

## *The role of Hydropower in the transition to a low-carbon future*

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### **Introduction**

The transition to a low-carbon economy is imperative in addressing climate change and reducing dependence on fossil fuels. Renewable energy sources, including solar, wind, biomass, geothermal, and hydropower, are essential in achieving carbon neutrality. Among these, hydropower has historically been a dominant source of renewable energy, contributing approximately 16% of global electricity generation. It provides base-load and peak-load electricity, offering storage and grid stability advantages that complement

intermittent renewable energy sources. Despite its advantages, hydropower faces environmental concerns such as habitat destruction, fish migration disruption, and greenhouse gas emissions from reservoirs. Additionally, climate change affects water availability, impacting hydropower reliability. This review examines the role of hydropower in the low-carbon energy transition, its environmental and economic impacts, technological advancements, and future challenges and opportunities.

### **HYDROPOWER AS A RENEWABLE ENERGY SOURCE**

#### **1. Types of Hydropower Plants**

Hydropower plants are classified into various categories based on their size, operational mode, and design:

- **Run-of-River Hydropower**

Uses the natural flow of a river without significant water storage.  
Has minimal environmental impact.

Suitable for regions with consistent water flow.

- **Reservoir-Based Hydropower**

Stores water in large reservoirs.  
Provides regulated power generation.  
Ensures energy security by controlling water release.

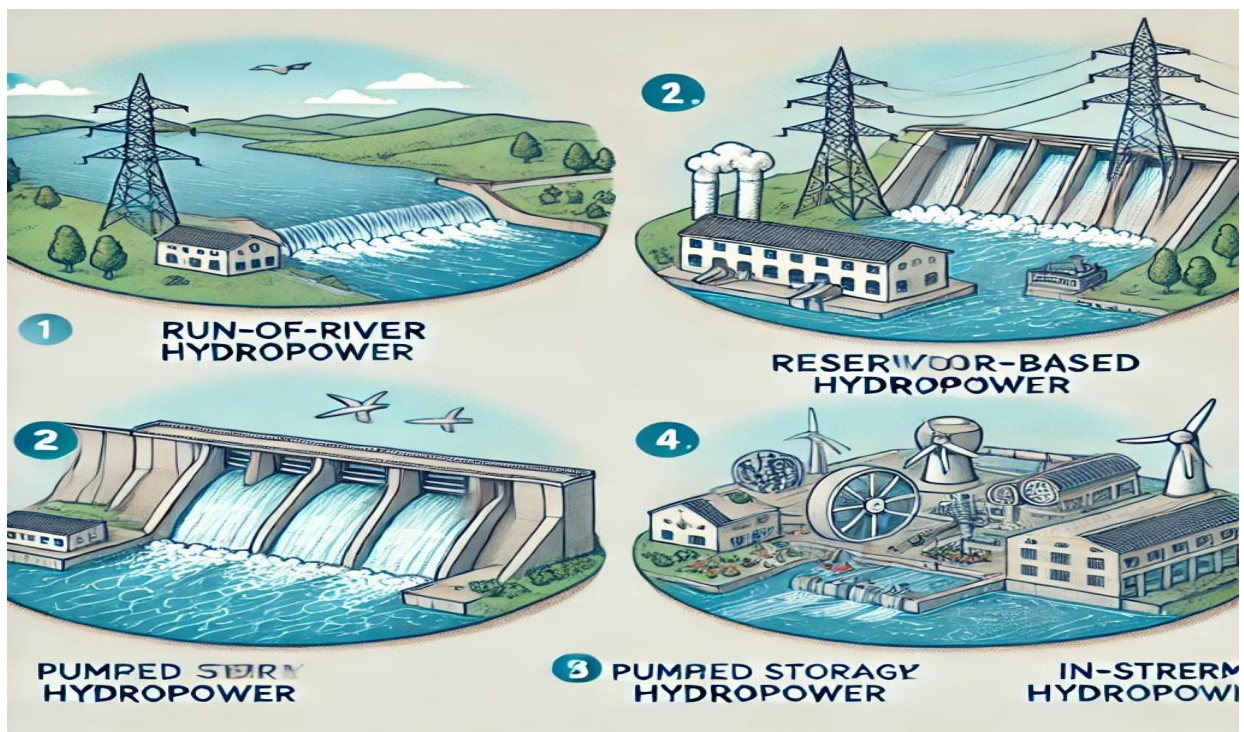
- Pumped Storage Hydropower (PSH)**

Works as an energy storage system. Pumps water to an upper reservoir during low electricity demand. Releases water to generate power during peak demand.

- In-Stream and Micro-Hydro Systems**

Small-scale hydropower projects. Suitable for localized and off-grid electricity supply. Low environmental impact and ideal for remote communities.

A figure showing different hydropower plants is shown in Figure 1.



**Fig.1. Different types of hydropower plants classified based on water source.**

## 2. Contribution to Low-Carbon Energy

Hydropower significantly reduces greenhouse gas emissions compared to fossil fuel-based electricity. Life-cycle assessments indicate that hydropower emits between 1-40 grams of CO<sub>2</sub> equivalent per

kilowatt-hour, significantly lower than coal and natural gas. Additionally, it supports decarbonization by enhancing energy storage capabilities and stabilizing power grids.

## ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACTS OF HYDROPOWER

### 1. Environmental Advantages and Difficulties

Although hydropower is a clean energy source, the size and location of the project affect how much of an impact it has on the environment. Benefits include reduced air pollution and less demand for fossil fuels. However, mitigation technologies are needed to address habitat fragmentation, sedimentation, and methane emissions from reservoirs.

### 2. Socio-Economic Considerations

The development of hydropower generation has economic benefits, such as creating jobs, developing infrastructure, and increasing energy access. However, large projects can lead to community evacuation and loss of cultural heritage. Simply guidelines and stakeholder commitments are key to clearing these concerns.

## TECHNOLOGICAL INNOVATIONS IN HYDROPOWER

### 1. Advances in Turbine Technology

Recent innovations in turbine design have significantly improved the efficiency, reliability, and sustainability of hydropower systems. Some key advancements include

- **Variable-Speed Turbines**

These turbines adjust their speed based on water flow conditions, optimizing power generation even in fluctuating environments.

- **Fish-Friendly Turbines**

Modern designs, such as Alden and Minimum Gap Runner (MGR) turbines, reduce fish mortality rates, enhancing ecological sustainability.

- **Advanced Materials**

The use of corrosion-resistant coatings and composite materials increases turbine longevity and reduces maintenance costs.

- **Hydraulic Efficiency Improvements**

Computational fluid dynamics (CFD) and 3D printing are used to refine blade shapes for higher efficiency and reduced cavitation.

### 2. Pumped Storage Hydropower (PSH) Enhancements

Pumped storage remains the most efficient large-scale energy storage solution, with innovations such as:

- Closed-Loop Systems: These systems reduce environmental impact by using off-river reservoirs.
- Variable-Speed Pumped Storage: Increases efficiency and enables more flexible grid integration.

### 3. Digitalization & Smart Hydropower

- AI & Machine Learning: Predictive analytics optimize water flow and turbine performance.
- Remote Sensing & IoT: Sensors monitor real-time conditions, reducing maintenance costs and improving operational reliability.

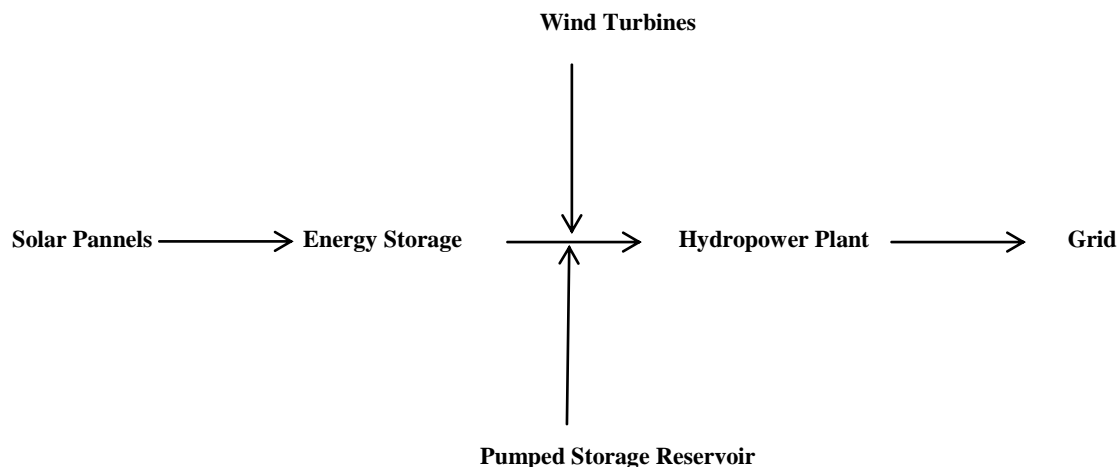
### 4. Small & Modular Hydropower Innovations

- Prefabricated Modular Systems: Reduce installation time and costs for small-scale hydropower.
- Run-of-River Technology: Enhances efficiency without large dams,

minimizing environmental disruption.

### 5. Hybrid Hydropower Systems

- Solar-Hydro Integration: Floating solar panels on reservoirs maximize energy output.
- Hydro-Wind Storage: Combines hydropower with wind energy to balance intermittent generation.
- Below is a conceptual diagram (Figure 2) illustrating a **Hybrid Hydropower System** integrating solar and wind energy with hydropower storage: This hybrid model optimizes renewable energy generation by balancing supply and demand using pumped storage as a backup system.



## FUTURE PROSPECTS AND CHALLENGES

### 1. Climate Change Adaptation

Changing precipitation patterns and glacier retreat impact water availability for hydropower. Adaptive measures, such as reservoir optimization and diversification of energy sources, are necessary.

### 2. Policy and Market Mechanisms

Supportive policies, carbon pricing, and incentives for sustainable hydropower are critical for continued investment in the sector.

### 3. Sustainable Development Strategies

Integrated water resource management, environmental impact assessments, and participatory decision-making processes enhance the long-term viability of hydropower projects.

## CONCLUSION

Hydropower remains a cornerstone of the global energy transition towards a low-carbon future. Its ability to provide clean, reliable, and flexible energy makes it an essential complement to other renewable sources. However, addressing environmental and socio-economic challenges is crucial for maximizing its benefits. Continued technological advancements, policy support, and sustainable management strategies will ensure that hydropower contributes effectively to global decarbonization efforts. With appropriate innovation and responsible implementation, hydropower can play a pivotal role in achieving a resilient and sustainable energy future.

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