

Run-of-River Hydropower Systems for Sustainable Energy: A Technical Survey with Global Comparisons and Case Study of the Ghazi Barotha Project

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ABSTRACT

Sustainable and resilient energy sources are essential for developing nations facing persistent power shortages, energy insecurity, water scarcity, and escalating environmental challenges. Because of its affordability, adaptability to a variety of terrains, and minimal environmental impact, run-of-river (RoR) hydropower is an appealing option. A technical review of RoR hydropower is presented in this study, with an emphasis on how it might improve the security of energy and water resources while contributing positively to climate change mitigation. An extensive case study is provided for the Ghazi Barotha Hydropower Project (GBHP) in Pakistan, which has been producing 1,450 MW of electricity since 2004. Its design effectively combines conventional dam-based infrastructure with contemporary RoR concepts. Critical insights into managing seasonal flows, environmental sensitivity, and grid-scale integration across diverse climatic zones can be gained by comparing the Chamera (India), Derwent (UK), and La Grande (Canada) projects. The results highlight how RoR hydropower may play a significant role in clean energy transitions, especially in areas with limited energy and water resources. RoR hydropower systems have the potential to be a key component of national water-energy planning if they are supported by laws, community involvement, and innovation. For stakeholders, engineers, and legislators looking to implement or expand RoR solutions internationally, this poll provides insightful advice.

Keywords: Climate Change, Green Energy Infrastructure, Run-of-River, Renewable Energy, Sustainable Water Use, Water Resource Management.

1. INTRODUCTION

The need for more dependable, sustainable, and clean energy sources is driving a major shift in the world's energy demand. This demand, when combined with ongoing power outages in emerging nations, impedes both social and economic advancement. Hydropower in particular is receiving more attention lately because of its maturity, scalability, and compatibility with carbon neutrality objectives. RoR systems have become a particularly appealing option among hydropower variations because of their faster development time and less environmental effect. With an emphasis on GBHP in Pakistan, this study examines how RoR hydropower can enhance energy security in underdeveloped countries. The study offers insights into global best practices and contextual flexibility by comparing GBHP with similar projects worldwide, as well as providing a thorough analysis of the project.

Severe energy shortages in many emerging countries limit social services, industrial expansion, and overall economic resilience. In Pakistan, dependence on thermal power and antiquated grid infrastructure has contributed to past peak-season electrical demand-supply imbalances of 5,000 MW [1]. In most developing nations, the urban population often relies on fossil-fuel generators

to fill the electricity supply gap left by the national grid, thereby causing a detrimental impact on the climate. In this regard, [2] proposes a potential approach to lower the upfront cost of PV system deployment to around 10% of the original value using the proven model to encourage clean energy generation. To better understand socio-economic and individual factors, [3] gathered a cross-sectional data set to examine household intentions to switch to wind energy and the moderated mediation interactions of the variable load. The goal was to shift to renewable energy sources (RES) to reduce generation costs, conserve natural resources, and protect our ecological system. The article in [4] provides a thorough and accurate explanation of the many defenders and individuals engaged in the global area scenario, reviewing the conceptual model, aims, architecture, potential advantages, and power grid challenges. The cost-benefit analysis of constructing a dam to lessen flood damage, encourage tourism, and improve agricultural production is examined in [5]. This aims to address problems such as pollution, inadequate resource management, climate change, and water degradation.

Decarbonization initiatives throughout the world have stimulated large investments in renewable energy. Despite significant advancements in solar and wind power, hydropower continues to be the world's greatest renewable electricity-producing source. It is a vital component of energy transition plans due to its dependability and storage capacity. The findings of a study in [6] not only clarify the current situation and the future direction of renewable energy adoption, but also highlight the importance of implementing specific laws, making targeted investments, and working together to hasten this worldwide change. The increasing integration of various RES necessitates robust grid stability solutions, as highlighted by a comprehensive review on battery energy storage systems and their role in frequency and voltage regulation

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within high RES penetration power systems, which is presented in [7]. A study presented in [8] on small-scale combined heat and power systems in Iran has extensively utilized techno-econo-enviro simulations with HOMER software to evaluate the integration of various RES like fuel cells, biomass generators, solar cells, and wind turbines for residential applications, often incorporating sensitivity analyses on economic parameters and investigating excess electricity management. By including energy investment, depletion, and saturation dynamics into energy transition scenarios, a work in [9] offers a thorough, open technique for developing a simplified global energy system model intended to quickly assess tradeoffs between energy and climate policy. The study presented in [10], aims to estimate current emissions of NO_x, SO_x, PM_{2.5}, and PM₁₀ from the energy sector and analyze their development trends during the global transition to 100% renewable energy.

Unlike conventional dam-based systems, RoR hydropower systems use the natural flow and reduction in elevation of rivers to produce energy without the need for huge reservoirs. As a result, they cause less disturbance to people and ecosystems and incur lower costs for construction and maintenance. According to [11], a RoR hydropower projects appear more appealing than traditional hydroelectric plants since they might be a more affordable and ecologically friendly option. Their anticipated pattern of energy generation, however, is highly dependent on a number of construction-related factors that require a suitable design utilizing certain models. The current study aims to provide a new analytical method for assessing and optimizing a RoR hydropower facility's performance. The design and optimization of a hybrid RES that supports a RoR micro-hydropower plant by combining solar photovoltaic and wind turbines with battery storage is the main emphasis of the work presented in [12]. The possibility of producing green hydrogen in a RoR hydropower plant is covered in [13]. Although there is no appreciable water buildup at this hydropower facility, there is a chance that limited hydrogen synthesis might occur because of a discrepancy between the timetable, a daily predetermined electricity generation schedule, and the actual water inflows. In order to lessen the negative consequences of climate change, which disturb hydrological cycles and streamflow regimes at the local, regional, and global levels, water storage in dams and controlled flow through ROR hydroelectric systems are essential. A similar study [14] used three general circulation models along with the soil and water assessment tool hydrological model to assess changes in water balance and hydrological extremes in Cambodia's Prek Thnot River Basin. The study evaluated these changes under two different climate change scenarios: RCP2.6 and RCP8.5. Their results highlight how important adaptive water management infrastructure is for mitigating the effects of climate change and guaranteeing water-energy security. Even in situations with low head and restricted water flow, RoR hydropower output may be efficiently captured by examining ramp rates and flow duration characteristics. In [15], the authors evaluate the applicability of 11 statistical distributions for generating flow-duration curves using data from 19 hydrological stations in northwest China. According to the study, the best model for effectively capturing the properties of flow duration across these stations is the log-normal distribution. A model-based control approach for the best asset management of hydroelectric units in RoR hydropower facilities is presented in the study [16]. The goal of the suggested control technique is to minimize component wear during frequency containment reserve provision, improve water flow management, and run the unit as efficiently as possible.

Hydropower has emerged as a key component of national energy strategy and water storage both in developed and underde-

veloped nations. These technologies provide a critical possibility for water storage, a resource necessary for maintaining life, in addition to reducing reliance on fossil fuels. It's critical to acknowledge the significance of water conservation, particularly in light of changing climatic circumstances. Because hydrological signatures are a crucial method for describing basin performance, the study in [17] uses these hydrological signatures to analyze the effects of climate change on Iran's Azarshahr Chay Basin. The need for low-carbon energy growth, the significant potential for hydropower development, and Asia's growing energy demand all suggest that hydropower will play a major role in South Asia's energy future, as noted in [18]. By incorporating hydrogen power into green development methods, a study in [19] presents a novel approach to solving urban energy transitions. In many regions, particularly in Europe, South Asia and Africa, projected needs for irrigation and hydropower exceed what future gray infrastructure might supply. By investigating how RoR hydropower may function as a sustainable link between energy generation and water resource management, the proposed study presented in [20] expands on such worldwide ideas. Its integration has significant ramifications for long-term resilience and environmental harmony in a time of rising water stress and climate unpredictability.

Following are the main study objectives of this article:

- Thorough technical analysis of one of Pakistan's largest RoR plants, the GBHP.
- In depth examination of the turbines, switchyard, power channel, intake structure, and other design elements of GBHP.
- Analyzing operational performance over the previous 20 years using efficiency trends and accessible generating data.
- GBHP's technical setup and site-specific modifications are discussed in relation to the RoR operating philosophy.
- Evaluation of the effects on the environment and society, encompassing ecological balance, water resource management, and resettlement.
- GBHP is compared to other worldwide RoR initiatives including Chamera (India), Derwent (UK), and LaGrande (Canada).
- Details on how GBHP is included into Pakistan's national grid and how it helps close the gap between supply and demand for power.
- Suggestions for improving, growing, and replicating RoR initiatives in other developing nations.
- Talk about issues including climate resiliency, sedimentation, and seasonal flow fluctuation.
- Participation in scholarly and policy debates on the development of sustainable hydropower in South Asia and across the world.

Section 2, presents the RoR technology overview. Section 3, presents the case study of GBHP. Section 4, discusses the environmental and social impact. Section 5 is the conclusion of the study, while Section 6 suggests the opportunities for optimization and future directions.

2. RUN-OF-RIVER HYDROPOWER TECHNOLOGY OVERVIEW

With limited water storage, a RoR hydropower plant uses a river's natural flow and the decrease in elevation (head) to produce energy. Large dams and vast reservoirs are not necessary for RoR plants, unlike traditional reservoir-based hydroelectric systems. Rather, a forebay or surge tank that stabilizes flow and pressure is created by redirecting some of the river's water, usually through an intake weir, into a headrace canal or tunnel.

Water from the forebay travels via a penstock, a high pressure

conduit, and is sent to the powerhouse's hydro turbines. Water's kinetic energy (from velocity) and potential energy (from elevation difference) are translated into mechanical energy as it passes through the turbine. A coupled generator then converts this mechanical energy into electrical energy. The river's biological continuity is preserved by returning the water to the river via a tailrace canal after it passes through the turbine.

Compared to large dam projects, this approach is seen to be more sustainable and environmentally beneficial since it preserves almost natural flow regimes, promotes aquatic life, and prevents substantial land submersion or resettlement. However, RoR systems may necessitate careful seasonal design considerations due to their considerable dependence on river flow fluctuation. Figure 1 displays the schematic diagram for a typical RoR hydropower system.

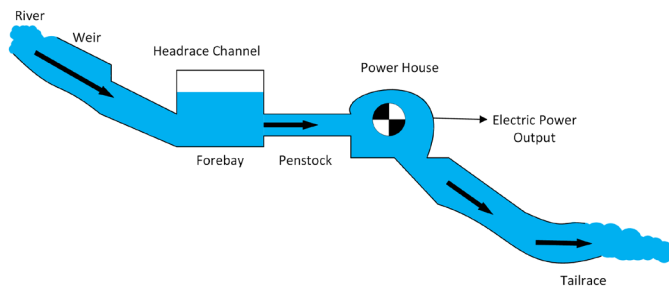


Fig. 1 Schematic diagram of a typical run-of-river hydropower system.

In Figure 1, there is a river flowing from left to right. The weir or intake structure diverts water into the system. Headrace channel stores that water and further conveys water towards the turbine. After the headrace channel, the Forebay tank provides a steady flow and manages pressure for the penstock, where a high-pressure pipe directs water to the turbine. The power house, containing turbines and generators, thus generates electricity, and the tailrace channel returns water to the river downstream. The transmission lines show electricity being transmitted to the grid.

Depending on sediment load, river hydrology, topography elevation (head), and environmental requirements, designs differ greatly. Depending on available head and flow characteristics, typical systems include low-profile diversion weirs for flow capture, power canals or tunnels for water conveyance, and low- to medium-head turbines such as Francis, Kaplan, or cross-flow turbines. Pelton turbines may be used in hilly areas with higher heads. RoR systems' scalability and adaptability make them perfect for integration with smart grid technologies as well as remote or rural locations.

Despite their environmental benefits, such as reduced greenhouse gas emissions, low reservoir-induced displacement, and minimal flooding, RoR systems are sensitive to seasonal river flow variations. Therefore, hydrological feasibility studies, flow-duration curves, and climate-impact assessments are critical to the design and successful operation of such facilities.

Countries like Switzerland, Norway, and India have successfully deployed RoR projects tailored to their river profiles. Technological innovations such as fish-friendly turbines and smart monitoring systems are improving their sustainability.

3. CASE STUDY: GHAZI BAROTHA HYDRO-POWER PROJECT (PAKISTAN)

The GBHP, completed in 2004, was designed to address Pakistan's power deficit by utilizing a significant hydraulic head on the Indus River [21]. Located in northern Pakistan, the GBHP is a strategically significant RoR hydroelectric plant. Using water released from the Tarbela Dam, located upstream on the Indus River, it covers the districts of Haripur and Attock. To efficiently supply high-volume flow to the powerhouse at Barotha, the diverted water travels via a 52-kilometer concrete-lined power conduit, one of the longest of its type in Asia.

The GBHP was created as part of a larger strategy to lessen Pakistan's reliance on imported fossil fuels and increase the country's capability for renewable energy. The Ghazi barrage controls the Indus River's flow diversion and guarantees a steady water supply to the infrastructure downstream. The five generating units that make up the Barotha power complex are located in a state-of-the-art turbine hall, connected to a sizable switchyard, enabling efficient evacuation of electricity to the national grid.

Because of its high energy conversion efficiency, low environmental impact [22], and its reliance on no large storage reservoir, this project is regarded as a model for sustainable hydropower in South Asia.

3.1 Design and Technical Specifications

The low head (76.8 ft) high flow hydraulic design of the GBHP is geared to maximize energy extraction from the flow volume discharged by Tarbela [23-24]. The powerhouse has the following:

- Five Francis turbines having a rated capacity of 290 MW each, oriented vertically.
- With 1,450 MW of installed capacity, the average yearly energy output is around 6.6 billion kWh.
- Synchronous generators are directly connected to turbines, which are made to produce steady output even in the presence of fluctuating flow.
- Water that is transported through the power channel with a discharge capacity of around 1,600 m³/s powers the system, which runs under a net head of 69 feet (21 meters).
- For long distance transmission to be efficient, a step up substation raises the voltage.
- Real time monitoring and automated control of generation, flow regulation, and grid integration are guaranteed by a Supervisory Control and Data Acquisition (SCADA) system.

The GBHP infrastructure diagram is shown in Figure 2.

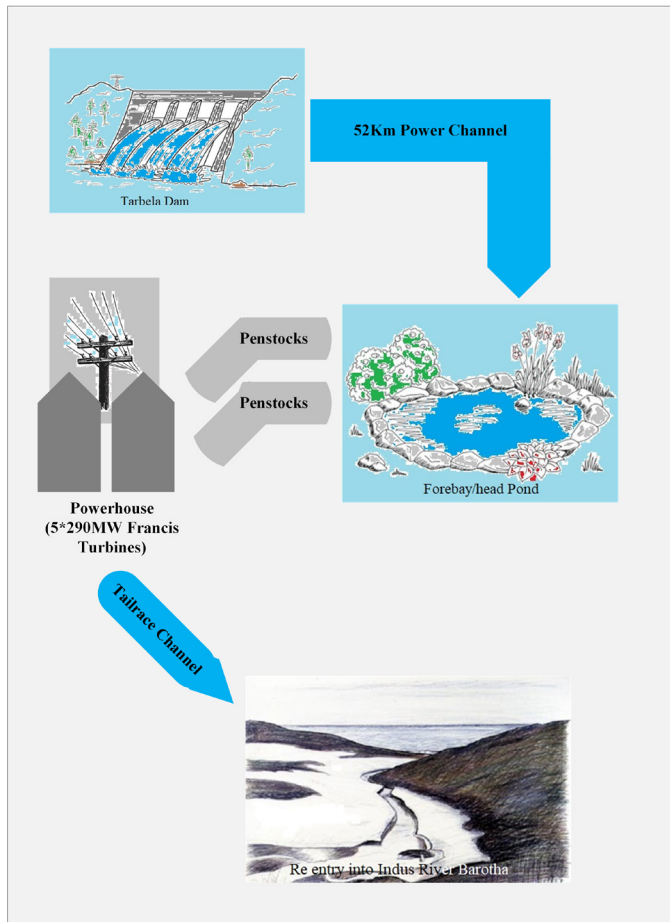


Fig. 2 Ghazi Barotha Hydropower Project infrastructure.

The key specifications of GBHP are tabulated below in Table 1, for the quick understanding of the reader.

Table 1 Key technical specifications of the Ghazi Barotha Hydropower Project.

Parameter	Specification
Project Type	Run-of-River Hydropower
Location	Ghazi (Haripur) and Barotha (Attock), Pakistan
Commissioning Year	2004
Installed Capacity	1450 MW (5*290 WM)
Turbine Type	Vertical Francis Turbines
Water Source	Indus River via Tarbela Dam
Power Channel Length	52 km
Barrage Type	Concrete Weir at Ghazi
Net Head	76 meters (approx.)
Discharge Capacity	1600 cubic meters per second (approx.)
Annual Generation	6.6 billion KWh
Powerhouse Components	5 Generating Units, Control Room, Switchyard
Transmission	500kV lines to National Grid
Re-entry Point	Indus River at Barotha

The GBHP has continuously generated electricity since it began operations in 2004, averaging 6.6 billion kWh per year. It is an essential component of Pakistan’s national electricity supply due to its substantial output and good operating availability.

Sediment buildup, typical turbine wear and tear, and seasonal variations in water flow are some of the persistent issues facing the GBHP functioning. Recent improvements have been made to improve performance and solve certain problems. These enhancements include the use of predictive maintenance tools to anticipate and prevent equipment failures, the installation of more efficient intake screening systems to reduce sedimentation, and the integration of a SCADA system for improved monitoring and control. The map presenting the layout and location of GBHP is depicted in Figure 3.

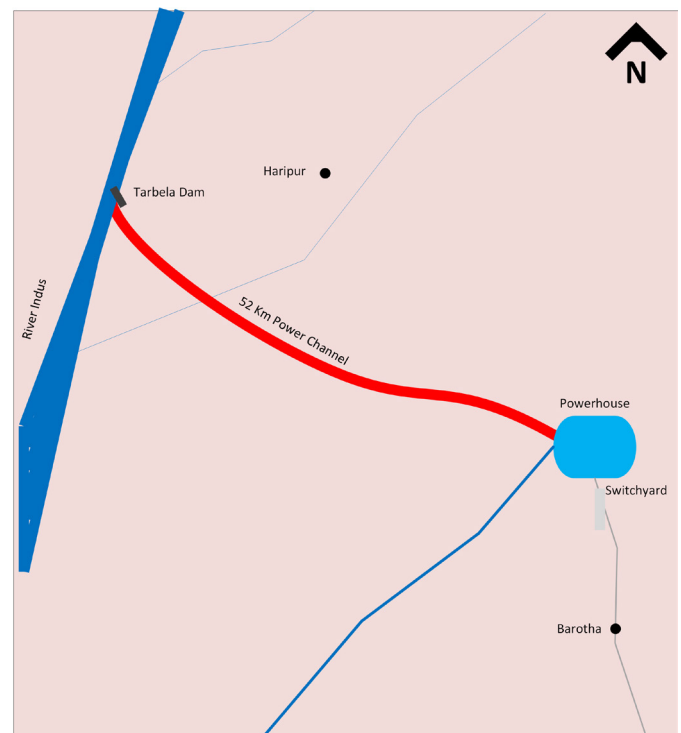


Fig. 3 Map showing layout and location of the Ghazi Barotha Hydropower Project.

3.2 Comparative Analysis with Global Run-of-River Projects

It is helpful to compare the GBHP with other RoR projects carried out worldwide to better understand its technical efficiency, design philosophy, and operational sustainability. Projects like the Derwent Hydroelectric Scheme (UK), Chamara Hydropower Plant (India), and La Grande Complex (Canada) set standards for energy production, environmental integration, socioeconomic effect, and regional adaptability. In light of global RoR best practices, this comparison study emphasizes GBHP’s advantages and disadvantages while highlighting areas for possible improvement and lessons gained. It is important to note that this comparative assessment is qualitative rather than capacity-normalized; the selected international projects are included to illustrate diverse hydrological conditions, design principles, and environmental integration strategies rather than for direct scale comparison.

3.2.1 Chamera (India) Design and Seasonal Flow Handling

The Chamera Hydroelectric Project is a well-known RoR project situated on the Ravi River in the northern Indian state of Himachal Pradesh [25-26]. It was created and is administered by the National Hydroelectric Power Corporation of India. The project is a vital component of India’s Northern Regional Grid and was constructed in three stages: Chamera I (540 MW), Chamera II (300 MW), and Chamera III (231 MW).

The Chamera system uses pondage to store water for peaking power generation during times of high demand, in contrast to the GBHP, which is completely RoR with no active storage. The Chamera project has more operational flexibility to this medium head, high variability flow arrangement, particularly when it comes to handling the monsoon season and protracted dry spells that are common in the Indian subcontinent.

The project’s powerhouse is subterranean to reduce environmental disturbance, and Francis turbines, appropriate for medium-head operations (Chamera I runs under a net head of around 139 meters), are used. The pondage system guarantees limited but consistent generation during low-flow months and helps reduce water spillage during peak monsoon flows, which vary widely by season. Because of these features, Chamera is a good example to study adaptive RoR architecture in areas with significant hydrological seasonality. The schematic block diagram of Chamera hydropower project is shown in Figure 4.

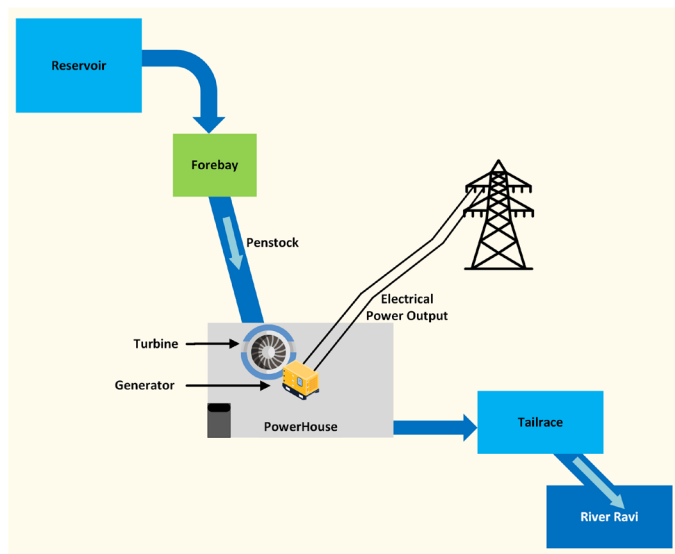


Fig. 4 Chamera Hydroelectric Project schematic diagram.

Chamera’s performance also illustrates the successful integration of flood management, power generation, and grid stability, all within a RoR framework. It provides an effective reference for countries like Pakistan in optimizing RoR design for seasonal and topographical challenges.

3.2.2 Derwent (UK) Environmental Integration and Low Impact Design

Another well-known example of a small-scale RoR project that strikes a balance between energy generation and rigorous environmental and historic protection measures is the Derwent Hydroelectric Scheme, which is situated in the Lake District of Cumbria, United Kingdom [27-28]. The plan, which is run by United

Utilities and backed by regional alliances, shows how low-head hydro systems can be installed with little disturbance in environmentally delicate and popular tourist areas.

Depending on the site characteristics, the Derwent system is made up of a number of micro to small hydropower facilities that use Kaplan turbines and Archimedean screws. These technologies are recommended because they are suited for rivers with high biodiversity and protected species like otters and Atlantic salmon, since they are fish-friendly and sediment-tolerant. Aesthetic integration with the natural landscape, local wildlife corridors, and river morphology preservation are given top priority in the project’s design, as required by EU Water Framework Directive and UK environmental legislation.

Although Derwent is not intended for grid-scale supply, its installed capacity of less than 5 MW helps to improve local energy security, reduce carbon emissions, and generate electricity in a decentralized manner. Its flow-through design permits efficient power generation at times of heavy rainfall with little disruption to the natural river dynamics.

Derwent’s case is a valuable counterpoint to large-scale schemes like Ghazi Barotha, offering insights into low-impact RoR engineering, environmental stewardship, and community-centric hydro planning. Figure 5 illustrates a spatial representation of a RoR hydropower configuration, adapted here to reflect the design principles seen in the Derwent Hydroelectric Project. The Derwent system, with its small-scale infrastructure and minimal visual intrusion, exemplifies environmental integration through careful siting, fish-friendly turbines, and ecological flow (e-flow) maintenance. This layout underscores the project’s commitment to low-impact design in alignment with the landscape and aquatic ecology.

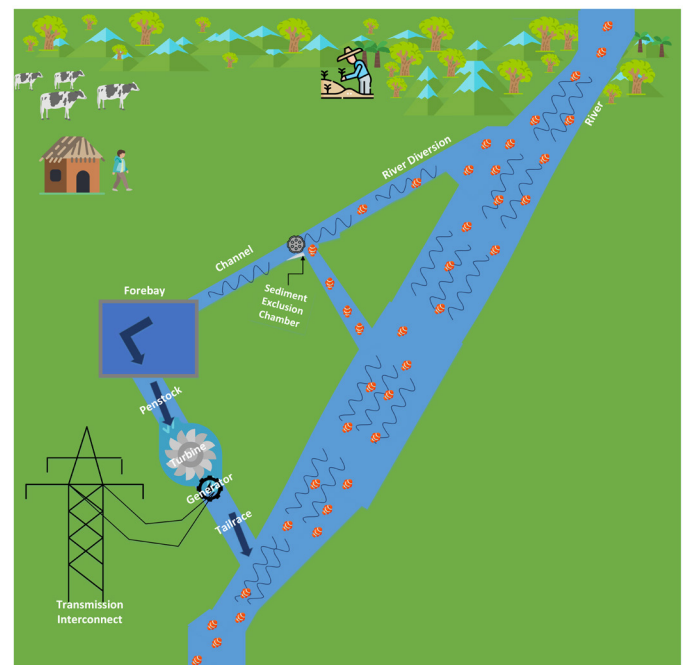


Fig. 5 Schematic representation of the Derwent Hydroelectric Project layout highlighting environmentally integrated, low-impact design features.

3.2.3 La Grande Complex (Canada) High Latitude RoR Integration and Grid Scaling

One of the largest and most ambitious hydroelectric networks in the world is the La Grande Hydroelectric Complex, located in northern Quebec, Canada [29-31]. This system, owned and maintained by Hydro Québec, combines RoR and storage-based systems in a large, cold-region water basin. The project, which spans many rivers, notably the La Grande and Eastmain Rivers, supplies over 40,000 MW of energy to Quebec and portions of the north-eastern United States.

Some subprojects inside this large system, such as La Grande-1 (LG-1), are classic RoR plants. With a 1,436 MW capacity, LG-1 runs in a low-head (~27 m) yet high flow arrangement, pushing water straight through turbines with little storage. This configuration enables efficient generation of base-load energy, especially during seasons when high flow rates are driven by melting snow. Figure 6 illustrates a conceptual layout of the La Grande Hydroelectric Complex in Canada, emphasizing the integration of high-latitude RoR units along the La Grande River. The simplified schematic highlights both major dam-based stations and intermediate RoR nodes, which work in coordination to harness energy in a cold climate environment. This configuration exemplifies hybrid hydro schemes in northern latitudes where seasonal flow variation and ecological preservation are crucial design parameters.

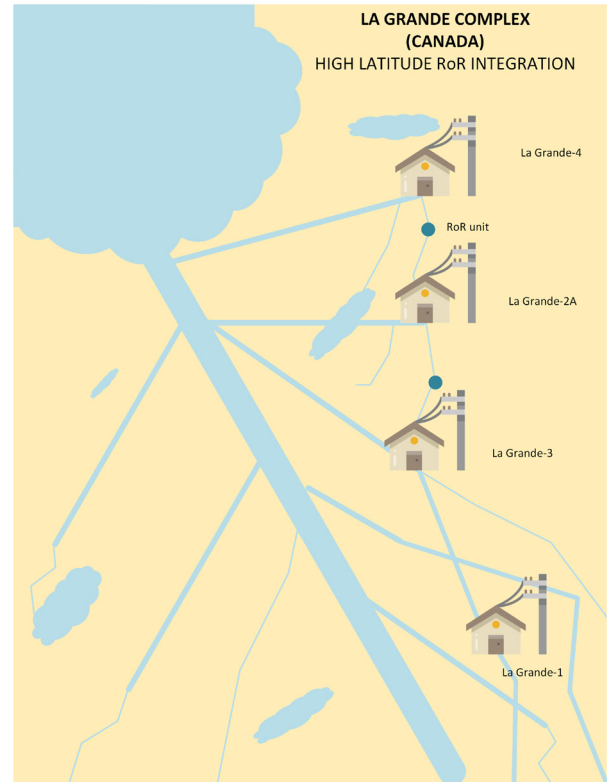


Fig. 6 Simplified schematic of the La Grande Complex showing high-latitude run-of-river integration along the La Grande River in Canada.

With connections spanning more than 1,000 kilometers via 735 kV HVDC lines, a grid-scaling achievement, the La Grande Complex serves as an example of how RoR projects can be integrated into high-voltage, long-distance transmission networks. Additionally, the development has established international standards for responsible hydro development by being a pioneer in environmental compensation techniques, including sedimentation management, fish habitat relocation, and discussions with indigenous communities.

This case underscores the potential of RoR systems at scale, especially when integrated into a broader cascade or hybrid hydro system. The engineering, environmental, and socio-economic frameworks established in La Grande provide actionable lessons for scaling projects like Ghazi Barotha while addressing regional challenges. The Comparative analysis of GBHP, Chamera, Derwent RoR, and La Grande Complex projects is given in Table 2.

Table 2 Comparative performance metrics of Ghazi Barotha Hydropower Project, Chamera, Derwent run-of-river and La Grande Complex projects.

Parameter	GBHP (Pakistan)	Chamera (India)	Derwent (UK)	La Grande Complex (Canada)
Type	Run-of-River (Low head)	Run-of-River (Medium head)	Run-of-River (Weir head)	Run-of-River with Storage
Installed Capacity (MW)	1540 MW	540 MW (Combined Storage)	4 MW	>16,000 MW (total complex)
Turbine Type	Francis	Francis/Kaplan	Kaplan	Francis/Kaplan
Water Source	Indus River	Ravi River	River Derwent	La Grande River
Head	76 meters	80-130 meters	Low (<10 meters)	Varies widely (upto 140 meters)
Annual Generation (GWh)	660 GWh	1200 GWh	12 GWh	>80,000 GWh
Operational Since	2004	1994	1950-1960	1970-1990
Key Features	Long Power Channel (52 km)	Reservoir Regulation Support	Heritage and Flood Control	Large Scale Integrated System
Seasonal Management	Depends on Tarbela Releases	Monsoon Surge Handling	Minimal Storage, Run of Flow	Regulated via Reservoirs
Environmental Design	Minimal Ecological Impact	Reservoir with RoR Benefits	Small Footprint	Large area, Mitigation Plans

4. ENVIRONMENTAL AND SOCIAL IMPACTS

This study relies on existing secondary climate and hydrological research related to the Indus Basin and Tarbela-regulated flows, as long-term climate projections and basin-scale modeling are beyond the scope of this technical survey. Emphasizing designs that match the particular setting, meaningfully involving local people, and establishing robust monitoring mechanisms are essential to ensure that initiatives continue to function successfully and sustain public support over time.

4.1 Ecological Impact of Run-of-River Systems

Because of their smaller reservoirs, less land submersion, and lower greenhouse gas emissions, RoR hydropower projects are frequently seen as environmentally superior to huge storage-based dams. By diverting only a part of the river flow, RoR systems such as the GBHP mostly preserve the natural hydrological cycle. This often permits sediment and nutrient continuity downstream, decreases thermal stratification, and lessens habitat fragmentation.

There are, nonetheless, environmental tradeoffs. If flow diversion is not appropriately matched with e-flow needs, it may have an effect on riverine ecosystems. Infrastructure like fish bypasses and sediment flushing systems are part of GBHP, but regular assessment is necessary to determine their long-term efficacy. Adaptive flow management techniques are necessary to maintain biodiversity during crucial aquatic species breeding seasons due to seasonal flow fluctuation, especially in the Indus River basin.

Environmental flow modeling, thorough Environmental Impact Assessments, and ongoing ecological monitoring are crucial components of RoR project design. The necessity of sediment management and fish migration concerns, particularly in rivers that sustain migratory species, is highlighted by lessons learned from projects like Chamera, Derwent, and La Grande Complex. Figure 7 highlights the main ecological effects and represents why RoR designs are becoming more and more popular in areas with strict environmental regulations.

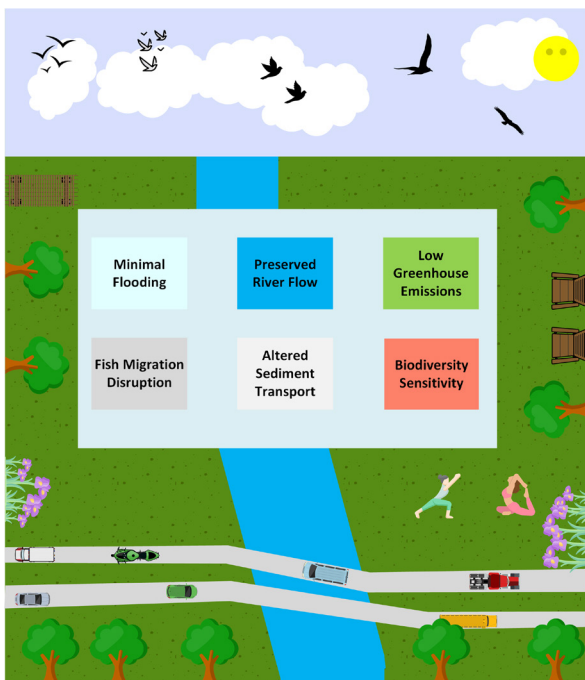


Fig. 7 Key ecological impacts of run-of-river hydro-power systems.

4.2 Rehabilitation and Displacement in the Community

Compared to conventional reservoir-based dams, the GBHP requires less displacement, which is one of its sociopolitical advantages. In cooperation with foreign development partners like the World Bank, a small number of homes were moved, and they were administered in accordance with Pakistan's national resettlement rules.

In addition to monetary compensation, resettlement packages included houses, utilities, and land-for-land arrangements. Programs for vocational training and preferred hiring during the building period gave the local economy short-term benefits. Long-term community well-being was also enhanced by the construction or renovation of social infrastructure in the project's immediate neighborhood, such as roads, schools, and health facilities.

Notwithstanding these initiatives, some research indicates that the degree to which livelihoods are restored after relocation may differ depending on how well projects are carried out and local government is maintained. As a best practice, ongoing stakeholder participation through public hearings and grievance resolution procedures is being used in projects of a similar nature.

4.3 Water Management and Long-Term Development

The socioeconomic development of Attock, Haripur, and the surrounding areas has been greatly aided by the GBHP. The expansion of textile factories, medium-sized industrial facilities, and agro-based sectors has all benefited directly from the consistent supply of energy. Additionally, more regular irrigation cycles have increased agricultural yield due to better downstream water control.

By serving as a buffer between the lower Indus area and the upstream Tarbela Dam, the GBHP promotes integrated water resource management from a basin-wide standpoint. It aids in balancing the distribution of water for agriculture, urban requirements, and power generation. Because of Pakistan's susceptibility to floods and water scarcity, RoR facilities like GBHP are strategically positioned within the river cascade system to improve water usage efficiency without posing significant upstream storage difficulties.

RoR projects provide reduced environmental threats, such as methane emissions and landslide induction, which are frequently linked to large reservoirs in the context of climate resilience. To predict changes in flow regimes and sediment load brought on by glacier melt and shifting precipitation patterns in the Indus watershed, hydrological planning must still take climate models into account.

5. CONCLUSION

Both inside Pakistan and in the larger framework of worldwide RoR infrastructure, the GBHP is a model for sustainable hydropower development. It differs from many conventional large-scale dam projects due to its advantageous socioeconomic effects, strong engineering design, strategic position, and little ecological disturbance. GBHP strikes an impressive balance between energy efficiency and environmental stewardship by using a low head, high flow arrangement and redirecting water from the Indus River through a regulated channel.

The engineering and operational significance of GBHP is further confirmed by comparison with global RoR projects such as Chamera, Derwent, and La Grande Complex. GBHP is a model for future hydropower development in emerging economies, as it

adheres to many of the world's finest standards for managing seasonal flows, ecological monitoring, and community involvement.

By reducing dependency on thermal power and advancing national objectives for renewable integration, the project makes a substantial contribution to Pakistan's energy portfolio. Although long-term monitoring of biodiversity, sediment movement, and climatic consequences is still essential, it avoids significant ecological and resettlement hazards. Socioeconomically, GBHP has stimulated regional growth, enhanced infrastructure, and generated job opportunities, demonstrating that, with careful planning, hydropower can provide more than kilowatt-hours.

This study also aligns with several United Nations Sustainable Development Goals (SDGs). RoR hydropower directly supports SDG 7 (Affordable and Clean Energy) through clean, low-emission electricity generation, and contributes to SDG 6 (Clean Water and Sanitation) by utilizing controlled canal flows with minimal storage losses. Furthermore, its reduced carbon footprint advances SDG 13 (Climate Action), while the development of reliable hydropower infrastructure reflects SDG 9 (Industry, Innovation, and Infrastructure). Owing to its lower ecological and social impact compared to large-reservoir systems, RoR hydropower also supports SDG 11 (Sustainable Cities and Communities).

The following are the key takeaways from the proposed study:

- GBHP is an excellent example of a Run-of-River hydropower scheme that has a low environmental effect and a large capacity (1,450 MW).
- It preserves biological flow by effectively using water from Tarbela Dam without building a sizable reservoir.
- Francis turbines and a 52 km power channel are part of the technological design, which guarantees peak performance during times of strong flow.
- In addition to providing a reproducible framework for relocation and livelihood restoration, GBHP shows little community displacement.
- It has made a substantial contribution to the socioeconomic growth of the region and Pakistan's energy security.
- GBHP is in line with global best practices for hydropower engineering, according to comparative analysis.

6. OPPORTUNITIES FOR OPTIMIZATION AND FUTURE DIRECTIONS

Even though the GBHP is an established, operationally successful project, there is still significant room for technical improvements, operational expansion, and wider replication. GBHP and related RoR systems may use a range of sustainable optimization techniques as hydropower infrastructure worldwide moves into a new stage of digital transformation and climate adaptation.

6.1 Digital Technology Integration for Intelligent Operations

The plant's situational awareness may be significantly improved by integrating contemporary digital technologies, including real-time analytics platforms, Internet of Things sensors, and SCADA systems. These technologies facilitate:

- Electrical output, flow rates, and turbine efficiency are continuously monitored.
- Sensor-based surveillance to discover faults early and set off alarms.
- Predictive load needs are used to optimize grid dispatch and

water consumption.

Such technologies provide real-time reactivity to flow variations for a high-flow, low-head system like GBHP, enhancing energy conversion efficiency and preserving equipment longevity.

6.2 AI-Powered Predictive Maintenance and Forecasting

Climate change-induced hydrological variability has a growing impact on river-fed RoR systems. In order to lessen this, GBHP could profit from:

- Hydrological forecasting based on machine learning, which enables operational tactics to be dynamically adjusted throughout periods of drought or flooding.
- Predictive maintenance algorithms schedule preventive repairs by examining wear-and-tear data from turbines and auxiliary systems as well as past performance.
- Modeling of seasonal performance, particularly using knowledge from global initiatives such as Chamera's approach to managing the monsoon.

In the face of unpredictable river flow regimes, these forecasting technologies assist in preserving grid dependability, saving downtime, and increasing equipment longevity.

6.3 Improving the Water Energy Nexus with Integrated Administration

GBHP is a component of the intricate Indus River basin, which is linked to water demands for industry, municipalities, and agriculture. Future enhancements ought to consist of:

- Using river basin simulation models, water release plans may be matched with ecological and agricultural goals.
- Cooperation to create a multifunctional water-energy governance framework with upstream and downstream stakeholders.

In this regard, Canada's La Grande Complex, which combines electricity generation with aquatic ecology, indigenous rights, and long-term basin sustainability, is a model.

6.4 Enhancement of Socioeconomic Conditions via Community Energy Initiatives

The function of GBHP may be extended to include local empowerment in addition to national grid supply:

- Creating training programs for renewable energy operations or mini-grid extensions run by the community.
- Collaborating with academic institutions on research projects and enhancing their energy and environmental monitoring capabilities.

With this strategy, local communities are guaranteed to go from being passive recipients of hydropower-led development to active participants.

6.5 Green finance and policy innovation

To ensure the long-term sustainability of RoR systems like GBHP, policymakers must:

- Power purchase agreements should be updated to account for performance-based incentives and seasonal fluctuations.
- Obtaining green funding for modernization and digitization initiatives from development banks or international climate funds.
- Fostering cross-border research partnerships and raising Pakistan's profile in global water energy policy forums by utilizing the GBHP paradigm.

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