Indonesian Journal of Interdisciplinary Research in Science and Technology (MARCOPOLO)
Vol. 4, No. 3, 2026: 205-226

Harnessing Pakistan's Mega-Hydropower Potential: A Comprehensive Review of Large-Scale Hydroelectric Projects

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A R T I C L E I N F O

Keywords: Hydropower Potential, Large-Scale Hydroelectric Projects, Pakistan Energy Sector

Received : 20, January
Revised : 24, February
Accepted: 28, March

A B S T R A C T

Hydropower is a vital solution for Pakistan to fulfill the escalating need of electricity as the country's energy sector is overwhelmed by large imbalances. This review article is to explore the possible effects of large hydroelectric project(>800MW) for the country. The paper discusses the impact of the large hydroelectric projects on the country's energy issues, supporting sustainable development in Pakistan that has an approximate capacity of 60,000MW untapped, while the country has managed to harness a small fraction of the hydro capacity to utilize its needs for electrical power. Due to economic institutional impediments and technical reasons, Pakistan faces difficulties in harnessing the entirety of the country hydropower potential despite of it possessing an abundance of water resources. The study sightsees the geographical distribution of potential sites focusing on the north of Pakistan that has the majority of the large -capacity hydroelectric potential. The impacts like environmental and socioeconomic of the large hydropower projects are discussed, stating along the emphasis on the environmental impact assessment and mitigation strategies. Furthermore, the policy farmwork and governmental actions are debated in footings of their role in encouraging hydropower development. Also, the involvement of private enterprises is evaluated as one aspect in realizing these hydropower ventures. This review clearly shows Pakistan NEEDS its huge hydropower projects to meet rising energy demand! They're sustainable, dirt cheap, relatively clean energy solutions and there is number a of untapped potential projects in Pakistan. It also presents certain drawbacks and prospects for long-term development. If energy production is to satisfy national demand without doing irreparable harm to the environment or negatively affecting communities, Pakistan should adopt a far more integrated strategy.

INTRODUCTION

The country is suffering from shortages of roughly 6,500MW in output and depends on imported and domestic fossil fuels to power the economy, at a huge expense. With enormous untapped hydropower reserves, Pakistan could alleviate much of this burden. (Sibtain et al., 2021; Wakeel et al., 2016). Hydropower provides clean, renewable, environmentally friendly, secure and cheap electricity to Pakistan and solves the problems the nation is facing in terms of its power supply crisis and energy sector problems. (Sibtain et al., 2021). Hydropower has very great importance for Pakistan and is currently contributing 6599 megawatts of electricity to Pakistan out of a total installed electricity generation capacity of 19,547 megawatts, while its actual potential identified is almost 41,722 megawatts. (Mirza et al., 2007). In truth, considering its potential, hydropower can diversify our country's energy sources. Pakistan's rivers can be harnessed to produce this power. (Bhutto et al., 2012). Pakistan's water resources are characterized by five large river basins with 36 sub-rivers, offering opportunities for developing more hydropower facilities. (Danish et al., 2017). Additionally, there are still large hydroelectric power potential resources that go unexplored, in the north areas of Pakistan. (Butt et al., 2023). For example, one study estimates that the Hunza River itself possesses considerable hydropower potential, with several viable areas to set up hydroelectric facilities. (Butt et al., 2023). In sum, it's vital that Pakistan tap into its vast hydroelectric capacity to surmount its ongoing energy shortages and propel the country towards a sustainable future. Pakistan possesses the geography and ample water sources required to expand the share of clean and renewable energy within its energy mix and decrease reliance on coal, oil and natural gas.

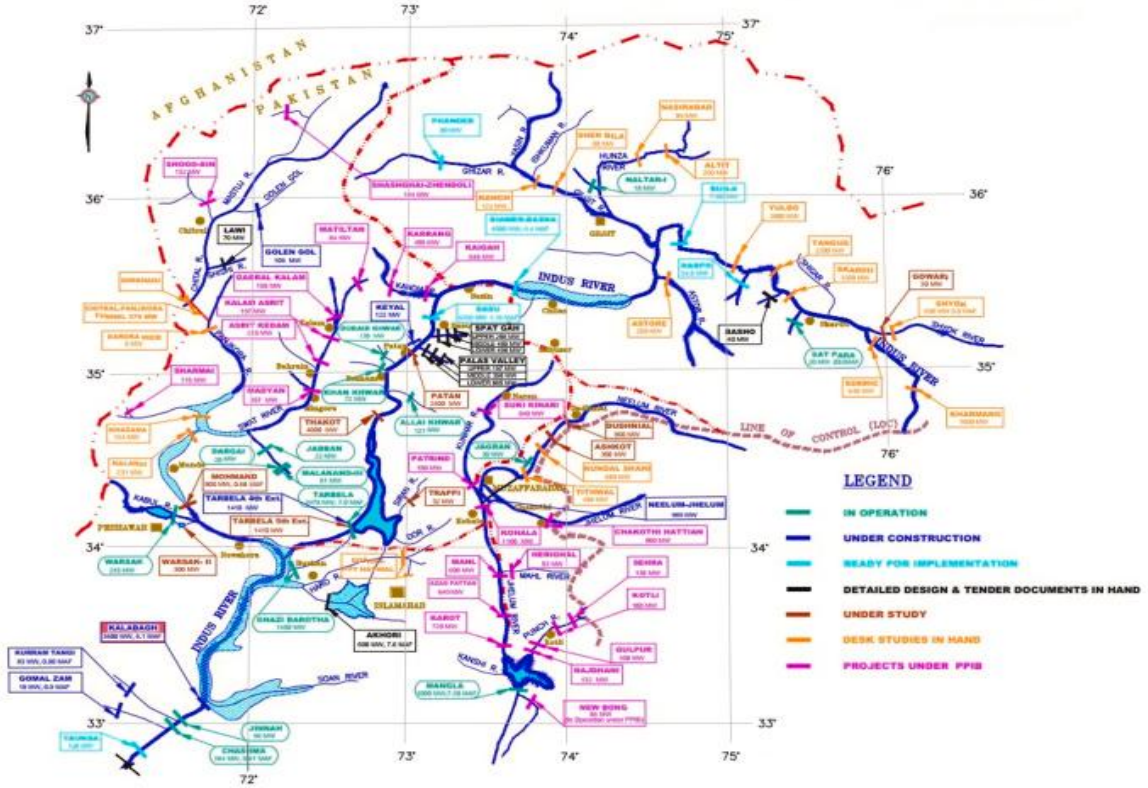

Figure 1: Hydropower potential sites in Pakistan (Sibtain et al.,2021)

LITERATURE REVIEW

Pakistan in 2007 was producing about 19,547MW of power in total, of which 6,599MW comes from hydropower, even though the hydropower potential is thought to be 41,722MW. Mirza et al. (2007) indicate that "the Government of Pakistan has a clear vision for harnessing its hydropower potential and hydropower development plays a prominent role in its national energy strategy." A 1993 study estimated hydropower's maximum potential output at a total of 41,722MW.

The progress of hydroelectric development in Pakistan since the country's independence and along with its most important milestones over time. The Water and Power Development Authority (WAPDA) has been a central player in hydropower development (Butt et al., 2024). Major projects like the Tarbela Dam and Mangla Dam have been instrumental in harnessing Pakistan's hydropower potential.

Interestingly, despite the vast potential, Pakistan has not fully utilized its hydropower resources. The share of hydropower in the country's energy mix has not exceeded 40%, despite the abundance of potential (Ullah et al., 2019). This underutilization is attributed to various factors, including slow progress in the public sector and challenges in attracting private investment (Ullah et al., 2019).

In recent years, there has been a renewed focus on hydropower development in Pakistan. The government has prioritized hydropower generation projects in both public and private sectors (Mirza et al., 2007). Recent power policies have attracted a good response from private entrepreneurs, with several projects in different stages of implementation (Mirza et al., 2007). Additionally, micro-hydropower development in the northern part of the country is benefiting previously under-privileged communities (Mirza et al., 2007).

The future of hydropower in Pakistan looks promising, with ongoing efforts to tap into the country's vast potential. The government's inclusion of Sustainable Development Goals in its national development strategy, making Pakistan the first nation to do so, further underscores the commitment to sustainable energy development (Butt et al., 2024). However, challenges remain, including the need for improved environmental impact assessments, better institutional frameworks, and addressing financial and political barriers to hydropower development (Butt et al., 2024; Ullah et al., 2019).

Pakistan's hydropower development has a rich history, with the sector playing a crucial role in the country's energy mix. The installed electricity generation capacity in Pakistan was about 19,547MW, of which 6599MW comes from hydropower (Mirza et al., 2007), whereas in FY2024 (june2023-june 2024) the total installed capacity as 46.2 GW but the actual generation was only 137 TWh (Renewable First, 2025). By now hydropower provides the majority of the country's electricity, but the actual development of hydroelectric resources is only one-quarter of the potential hydroelectric power of approximately 41,722 MW in Pakistan (Mirza et al., 2007). As a developing country, the Water and Power Development Authority (WAPDA) is often a major shareholder (Butt et

al., 2024). Major projects such as Tarbela Dam and Mangla Dam have contributed greatly to the utilization of Pakistan's hydropower potential. Interestingly, despite the vast potential, Pakistan has not fully utilized its hydropower resources. The share of hydropower in the country's energy mix has not exceeded 40%, despite the abundance of potential (Ullah et al., 2019). This underutilization is attributed to various factors, including slow progress in the public sector and challenges in attracting private investment (Ullah et al., 2019).

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Additionally, micro-hydropower development in the northern part of the country is benefiting previously under-privileged communities (Mirza et al., 2007). Hydropower in Pakistan promises significant potential, as it strives to exploit its natural endowment, being the first country to incorporate SDGs in its national development strategy. (Butt et al., 2024). The necessity for better Environmental Impact Assessments (EIAs), enhanced institutional and governance mechanisms and tackling the finance and political barriers are challenges facing hydropower (Butt et al., 2024; Ullah et al., 2019). The history of hydropower development in Pakistan has been lengthy, with this industry playing a role in the total energy generation in Pakistan. As of 2007, total installed capacity for power generation in Pakistan is 19,547 MW, of which the hydropower sector's contribution is 6,599 MW (Mirza et al., 2007). The country generates a notable portion of its power from hydroelectricity, but it has only achieved around one-tenth of the 41,722MW of its hydropower potential (Mirza et al., 2007). In Pakistan, hydroelectricity's origins date back to its inception. In years past, a number of noteworthy dams, some of which were vital for meeting electricity demands, were built and operated. WAPDA has played the main role in promoting the usage of hydroelectricity since independence. The most noteworthy power generators are the Tarbela Dam, located in the Attock District and Swabi District of Khyber Pakhtunkhwa province, Pakistan, on the Indus River and the Mangla Dam, situated on the Jhelum River, 7 miles west of Mirpur in Azad Kashmir.

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further leverage hydropower, taking full advantage of its substantial resources. Pakistan, the first country ever to align itself with the sustainable development goals set by the United Nations (UN), plans to consider this policy in its national development plans (Butt et al., 2024). Still, further improvements are needed in developing guidelines for environmental risk assessment, implementing clear legal/institutional frameworks and solving existing financing and political hurdles associated with hydropower development (Butt et al., 2024, Ullah et al., 2019).

METHODOLOGY

Technical aspects:

A lot of Pakistan's rivers are extremely steep. Pakistan does have large potential for hydropower. In fact, depending on the power of the river and on what part of the country you decide to harness this power, it can be environmentally friendlier than anything else and definitely cheap as well. (Zaidi &Khan,2018) You can see how such projects can come on the Kunhar river and you don't need to dam off half of Northern Pakistan, either.

Geospatial data techniques along with Digital Elevation Model (DEM) of potential locations is one method used to locate the optimal plant location. Large hydro plants on dam-controlled reservoirs are another form of generation and source for Pakistan due to plentiful hilly terrains allowing for dams and associated electricity needs. However, building these along the border waters of a region with India results in similar ecological problems and friction, the most discussed case being Bursar Hydroelectric Project in Pakistan (Ali et al., 2020).

Small Hydropower (SHP), which typically involves capacities of less than, is a suitable option that Pakistan can explore to further utilize the country's hydroelectric potential. SHPs are appropriate for deployment on rivers and small stream networks, serving local demand and aiding in rural electrification. Improvements and modernizations to existing SHP plants can result in higher efficiencies and greater economic profitability. For Pakistan Energy Mix, an important type of hydro plant known as Pumped Hydro Energy Storge Plants (PHEP) would be an additional treasurer that should be considered. During the intermittences of renewables plants such as solar or wind, Pumped Hydro Energy Plants can store the surplus energy at the time of low -demand periods which could be utilized during the peak time, assisting to stabilise the grid (Ardizzon et al., 2014). Pakistan faces numerous technical challenges in developing the country’s hydropower dams in spite of have the potential. The life span of hydropower projects reservoirs is primary affected by sedimentation issues (Jamali et al., 2014). The Design and operation of hydropower plants in a Competitive Power Market is another big challenge. There a number of unique hurdles such as spatiotemporal hydraulic coupling of cascaded hydropower plants, runoff uncertainties, nonlinear operation constraints, and coordination of multiple time scales that are related to the hydro-dominated electricity market (HEM) (Shen et al., 2022). To overcome these challenges, hydropower enterprises need to improve their generation prediction capabilities, implement multiscale nested operations and bidding strategies, and analyze market demands and

competitors (Shen et al., 2022). The integration of hydropower with other renewable sources and the grid also poses technical challenges. The increasing penetration of new energy power generation requires more stringent auxiliary services from hydropower plants, particularly in terms of automatic generation control (AGC) (Liang et al., 2023). A coordinated optimization control strategy for joint scheduling of hydropower and thermal power AGC units has been proposed to address this issue, aiming to maximize the use of clean energy while reducing overall grid operating costs (Liang et al., 2023).

RESEARCH RESULT AND DISCUSSION

Current Status of Large Hydropower Plants:

Pakistan possesses a number of large-scale dams with generation capacities greater than 800 megawatts (MW) each, such dams are vital for meeting the energy demand of Pakistan and diminishing dependence on non-renewable fuels, like coal, gas or oil.

Located on the Indus River, Pakistan's Tarbela Dam is the country's largest hydroelectric power station with an installed capacity of 3,478 megawatts (Mirza et al., 2007). Its construction was finalized in the 1970s. The dam provides electricity for the country as well as a water supply for the irrigation of farmlands, making it a crucial multipurpose project.

Next is the Ghazi Barotha Hydropower Project, which is also massive with its total of 1,450 MW power capacity (Rauf et al., 2019). The run-of-the river project is located below Tarbela Dam and utilizes the released water from Tarbela to make electricity. Ghazi Barotha is an example of good energy use, as it makes use of water being released to serve agricultural irrigation to create power for the country.

Another major hydropower dam is on the Jhelum River known as the Mangla Dam, the second-largest in Pakistan, with an installed capacity of 1,000 MW (Mirza et al., 2007). Like Tarbela Dam, Mangla Dam has been utilized for flood control, irrigation and power generation purposes.

Although it's not specified, the Neelum-Jhelum Hydroelectric Plant is a large run-of-river power project on the Neelum-Jhelum Rivers in Pakistan, with an installed capacity of 969 MW and it started full operation in 2018.

Pakistan suffered from a major electricity shortage in 2018-201, with urban and rural areas experiencing average blackouts for 10-12 hours and 14-20 hours per day, respectively which reduced to 3-6 hours and 6-12 hours in 2024 (Uddin et al. 2019; Proft ,2026). The demand is for electricity 15,000 MW in 2019 and the projected 2050 electricity demand is 49,078 MW, while the plants at Bargui. Tarbela Dam, Ghazi Barotha and Tarbela IV hydropower complex provide a very small fraction of this enormous supply.

Pakistan's hydropower potential is claimed to be 60,000 MW but it's estimated that only approximately 11% has been utilized, generating 7,228 MW of electric power (as of 2007), though this has expanded recently. The potential hydro resources have been determined as 60,000 MW by authorities and Pakistan Government has utilized only some portion of its hydropower potential, it's said only approximately eleven per cent of total capacity was 7,228 MW.

Large hydropower plants are the largest suppliers of electricity in Pakistan, though other barriers hinder hydropower growth. Ullah et al. (2019) outline a variety of hindrances, including: low private sector involvement in the electricity market, a lack of coordinated planning, financial hurdles and structural institutional barriers. Mitigating such impediments would aid in the progress of small- and large-scale hydropower projects countrywide.

In conclusion, Pakistan's existing hydropower plants above 800 MW, including Tarbela, Ghazi Barotha, Mangla, and Neelum-Jhelum, play a crucial role in the country's energy mix. The above-mentioned hydro power plants play an important role in addressing the country's electricity deficient and the reduction on the dependences on fossil fuels generating greenhouse gases.

Table 1. Operational Hydro Power Potential of Pakistan. WAPDA (2025)

Name of the Hydro Power Dam	Name of the River	Type of the Dam	Commence-ment Year	Completion Year	Power Generation Capacity (MW)	Project Cost in (USD)
Tarbela Dam	Indus	Earth &Rock filled Dam	1968	1976	4888MW	2.85 Billion
Mangla Dam	Jhelum	Embankment	1962	1976	1070 MW	1.5 Billion
Karot Dam	Jhelum	Embankment Rock Filled	2017	2022	720MW	1.72 Billion
Suki Kinari	Kunhar River	Embankment, asphalt concrete face, rock-fill	2017	2024	884MW	2 Billion
Ghazi Barotha	Indus	Run of the River	1999	2004	1450MW	2.1 Billion

Potential Sites for Future Development:

The planned projects for future development along with the regions that have untapped hydropower potential are included: Kunhar river in north of the country has been recognized as a gifted site for a run-of-river hydropower system. Research in which geospatial data techniques and ASTER digital elevation models are included show results of some high-potential sites along the Kunhar river (Zaidi & Khan, 2018). Using GIS and hydrological modelling, 13 proposed sites were analyzed, with sites 13, 4, and 9 emerging as the furthermost promising alternatives for future hydropower development (Butt et al., 2023).

There are various significant potential promising sites that have been identified for future development in Pakistan. The Hunza River in the northern areas of Pakistan offers substantial opportunities for hydropower projects. A study conducted on thirteen proposed sites along the Hunza River revealed that site 13, site 4, and site 9 were the most promising locations for hydropower development (Butt et al., 2023). These locations were selected via the utilization of a MCDA method using variables: Head, Discharge and Locations with limitations in geographical factors. Notably, hydropower potentials can be developed extensively in north areas, but none has been yet exploited as far as we know, according to Butt et al. (2023). This may seem contradictory with growing energy demands for an energy crisis due to increase in population as well as fossil fuels dependence for imported energy as we've seen the case from

a previous study on Pakistan's current scenario for solving its energy crises by using the same power source Ghafoor et al. (2016). Development of hydropower along the northern regions, especially on the Hunza River, may be promising to alleviate the current deficit in Pakistan's energy needs.

Potential opportunities for sustainable power generation are reflected in identified sites. It is necessary for a comprehensive approach to energy development. Other renewable energy sources should also be considered, such as solar, wind, and biomass to form a diverse and sustainable energy mix for Pakistan's future despite hydropower having a significant potential (Farooq & Kumar, 2013; Ghafoor et al., 2016).

Table 2. In progress and Future Hydro Power Potential in Pakistan, WAPDA (2025)

Name of the Hydro Power Dam	Name of the River	Type of the Dam	Projected Commence-ment Year	Projected Completion Year	Power Generation Capacity (MW)	Estimated Cost in (USD)
Azad Pattan	Jhelum	Gravity	--	---	700.7	1.6 Billion
Diamer Basha	Indus	Gravity	2020	2029	4500MW	14 Billion
Kohala	Jhelum	Gravity, Roller-compacted concrete	2019	2025	1124MW	2.4 Billion
Dasu	Indus	Gravity RCC	2020	2027	4320MW	4.278 Billion
Mohmand Dam	Swat	Concrete-faced rock-filled	2019	2026	800MW	1.2 Billion
Bunji	Indus	Gravity RCC		----	7100MW	8.1 Billion

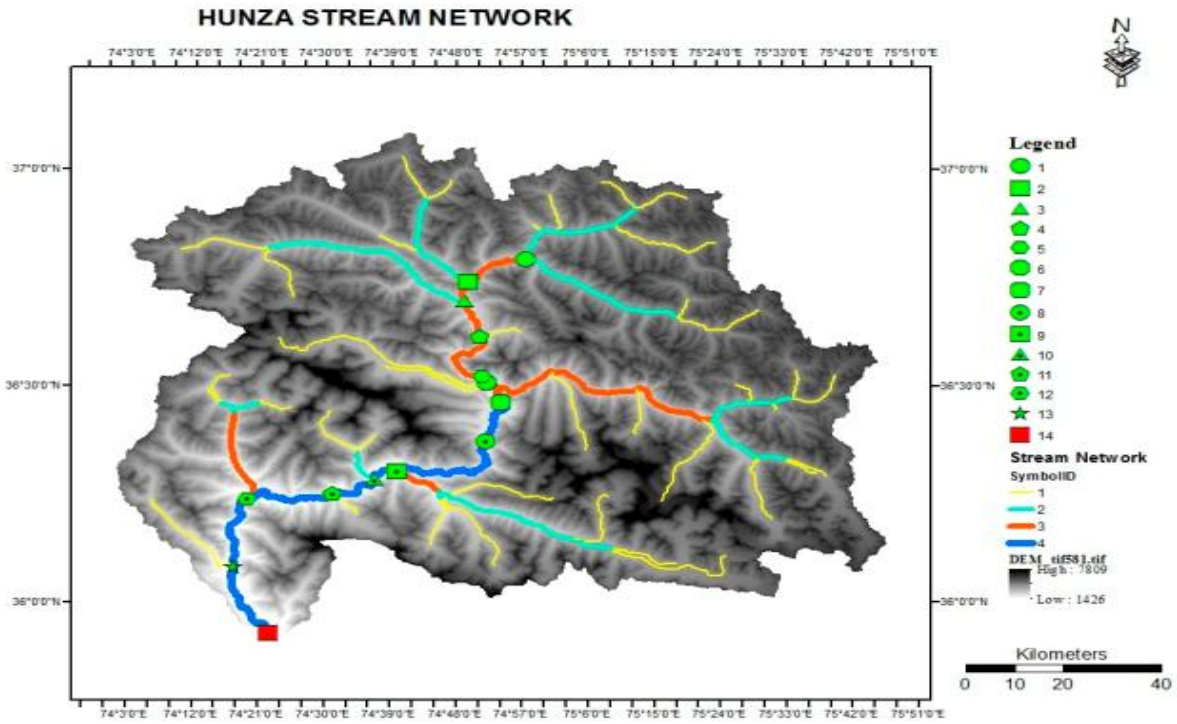

Figure 2 Potential hydro Power Sites in Hunza River Basin. for Future Development (Butt et al.,2023)

Environmental and Social Considerations:

There are significant environmental impacts caused by large hydropower projects which need careful assessment and mitigation strategies. It has become mandatory in Pakistan for implementation of Environmental Impact Assessments (EIAs) for hydropower projects with the country incorporating Sustainable Development Goals into its national development policy (Butt et al., 2024). The environmental impacts of large hydropower projects are multifaceted. Studies have shown that large hydropower projects tend to have a lower degree of environmental impacts compared to many small-scale projects, although there is uncertainty in these results due to data limitations and methodological weaknesses (Bakken et al., 2012). However, large-scale hydropower projects can still strain local infrastructure and reduce access to resources for nearby communities (Mayer et al., 2023). In case of Pakistan different laws such as the Pakistan Environmental protection Agency (EPA) guidelines, the wildlife ordinances along the laws for regulating water flow release are considered for hydro power project construction (Butt et al., 2024). One of the examples is the Gulpur Hydropower Plant Project in Kotli Azad Kashmir for which the EAIs are conducted in Pakistan. The study of the Gulpur Hydropower plant project revealed that had some sensitive areas that would have potential environmental risks reflecting that EIA had a significant impact on the project design (Butt et al., 2024).

Large hydro power projects have serious concerns with respect to relocation issues. The process of the displacement of the natives and the stress on the community of the site are the two primary mechanisms, that are created due to the relocation of the communities (Mayer et al., 2023). The EIA process for the relocation concerns was considered by the land acquisition ACT of 1984 in Pakistan (Butt et al., 2024). It is a requirement for the developers in the United States to implement the mitigation measures, the expenses changing widely across the project classes and the specific measures (Oladosu et al., 2020). Productiveness of these measures however under documented and poorly understood (Trussart et al., 2002). The Potential Effects and compensations of the Gulpur Hydropower project showed the EIA process were solved legally and effectively in Pakistan (Butt et al., 2024). It is proposed that there should be a feasibility for the environmental impact in order to guarantee the maximum mitigation of its negative impacts for all the hydro power project in Pakistan. In Pakistan despite of these efforts there are constrains in the implementation of the EIAs and Mitigations strategies. A comprehensive analysis of the EIA system revealed several areas for improvement, both in the institutional framework and in actual practices (Butt et al., 2024). More than 20% of decision-makers surveyed disagreed with the compliance of the current Institutional Framework with EIA guidelines, and 25% believed that existing guidelines in Pakistan are not aligned with international standards and practices for hydropower (Butt et al., 2024). One of the key issues in Pakistan's EIA process is the limited impact on decision-making due to insufficient technical and financial resources (Butt et al., 2024). To

address this, recommendations include establishing a think tank with experts to meet present and future needs, improving public communication and education about EIAs, and providing international training for officers and decision-makers, particularly those in the Water and Power Development Authority (WAPDA) (Butt et al., 2024). The resettlement of communities affected by hydropower projects remains a complex issue in Pakistan and other developing countries. The case of the Orang Asli community in Malaysia, displaced for the Kelau Dam, illustrates how impact assessments can sometimes serve as "window-dressing" to legitimize the imposition of new institutions that may not adequately address the social security and welfare functions of existing land-based institutions (Nor-Hisham & Ho, 2016). In Pakistan, as in other developing countries, there is a need to recognize that land-based institutions in rural contexts often play a role in providing social security and welfare, rather than functioning solely for economic transfer (Nor-Hisham & Ho, 2016).

Economic factors

Large hydropower projects require significant investment and have long gestation periods, making cost-benefit analysis crucial for decision-making. The analysis must consider various factors, including economic, environmental, and social impacts, as well as potential risks and uncertainties. From an economic perspective, large hydropower projects can provide substantial benefits in terms of electricity generation and energy security.

In Pakistan, for instance, the development of hydropower projects is seen as a way to cope with energy shortfalls and monetary crises (Butt et al., 2023). There are various gifted sites for the development of significant hydropower potential project that have been identified on the Hunza River in the Northern Pakistan. It is necessary for the Cost -benefit analysis (CBA) to account for required early investment for these hydro projects. In the planning and implementation of large-scale hydro projects is played by Global monetary organizations. In the Nam Theun 2 Hydropower Project in Laos, it was proved how these institutions i.e. the Asian Development Banks can impact public involvement, distributional justice and impact procedural (Mirumachi & Torriti, 2012).

Though this study tells the potential constrains i.e the late contribution to the project appraisal stage and the challenges in the calculations of full social and environmental expenses. China has globally constructed hydro project for the promotion of energy infrastructure that would help in economic development in partner countries through the China belt and Road initiative (BRI) (Bega & Lin, 2023). China partnerships with other countries for the construction of large dams specifically has absorbed a large amount of finance in this sector. No doubt these collaborations has reflected positive results; however, it raises some concerns related to a more balanced approach which should show social and environmental improvement. Environmental impacts are a critical consideration in the cost-benefit analysis of large hydropower projects. A study comparing the accumulated environmental impacts of small-scale and large hydropower plants suggests that large projects may have a lower degree of impacts than many small-scale projects (Bakken et al., 2012). However, the lack of precision in data and

weak methodological foundation introduces uncertainty in these results. The study also notes that large hydropower projects may provide additional benefits, such as regulated power, which should be factored into the analysis. In Pakistan, the implementation of Environmental Impact Assessment (EIA) guidelines for hydropower development is an essential aspect of the cost-benefit analysis. While an adequate mechanism is available, and international donors like the Asian Development Bank and World Bank observe the implementation process, there are areas for improvement in both the institutional framework and actual practices (Butt et al., 2024). The study reveals that more than 20% of decision-makers disagree with the compliance of the current Institutional Framework with EIA guidelines, and 25% believe that existing guidelines are not aligned with international standards and practices for hydropower. Funding mechanisms play a crucial role in the viability of large hydropower projects. In some countries, renewable energy projects, including hydropower, benefit from subsidies to increase their financial viability. For example, in Korea, Feed-in-Tariffs (FITs) and the Clean Development Mechanism (CDM) provide additional revenues for renewable projects (Koo, 2017). This study however emphasizes that CDM is inclined to large-scale power projects that reduces greenhouse emissions can create biases in the project selection and implementation. Countries such as Pakistan would benefit from global partnerships like the investment of China in hydropower projects via BRI as it provides vital funding and technical expertise. However, it is essential to carefully calculate the possible restrictions of such arrangements and to make it sure that there is an alignment with national development goals and broader sustainability targets (Bega & Lin, 2023). The equitable distribution of paybacks amongst affected stakeholders within the cost-benefit analysis is similarly necessary for such large projects. In this vein, rather than transferring the reservoir-displaced communities to the passive role of "compensation receivers", the research on Chinese hydropower development advocates for recognising them as formal project stakeholders, (Xia et al., 2018).

Policy and Regulatory Framework

Pakistan has found that hydropower is one way for it to help solve its current energy deficit and make a transition toward renewable energy generation. To encourage hydropower development in Pakistan the government has established several policy initiatives to support this type of renewable energy; however, challenges continue to exist in relation to the regulatory environment. Pakistan was one of those first countries to include the Sustainable Development Goals (SDGs) into their National Development Strategy (Butt et al., 2024). Though, there are several challenges that are faced during the implementation of these policies. The study by Environmental Impact Assessment (EIA) system shows that several areas for improvement of the institutional framework and actual implementation (Butt et al., 2024).After survey, more than 20% of decision-makers were not in the view with the compliance of the present Institutional Framework made with the help of EIA guidelines, whereas 25% believed that current guidelines are not aligned to the international standards and for hydropower in actual practice (Butt et al., 2024). There are both incentives and challenges of the hydropower development

because of a regulatory environment in Pakistan. On the brighter side, the Asian Development Bank and World Bank are donors that observe the EIA implementation process in Pakistan, due to which some level of oversight and support are provided (Butt et al., 2024). Because of inadequate technical and financial resources, the EIA has a limited impact on the decision making (Butt et al., 2024). Although, there are mechanisms for backing sustainable hydropower development, their success is hindered by resource constraints. Through several policy frameworks and institutional measures, the private sector investment is being attracted by the governments (Ullah et al., 2019). As notice the private investment is more focused towards the thermal sector more than hydropower, that reflects that these efforts are less successful (Ullah et al., 2019). This shows that in order to make development in hydropower more attractive to private investors, there is a need of more target incentives and policy adjustment. There are four key discourses on the challenges according to a Q methodology analysis to hydropower development in Pakistan: 1. Less involvement of the private sector in running electricity market operations, 2. Incoherent planning, 3. Financial barriers, and 4. Institutional barriers (Ullah et al., 2019). The complex challenges in the regulatory environment are highlighted in above finding which need to be addressed to promote hydropower development successfully. Hydropower still remains a significant choice for attaining renewable energy targets in Pakistan despite of these barriers. About 12% of the total hydropower potential has been tapped despite Pakistan having a commercially feasible hydropower penitential of about 190GW. (Hussain et al., 2019). Several recommendations have been suggested in order to overcome these barriers and capitalize on the opportunities in hydropower development. The following are to establish think tank with specialists who can meet present-day and future needs, to improve public communication and education about EIA, and as well as to provide international training for officers and decision-makers, such as those in the Water and Power Development Authority (WAPDA) (Butt et al., 2024). Additionally, Political and policy/institutional barriers need to be addressed by the government, that are mainly the most important obstacles to the renewable energy development in Pakistan (Shahzad et al., 2023). A stable Political government, in particular, has been also noted as a serious sub-obstacle that is to be addressed (Shahzad et al., 2023).

Though Pakistan has formed policies to promote hydropower development, considerable barriers within the regulatory framework still exist. The barriers are 1. Inadequate enforcement of EIA guidelines, 2. Low participation of private sector, 3. Inconsistent planning, 4. Various financial and 5. Institutional obstacles. To tackle these issues, A comprehensive plan is needed in order to deal with these issues, in which 1. strengthening of institutional capacity, 2. improving policy alignment, 3. giving targeted rewards for private investment, and 4. ensuring stable political system.

Comparison with other Renewable Energy Sources*:*

Pakistan is currently facing serious energy issues and is in need of finding ways to fill the large gap that exists today between electricity supplied and demanded. Pakistan's energy system depends significantly on foreign fuel

resources, which creates major problems from an economic standpoint and also creates major security concerns. Renewable energy systems including hydroelectric power, solar and wind are all possible solutions for addressing Pakistan's current energy crisis and achieving secure energy supplies. Hydroelectric power has developed into one of the most important renewable energy options for Pakistan. According to Asif (2008) there is over 42GW of hydroelectric power available in Pakistan and only about 6.5GW of it has been utilized thus far.

Hydropower offers several advantages over other renewable sources, including its ability to provide baseload power, flexibility in operation, and additional benefits such as water management, flood control, and irrigation (Killingtveit, 2018). In contrast, there is a vast potential of solar power in Pakistan. In terms of solar resources Pakistan is one of the richest countries that has a yearly global irradiance of 1900–2200 kWh/m² (Asif, 2008). Solar energy can be Specifically for off-grid communities mostly in the northern areas, southern and western deserts Solar power can be an advantage. (Mirza et al., 2003). Though, there are challenges that solar power pose for grid integration and need complementary technologies for effective operation due to its intermittent nature. On the other hand, in Pakistan, Wind energy, is a potential source that is yet to be fully exploited. The coastline in the south and some northern areas offer exceptional wind resources (Mirza et al., 2006). Wind energy may have different applications, it may be harnessed for community-scale, wind farm-scale electricity production, as well as water pumping. After comparison done among these renewable sources, it is seen that hydropower is known for a stable flow of power supporting the integration of variable renewable energy (VRE) sources like wind and solar. Hydropower is a robust and stable source of energy that plays a vital role in allowing the integration of more variable renewables (Jin et al., 2021). It is important for this synergy between variable renewable and hydropower in order to creating a stable and a dependable energy mix in Pakistan. The whole energy system's performance can be significantly enhanced by combining hydropower with wind and solar energy. An example is the research conducted of a wind-solar-hydro hybrid pumped storage (WSHPS) system that indication was that it achieved maximum power generation and reduce curtailment of solar and wind energy in comparison to a wind-solar-hydro hybrid network which did not apply pumped storage (Liu et al., 2024). The synergy between hydropower, wind power, and solar energy can make a big difference in system performance. For instance, research on wind-solar-hydro hybrid pumped storage (WSHPS) system showed that it had higher total power generation and less solar and wind energy curtailment compared to a wind-solar-hydro hybrid system without pumped storage (Liu et al., 2024). The need for close co-ordination in developing an appropriate mix of renewable energy technologies in Pakistan is clearly demonstrated by this example. As regards energy security, hydropower has a particularly important function within Pakistan's overall energy mix. Due to its lack of sufficient fossil fuel resources and poor economic status, Pakistan cannot import substantial amounts of imported fossil fuels at scale (Mirza et al., 2003; Mirza et al., 2006), therefore it is

essential for Pakistan to develop indigenous energy sources such as hydropower. Hydropower can be used to produce low-cost, renewable and predominantly carbon-free electricity. It also offers other advantages which improve energy security. Frequency regulation, voltage support, contingency reserve, load following and black start services provided by hydropower help to improve system reliability and ensure secure supplies of electricity (Killingtveit, 2018).

Future outlook

Pakistan's hydropower resources are a substantial untapped resource for addressing its energy needs, and for reducing dependency on imported fossil fuels. Yet despite this, the process of developing hydropower projects in Pakistan has encountered numerous barriers which have resulted in slow progress toward development. There appear to be some positive trends at present; the government is attempting to expand hydropower production as part of an overall effort to increase the percentage of renewable energy, including hydropower, within the total amount of electric power generated in the country. According to the country's future goals Pakistan is to attain 30% of renewable energy by 2030 (Uddin et al., 2021). This lines up with worldwide trends towards renewable energy sources that will also to meet the growing electricity demands sustainably.

The following are the main factors that are likely to have a influence the hydropower developments in Pakistan:

Increasing energy demand:

It has been noticed that over the past 3 decades Pakistan's energy consumption has shown a surge due to industrialization, different development activities and growth in population (Khalid et al., 2024). The necessity for additional power generation will keep on driving up due to these growing demands.

Economic considerations:

In terms of economic advantages, as compared to thermal power plants, hydropower projects show long-term economic benefits, thermal power plants are financially burdensome and environmentally harmful (Khalid et al., 2024). Development of domestic hydropower project may be encouraged as Pakistan pursues to decrease its vulnerability towards global oil prices as Pakistan pursues to reduce its vulnerability to global oil price volatility, improving its trade deficit.

Environmental concerns:

The necessity to mitigate greenhouse gas emissions and combat climate change was partially driven by the shift towards sustainable energies, including hydropower (Khalid et al., 2024). This will an impact Pakistan's energy policies.

Institutional and policy frameworks:

In order to include private sector in the development of hydro power numerous policy frameworks and institutional guidelines are introduced by the government (Ullah et al., 2019). Though, there has been a limited success on these efforts. Future trends will depend on the success of policy restructurings and incentives to pull private investment in the hydropower sector.

Regional cooperation:

Need of regional collaboration and diplomacy with bordering countries with respect to the hydropower projects due to the transboundary waters of

Pakistan (Sibtain et al., 2021**).** Pakistan despite of having large hydropower potential, the development has been slow. Several hindrances facing the development of the hydroelectric sector in Pakistan are illustrated due to this paradox, such as financial limitations, institutional barriers, and discrepancies in planning (Ullah et al., 2019). Turkey and Pakistan are good examples for comparison. They both depend heavily on importing fossil fuels.

Key Technological Trends Impacting Future Hydro Projects in Pakistan

Based upon the information in the prior section, a number of technology trends will likely influence the construction of new hydroelectric power facilities in Pakistan including:

- Small hydroelectric facilities represent an important area of growth in hydroelectric facility developments (Xu et al., 2014) The smaller size of these developments can make them easier to build and they also have fewer negative environmental impacts than larger dam-based developments. In Pakistan, it is possible that increasing focus on developing small hydroelectric facilities would allow for expansion of electricity generating capacity while at least partially reducing the impediments to development found with the major projects.
- As stated by Butt et al. (2024); Butt et al. (2024), Environmental Impact Assessments (EIAs) and environmental mitigations for hydroelectric power plants are rapidly gaining importance in the development of new hydroelectric plants. In order to secure government approvals and achieve social acceptance of new hydropower facilities in Pakistan, it is highly probable that these new facilities will be required to utilize enhanced EIAs, as well as provide a greater array of environmental protections.
- Better project planning and management techniques can help reduce many of the delay issues and cost overruns associated with many previous hydroelectric facility developments in Pakistan (Batool & Abbas, 2017). These include improved site investigations, time management and financing.
- While not explicitly mentioned for Pakistan, global trends in hydropower technology like digitalization, advanced turbine designs, and pumped storage systems could also impact future projects as the sector evolves (Xu et al., 2014). Adopting these innovations could improve efficiency and grid integration of hydropower in Pakistan's energy mix.

In future hydropower development in Pakistan is probable to be designed by such that will focus towards smaller-scale projects, hybrid projects, environmental protection, optimized project delivery and modernized hydroelectric tech. Embracing these trends could help Pakistan more effectively harness its substantial hydropower potential.

Challenges and opportunities:

Pakistan possesses significant hydropower potential, with an estimated capacity of approximately 41,722MW (Mirza et al., 2007). However, despite this vast potential, the country has only developed about 16% of its hydropower resources, with an installed capacity of 6,599MW (Mirza et al., 2007). This underutilization of hydropower resources can be attributed to several obstacles that hinder large-scale hydropower development in Pakistan.

One of the primary barriers to hydropower development in Pakistan is the lack of a coherent policy framework and institutional arrangements. The slow pace of hydropower development under the public sector has led to various policy initiatives aimed at involving the private sector (Ullah et al., 2019). However, these arrangements have not succeeded in attracting private investment towards hydropower, with investors favouring the thermal sector instead. The political and policy/institutional barriers are identified as the most significant obstacles, with a weight of 0.2281 according to the Pythagorean fuzzy analytic hierarchy process (Shahzad et al., 2023).

Economic and financial constraints also pose significant challenges to large-scale hydropower development in Pakistan. There is a need of long development periods as well as significant financial commitment for hydropower projects. (Sibtain et al., 2021). It is crucial for Pakistan to develop domestic energy resource such as hydropower as the country lack's ability to import fossil fuels due to its sluggish economy (Mirza et al., 2006).

Fiscal constraints and the country dependence on foreign funding may hinder the accomplishment of hydropower projects (Ullah et al., 2019; Sibtain et al., 2021). Likewise, technical Hurdles/Infrastructural hurdle may stymie hydropower expansion in Pakistan. With the passage of time reservoir sedimentation and the effect of seasonal patterns on hydropower generation are prominent weaknesses (Sibtain et al., 2021)

Other factors such as environmental and social concerns which are obstacles to large-scale hydropower development. To certify sustainable development environmental repercussions of large-scale hydropower plants should be carefully addressed (Butt et al., 2024).

These factors contribute to an uncertain investment climate, deterring both domestic and foreign investors from participating in hydropower development.

Despite these challenges, there are several opportunities and potential solutions for promoting large-scale hydropower development in Pakistan. There are substantial opportunities for growth due to the country's untapped hydropower potential and increasing demand-supply gap in the energy sector (Sibtain et al., 2021). Addressing both energy independence and Climate protection efforts, hydropower provides a cost-effective, sustainable, emission free, and reliable source of energy for Pakistan (Sibtain et al., 2021).

A need of Pakistan to from systematic energy policy structure that prioritizes hydropower development to resolve the policy and institutional barriers. Explicit instructions for private sector involvement, expedited approval, and attractive incentives for investors should be included (Ullah et al., 2019). Establishing a think tank with experts who can address present and future challenges in the hydropower sector could help in formulating effective policies and strategies (Butt et al., 2024).

Addressing the financial constraints requires a multi-faceted approach. The Pakistani government could utilize novel forms of funding to provide investors with an incentive to invest in large scale hydropower developments by developing public/private funding models and utilizing green bonds and

climate funds to draw-in international funding. The provision of monetary incentives, including but not limited to tax abatements and subsidies to the private sector may help increase its participation in large scale hydropower developments.

CONCLUSIONS AND RECOMMENDATIONS

Pakistan has considerable unexploited hydropower potential which it can use as much as 83,000MW. Although, for many years, Pakistan has been using only a small percentage of that potential approximately less than one percent of all energy used in the nation comes from hydroelectricity. The fact that Pakistan's current energy shortfall and lack of reliable electric service have resulted in an energy crisis makes its failure to utilize even more of its hydroelectric capacity especially worrisome.

There are several factors preventing the development of large-scale hydroelectric facilities in Pakistan inadequate management, low hydro power contribution to the energy matrix, circular debt, energy insecurity and environmental-social implications associated with large-scale hydropower schemes (as well as their possible transboundary effects) require a comprehensive evaluation of both positive and negative aspects in order to ensure their sustainable nature.

While many obstacles exist in developing Large hydroelectric power in Pakistan, it is still important that the hydroelectric power be developed in order to develop an alternative source of energy to help solve Pakistan's energy crisis and reduce reliance on foreign oil. A multi-faceted strategy needs to be employed to develop large-scale hydroelectric projects. This includes improving project planning processes; incorporating sustainable design principles into hydroelectric engineering; and, promoting greater public participation throughout each phase of development of hydroelectric projects. In addition to creating cost-efficient hydroelectric sites, policymakers need to make certain that all aspects related to protecting the environment are considered when developing new hydroelectric projects and also address concerns of social equity. When the above-mentioned issues have been resolved with regards to development of hydroelectric power, then Pakistan will be able to tap into some of the largest sources of hydroelectric power available anywhere and create a more sustainable and reliable energy future.

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