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The Implementation of Hydropower Electric Generation That Is Able to Be Sustained Well into the Twenty-First Century

Dr. Sanjeev Gill*
Prof & Head of Department of Civil Engineering, JBIT, Dehradun (U.K)

Abstract

Hydropower supplied about 71 % of the world's renewable electricity in 2016, making it the dominant renewable source at that time. In Europe and North America, the boom years for dam construction were roughly 1920 to 1970; since most prime sites are now occupied and social-environmental costs have risen, both regions are dismantling more dams than they build. From the 1970s onward, developers shifted their attention to large rivers in lower-income regions especially the Mekong, Amazon, and Congo where new projects often come with familiar downsides: altered river ecology, deforestation, diminished aquatic and terrestrial biodiversity, greenhouse-gas emissions from reservoirs, mass displacement, and major disruptions to local food systems, water quality, and agriculture.

This paper reviews the surge in large-scale dams across the Global South; evaluates how climate-change projections should shape siting decisions; and discusses persistent governance gaps, compensation shortfalls, and the tendency to overstate benefits while downplaying true costs. Finally, it outlines design and policy adjustments such as pairing hydropower with solar, wind, and other renewables that could help the sector deliver electricity with far lower social and environmental impacts.

Keywords: hydropower energy; environmental implications; sustainable development; greenhouse gases; climate change

Introduction

Achieving global energy, food, and water security demands innovative and sustainable approaches. Historically, dams have been essential for managing land and water resources facilitating flood control, irrigation, agriculture, recreation, navigation, and ecosystem regulation. In the United States alone, there are around 82,000 major dams and over 2 million smaller low-head dams scattered across rivers. However, the cumulative environmental and ecological impact of these structures remains largely unassessed.

Hydropower development began in the late 19th century when early turbines provided electricity to a theater in Grand Rapids, Michigan, and later powered lamps near Niagara Falls, New York. The first hydroelectric plant utilizing alternating current was established in 1893 at Redlands, California. By the 1920s, the U.S. Army Corps of Engineers started constructing

*Corresponding Author Email: Hodcivil2017@gmail.com
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hydropower facilities. A landmark project came in 1933 when the Tennessee Valley Authority began generating hydroelectricity on the Tennessee River, helping to electrify rural America. The Hoover Dam, completed in 1937, became another major symbol of this era. These projects, part of the New Deal initiatives, led to a threefold increase in hydropower output within two decades accounting for 40% of U.S. electricity generation at its peak.

Hydropower was a cornerstone of energy development in North America and Europe during the early to mid-20th century. However, by the late 1960s, the construction of large dams declined in industrialized nations due to several factors: most optimal sites had already been developed, costs of construction rose significantly, and growing awareness of the social and environmental consequences led to public opposition.

As a result, hydropower's share in the U.S. energy mix has steadily decreased, now accounting for only about 6.1% of total energy consumption. Alternative energy sources such as nuclear power, natural gas, coal, solar, and wind have taken on greater prominence. Today, dam removal has become more common than new construction in North America and Europe. Many older dams especially those built before 1950 have reached or surpassed their design lifespans, are expensive to maintain or upgrade, no longer fulfill their original functions, and are associated with significant ecological and societal drawbacks.

Hydroelectricity in the World's Developing Countries

In developing countries, 3,700 dams producing more than 1 MW are planned or under construction. Hydropower is the largest renewable source of electricity (71% of global production) , but only 22% of its global potential has been tapped to yet . Sustainable Development Goals include substantially boosting renewable energy use by 2030. Hydropower development is a global phenomenon. It affects the Amazon, the Congo, and the Mekong, causing ecological damage. Many say the dams' benefits don't exceed their expenses. Large dams and reservoirs have enormous hydrologic repercussions, while micro hydropower has limited environmental impact. Sharp losses in accessible freshwater owing to dam construction affect river discharge, downstream freshwater habitat, floodplains, and coastal erosion and salinity

The negative effects on ecosystem structure, composition, and function (e.g., habitat fragmentation, biodiversity loss) can be severe. Reservoirs can be major emitters of greenhouse gases, especially methane, and river flow cutbacks can increase pollution levels. Large dams have significant human consequences. Populations near dams face social, behavioral, cultural, economic, and political disturbance. Ansar et al. analyzed 245 big dams built between 1934 and 2007 and found that expenses were 96% higher than projected and 1 out of 10 dams cost up to three times more than estimated. Big dams' alterations to the biological system harm subsistence fishermen. 40–80 million people were displaced by dam development projects, and it's been difficult to resettle them. Dams displaced 80 million people in the last century, according to Scudder. Downstream people' living standards and food security are also threatened. In the Tucuru Dam region of the Brazilian Amazon, fish catch dropped by 60% almost quickly, and more than 100,000 people living downstream experienced negative impacts due to the decline of fisheries, flood-recession farming, and other ecosystem services. Globally, it is conservatively estimated that dam construction has adversely affected around 472 million people living in downstream areas. Despite the scale of these impacts, downstream communities remain insufficiently studied in current research.

Large dams often contradict the principles of sustainability. For hydropower to be a viable solution in the future, it is essential to account for the potential impacts of climate change on water availability and power generation. Sustainable development in this sector must also aim to reduce the environmental and social burdens placed on communities living near dam sites. Fair and adequate compensation should be provided to those affected, while efforts must be made to minimize displacement. Additionally, investment in innovative technologies such as in-stream turbines and alternative renewable energy sources can offer more environmentally responsible and socially equitable solutions for meeting energy demands.

Dams, Climate Change, and the Transformation of Land Use

In numerous developing nations, hydropower projects are still being proposed and carried out without properly accounting for the long-term effects of climate change. In contrast, more developed countries have started to address these risks. For instance, the Hoover Dam in the United States is being modified such as by installing new turbines to adapt to falling water levels in the Colorado River. Lake Mead, which supplies water to the Hoover Dam, has seen its water level drop by around 40%, causing a decline in the dam's maximum energy output from 2 gigawatts to about 1.5 gigawatts. In the southeastern part of the U.S., several hydropower stations have undergone improvements during the relicensing process. These upgrades include better river flow regulation, enhanced fish passage systems, and increased dissolved oxygen levels in the water all aimed at restoring and maintaining ecological balance in downstream ecosystems.

Even with these advancements, global trends show that many new renewable energy projects in developing countries are still centered on hydropower. As per a recent forecast by the U.S. Energy Information Administration, a significant share of upcoming renewable energy projects worldwide will consist of hydropower plants situated in less affluent regions. Unfortunately, climate variability is often overlooked in the planning and construction phases in these areas.In the Amazon Basin, climate models especially under scenarios of high greenhouse gas emissions predict a drying trend in the southern and eastern regions, accompanied by more frequent droughts. This change poses a threat to water availability for hydropower generation. The Jirau and Santo Antônio dams, built on Brazil's Madeira River and commissioned only a few years ago, are already operating below their intended generation capacity of 3 GW each due to limited water storage in their run-of-the-river reservoirs. Likewise, the Belo Monte Dam on the Xingu River, completed in 2016, is expected to produce only about 4.46 GW for much of the year, significantly less than its designed output of 11.23 GW. This shortfall is due to erratic rainfall and the limited size of its reservoir. Since 2005, the Amazon Basin has witnessed three major droughts and three severe floods, underlining the urgent need to reevaluate the design and resilience of future hydropower initiatives in this sensitive region. Most climate models expect greater temperatures and decreased rainfall in Xingu, Tapajos, and Madeira.

Intensity and frequency of extreme events test energy claims from large hydropower projects. Hydropower is the world's primary renewable energy supply, however its reliability has been questioned. Brazil depends on hydropower for up to 67% of its electrical energy. In response to the anticipated decline in hydropower capacity due to climate change, many regions have accelerated dam construction within affected sub-basins. This has often occurred without adhering to international standards requiring transparent and inclusive consultation with local and Indigenous communities. Rather than prioritizing alternative technologies with lower environmental footprints such as in-stream turbines or expanding into other renewable sources like solar, wind, and biomass to create a more diversified energy mix, the focus has remained heavily on traditional dam infrastructure. Most future electricity in South America will originate from the Amazon Basin, which might have major environmental and social effects . The Mekong is being dammed rapidly in Asia. The construction of dams in these river basins poses serious threats to fish biodiversity and the food security of local populations. Much like with the issue of climate change, dam developers often overlook the influence of land use changes such as deforestation on the long-term viability of hydropower. A study by Stickler et al. analyzed the reduction in energy generation potential under various deforestation scenarios within the Amazon Basin. Specifically, in the Xingu River Basin where the Belo Monte Dam is located the researchers projected that up to 38% of the expected energy output could be lost due to anticipated deforestation. They further estimated that, for ten months of the year, the dam may operate at less than half its installed capacity. Deforestation in tropical moist forests can significantly reduce both rainfall and soil moisture, impairing energy production capacity . In fact, approximately half of the Amazon Basin’s precipitation is believed to result from internal moisture recycling. Therefore, forest loss can independently reduce rainfall, apart from the declines expected from global climate change .Given these risks, relying heavily on large-scale hydropower projects may not be a dependable energy strategy under shifting climate conditions. Alternative solutions are necessary to address potential energy deficits during prolonged dry periods. Recent evaluations suggest that the most effective path forward includes the accelerated deployment of renewable technologies like wind, biomass, and solar power. These sources would supplement existing hydropower, which could then serve as a stabilizing force for the electricity grid, rather than the primary energy provider .

It's easy to overlook that dams have a finite lifespan while seeking "green energy" options (i.e., that they are not really a sustainable long-term strategy). Brazil's dams have a 30-year lifespan that can be extended with retrofits and new turbines . Aging structural materials and sediment buildup behind the dam can cause failure. As dams age, they might fail, causing deaths and property damage. In 1994, a tropical storm caused 230 dams in Georgia to crumble . In 2016, torrential rains caused the Oroville Dam Spillway to rupture, evacuating 190,000 people. The Teton Dam in Idaho failed in 1976, costing about $2 billion in 2017 dollars. Many US dams could fail. Many buildings built during the United States' greatest construction period (1930–1950) will be 50 years old by 2020. (58).Repairing a minor dam can cost three times as much as removing it (59), which is why dam removal is on the rise. Considering dam removal expenses, is dam construction justified? Since 2006, the U.S. has destroyed more than 60 dams per year. Quantity-based

River sedimentation concerns arise faster than structural damage (60). Before 1960, sedimentation rates weren't systematically integrated into dam design standards, hence many dams fill faster than projected (61, 62). Engineers create reservoirs with 100-year sediment pools. These models generally fail to consider changes in watershed land use (such as road development, which can double sediment yield) and forecasted climate change extreme events that will likely enhance sediment movement into reservoirs. Tropical countries continue to disregard elements that increase silt burdens. The Madeira River discharges 430 Mt of silt every year (63), more than other rivers. Two dams on the Madeira Jirau and Santo Antonio were completed this decade, and more are planned despite warnings that their designs overestimated sedimentation rates (64–66).In less than 5 years following their completion, experienced dredgers who mined for gold in the Madeira (and were removed to build the dam) have been called back to clear sediment building at "unexpected" rates in these two reservoirs. This is surprising given the quantity of scholarly studies that predicted rapid sedimentation (64–67).

Threatened Regions

Despite extensive academic research predicting swift sediment build-up, many hydropower projects continue to be approved. In several river basins prioritized for their hydropower capacity, the potential environmental and social consequences are often overlooked. A comparative table highlights the situation in three biodiversity-rich river systems. In the Amazon Basin alone spanning 6 million km² 147 dams are currently planned, with 65 of them located in Brazil. Moreover, Brazil is investing in the hydropower potential of neighboring Bolivia and Peru, aiming to utilize their combined capacity of 200 GW (180 GW in Peru and 20 GW in Bolivia). These large-scale developments affect ecologically sensitive regions, indigenous communities, and millions of people living within these areas.

Brazil's total hydropower potential is approximately 260 GW, and about 41% of this lies in the Amazon Basin, making development in this region appear inevitable. Notably, three rivers the Xingu, Tapajós, and Madeira hold about 80% of this potential.

The Amazon River system is renowned for supporting some of the world's most productive inland fisheries and holds the highest diversity of freshwater fish, with over 2,320 species. In comparison, the Congo and Mekong river systems contain 1,269 and 599 species respectively. For communities living along these rivers, fish constitute the primary source of animal protein. However, research indicates that dam construction has already impacted fish populations and ecological dynamics. For instance, fish populations in the Tocantins River dropped by 25% following dam construction.

One of the main causes of this decline is the obstruction of fish migration pathways. Additionally, dams disrupt the natural flow of nutrients like carbon and phosphorus, which further affects aquatic ecosystems and fisheries.

Sustainable hydropower governance

In major river basins such as the Amazon, Congo, and Mekong, the social and institutional implications of hydropower projects are often overlooked. Local communities are rarely involved in the planning or decision-making processes, which allows urban and industrial interests to take precedence while community-level concerns go unheard. Furthermore, national and regional policies generally fail to address the complexities of transboundary river systems, often ignoring the rights, cultural values, and access to resources of local populations.

Governance structures influencing water, food, and energy access can be sector-specific such as laws on water rights or land ownership or cross-sectoral, including political rights and decentralization policies. These frameworks, whether rooted in traditional practices or formal legal systems, directly shape how communities make choices about essential resources. Therefore, governance must be viewed not as isolated sectors, but as an interconnected "nexus" with multiple layers spanning sectors, regions, and institutions.

To develop effective and inclusive policies, case studies must be evaluated through an institutional lens. The allocation of water for energy generation often creates unequal distribution of benefits and burdens, affecting livelihoods, food security, and local access to resources. While large dams are frequently promoted with promises of local development, the reality often diverges significantly. A survey of 220 hydropower-related disputes revealed a troubling pattern of suppression, criminalization, and violence against affected communities and activists. Ultimately, hydropower initiatives have struggled to confront the deeper governance and sustainability challenges they create.

Conclusion

- The construction of dams should only proceed after thorough environmental and social impact assessments (ESIAs) are conducted to evaluate and mitigate potential harms.
- To overcome the limitations of current dam-building practices, it is essential to integrate regional and national policy considerations into project planning. These policy impacts must be clearly communicated to local communities through transparent and inclusive processes.
- Instream turbine technologies, often referred to as "zero-head" systems, offer a promising environmentally friendly alternative to traditional damming. These systems harness hydropower without significantly altering river flow or ecosystems.
- While dams contribute to renewable energy generation, the broader governance dimensions of their construction, operation, and resource distribution must be fully considered to ensure equity and sustainability.
- Migratory aquatic species continue to suffer due to the absence or failure of fish passage solutions, such as fish ladders. In cases where these measures have proven ineffective, dam removal should be seriously evaluated to restore ecological connectivity.
- Prior to any final approval, adequate public consultation and discourse must be held. Social Impact Assessments (SIAs) are critical for estimating the number of people to be resettled, and for setting up fair compensation and rehabilitation mechanisms.

- The distinction between small and large hydro dams lies primarily in scale rather than function. Countries like China and India have demonstrated the potential of small hydropower, particularly in supplying electricity to remote and mountainous regions. These systems should not be overlooked as part of a diversified, decentralized energy strategy.

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