The Interplay between Climate Change and Hydroelectricity: Impacts and the Role in Combating Climate Change

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Abstract: Hydropower plays a crucial role in global energy production and sustainable development, but its reliability and efficiency are increasingly threatened by climate change. This study examined the impacts of climate change on hydropower and its role in combating climate change, with a focus on Nepal. The research gap addressed is the lack of comprehensive studies on the interplay between climate change and hydropower in Nepal. The methodology involved a literature review and analysis of existing policies and projects related to hydropower and climate change adaptation in Nepal. The findings revealed that climate change has led to changes in precipitation patterns, temperature fluctuations, and river flow, affecting the reliability and efficiency of hydropower plants. Despite these challenges, hydropower remains a vital component in combating climate change, offering a clean energy alternative and contributing to sustainable development. The study recommends effective coordination and collaboration with stakeholders, along with the implementation of policies and agreements promoting renewable energy sources like hydropower, to address the challenges posed by climate change and ensure the efficient development and management of hydropower projects in Nepal.

Keywords: *Climate change, Hydropower, Nepal, Renewable energy, Sustainable development*

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1. Introduction

Hydropower remains the major renewable energy source globally. Renewable energy sources are seen as catalysts for a country's socio-economic growth, ensuring access to electricity for all while promoting economic activity (Singh et al., 2020). Compared to fossil fuels, renewable energy sources such as solar, wind, hydro, and geothermal power emit significantly fewer carbon emissions. Climate change can significantly impact hydropower projects, primarily through changes in water availability and extreme events like floods, droughts, and other environmental impacts (Chiluwal et al., 2021). Countries can reduce the effects of climate change, air pollution, and conserve ecosystems by transitioning to renewable energy, fostering a healthier environment for a sustainable future. In Nepal, traditional energy sources account for over 70% of energy consumption, while renewable energy sources make up about 3% (Suman, 2021). Nepal imported fuel worth Rs 214.48 billion in 2020, accounting for nearly 15% of the country's total budget for that fiscal year (Neupane, 2022). Given Nepal's geography, topography, including mountainous terrain and potential for water resources, it has significant potential for renewable energy development, particularly in the hydropower sector.

Nepal has a hydroelectricity generation capacity of 83,000 Megawatts (MW), but its current built capacity is just 1,129 MW (Schulz & Saklani, 2021). It is important to note that Nepal's actual built capacity of hydroelectricity is currently much lower than its potential. A major issue in Nepal is the lack of widespread access to electricity, especially in rural areas where a large portion of the population lives, with only 51.5% being electrified (Agrawal & Pandey, 2019). Some of the main challenges include limited investment and funding, technical and engineering constraints, political instability, unfavorable government policies, and ineffective regulatory mechanisms (Nepal, 2012). According to a study by the Nepal Electricity Authority (NEA), the electricity demand in 2029/30 is estimated to be 4,280 MW. Similarly, the Water and Energy Commission Secretariat (WECS) predicts that in 2030/76, the electricity demand will rise to 11,111 MW, assuming a 7.2% economic growth rate (Shrestha, 2020). This suggests that with expected economic growth, there will be a higher need for electricity to meet the increasing demands of various sectors, industries, and households. The unconstrained electricity demand is substantial and reflects the growing need for energy. The demand for unrestricted electricity is anticipated to rise from 10,138 gigawatt-hours (GWh) in 2019-2020 to 31,196 GWh in 2029-2030 (Gunatilake et al., 2020). The majority of hydropower projects in Nepal are of the Run-of-River (RoR) type (Singh et al., 2022). This means that the hydroelectricity that uses the natural flow of rivers avoids the need for massive water storage reservoirs. Due to its direct impact on the seasonal discharge available in the river, climate change has a considerable impact on reservoir-based hydropower (Shrestha, 2020). Climate change impacts on hydropower can also bring about changes in temperature and precipitation patterns, thereby reducing the flow of the river. Nepal's energy consumption by fuel types includes fuelwood (60.4%), animal waste (2.9%), petroleum products (14.3%), coal (9.3%), LPG (3.5%), electricity (4.2%), and other renewable sources (2.4%) (Government of Nepal, 2022). As reflected in Sustainable Development Goal 7 (SDG 7) established by the United Nations, "ensure access to affordable, reliable, sustainable, and modern energy for all," energy plays an important role in advancing various aspects of sustainable development (Bocchiola et al., 2020). As a critical enabler of sustainable development, energy is fundamental in eradicating poverty, driving economic growth and industrialization, mitigating climate change, and conserving the environment. IRENA (2018) suggests that a key target of the Paris Climate Agreement was to increase the share of renewable energy in total global electricity production from 33.3% in 2018 to 85% by 2050 (Bhattarai et al., 2023). As a form of renewable energy, hydropower generates electricity by harnessing the power of flowing or falling water. It should be noted that hydropower is also crucial in reducing the use of carbon-intensive energy sources (Ojha, 2020) as hydropower plants produce minimal greenhouse gas emissions, making them an environmentally friendly alternative to fossil fuel-based power generation. The phenomenon of climate change is global. According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change refers to a significant and long-term alteration in the earth's climate system that can be attributed directly or indirectly to human activities (Shu et al., 2018). This shows that human activities, particularly the release of greenhouse gases into the atmosphere, are responsible for altering the composition of the atmosphere and causing changes in the climate system. Hydropower is among the industries vulnerable to the impacts of climate change, as it depends on water resources to produce electricity, changes in water availability and quality brought on by climate change could affect this sector (Ghimire et al., 2019). Climate change is known to alter precipitation patterns, increase the frequency and intensity of weather patterns, and accelerate the melting of glaciers. This can affect the long-term availability of water essential for hydropower generation. Hydropower contributes to reducing Greenhouse Gas (GHG) emissions. Hydropower is considered one of the cleaner sources of power generation compared to fossil fuels such as coal, oil, and natural gas, helping the environment through carbon trade (Karmacharya, 2008). Hydropower plants have relatively low operational emissions and contribute to reducing the overall carbon footprint. Nepal's energy policy prioritizes the utilization of its abundant hydropower potential to meet domestic energy demand (Thapa et al., 2023). Renewable energy sources such as hydropower produce little to no direct greenhouse emissions during operation, making them a crucial part of any climate-focused policy. Hydropower prevents the emission of about 3 gigatons (GT) of CO_2 per year (equivalent to about 9% of global annual CO_2 emissions), underscoring the substantial positive impact that widespread adoption of hydropower can have on reducing global GHG emissions (Berga, 2016). Thus, hydropower can be a crucial component in transitioning to cleaner and more sustainable energy sources.

The main objective of this paper was to evaluate the anticipated effects of climate change on the hydropower sector. The specific objectives of the paper were: i) to analyze the relationship between hydroelectricity as a renewable energy and climate change; ii) to understand the causes and effects of climate change on hydroelectricity; and iii) to discuss the role of hydroelectricity in combating climate change. This research offers new insights by exploring the complex relationships between climate change and hydropower. This paper emphasizes the vulnerability of the hydropower sector to climate change in terms of changing environmental conditions. The paper also highlights how using hydropower might help to mitigate climate change by lowering greenhouse gas emissions. This paper will be insightful for policymakers, environmental organizations, engineers, researchers, and local communities, assisting them in comprehending the crucial part that hydropower plays in ensuring energy security and reducing climate change.

2. Materials and methods

The methodology for this review paper involved the selection of keywords to guide the literature search, focusing on terms related to climate change, hydropower, renewable energy, and their interrelationships. Researchers conducted a comprehensive search using databases such as Springer, ScienceDirect, Google Scholar, and ResearchGate, employing a combination of keywords and Boolean operators to refine their search. A total of 103 articles were reviewed, and selection was based on relevance to the study objectives, with a focus on providing insights into the anticipated effects of climate change on the hydropower sector.

After reviewing the articles, 63 were categorized into different themes, likely based on the relationship between hydroelectricity and climate change, the causes and effects of climate change on hydroelectricity, and the role of hydroelectricity in combating climate change. Data extracted from the selected articles were then analyzed to fulfill the specific objectives of the paper, including synthesizing findings to provide a comprehensive understanding of the subject matter. The researchers offered new insights into the complex relationships between climate change and hydropower, emphasizing the vulnerability of the hydropower sector to changing environmental conditions.

Table 1: Types of articles reviewed and their numbers

Types of articles	Total numbers
Journals	45
Books	2
Conference papers	8
Government reports	6
Websites/online sources	2

3. Results and discussion

The Earth's surface temperature has risen by 1.1°C in the last decade compared to the 1800s (industrial revolution), primarily due to human activities like unsustainable energy consumption, land use changes, and alterations in lifestyles (IPCC, 2021). The major reason for the significant rise in global temperature is the excessive consumption of fossil fuels like coal, oil, and natural gas, which release large amounts of greenhouse gases (GHGs) that trap heat in the earth's atmosphere (IPCC, 2021; Surendra et al., 2011). Furthermore, the Himalayan region has experienced a temperature rise at a rate of 0.06°C per year between 1978 and 1994 (Shrestha et al., 1999).

Significant effects of rapid warming are being witnessed across various sectors such as food and water security, human health, and ecosystems, including hydropower generation. Hydropower is considered a major renewable energy source worldwide, and its potential vulnerability to climate change has been studied in recent years (Mimikou & Baltas, 1997; Carless & Whitehead, 2013; Shrestha et al., 2014; Savelsberg et al., 2018; Solaun & Cerdá, 2017; Fan et al., 2020; Baral et al., 2023). Shu et al. (2018) conducted a thorough analysis of the effects of climate change on hydropower at global, national, and regional scales. Their findings revealed that runoff changes could have a considerable impact on power generation in Asia, particularly in countries bordering the Himalayan region, leading to considerable impacts on power output.

Additionally, by the 2070s, Europe's hydropower potential is expected to shrink by 6%. However, in Africa, limited research has been conducted due to the scarcity of hydropower generation. North America and South America have also witnessed erratic rainfall and runoff patterns impacting hydropower production. Savelsberg et al. (2018) assessed the impacts of climate change on Swiss run-of-river (ROR) and storage hydropower plants, revealing mixed effects depending on hydrological conditions. While positive effects were observed during average or wet conditions, negative effects were noticed during dry periods. However, Hamududu & Killingtveit (2012) revealed that hydropower plants with large storage capacity have little risk of climate change compared to hydropower with low storage capacity. Similarly, Carless and Whitehead set up conditions according to the Environmental Agency for an imagined micro-hydro plant at Plynlimon for different climatic scenarios for the 2020s and 2050s. They found that annual output remains unaltered, as low power production in summer will be compensated by increased generation in the winter season.

In the context of Nepal, most of the hydroelectric projects rely heavily on Runoff River (RoR) for electricity generation. S. Shrestha et al. (2014) investigated the impact of climate change on the hydropower production of the Kulekhani hydropower project of Nepal, which concluded that average power production decreased by at least 30% for two different scenarios in the HADCM3 global circulation model (GCM) for three time periods. Moreover, the study has shown that Nepal will have a significant impact on hydropower generation over the next few decades due to the rapid melting of Himalayan glaciers. It is obvious that a minor change in the hydrological cycle and water resources availability affects the reliability and efficiency of power generation. According to several studies, global warming results in changes in precipitation patterns, snow, and glacier melting, increase in evaporation, alterations in river runoff, and other environmental concerns (Berga, 2016; S. Nepal, 2016).

Mimikou & Baltas (1997) concluded in their study that the storage volume of water in large multipurpose reservoirs in northern Greece should be increased to maintain constant energy production under two scenarios (UKHI and UKTR) referring to different periods of years. On the other hand, Bahati et al. (2021); Park & Kim (2014) pointed out that hydropower generation will rise considerably in the future under different scenarios. Despite the effects of climate change on the hydropower sector, hydropower energy plays a significant role in reducing the effects of climate change and maintaining the global energy balance (Shu et al., 2018).

The development of hydropower and other renewable resources will lead to less use of fossil fuels and emission of GHGs into the air. As part of the Kyoto Protocol's clean development mechanism (CDM), Small hydropower production (SHP) has assisted industrialized countries in reducing GHG emissions. Multiple studies have argued that the increase in the use of renewable energy technologies such as hydropower, biogas, wind energy, etc., reduces GHG emissions (Kumar & Rathore, 2023; Özbuğday & Erbas, 2015; Saidi & Omri, 2020). Using the simple additive weighing (SAW) method, Shaktawat & Vadhera (2020) assessed hydropower for its potential for coping with climate change based on technical, environmental, and socio-economic criteria. In addition, they compared it to other renewable sources like wind, solar PV, geothermal, and biopower. In comparison to coal power plants, hydropower prevents the emission of 3 GT CO_2 per year or about 9% of global annual CO_2 emission. Moreover, ROR hydropower emits 3-4 tons of CO_2 emissions per GW-h, while reservoir hydropower releases 10-33t, which is nearly 100 times less than emissions from thermal power plants (Berga, 2016). From the analysis, it was determined that hydropower ranked higher than other renewable sources in terms of RET for reducing climate change.

Suman (2021) investigates the significance of Renewable Energy Technologies (RETs) in Nepal's initiatives to combat climate change. If numerous RETs, including hydropower, were taken into consideration, Nepal's annual GHG emissions might be reduced by 4.45 million tCO_{2e} by 2030 if technologies developed after 2012 were adopted. Furthermore, about 4020 tCO_{2e} less greenhouse gas is produced by mini and micro hydropower (AEPC, 2021). The 1997 Kyoto Protocol, the 2015 Paris Agreement, Nationally Determined Contributions (NDCs), UNDP Sustainable Development Goals (SDGs), and other policies, plans, and agreements have all been developed at the international, national, and regional levels to combat climate change. Despite not specifically aiming to harness hydropower, the Kyoto Protocol emphasizes minimizing greenhouse gas emissions (GHG), which includes carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (No_2), to slow down the effects of global warming. Even though developed nations like France, the UK, and Germany have met their targets for reducing CO_2, rising nations like China and India continue to produce significant amounts of GHG emissions, consequently making it unlikely that the level of CO2 in the atmosphere will stabilize.

Similarly, the Paris Agreement aims to hold global warming well below 2°C and pursue measures to limit the temperature increase to 1.5 degrees Celsius. It highlights the role of renewable energy sources, including hydropower, in the worldwide stand-up against climate change. Participating nations should submit NDCs as part of their strategy, which should include a variety of renewable energy initiatives, to lessen emissions and transition to a sustainable energy system. However, major CO2 emitters are not effectively implementing their NDCs, which could lead to the failure of the Paris Agreement.

Nepal has also developed several plans and policies regarding climate change and RETs. A few of the policies include the Climate Change Policy (2011), Rural Energy Policy (2006), National Adaptation Programme of Action (NAPA, 2016), National Framework on Local Adaptation Plans for Action (LAPA, 2011), National Energy Crisis Mitigation and Energy Development Decade (2016), Sustainable Development Goals- status and Road Map (2016-2030), Nationally Determined Contributions (NDC,2020), etc. While each of these policies has its own goals, they are all connected to RET promotion and climate change adaptation and mitigation. However, these policies have failed to meet their target in the last decade.

Climate change presents significant challenges and opportunities for hydropower generation. Alterations in precipitation patterns, temperature fluctuations, changes in river flow, floods, droughts, seasonal weather variations (Giri et al., 2023a; Giri et al., 2023b), and sedimentation of reservoirs due to erosion are main factors that cause uncertainty and pose challenges in harnessing hydroelectricity generation. During climate change, geohazards (Glacial Lake Outburst Flood), hydrological variability, and extreme flooding are major challenges for Nepal's hydropower sector. Despite these challenges, hydroelectricity generation has offered opportunities to combat climate change. The production of hydroelectricity contributes to reducing the usage of fossil fuels, which lowers GHG gas emissions and supports worldwide efforts to address climate change. Additionally, it contributes to sustainable development by offering clean energy, managing water resources, and aiding with irrigation and drinking water supply.

Effective coordination and collaborations with stakeholders (planners, government authorities, civil society, researchers, investors, local peoples, etc.) who are either impacted or impacting the project can address challenges and ensure the development of hydroelectricity generation efficiently. Therefore, for successful development and management of multipurpose hydropower, the share concept, which depends mainly on five principles notably, shared vision, shared resources, shared responsibilities, shared rights and risks, and shared costs and benefits should be deployed. Singh et al. (2020) evaluated the status and relative positioning of five different hydropower categories in Nepal using multi-criteria decision making (MCDM) along with consultation from stakeholders, which aid the government to make appropriate strategies and policies to harness hydropower production effectively and efficiently. Tan-Mullins et al. (2017) outlined the significance of the involvement of Chinese stakeholders, which includes Government agencies (state council and political bureau), local NGOs, financiers (ExIm bank, Sinosure), researchers, etc. in large hydropower projects in Asia and Africa. The optimum use of hydropower generation can be done by building on the world commission on the Dam (WCD) guidance to adopt more practical, consensus-based multi-stakeholder sustainability standards and strict climate change regulations that restrict the detrimental effects because of hydropower constructions. Watkin et al. (2012) came to a conclusion in their study that the role of stakeholders is very significant for hydropower development.

Table 2: Summary of findings

Effects of climate change on hydroelectricity	Roles of hydroelectricity in combating climate change
a. Climate change can alter precipitation patterns, leading to changes in water availability for hydropower generation. b. Rising temperatures can affect snowmelt patterns, which in turn can impact water availability for hydropower. c. Climate change can result in changes in river flow, affecting the efficiency and reliability of hydropower generation. d. Increased frequency and intensity of extreme weather events such as floods and droughts can disrupt hydropower generation. e. Erosion caused by extreme weather events can lead to sedimentation of reservoirs, reducing their storage capacity and efficiency.	a. Hydroelectricity generates electricity with minimal greenhouse gas emissions, reducing the overall carbon footprint of the energy sector. b. Hydroelectricity helps to diversify the energy mix and reduce dependence on fossil fuels. c. Hydroelectric power plants can enhance resilience to climate change by providing a stable and reliable source of electricity, particularly during extreme weather events. d. Hydroelectric facilities often involve water management systems that can help manage and adapt to changing water availability patterns, contributing to overall water security. e. Reservoirs created for hydroelectric projects can act as carbon sinks, sequestering carbon from the atmosphere through the accumulation of organic matter. f. Hydroelectricity contributes to sustainable development by providing clean energy, supporting economic growth, and improving access to electricity, particularly in rural areas.

4. Conclusion

The study found the significant impacts of human-induced climate change on hydropower generation, emphasizing the need for sustainable solutions. The rise in Earth's surface temperature, driven by human activities, resulted in noticeable changes in precipitation patterns, temperature fluctuations, and river flow, all of which directly affected the reliability and efficiency of hydropower plants. Despite these challenges, hydropower played a crucial role in the global effort to combat climate change. Its role as a clean energy alternative not only helped reduce greenhouse gas emissions but also contributed to sustainable development goals.

Effective coordination and collaboration among stakeholders are essential for addressing the challenges posed by climate change and ensuring the efficient development and management of hydropower projects. Additionally, the study emphasized the importance of implementing policies and agreements that promote renewable energy sources like hydropower. However, the success of these policies relied heavily on their effective implementation. Thus, it was imperative to prioritize sustainable practices and stakeholder engagement in harnessing the potential of hydropower to combat climate change effectively.

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