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Research article

Evolution and future prospects of hydropower sector in Nepal: A review

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ABSTRACT

Nepal is one of the pioneers of hydropower development among Asian countries. The plethora of fast-flowing rivers provides immense potential for hydropower generation. However, Nepal still lacks a clear blueprint for the overall development and management of this sector. This paper aims to review the evolution of hydropower development, future prospects and roadblocks to hydropower development. With the growing energy demands projected to reach as high as 41,264.82 Gigawatt hours (GWh) in 2030 and 115,294.4 GWh in 2040 under different scenarios, this paper highlights the huge prospects the sector holds. It also proposes a focus on storage-type hydropower plants and concepts of energy banking to address the incipient condition of seasonal energy mismatch in the country, which has developed a condition of energy shortage during the winter and energy surplus during the monsoon. Moreover, projected changes in hydro-climatic extremes under the climate change scenarios is likely to affect water availability and subsequently the energy production in the majority of hydropower projects. Thus, this review can serve as a guideline to help understand the current scenario and make rational decisions and policies for the future management of the hydropower sector of the country.

1. Introduction

Hydropower is a renewable source of energy that relies on the hydrologic cycle of water [1]. Hydroelectric energy is regarded as one of the most important renewable and clean energy sources across the world and has the advantages of producing relatively low levels of greenhouse gases, storing vast amounts of electricity at low cost, and having the adaptation capacity to meet customer demand [2]. Hydropower can also be a massive booster to decarbonize the environment and limit the rising temperature [3]. The hydropower industry can have major implications in diverse fields including tourism, agriculture and information technology to bolster a country's economy and to develop a sustainable society [4–6]. Moreover, reasonable operating and maintenance costs, and its technology allow for a stable and flexible operation, providing higher efficiency and longer life spans [1]. The growth of hydropower sector in the world has been rapid, and as per the latest World Hydropower Outlook 2023 developed by International Hydropower Association (IHA), the total hydropower installed capacity of the world in 2023 is 1397 Gigawatt (GW), where China alone shares 415

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GW of installed capacity, followed by Brazil (110 GW) and United States (102 GW). The installed capacity is dominated by pumped storage type hydropower plants (about 40 %), followed by storage type plants (about 30 %) and Run-of-River plants (RoR) (10 %) [7].

In the case of Nepal, the total theoretical hydroelectric capacity is 83 GW, with 43 GW being technically and economically achievable [8]. However, on a more recent note, a study by Water and Energy Commission Secretariat in 2019 revealed a gross hydropower potential of 72.5 GW, with a techno-economical potential of 32.7 GW, and total installed capacity of reservoir projects of 48.1 GW [9]. Despite the potential, the hydroelectricity development in Nepal has not been as smooth as expected. Since 2006, Nepal had to face an electricity crisis for over a decade [10]. The country had to overcome technical, social, policy, economic, and institutional barriers, some of which are still in place [11]. Nepal lacked all the basics for sustainable hydropower growth including political stability, government effectiveness, rule of law, and control of corruption [12]. However, in recent years, growth trend has been remarkable with development of a large number of hydropower projects. The recent inauguration of the Upper Tamakoshi Hydropower Project with an installed capacity of 456 MW marked a great shift in the country's hydropower status. Nepal now produces surplus energy with the capacity to export it, at least during the wet seasons [13].

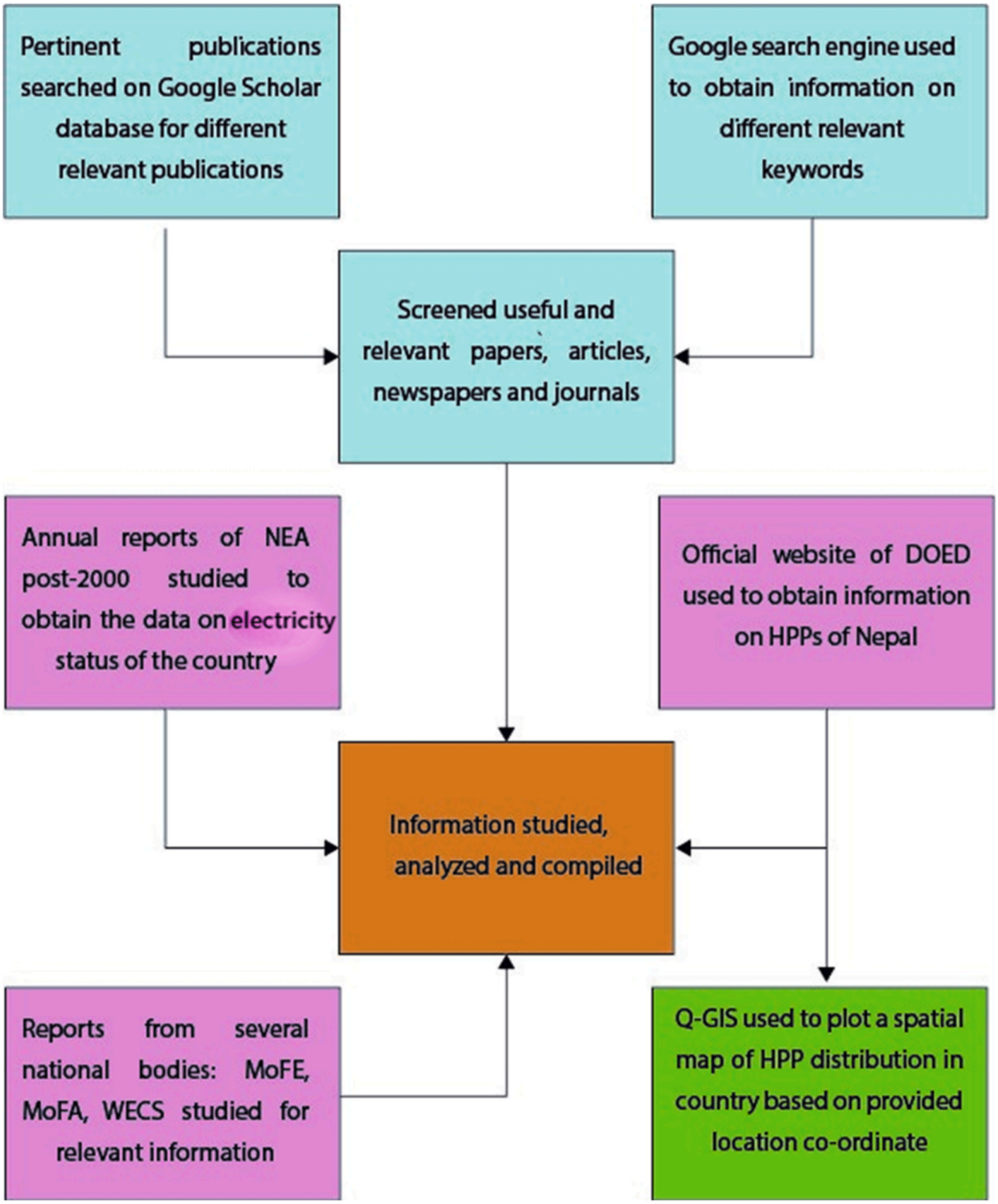

Fig. 1. Methodological framework.

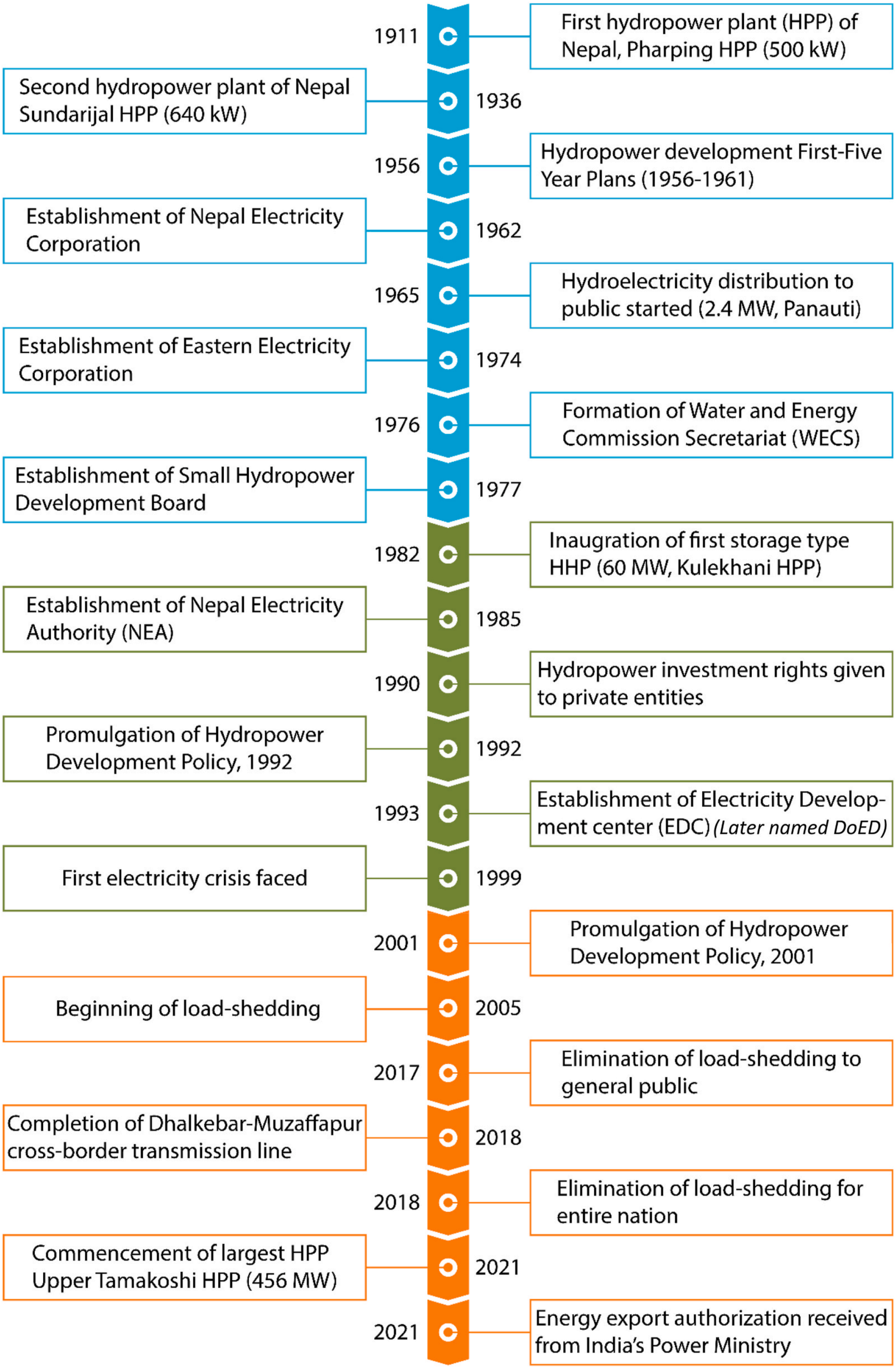

Fig. 2. Overview of major historical developments (1911–2021) of hydropower in Nepal (Compiled by authors based on information from Refs. [1,10,21,23]).

Despite the surplus energy during the wet season, there are still immense prospects for the development of other aspects of hydropower in the country. Nepal, which is dominated by run-of-river (ROR) projects, can increase its potential through the development of storage types as well as pumped hydropower projects. Moreover, Nepal has already committed to reaching net-zero carbon emissions by 2045 and has expressed plans to meet 15 % of its entire energy demand with clean energy sources by 2030 at the 26th Conference of Parties (COP26) to the United Nations Framework Convention on Climate Change [14]. In order to meet these ambitious targets, Nepal is planning to increase its focus on hydropower projects along with the implementation of smart grid technologies, both of which can modernize the power sector and reduce the carbon footprint of fossil fuels by enhancing the penetration of renewable energy sources and minimizing losses [15]. Similarly, there is also a huge possibility for Nepal to establish itself as an export hub through cross-border electricity trade with power-short neighbors, especially India and Bangladesh [16].

Nepal's vision to expand its hydropower sector significantly faces ongoing challenges that constrain its development and limit its potential contributions to the country's renewable energy goals and energy security [7]. Unmanaged and haphazard hydropower growth can disrupt ecosystems and ecology, with varying impacts on fish supply, habitat, and land use for developed and developing countries [17,18]. Nepal requires a well-planned and managed approach to fully harness its substantial hydropower resources, to meet rising electricity demand, and to strengthen energy independence. However, there is a dearth of comprehensive research synthesizing the current status and prospects of the sector. This study serves as a comprehensive review, examining the sector's growth, opportunities, persistent obstacles, and strategies, aiming to inform policies and actions supporting its advancement, thereby facilitating informed decision-making to unlock the country's hydropower capabilities and maximize its benefits [3,11].

Therefore, this study aims to serve as a portrayal of the latest status of the hydropower sector of the country. The paper has four-fold objectives: i) to characterize the growth of the hydropower sector and its contribution to the country's energy security, ii) to enlighten the prospects of the sector with a focus on the necessity of storage type plants, iii) to address the barriers and constraints of hydropower development, and iv) to synthesize the impacts of climate change on the sector and discuss its mitigation measures. The paper can be used as a guide for policy recommendations and to alert relevant authorities to act quickly based on the sector's current standings. This is critical for developing nations to enhance their use of renewable energy and to improve their energy access and security.

2. Methodology

Relevant literatures were identified via "Google Scholar" *(*https://scholar.google.com/*)*, "ScienceDirect" *(*sciencedirect.com*)* search engines and reviewed. The search was conducted for different relevant keywords like 'Nepal hydropower', 'history', 'growth', 'energy security', 'demand projection', 'barrier', 'storage HPP' and 'climate change' and the pertinent publications were screened out. Similarly, the Google search engine *(*https://www.google.com/*)* was used to search relevant articles and reports. This review relied heavily on publications from Government of Nepal, as peer-reviewed studies comprehensively analyzing the country's hydropower sector are limited. We conducted thorough searches for relevant Nepali government reports across ministry databases and archives to capture historical development through recent data and selected over 70 publications. While initial selection incorporated all publications that corresponded to the keywords, screening of 22 articles was made based on relevance of contents to the objective of this study. Further study was carried out through the compilation of data and information from the remaining publications. The overall methodological framework is summarized in Fig. 1.

Data on the capacity of existing hydropower projects (HPP) in MW, the Commercial Operation Date (COD), and their geographical coordinates were obtained from the Department of Electricity Development's (DOED) official website *(*https://www.doed.gov.np/*)*. Based on the coordinates, a spatial map was plotted using QGIS, where 82 small (<15 MW), 24 medium (15–100 MW) and 2 large (>100 MW) hydropower projects were plotted (Fig. 5.). Annual reports of Nepal Electricity Authority (NEA), after the year 2000, were obtained from the official website of NEA *(*https://www.nea.org.np/*)* to obtain the values of annual electricity demands, total available energy, and total energy produced from HPP under NEA. In Nepal, NEA is the only governing body responsible for the transmission and distribution of the generated electricity after connection to the National Grid. Energy generated can be returned to the grid, and there are provisions for independent power producers (IPPs) to sell electricity to the national grid governed by Power Purchase Agreements (PPAs) between the IPPs and NEA. Also, reports from several national bodies were studied including The Ministry of Forest and Environment (MoFE), The Ministry of Foreign Affairs (MoFA), and Water and Energy Commission Secretariat (WECS) to obtain relevant information. The data and information from all these sources were thoroughly studied, analyzed, and compiled to prepare this review paper. At a glance, this review paper is compiled and organized from the sources mentioned to provide a coherent storyline and integrated perspective on the topic. The diverse data of the sources are analyzed, compared, and contextualized to identify key patterns and build a holistic narrative. This review paper thus differs from the research papers of the similar field which adopts a more research-oriented methodologies [17,19,20].

3. Growth of the hydropower sector: contribution to national energy security

Nepal's journey in the hydropower sector (Fig. 2.) began in 1911 with the inauguration of the Pharping HPP, which was also the second HPP in South Asia [21]. However, this early start was not capitalized, as the next HPP was established 23 years later while it took till 1965 to make electricity accessible to the public [21]. Hydropower development in Nepal was slow for almost a century since inception due to funding constraints and the lack of prioritization of the sector [21]. As Nepal's political structure changed in 1990, the government's position on hydropower investments also shifted. The Hydropower Development Policy (1992) and the Electricity Act and Water Resource Act (1992) marked a turning point in the liberalization of the hydropower sector. By attracting private sector investment through the "build, own, operate and transfer (BOOT)" mechanism, the sector was liberalized to ensure hydropower development which was previously owned and developed by the government-affiliated NEA [22].

Nonetheless, despite the desire to encourage private investment in the industry, due to armed conflicts, political battle between the parties and environmentalist movements (e.g., Arun III forcing to withdraw 404 MW), progress was all but stalled for over a decade after the political shift. National and foreign investors' reluctance to make investments in the country was exacerbated by political disputes and violent wars. Despite this, two government-affiliated projects (144 MW Kali Gandaki A and 70 MW Middle Marsyangdi) and two projects with foreign investment (60 MW Khimti and 36 MW Bhotekoshi) were finished between 2000 and 2008 [21]. This mid-2000's sluggish growth marked the beginning of a decade-long energy deficit, or 'load-shedding' [10]. However, after Nepal's declaration as a Federal Democratic Republic in 2008, the sector slowly stated to flourish (Fig. 3) with a diverse range of Nepali investors, including local institutional investors, commercial banks, and companies established by investors specifically for hydroelectric project development. Chinese suppliers have recently entered the Nepali market with competitively priced hydroelectric technology, attracting IPPs with their low bid pricing. This growth has helped significantly to reduce load-shedding in Nepal, with hydropower playing a major role in improving the national energy security.

3.1. Trends in energy demand-supply

The positive difference between energy demand and supply directly correlates to an energy crisis or load-shedding. In Nepal's context, energy available is the sum of energy produced by, i) IPPs; ii) Import iii) NEA's ROR and Peaking ROR projects, and iv) NEA's storage projects [10]. For energy demand, annual reports from NEA were taken as a basis. It showed a linear relation of $y = 386.78x + 2772.7$ ($x = 1, 2, 3$ such that it represents start of the analysis year i.e., 2006/07 = 1, 2007/08 = 2 and so on; and y = Energy demand in GW) with an $R^2 = 0.9911$ (Figs. 4 and 9). The demand line equation was used to fill the missing data for the years 2014/15–2017/18. Fig. 4 shows a decade-long energy deficit which resulted in up to 18 hours per day of load-shedding in dry season. Post 2016, reduction in demand-supply gap has been achieved through the help of an increasing number of hydropower stations being added to the national grid line along with strict leakage control, as well the promotion of electricity-efficient devices like LEDs [13].

3.2. Current development in Nepal's hydroelectric sector

At present, the number of hydropower stations has seen a massive rise, with the stations distributed all over the country, primarily in the central and eastern regions (Fig. 5.). There is still a challenge to emulate such developments in the mid- and far-western parts of the country, given the regions' complex topography and remoteness. Overall, these recent developments have led to Nepal becoming an energy surplus nation, at least during the monsoon. This can be corroborated by Fig. 3., where the slope of installed capacity has seen a tremendous rise. Nepal's sluggish pace in the operation of new power plants has also now picked up pace, with six major HPPs being operated in 2021 itself (Fig. 6.). Furthermore, the government and private ventures have also looked positive on the development of new HPPs as the applications for hydropower construction licenses have been increasing in recent years [Table S1].

For the fiscal year 2021/22, the country produced 2190 MW from hydroelectric projects only [13]. The country still faces deficit energy in the dry seasons, however, during the wet seasons, it enjoys excess energy even in the peak hours (7–8 pm), when the demand is as high as 1500 MW, with over 300 MW of surplus energy [13]. Moreover, the demand ranges only between 900 and 1100 MW during the night, and 1200–1300 MW is consumed during the day when the demand is the least [13].

3.3. Rise in export and trade opportunities

Nepal has now become the first country in South Asia to sell surplus electricity on the Indian Energy Exchange market following the authorization from India's Power Ministry's Energy Exchange in November 2021 [13]. In the first phase, The Indian Energy Exchange had cleared the trade of 39 MW of power, comprising 24 MW from the NEA-owned Trishuli hydropower plant and 15 MW from Devighat power plant [13]. In addition, during the wet season, the Indian government has granted Nepal permission to export an additional 326 MW of power to the Indian energy market. The NEA will be permitted to export 140 MW of power from Kaligandaki A, 68 MW from Middle Marshyangdi, 67 MW from Marshyangdi, and 51 MW from Likhu-4, a private venture, under a new agreement. Following this, Nepal will be able to sell up to 365 MW of electricity at a competitive price in the Indian energy exchange market [13].

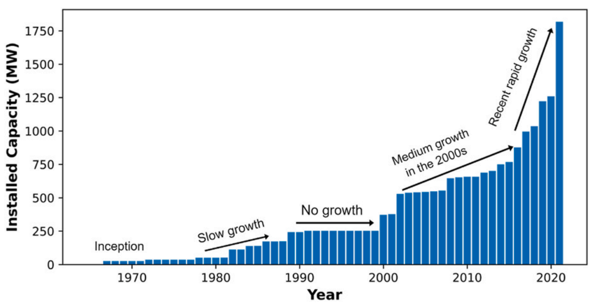

Fig. 3. Cumulative growth of installed capacity (1965–2021) [24].

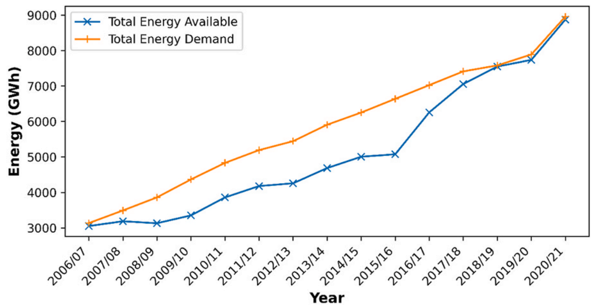

Fig. 4. Total Energy Demand vs Total Available Energy (Data derived from NEA annual reports (2006–2021)).

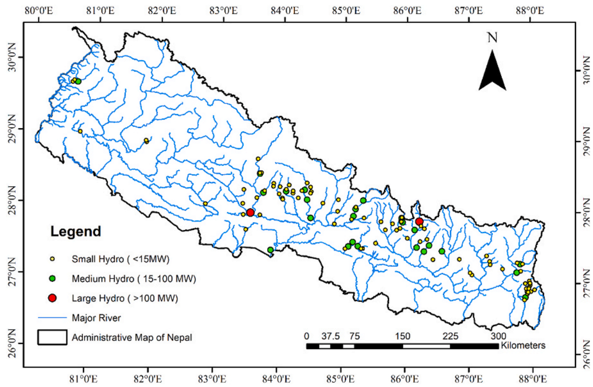

Fig. 5. Distribution of hydropower plants in Nepal till 2022.

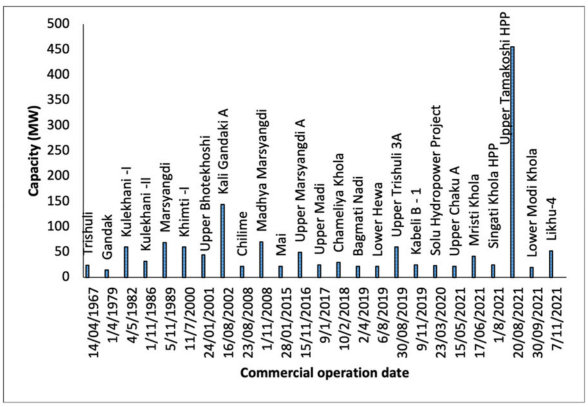

Fig. 6. Timeline of operation of major hydropower projects in Nepal (based on COD) (1967–2021).

The electricity export shall be done via the 400-kV Dhalkebar-Muzaffarpur cross-border transmission line. This transmission line was only used to import power previously. Nepal has recently proposed to India to sell more electricity, notably the electricity produced by the 456 MW Upper Tamakoshi Project, during the monsoon, when Nepal's main ROR hydropower facilities are operating at full capacity. Similarly, the Nepal-Bangladesh electricity export treaty is also taking shape; with an agreement completed between the countries to import 9000 MW of electricity by 2040. However, a mutual agreement with India for transmission paths is still pending [13].

Moreover, in the 14th Joint Technical Team (JTT) conference held on September 2023, India and Nepal have agreed on terms to boost cross-border electricity capacity. They have agreed to: (a) upgrade the capacity of Dhalkebar-Muzzaffarpur transmission line between India and Nepal to 1000 MW from the previous 800 MW limit, (b) to expedite the Dodhara-Bareilly 400 kV cross-border line, targeting completion by 2028–29; and the Indian government has promised to import 10,000 MW of electricity from Nepal in the next 10 years [25]. This agreement paves the way for greater India-Nepal cooperative in the power sector across transmission interconnections, grid connectivity, power exchange and trading.

3.4. Lack of energy consumption market and concerns of power wastage

The cause for the sudden curtailment of the country's electricity deficit can be attributed to two facets. The first part is a bright aspect: the proper management of overall production. The second part is somewhat of a sad reality: the lack of a proper growth of a suitable electricity consumption market. The clear evidence of the lack of growth in electricity consumption can be elucidated by analyzing a report published in 2014 titled "Electricity Demand Forecast Report" by WECS. The report forecasted the country's power demand using the Model for Analysis of Energy Demand (MAED). MAED forecasts a country's or region's future energy consumption based on a set of consistent assumptions about the medium-to-long-term socioeconomic, technological, and demographic trends [26]. For the year 2020, a minimum of 3384 MW of electricity demand was predicted for the business-*as*-usual (BAU) scenario at 4.5 % (Table 1). But the problem of power cuts, at least for wet seasons, has been solved at a mere production level of around 1800 MW, which indicates that the WECS study could possibly be a bit overestimated but still, it shows the lack of growth in the electricity market in the country.

A study by Parajuli et al. [27], which focuses on the energy consumption projection of Nepal from an econometric approach, examined installed capacity requirements until 2030 under three distinct scenarios: BAU, Medium Growth Scenario (MGS), and High Growth Scenario (HGS). While the values projected in Parajuli et al. [27] fall below WECS's projection made in 2014, they nonetheless indicate potential for further expansion of the electricity market. In the case of the HGS scenario, the projected installed capacity requirement exceeded 2000 MW, while for the MGS scenario, it amounted to approximately 1800 MW (Fig. 7.), which seems more factual [27]. Significantly, the problem of energy deficiency was resolved at an installed capacity of 1800 MW, underscoring the untapped potential for market growth.

Owing to the lack of proper expansion of electricity usage, there is now a serious risk of power wastage during the monsoon. Without a comprehensive energy trading plan, IPPs warn on the wastage of billions of dollars' worth of electricity. With even more power planned to be added to the national grid line soon, Nepal must either set up proper export policies or increase the electricity market within the country. However, establishing comprehensive export policies and expanding domestic electricity usage face considerable challenges. Power export is constrained by strategic decisions of neighboring countries regarding cross-border trade. Expanding the domestic market requires huge investments in transmission infrastructure and industrialization that Nepal is working to secure. While increasing electricity usage is imperative, it will take concerted effort and collaboration to achieve.

Nepal's hydroelectric growth has been rapid, but there is still room for ample development. Hydroelectric power only serves to fulfill 4 % of the total energy demand of the nation [28]. Fig. 8 shows how the energy consumption by source has been changing from 1990 to 2019. Although electricity usage has increased from as low as 1 % in 1990 to 4 % in 2019, the percentage is still very poor. Meanwhile, biofuel usage is as high as 72 %, indicating dilatory development [28]. Comparing with the global statistics, electricity fulfills 20 % of global energy demands. The contrast in the global and national data shows room for improvement within the country [29]. The dependence on biomass also strains forests and farmland that could otherwise provide timber, crops, and livestock for local communities. Expanding hydroelectricity would allow households to transition away from biomass fuels, reducing pressure on these natural resources. Investing hydrocarbon revenues into modernizing agriculture can also enhance productivity and strengthen food security [30]. With climate change threatening Nepal's seasonality and precipitation patterns [31], efficiently harnessing water resources through hydropower projects with storage capacity provides a buffer against droughts or variability in crop yields. Thus, strategic development of hydroelectricity and investment of energy revenues represents a pathway for improving resource sustainability and resilience of rural food systems as Nepal continues to advance economically.

This presents an interesting challenge as well as an opportunity for Nepal's hydroelectric sector to increase its access to the remote regions, especially on the western side of the country. The problem has been somewhat solved for the current energy demand scenario, however, to conform with the global energy demands, meet its own energy needs, develop a prosperous domestic energy consumption market, and flourish in the trade and export sectors, Nepal needs to continue its current hydroelectric growth trend and further improve its management and policy sectors. Nevertheless, the potential and prospects of hydropower development look promising.

4. Prospects for hydropower development in Nepal

The Nepal Development Vision 2030 outlines the government's long-term goal of becoming an upper-middle-income country by 2030 and envisions hydropower as a significant engine of progress [32]. By 2026, Nepal seeks to expand its total capacity to 10,000 MW, with about 4000 MW of HPPs expected to be added to the national grid in the next three to four years. According to the NEA's simulation, Nepal would stop electricity imports during the dry season by 2026 and become an exclusive power exporter. Nepal will have a maximum surplus of 2456 MW and an annual surplus of 14,022 million units of energy available for export by the fiscal year 2025–2026 [13].

Table 1
Installed capacity requirement (MW) in different scenarios for 2020 [26].

BAU 4.5 %	Reference Scenario 7.2 %	High scenario 9.2 %	7.2 % growth with policy intervention	9.2 % growth with policy intervention
3384	3611	3794	6621	6814

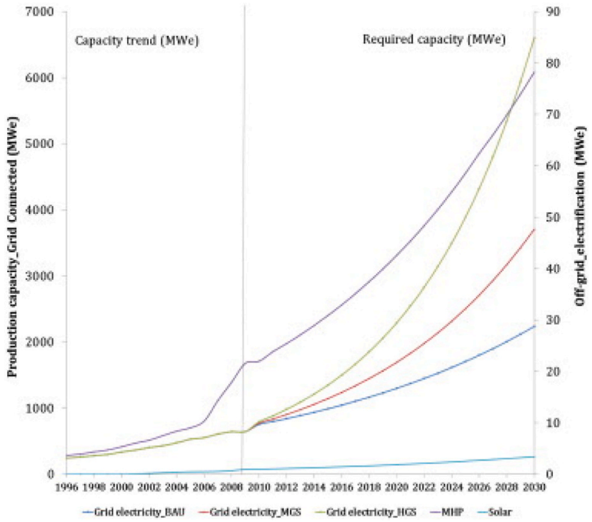

Fig. 7. Production capacity required to meet the future electricity consumption. (Plot derived from [27].

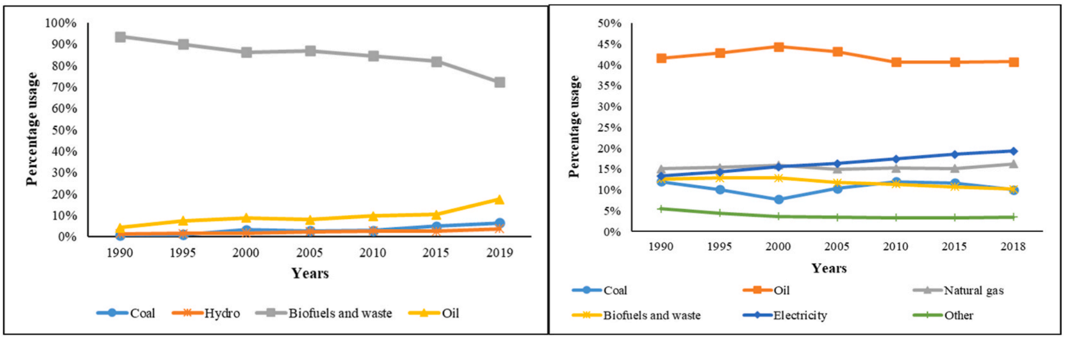

Fig. 8. Trends in usage of energy from different sources in Nepal (left) vs world (right).

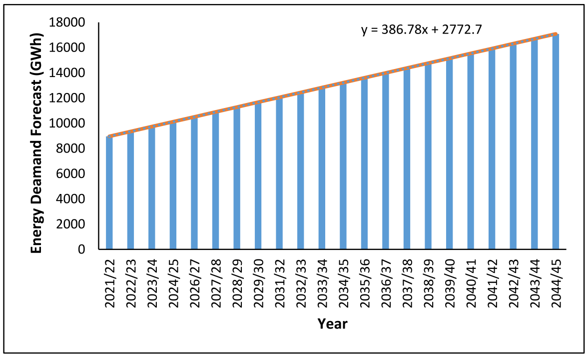

Fig. 9. Extrapolation for energy demand forecast (GWh).

4.1. Growing domestic energy demands

The demand for electric energy is projected to increase in the future, thus, indicating a huge prospect for hydroelectricity development in Nepal. Extrapolation of the historical demand records (Fig. S1.) provides the demand forecast for electric energy with a sound degree of accuracy when the increase in demand is only accountable for i) the extension of the gridline, ii) stagnant economic growth, and iii) growth in population within grid coverage areas [26]. The energy demand forecast until 2045 from extrapolation is shown in Fig. 9. However, scenarios including specific governmental actions to grow the economy as well as increase power consumption by converting customers from other energy sources to electricity are not included in these projections. WECS has forecasted the country's future energy consumption based on a set of consistent assumptions about medium-to long-term socioeconomic, technological, and demographic trends [26]. Three scenarios were used for modeling, namely: a) a BAU level economic scenario of 4.5 % Gross Domestic Product (GDP) growth rate, b) a reference level economic scenario of 7.2 % GDP growth rate, and c) a high-level economic scenario of 9.2 % GDP growth rate. In addition to these, two policy intervention scenarios were also studied for 7.2 % and 9.2 % growth rates, as shown in Table 2.

However, Table 2 shows that the projection is massively overestimated based on the present scenario of power production and power shortage. Hence, another study was reviewed which is more accurate with the present scenario of energy production to estimate the demand forecast for electric energy. Based on [27], the projected electricity demand for BAU is 2235MW, for MGS is 3706MW and for HGS is 6600MW (Fig. 7.). Although the projected values are substantially lower than the WECS projection, it still shows that the potential for growth is huge.

4.2. *Economic growth through export*

With an increase in production, Nepal can firmly establish itself as an export hub, primarily for India (significant hydro export possible) and Bangladesh (hydro power connection via India possible) [16]. In June 2022, NEA was able to export excess electricity worth NRs. 1.72 billion, at an average monthly rate of NRs. 9.67 per unit, on the Indian Energy Exchange (IEX). Since, June 10, 2022, NEA has sold 364 MW/day of excess energy on the IEX [13]. Bangladesh is also expected to import up to 9000 MW of hydropower from Nepal by 2040. Bangladesh has previously also agreed to purchase 300–500 MW of energy generated by the Upper Karnali HPP in Nepal [33]. This will be a tremendous opportunity to strengthen the nation's economy, as export revenues, which were less than US$ 1 billion in FY 2018–19, could be quadrupled [34]. Nepal can earn export revenues of NRs. 310 billion in 2030, rising to NRs. 1069 billion by 2045, if it focuses on the advancement of cross-border power-trading [34]. Also, transitioning households from biomass dependence to hydroelectricity could reduce pressures on natural resources while investing energy revenues in agricultural modernization could boost productivity, food security as well as economy.

4.3. *Nepal's pledge for carbon neutrality*

On the occasion of COP26, Nepal has committed to being carbon neutral by 2045 [14]. By 2030, Nepal plans to meet 15 % of its entire energy demand with clean energy sources. By 2025, it plans to make e-vehicles account for 25 % of all private passenger vehicle sales, including two-wheelers, and 20 % of all public passenger vehicle sales, and by 2030, increase them to 90 % and 60 %, respectively (currently, electric vehicles account for only 1 %) [35]. By 2030, Nepal plans to set up a 200 km electric rail network, boost the use of electric stoves, and ensure that 25 % of households use it as a primary mode of cooking (currently, electric stoves account for 5 % of household use) [35]. For these, the aim is to grow the clean energy output ten-fold to 15000 MW (currently around 2000 MW), of which 5–10 % shall be produced from small and micro hydropower, solar, wind, and bioenergy [35].

4.4. *Prospective areas for hydropower growth*

Nepal still lacks sufficient energy during the winter, when the water levels in rivers decrease. Industries had to face power cuts for up to 14 hours per day during the dry periods of 2022, even four years after the country was declared load-shedding free [36]. Electricity generated by ROR power plants, which dominate the Integrated Nepal Power System (INPS), must be consumed immediately; it cannot be stored. Their production capacity reduces during the dry season, and during wet seasons, they create excess electricity, resulting in plant shutdowns, pollution, energy spills, and a decline in plant economics [37]. From December to April, when supply capacity is low, demand rises, and from July to October, when supply capacity is high, demand falls.

4.4.1. *Storage type plants*

During the dry periods of winter and pre-monsoon, supply capacity for ROR- and PROR-type HPPs falls to about 50 %, and in some years to around 40 %. So, the installed capacity of ROR-type hydroelectric power generation to fulfill demand in the dry season should be almost double that of demand. For storage-type HPPs during dry seasons, with presumed equivalent peaking hours of 12 h and a dry

Table 2
Final Energy Demand (GWh) under different scenarios [26].

Year	Final Energy Demand (GWh)				
	BAU	Reference Scenario	High Scenario	Policy Intervention @ 7.2 %	Policy Intervention @ 9.2 %
2015	3866.4	3866.4	3866.4	3866.4	3866.4
2020	7600.8	8110.7	8522.0	14870.9	15304.3
2025	12998.3	14863.7	16545.8	22431.7	24265.1
2030	20073.8	24956.8	29864.1	35334.7	41264.8
2035	29744.7	40709.8	52983.2	51771.8	65657.5
2040	43016.7	66096.6	94851.1	81958.0	115294.4

season load factor of 57 %, the supply capacity is projected to be at 88 % $\left(\frac{\left(\frac{12\ hrs}{24\ hrs}\right)}{0.57}\times 100\right)$ of installed capacity [38]. As a result, storage-type HPPs, whose producing capacity does not or only slightly decrease during the dry season, are the most practical countermeasure to the seasonal energy mismatch [38]. Following this, the government planned to maintain a mix of 40–45 % of storage-type HPPs in the new planned HPPs. However, with the reluctance of investors towards storage plants owing to their high costs, the government has been forced to reduce the mix percentage of storage plants to 25 % [13].

However, when we analyze the rate of progress for both under construction and planned storage projects, the current mix percentage of 25 % appears to be an ambitious target. Currently, the only major storage-type project under construction is the 140 MW Tanahu Hydropower Project, with an expected completion date in 2026 [39] while all other storage-type projects are still in their preliminary stages. The Aandhi Khola Storage HEP and Begnas Rupa Pump Storage HEP are still under study. The 635 MW Dudhkoshi Storage HEP has yet to submit its Detailed Design Report to NEA [39]. The 828 MW Utterganga Storage HEP had its Detailed Design terminated, and the project is now seeking to re-invite Expression of Interest (EoI). Additionally, numerous other projects are only in the identification phase, such as the Upper Mustang Storage HEP, Syarpu Pumped Storage HEP, and several others [39].

Hence, storage-type HPPs, which can serve as an electrical energy battery through reserves maintaining demand-supply balance, provides a substantial gain to stabilize INPS to meet peak demands and reduce the import of expensive power from India. Moreover, storage projects are a way to use “unused” water resources from the rainy season to use during the dry season, when there is a shortage of natural resources. This can help ensure the security of food, energy, and water during the dry season [40]. This can, in turn, reduce the effects of climate change and increase the nation’s resilience to it.

4.4.2. Energy banking

Another feasible alternative is the concept of energy banking which involves exchanging electricity for electricity instead of currency. When one country has a surplus, it exports electricity to another, and when it has a deficit, it buys an equal amount of energy [41]. However, it must account for the different values of electricity during peak versus off-peak periods. For energy banking to be fair and effective, the electricity banked during peak supply times should be able to be withdrawn during other peak demand times, whether peak hours of the day or peak seasons. Accounting for these differences in the value and timing of electricity supply and demand will be key for Nepal to implement energy banking across seasons and with neighboring countries.

Nepal has reached an agreement to export power to India during the wet season and import it back during the winter using this concept. Following the same, Nepal exported 200 MW of electricity to India in June of 2019, when the production was higher than the demand due to the shutdown of various facilities owing to floods in the country [13]. NEA is confident that this can be an efficient

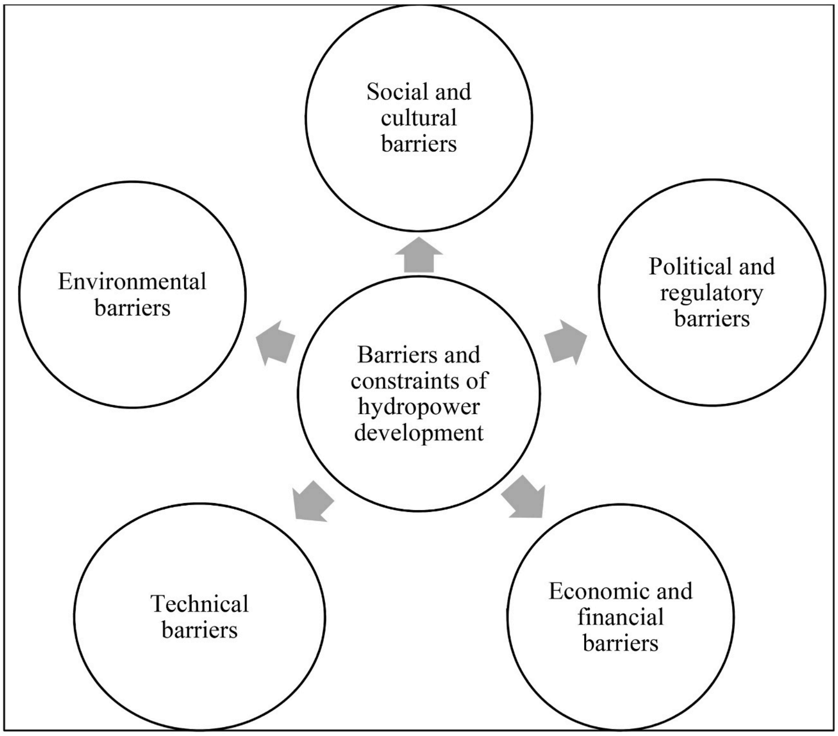

Fig. 10. Barriers and constraints of hydropower development.

solution to the country's seasonal energy mismatch, and hence, emphasis should be given to enhancing the cross-border transmission lines and efficient communication to aid the same. When implementing cross-border energy banking, Nepal must recognize that electricity supplied during high demand periods in India may be more valuable than electricity supplied during Nepal's high supply seasons. Agreements for energy exchange should account for these differences in value.

In conclusion, with the increasing energy demand and with Nepal exploring the potential of power exports to neighboring countries, the prospects of the hydropower sector also increase simultaneously. Thus, to meet such demands, many HPP projects will be necessary in the future. Nepal already faces a serious problem of seasonal energy mismatch as a result of ROR overdependence on INPS. Thus, Nepal must focus on concepts of energy banking and storage type plants whose production capacity does not alter throughout the year. Also, the government's 2018 white paper set ambitious electricity generation goals, targeting 5000 MW capacity and 700 kWh per capita consumption by 2023. However, as of June 2023, total capacity stands at only 2684 MW with per capita consumption of 351 kWh [39]. These targets were likely unrealistic, failing to account for Nepal's economic growth trajectory. Shrestha's (2014) analysis shows attaining the white paper targets would require 10 % annual GDP growth, far exceeding Nepal's current 4.4 % projections [42]. The mismatch between ambitious development goals and economic realities has led to significant shortfalls in delivery. While increased capacity and consumption are crucial for Nepal, a critical analysis shows the original targets were not grounded in evidence-based projections. Moving forward, setting achievable electrification benchmarks tied to economic expansion will be vital for sustainable power sector planning.

5. Barriers and constraints for hydropower development

Despite the huge hydropower potential of the country, Nepal has not been able to bear its fruits. Thirty percent of Nepal's population still has to depend on off-grid and other alternate energy sources [43], whereas for international trade, Nepal lacks proper transboundary power networks [44]. In addition, there are numerous barriers halting the growth of the hydropower sector in the country, as outlined in Fig. 10.

5.1. Social and cultural barriers

There are still challenges in expanding renewable energy adoption in some communities in Nepal. Factors like lack of local engagement in project development, preference for traditional energy sources, and limited knowledge about new technologies can inhibit renewable energy growth in certain areas [11]. As a result, various difficulties have emerged during the construction of hydropower projects in local areas. There have been growing disputes regarding water rights and financing in the upstream and downstream communities. Moreover, local communities "empowered with information" have become more assertive in their demands [45]. In some cases, people have been relocated as a direct or indirect result of hydropower projects in Nepal, thus impacting their livelihoods and social lives. A recent example can be found in the Budhi Gandaki Hydropower Project (proposed installed capacity: 1200 MW), where over 200 residents of Kotale, Gorkha, were asked to relocate without consultation. With an increasing population, the demand for drinking water has also seen a rise, which has led to a shortage of water for electricity production and the shutdown of some plants like the Pharping plant.

Hydropower project developers, investors, and financiers consider electricity exports to India to be more appealing than domestic consumption. However, owing to Nepal's long history of power outages, people have reservations regarding energy export, which has led to a lack of local support for hydropower projects and the halting of some projects in the middle of the funding process. The Arun III hydropower project and the West Seti hydropower project, for example, were both planned with export in mind. Both funding plans, however, were later dropped after running into domestic obstacles and challenges as a result of their power export-oriented designs [44]. Similarly, Jhimruk Hydropower, a 12 MW plant in the Pyuthan district, was shut down when locals assaulted the plant, causing the corporation to lose roughly NRs. 60 million.

5.2. Political and regulatory barriers

The most significant impediment to hydropower development in Nepal is the country's unstable political situation, followed by a lack of institutional capacities [44]. Nepal's government is unstable due to differing political views at various levels, resulting in a plethora of internal disputes. Political leaders' promises to renewable energy development may be insufficient as a result of this uncertainty, as the goals of each government differ [11]. As a result of Nepal's political instability and inadequate governance institutions, the business and investment climate has deteriorated, discouraging international investment [44], and cross-border energy trading [46]. Similarly, NEA has suffered from a lack of adequate planning, control, and management and a constantly changing organizational body. Lack of transparency in decision making and external political influences have halted many of NEA's projects [44]. There is also a lack of comprehensive policies as well as a robust statutory body that governs regulation and rules regarding renewable energy sources.

Moreover, the existing governmental bodies that oversee this sector lack coordination within themselves as well as with each other, resulting in miscommunication, delays, and disputes. Large hydropower/water resources projects require documentation from different departments under different ministries, such as the Department of Forest and Soil Conservation, and the Department of the Environment. Poor workflow and management in these have resulted in unnecessary time lags as well as unwarranted rejection of documents in the past. In addition, the ecological aspects: margin principles (defined by 1993 EIA parameters [47]) and release rates (defined by the Water Resources Development Policy 2001) have been rigidly instituted, making it unfeasible for application to every type of hydropower project. This has also led to partial access and less usage of electricity, especially in rural areas [48].

5.3. Economic and financial barriers

The high capital cost for hydropower projects as compared to traditional energy resources is another key impediment to the development of renewable energy [11]. Nepal's economy is limited, and the country's financial capability, including its banking system, is so limited that it is impossible to achieve our hydroelectric potential without foreign aid. Poor financial and managerial health of NEA and frequent local conflicts have been creating doubts in the mind of foreign investors [45]. On top of that, there is a lack of sufficient market size, with the domestic electricity market not properly utilized and the foreign market yet to be explored. This affects the revenue potential and discourages investment. The other economic challenge is the considerable time it takes to complete projects. Even minor projects, according to the power firms, might take around 5–20 years to complete due to political and other issues [45].

According to the latest NEA annual report [39], the average cost of power acquired from IPPs and India remains quite expensive at NRs. 11 per kWh (8.1 US cents). However, with the addition of numerous IPP-owned projects totaling 2,023 MW from 159 in operation, the average cost has dropped significantly to NRs 5.48 per kWh, while NEA's average selling price stands at NRs. 9.66/kWh. The primary causes of Nepal's high expenses include i) high power purchase costs from India and local private IPPs, and ii) Nepal's high transmission and distribution system losses, and iii) a high system loss of 17.18 % [13] due to inadequate maintenance [44]. However, the retail electricity tariffs charged to consumers are set below the actual supply costs. As a result of insufficient tariff rates and cost collection, NEA has accumulated financial losses over time. The cost recovery concept was traditionally overlooked in the setting of Nepal's tariff and worsened from 78 % in 2012 to 71 % in 2016. Thus, NEA has had little budgetary room to invest in the new generation, transmission, and distribution projects, and little space to cover even the operating and maintenance costs of the existing facilities [44].

5.4. Technical barriers

Most of the hydropower projects in Nepal are of ROR type, which can only work at full capacity during the rainy season. This mismatch between when water is accessible (summer) and when it is required (winter) causes hydroelectricity generation throughout the year to be a challenging task. In addition, the hydropower projects come with a certain technological risk and may face maintenance and repair problems, especially in rural locations. Nepal still lacks a proper network of transmission lines and grid connections for the supply of high voltage electricity [11]. Sedimentation is another technological roadblock, as Nepal's fast-flowing rivers have a huge sediment-carrying capacity that interferes with the operation of the hydropower facility. For a hydroelectric plant to perform successfully, the topographical and water conditions must be ideal, yet many sites are isolated at high altitudes, and freeze over in the winter. Material imports are another concern; copper, steel, and concrete can take over three months to arrive, and since casting materials and building blocks must be imported, this can cause significant delays [45].

The country's data collection is found to differ at the municipal and national levels, which has resulted in a data gap [49]. Lack of a robust hydrological and meteorological monitoring network due to difficult topography and monitoring capabilities has limited our capability for hydrological estimation with a high degree of confidence. The precision of quantitative hydro-meteorological forecasting, which includes numerical modeling of design discharge along with severe hydro-meteorological events, is critical to the accuracy of data obtained from hydro-meteorological station networks. In the absence of such data, the hydrological prediction for many ungauged river systems is conducted through different empirical and regional methods like WECS/DHM (Water and Energy Commission Secretariat/Department of Hydrology and Meteorology) and MIP (Medium Irrigation Project), Hydest, Modified Hydest, and MHSP (Medium Hydropower Study Project) [50], which have been utilized without updating or testing their dependability since their development. Also, for many HPPs, to estimate the discharge, the long-term discharge method is adopted using the catchment area ratio method. The results of these methodologies are inconsistent and often unreliable [51].

5.5. Environmental barriers

Nepal, as a tectonically active country, also faces challenges posed by geological complexities. The majority of the hydropower potential areas are located in mountainous regions, and the major power project structures are possible only by piercing through geologically sensitive tunnels [52]. During the subsurface construction of underground structures, faulty, sheared, and jointed rock masses offer major challenges such as tunnel collapse, rock squeezing, water intrusion, and landslides. Khimti Hydropower Project, a 60 MW project located 175 km due east of Kathmandu, Nepal, was launched from the pre-feasibility stage to the construction stage directly without realizing gently dipping Schists bands of a few centimeters to tens of meters thick holding groundwater above. This created difficulty during tunnel excavation due to the presence of tunnel cave-ins, rock squeezing, water leakage, and slope instability, resulting in a high remedial cost for rock support [52]. Moreover, in the absence of advanced methods of tunneling like the Tunnel Boring Machine (TBM), methods of Drilling, Blasting, and Mucking (DBM) are being adopted, which is more time-consuming, requires huge investments for rock support, and face many cases of unplanned delays [53]. Further, the poor road network of the country has caused the costs and completion times of many hydropower projects to skyrocket [11].

Glacial Lake Outburst Floods (GLOFs) and Landslide Dam Outburst Floods (LDOF) are other vulnerabilities that can damage projects situated in high hill and mountain regions. In Nepal, there are 3252 glaciers and 2323 glacial lakes, 20 of which are extremely vulnerable to floods [54]. Over the last fifty years, there have been seven major GLOFs that damaged several hydropower projects. The

Zhangzangbo GLOF (July 11, 1981) wreaked havoc on the Sun Koshi Hydropower Plant's diversion weir and other infrastructure, causing a total loss of over $3 million [55]. Also, on August 4, 1985, the Dig Tsho GLOF struck the Khumbu area and destroyed the Namche small hydropower station along a 42-km stretch, costing an estimated loss of US $1.5 million [56]. On August 2, 2014, a landslide occurred on the Sunkoshi River in Sindhupalchok District, Nepal, forming an artificial lake 47 m deep and 400 m long, which threatened downstream villages and the Lamisanghu Hydropower Dam [55].

6. Impacts of climate change in the hydropower sector and mitigation measures

Following the global variations in climatic parameters, the hydropower sector is considered one of the most vulnerable sectors as it is closely related to water resources [57]. HPPs have a lifespan of more than 50 years, so, even if the majority of the changes take place in the distant future, the ramifications will be inescapable [57]. Changes in evaporation, river flow, temporal precipitation patterns, and glacier melt rate have the potential to create large changes in hydroelectric output [58].

6.1. Change in inflows

Floods, droughts, fast glacier melt, rising temperatures, and variations in precipitation timing, location, and volume will all influence hydroelectric generation, boosting water supplies and hydropower potential in certain locations while reducing it in others [58]. Fluctuations in precipitation periods will result in variations in flow available for hydroelectric power generation. Eighty percent of Nepal's yearly precipitation occurs between June and September, which is a seasonal mismatch that could be exacerbated by climate change impacts [21]. Fluctuations in river discharge can affect the production of current projects, as well as the generating potential of "to-be", created plants [21]. In the case of Nepal, except for the Kulekhani (I, II and III) HPPs, I the seasonal storage and II & III the cascades of I, most hydropower projects are susceptible to fluctuations in inflows [59], which is also evident through the comparison of production in the last decade (Table 3**)**. The decrease on 2015/16 is attributed mostly to the devasting earthquake. However, the important thing to consider here is that although the years 2016–2020 saw a substantial growth in energy production through addition of various HPPs in the grid line, climatic patterns do play an impact in energy production. Fig. 11 shows the dynamic precipitation pattern (very wet 2019/20 compared to very dry 2020/21) observed in Nepal and such a difference was enough to induce a decline in production (Fig. 12.). This, again, highlights the role of available water/inflow in energy fluctuations as well as revenue generation. Thus, in the face of this, it is imperative that alternative solutions be met for smoother production in changing climatic conditions.

6.2. Effects of extreme natural events

Similarly, climate change induced extreme rainfall occurrences, which bring about various hazards including an increase in sediment load, floods, and geo-hazards such as GLOFs and LDOFs, are all anticipated to become more common [60]. In 2021 alone, high-rainfall-induced floods and landslides have damaged NRs. 3 billion worth of property; damaging 16 under-construction projects and 10 power-generating projects [61]. Such impediments eventually induce decrements in energy production as well (Fig. 12.). The 44 MW Super Madi Hydropower Project, which is now under development in Madi, Kaski, is reported to have alone cost about Rs. 1 billion. Also, only days before the inauguration of Nepal's largest hydropower plant, Upper Tamakoshi, Nepal received word from China that a large landslide had blocked the upstream portion of the Tamakoshi River, jeopardizing the NRs. 55 billion-worth projects. Fortunately, the river was able to navigate its way around the obstruction [62].

6.3. Projection from climatic models

The total annual water availability in Nepal's major river system is predicted to increase under two scenarios, RCP 4.5 and RCP 8.5, for the 2030s and 2050s, respectively. Water availability may increase under different scenarios in different river systems, as represented in Fig. 13. While around 80 % of models project an increase in monsoon precipitation, the variation is estimated to be from 6 % to 33 %. They find that in the RCP 4.5 scenario, monsoon precipitation would rise by 10.3 % in western Nepal and 7.6 % in eastern Nepal, and in the RCP 8.5 scenario, by 15.2 % in western Nepal, and 10 % in eastern Nepal [60]. In more recent studies, dryer winter

Table 3
Annual Energy production from hydropower under NEA (MWh) [13,39].

Fiscal Year	Energy (MWh)	Variation between successive years
2011/12	2,349,968.28	
2012/13	2,247,189.21	−4.4 %
2013/14	2,273,594.26	1.2 %
2014/15	2,352,581.49	3.5 %
2015/16	2,122,752.79	−9.8 %
2016/17	2,287,524.14	7.8 %
2017/18	2,296,076.97	0.4 %
2018/19	2,541,000.47	10.7 %
2019/20	3,011,372.13	18.5 %
2020/21	2,800,829.06	−7.0 %

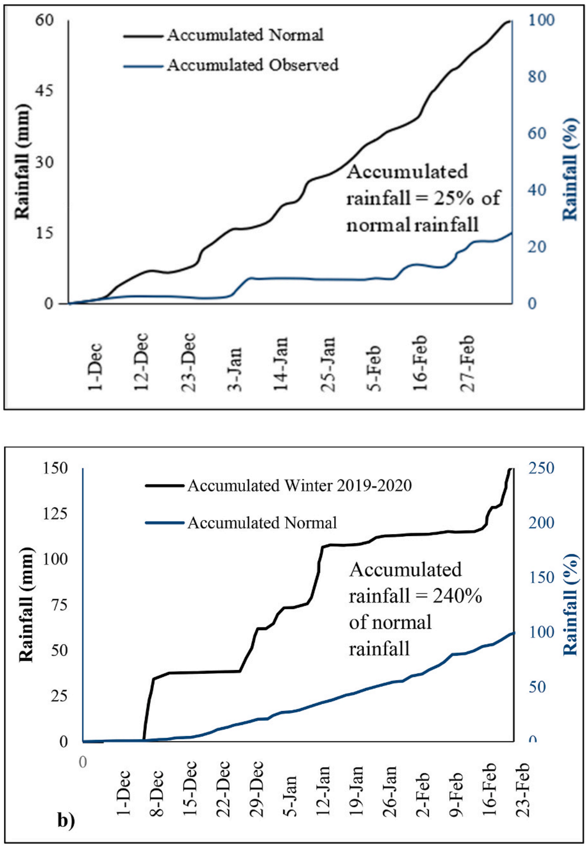

Fig. 11. Accumulated rainfall vs normal rainfall during winter of the year: a) 2020/21 and b) 2019/20 (Data derived from [13].

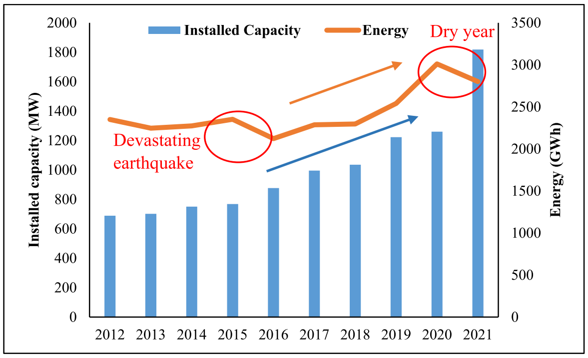

Fig. 12. Anayzing trends in installed hydropower capacity and energy production (Data Source [7,24]).

periods are projected in SSP scenarios across near to far future period (till 2100) [63], while susceptibility to flood events under wetter monsoons has also been highlighted [64]. There is also an increased possibility that some plants, which cannot operate during the dry seasons due to insufficient discharge, may face even worse conditions due to the drying up of rivers, while others may face a change in seasonal and yearly power output. Because of the influence of climate fluctuation on power generation, yearly expenditures might be as high as 0.1 % of GDP on average, and as high as 0.3 % in particularly dry years [65].

Models predict continued increases in extreme rainfall and flooding could further threaten infrastructure and reduce power output. Glacier lake outburst floods may also become more frequent as glacial melt accelerates, damaging projects downstream. Droughts could conversely lower reservoirs and reduce electricity generation during dry seasons. Adaptive strategies like improved flood protection, diversifying energy sources, and forecasting tools will be essential to increase the resiliency of Nepal's hydropower sector in the face of climate change.

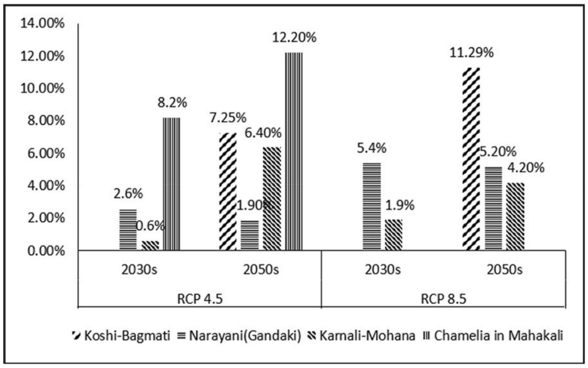

Fig. 13. Projected increase in water availability in major river systems [65].

6.4. Mitigation measures

Certain adaptations must be adopted to mitigate the effects of climate change on hydropower generation. Instead of one large-scale generating unit, numerous small-scale generating units should be used for electricity generation. This will allow incremental hydropower generation in cases of increased runoff and also ensure the minimum design flow to specific turbine units in cases of reduced runoff. Also, turbine technologies that can work efficiently in a variable flow environment as well as with poor quality water should be adopted. Hydropower hydraulic infrastructures such as barrages, dams, weirs, and settling basins must incorporate climate change technical adaptation techniques such as flood attenuation and sediment extraction [66]. Increased seasonality in hydrological series may be accommodated by hydropower facilities with some storage capacity over run-of-river types [57].

7. Conclusions

This review paper analyzed the all-encompassing status of hydropower in the country, from its history to its present state. It also highlights the need for storage-type HPPs, the prospects the sector holds, barriers and restraints faced; and the climate change risks faced by the sector. The major conclusions from this study are summarized as follows:

- The growth of hydropower capacity has been rapid, but our analysis finds a concerning mismatch - spikes in monsoon generation are not matched by growth in dry season supply or export capability. This underscores systemic planning issues that must be addressed.
- The hydropower market's growth has been slow-paced, with only about 4 % of the country's demand being fulfilled by hydropower. Moreover, the energy export is far from its potential. This has resulted in a serious risk of power wastage during monsoon. Plus, market growth has lagged behind capacity expansion. This highlights the need for consumer-focused strategies beyond just adding generation.
- Over-reliance on run-of-river exacerbates seasonal imbalances. However, we found storage projects can also face substantial climate risks from flooding, landslides, and shifting precipitation patterns. This complicates the pursuit of year-round supply through reservoir projects.
- The sector has been facing various socio-cultural, political, economic, technical, and environmental hindrances as major impediments to its development. However, there are brighter prospects with Nepal committing to become a carbon-neutral country by 2045 and planning to establish itself as an energy export hub for South-Asian countries. Realizing this requires both infrastructure and trusted partnerships.
- The hydropower plants are vulnerable to climate change, which is projected to pose a serious risk in the future. The effects of climate change from damage to hydropower plants to fluctuations in yearly production, have been seen in plants across the country. Thus, the focus must shift on resilient hydropower infrastructures, flexibility in plant operation in changing inflows as well as development of seasonal storage plants in the future. Climate impacts are already measurable, but preparedness is lagging. Mainstreaming resilience measures, forecasting tools, and adaptive operations is critical to preserve generation capabilities.

While this study was focused on Nepal, some of the key conclusions may be relevant for other developing countries, particularly in South Asia, that share similar socio-political conditions and topography. The approaches around building climate resilient hydropower infrastructure, expanding energy storage through pumped hydro facilities, and addressing local barriers to development could have broader applicability. However, the specific strategies proposed here were tailored to Nepal and would need to be adjusted to match the unique geographical, governance, and economic contexts of other regions. Comparative research could help identify common challenges as well as localized solutions across countries pursuing hydropower development.

The government should prioritize diplomatic negotiations to establish power purchase agreements with neighboring countries, especially India, to expand cross-border electricity trade. Policies incentivizing domestic consumption during surplus generation periods could encompass discounted pricing for industrial consumers to encourage manufacturing growth. Workforce training programs are needed to develop technical capacity across hydropower professions. Environmental regulations should mandate sustainability standards while streamlining approval processes. Additionally, community-based natural resource management models could enhance local participation and benefit sharing. Transitioning from sole reliance on run-of-river projects requires policies that improve financing terms and risk management for storage-type facilities. Mainstreaming climate resilience planning necessitates stronger coordination between forecasting agencies, project developers and grid operators.

Energy wastage from HPPs can cause losses of billions of dollars. Authorities should focus on the expansion of both the international and national energy markets. India faces its greatest energy need during the monsoon, when Nepal produces the most surplus energy. Diplomatic talks to increase energy exports should be of prime concern. Transboundary transmission lines to support the present Dhalkebur-Muzzaffarpur line should be planned. For domestic market expansion, promotion of electricity consuming devices from household appliances to e-vehicles should be undertaken. A reduction in the electricity tariff and tax for electric appliances can help boost the use of such devices. Along with this, innovative ideas like using electricity to pump water from large and mostly untapped deposits of renewable groundwater in Terai and different river basins in the mid-hills for irrigation, and drinking water, among others, should be explored.

The electricity deficit during the dry seasons cannot be solved unless Nepal focuses on storage-type plants. These plants are also less susceptible to the impacts of climate change. Thus, the private sector, which is more reluctant to invest in storage-type plants should be provided with additional incentives if it builds reservoir projects. Moreover, stakeholders and authorities need to create an entire supportive atmosphere for the success of any hydropower project by spreading social awareness, encouraging a participatory approach, developing effective regulations, addressing corruption, and strengthening institutional capacity.

While this study makes important contributions, there are some inherent limitations. The hydropower data was confined to publicly available sources, which may miss nuances at individual facilities. The analysis relied heavily on retrospective information, while projections of climate impacts and growth involve uncertainty. Furthermore, the proposed strategies require validation through modeling and field studies. Broader participation from policy makers and communities would strengthen the recommendations. Ongoing monitoring and assessment are needed to evaluate the effectiveness of implementation. Further research should aim to address these gaps through more comprehensive data collection, participatory processes, predictive analyses, and pilot testing. However, despite these limitations, this study meaningfully synthesizes current knowledge and offers evidence-based guidance to advance hydropower sustainability in Nepal. While further work remains, this study provides a foundation and direction for continued research into resilient, equitable hydropower development in Nepal and beyond.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article, its supplementary materials as well as the supporting links presented in the manuscript as required.

CRediT authorship contribution statement

Saugat Aryal: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Swastik Ghimire:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Suraj Tiwari:** Writing – review & editing, Visualization, Validation, Methodology. **Yubin Baaniya:** Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Vishnu Prasad Pandey:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

BAU	Business as Usual
COD	Commercial Operation Dates
COP	Conference of Parties

DOED	Department of Electricity Development
GDP	Gross Domestic Product
GLOF	Glacier Lake Outburst Flood
GW	Gigawatts
GWh	Gigawatt hours
HPP	Hydropower projects
IEX	Indian Energy Exchange
INPS	Integrated Nepal Power System
IPPs	Independent Power Producers
LDOF	Landslide Dam Outburst Flood
MHSP	Medium Hydropower Study Project
MIP	Medium Irrigation Project
MoFA	The Ministry of Foreign Affairs
MoFE	The Ministry of Forest and Environment
MW	Megawatts
NEA	Nepal Electricity Authority
PROR	Peaking Run-of-River
ROR	Run-of-River
WECS	Water and Energy Commission Secretariat
WECS/DHM	Water and Energy Commission Secretariat/Department of Hydrology and Meteorology

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e31139.

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