ unit. However, Nepal cannot be seen exporting more energy than importing for a few years without a good storage system.

Even at the minimum current rates of electricity consumption growth i.e. 14.53% [between 2022 and 2023], and NEA expected annual rate 8.1%, we seem to lose a significant amount of energy without storage system; the targeted production is over 5251MW in 2025 and over 15000MW in 2035 [22, 23]. Storage systems present a solution to the recurring issue of power spillage. A 2017 incident portrays this challenge - around 40 Gigawatt-hour(GWh) of energy went unused within a week, translating to a potential revenue loss of approximately Rs. 200 million [24]. By efficiently capturing and storing surplus energy,we can prevent such losses and

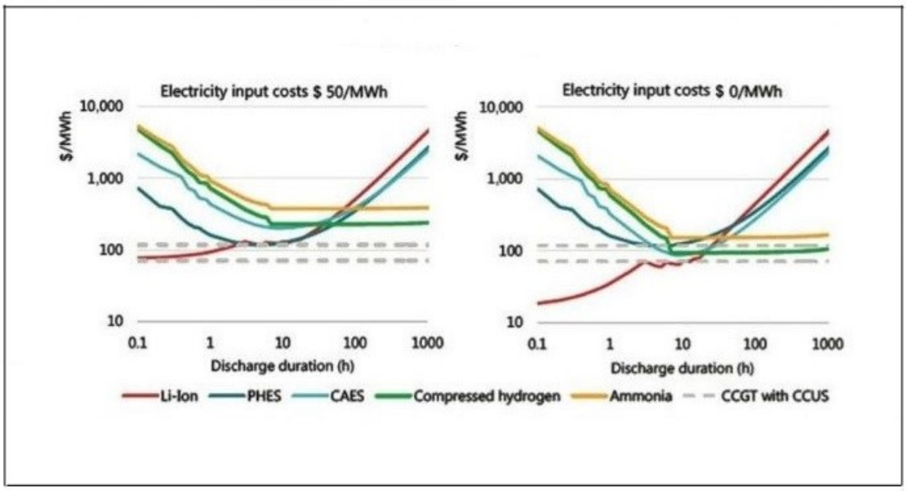

Figure 1: The Impacts of Discharge Duration and Electricity Input Cost on Levelized Costs of Electricity Storage [8].

contribute to a more stable and efficient energy grid. One potential option to achieve this is pumped hydro storage.

4.1. Pumped hydro

Drawing on research by Hunt et al. [19], this study identified 57 potential locations for seasonal pumped hydro storage in Nepal (Fig. 4). These locations offer long-term storage solutions, crucial for addressing the seasonal surplus of hydropower during wet seasons and the increased demand during dry seasons. The cost estimates for these projects range from USD 6.52 to USD 49.80 per MWh, encompassing land acquisition, excavation, tunneling, water storage, and other related expenses. While the average cost across all 57 locations sits at USD 26.843/MWh, it's important to consider that the storage capacities of many sites exceed Nepal's current needs. In fact, some single pumped hydropower projects could potentially handle the entire energy demand of Nepal (Table 1). This suggests that the average cost might be a somewhat pessimistic estimate, with several projects offering lower costs.

Our analysis focuses on pumped hydro projects with a storage capacity below 5 TWh. While larger projects exceeding 5 TWh offer a potential for further cost reduction due to economies of scale, this research prioritizes the LCOE implications for smaller-scale projects. This is done with the assumption of a minimum level of curtailed renewable energy, which necessitates a storage solution without excessive upfront costs associated with massive pumped hydro facilities.The cheapest base option fulfilling our criteria costs USD 13.225/MWh.

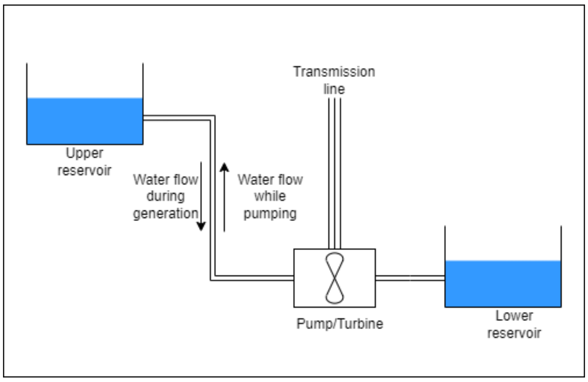

Figure 2: Schematic diagram of pumped hydro storage

Interest rates play a crucial role, impacting the present value of future costs and benefits. While Hunt et al. [19] consider a global interest rate of 4.5% (discount factor: 18.2 over a 40-year project lifespan), Nepal's higher assumed interest rate of 8% (discount factor: 11.92) increases the cost to USD 20.19/MWh. Additionally, the cost of electricity used for pumping during summer impacts the overall cost. Assuming a cost of USD 50/MWh for pumping, the total average cost becomes approximately USD 70.19/MWh. Finally, energy loss during storage also needs to be factored in. With a 90% storage efficiency assumption, the average cost increases to USD 77.99/MWh.

A significant cost-saving opportunity emerges when considering the source of electricity used for pumping. Notably, utilizing currently curtailed excess summer electricity (essentially free) for pumping dramatically reduces storage costs. This approach brings the LCOE down to a highly attractive USD 22.43/MWh, translating to a range of Rs 2.99/kWh to Rs 10.38/kWh depending on the electricity cost during pumping.So, compared to the average import price of electricity from India (Rs. 10.48/kWh), pumped storage offers a clear economic advantage, even when considering different pumping costs. Therefore, the most cost-effective approach prioritizes using Nepal's free, curtailed summer electricity for pumping.While using USD 50/MWh electricity for pumping also falls below import costs, it's important to note that Nepal may not require winter imports in the

Table 1: Most economical potential projects in Nepal.

Longitude	Latitude	Energy storage with cascade (TWh)	Energy Storage cost (USD/MWh)
82.875	29.1	15.818	6.522
82.020833	29.229167	20.698	7.468
83.704167	27.958333	11.384	9.137
81.8875	29.183333	12.133	11.007
81.975	29.233333	8.553	11.585
81.7375	29.791667	7.810	12.911
82.179167	28.416667	4.112	13.225
82.566667	29.120833	7.236	14.077
82.966667	28.15	9.133	15.090
83.758333	27.983333	7.004	16.342

future, even without pumped storage. Therefore, the most relevant cost comparison lies with the current winter power purchase agreement (PPA) rate of Rs. 8.4/kWh. Pumped storage using free summer electricity offers a significant cost advantage over winter PPA rates, highlighting its economic attractiveness.

4.2. Hydrogen storage

Turning into hydrogen storage, the sum of capital expenditure and operational expenditure components represents a significant portion, but not the entirety, of the total levelized costs for hydrogen combined cycle gas turbine and hydrogen fuel cell technologies, which are approximately $80/MWh and $100/MWh, respectively [8], considering the optimum cost and suitable conditions (0 USD electricity input cost and discharge duration greater than 60-70 hours).

For Nepal, current production projections already surpass anticipated consumption levels for 2025. This indicates a surplus of about 50% more electricity than needed in the near future, leading to discharge durations significantly exceeding 60-70 hours. Consequently, only the surplus energy from the estimated production is considered here as a hydrogen storage option, instead of constructing new hydropower plants solely for storage, effectively reducing the input cost of electricity to USD 0. However, considering the option of new hydropower plants, the current rate for energy is Rs 11.2 per kWh for commercial purposes [18]. This translates to approximately USD 84 per MWh at the current exchange rate. For the base cost projection, a lower value of USD 50 per MWh is taken for now, which remains below the current market price of USD 84/MWh.

According to [8], current technology allows 1 kg of hydrogen to generate only 20 kWh of electricity Additionally, approximately 55 kWh of electricity is required to produce 1 kg of hydrogen [10, 11]. Based on this, the cost of producing 1 kg of hydrogen gas in 2024 is approximately USD 2, assuming zero electricity input cost. However, this cost increases significantly when electricity input cost is considered. With an electricity input cost of USD 50, the production cost becomes USD 237.5/MWh or USD 4.75/kg H_2, making it 2.375 times higher. This exceeds the market price of green hydrogen in many regions of the world in 2024, where we can buy green hydrogen for 4-7 USD/kg depending on the region [25]. Consequently, the cost of using hydrogen for electricity generation translates to around USD 0.1 per kWh. This is more expensive than the market price of commercial electricity in Nepal, which is about USD 0.08 per kWh. Even with zero electricity input cost, hydrogen remains a less cost-effective option compared to other available sources.

By 2030, technological advancements are expected to reduce the life-cycle cost of hydrogen production through electrolysis to between USD 1.60 and USD 1.90 per kg [9], making it a more attractive energy option. In the future, if the price of electricity for hydrogen electrolysis can be kept at 0 USD and output efficiency of hydrogen cells is to be increased i.e. 1 kg Hydrogen producing 30 kWh of energy, hydrogen-based storage and fuel cell production would become economically viable between (USD 53.33/MWh- USD 63.33/MWh).

After 2030, we consider an overall increase in the efficiency of hydrogen cells. In this scenario, 36 kWh produces 1 kg of hydrogen, which in turn generates 32 kWh of electricity (falling within the range of high-efficiency cells at 32-40 kWh). Achieving a LCOH under USD 1 per kilogram (as targeted by the US Department of Energy would result in a LCOE of USD 31.25 per MWh. This represents a cost reduction by half compared to current prices. However, if the electricity input cost is USD 50 per MWh, the LCOE would rise to USD 87/ per MWh, which is near the current commercial electricity price in Nepal.

4.3. Cost comparison

Pumped hydro and hydrogen storage present contrasting cost structures for Nepal's energy storage needs. Here's a breakdown of their LCOE per MWh for each technology under different electricity input costs:

In an ideal scenario with free electricity, pumped hydro enjoys a significant advantage. Our analysis suggests a pumped hydro LCOE of approximately USD 22.43/MWh. Conversely, hydrogen storage faces a cost disadvantage even with free electricity for electrolysis. LCOE for hydrogen storage will still be around USD 100/MWh which is significantly higher compared to pumped hydro. However, by 2030 AD, the LCOE can be expected to be reduced between USD 53.33/MWh to USD 63.33/MWh and future advancements in hydrogen technology could lead to a competitive LCOE of around USD 31.25/MWh . This future cost for hydrogen becomes especially attractive for scenarios requiring relatively low energy storage, as pumped hydro's LCOE often increases as the total energy stored decreases.

Pumped hydro remains the more cost-effective option even with a paid electricity cost of USD 50/MWh for pumping. Its LCOE in this scenario reaches USD 77.99/MWh, still significantly lower than hydrogen storage with free electricity input. For hydrogen storage, factoring in the USD 50/MWh electricity cost for electrolysis would inflate its LCOE well above USD 237.5/MWh. Still, advancements in hydrogen technology could lead to a future LCOE of around USD 87.5/MWh, which again is competitive when low energy storage is desired.

Hydrogen storage is currently hindered by limitations in

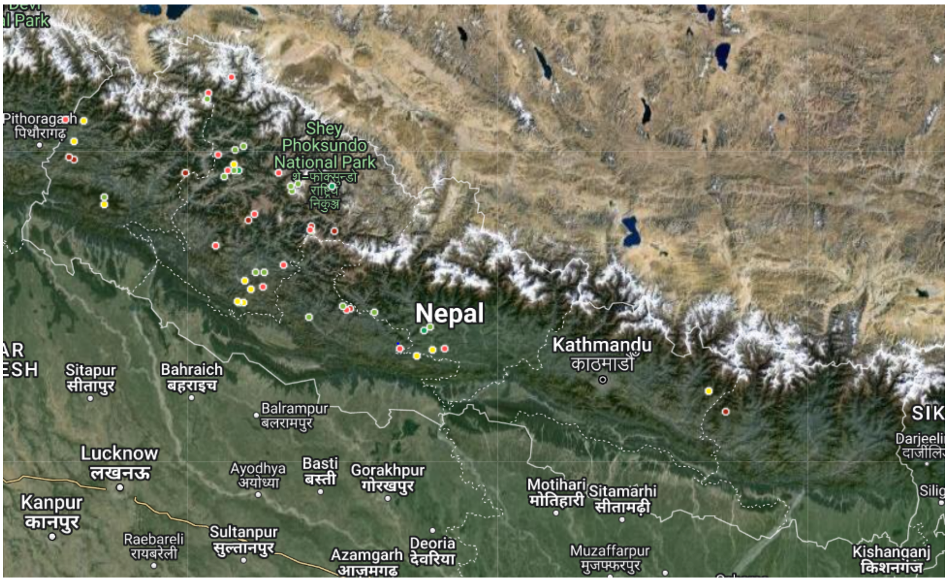

Figure 3: Economical Seasonal Pumped Hydro Locations (Hunt et al., 2020)

Table 2: LCOE in USD/MWh for different costs.

Types of storage	Input Electricity Cost	
	USD 0/ MWh	USD 50/MWh
PHES	22.43	77.99
Hydrogen Storage (With present technology)	100	237.5
Hydrogen Storage (With optimum efficiency)	31.25	87.5

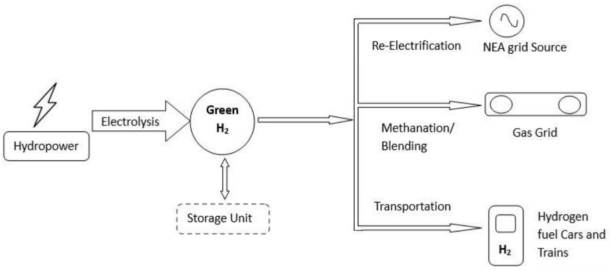

Figure 4: Schematic diagram of hydrogen chain.

efficiency and upfront costs. While advancements promise future viability, significant cost reductions are necessary for it to compete with pumped hydro. However, hydrogen's potential extends beyond seasonal storage. Its clean energy characteristics make it a promising option for transportation and other sectors, potentially aiding Nepal's path towards energy independence [26]. The recent opening of Nepal's first Hydrogen Lab at Kathmandu University Dhulikhel exemplifies the growing interest in hydrogen fuel.

5. Conclusion

This study evaluated pumped hydro and hydrogen storage as solutions for Nepal's seasonal hydropower challenge. Our analysis reveals that PHES currently presents the most cost-effective solution for large-scale seasonal energy storage in Nepal. Specifically, PHES achieves a levelized cost of electricity (LCOE) of USD 22.43/MWh when utilizing surplus electricity at no cost and USD 77.99/MWh with an input electricity cost of USD 50/MWh. In contrast, hydrogen storage, with its current technology, has an LCOE of USD 100/MWh in ideal conditions and USD 237.5/MWh with a paid electricity input.

Future advancements in hydrogen storage technology could potentially reduce its LCOE to USD 31.25/MWh under optimal efficiency, making it a competitive option for scenarios requiring lower energy storage. However, in the near term, PHES remains the more practical solution due to its established technology and economic advantage. Nevertheless, continued research and development in hydrogen storage are essential to unlock its long-term clean energy potential beyond seasonal applications.

These findings highlight the importance of leveraging PHES for immediate energy storage needs while exploring the promising possibilities of hydrogen storage to ensure a sustainable and secure energy future for Nepal.

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