

Exploring Sustainable Energy Futures: Assessing the Viability of CanmetENERG's Hydropower Initiatives in Cameroon

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Abstract

This study examines how hydroelectric power projects, specifically the CanmetENERG initiative in Cameroon, play a crucial part in promoting sustainable development. Hydropower, seen as a cheap, local, and sustainable power source, is given top priority in government funding plans, especially in emerging nations. By making use of the RETScreen Clean Energy Project Analysis Software, the analysis examines the financial feasibility of different choices for CanmetENERG, emphasizing the importance of a holistic strategy that incorporates economic, environmental, and social factors in project development. The importance of factoring in environmental, social, and cultural aspects in project development is highlighted by the substantial influence of tunnel construction on total expenses. The paper suggests harnessing Cameroon's unused hydroelectric capacity while following sustainable development principles and international standards. It emphasizes the need for a well-rounded strategy that focuses on economic sustainability in addition to environmental and social issues to guarantee Cameroon's energy market can sustain itself. Moreover, the research emphasizes the continuing need for advancements in hydroelectric power through research and technology, encouraging cooperation between academia, industry, and policymakers. Community involvement and stakeholder engagement are considered essential for inclusive decision-making and socially responsible project development. It is advised to use adaptive management tactics to deal with changing environmental and socio-economic circumstances. The CanmetENERG case study showcases a model for responsible and sustainable hydropower development that boosts the country's energy security and environmental resilience. Apart from this particular instance, the study provides more extensive perspectives on effective

methods for sustainable energy development, emphasizing the difficulty of maintaining a good balance between energy security, economic feasibility, and ecological sustainability. It requires a strategic shift towards self-sufficiency in energy and decreased reliance on imports. The article envisions a collaborative, interdisciplinary approach to shaping the future of hydroelectricity, emphasizing continuous research, technological advancements, and the involvement of key stakeholders. By promoting creativity, eco-friendly practices, and community engagement, hydroelectric projects can act as catalysts for sustainable development, making valuable contributions to society.

Keywords

Hydroelectricity, Clean Energy, Sustainable Development, Cameroon Energy, Management Strategy

1. Introduction

Due to population expansion and industrialization, the world's energy demand has increased by 70% since 1971 and is expected to rise by an additional 40% by 2030 [1]. Still, 1.6 billion people do not have access to power, highlighting the critical need for sustainable energy sources. The energy sector, primarily reliant on fossil fuels and significantly contributing to global warming, is facing increased scrutiny due to international agreements like the Kyoto Protocol and growing public awareness of climate change [2]. As a result, governments all over the world are shifting to renewable energy sources, with hydropower developing as a widely used and reasonably priced technology [3].

Even though hydropower is a well-established technology, only about one-third of its potential has been used commercially worldwide, leaving a large amount of unrealized potential, particularly in South America, Africa, and Asia [3]. Hydropower is acknowledged for its low greenhouse gas emissions and compliance with social justice ideals. It is an essential tool in reducing global warming and halting the depletion of non-renewable fuel reserves [3]. To alleviate negative effects on river ecosystems, however, environmental impact assessments and public awareness campaigns are essential.

Even though it has historically used hydropower, Cameroon barely uses 35% of its potential for economic hydroelectricity [4]. The fast-growing economy and the expected 6% to 7% yearly increase in electricity demand over the next ten years create an urgent need for more power generation capacity [4]. The competitiveness between businesses seeking for hydropower projects is heightened in this highly competitive environment by the privatization of energy markets.

Developers aiming to expedite project advancement must allocate significant resources in terms of time, funding, and engineering expertise. Tools such as Canmet-ENERGY's RETScreen Clean Energy Analysis Software have proven invaluable in

assessing the economic feasibility of projects [5]. While RETScreen hasn't seen widespread use in Cameroon, this study utilizes the software to evaluate different formulations for the CanmetENERG project, providing critical insights into optimization and economic viability [5].

The study underscores the enduring relevance of hydropower in the global electricity sector, particularly in addressing escalating energy demands [6]. Electricity serves as the cornerstone of modern society, making the shift towards renewable energy sources imperative for sustainable and resilient energy systems [6]. Embracing renewables like hydropower is crucial for meeting current and future energy needs. Additionally, the paper explores various renewable energy sources, including photovoltaic systems, highlighting their role in decentralized electricity generation and the transition to sustainable energy.

1.1. Wind Power

Wind energy is considered the world's fastest-growing renewable energy source, prized for its purity and sustainability and a strong history spanning centuries in Europe, the United States and elsewhere. The contribution of small and large turbines to electricity generation has benefited households and remote villages. More energy sources promise a cleaner, safer and more sustainable future by improving the quality of the environment for people and animals. Renewable energy sources, including wind energy, play an important role in economic growth, job creation, national security and reducing greenhouse gas emissions. It seems that wind energy has made remarkable progress and has surpassed other technologies such as solar, cell and wave energy with less research and development costs [7]. However, the distribution of wind energy in the world is unequal in European countries. The increase in energy consumption due to economic and technological developments has led to a significant increase in energy consumption worldwide. Wind energy has the potential to meet this increasing demand, and there are areas with sufficient wind speeds for development in almost every country. However, potential energy consumption depends on various factors; Wind data must be captured in the system in order to be evaluated appropriately. Wind farms take cores, while offshore farms show impressive potential despite higher installation and maintenance costs. Constraints such as low energy concentration, flexibility and selectivity create challenges for energy producers. However, wind is an additional source of renewable energy at the right time, offering a range of benefits and supporting energy security, trade balance and employment. International forecasts show a significant increase in wind energy construction and the potential to make a significant contribution to global energy supply in 2020, possibly competing with large-scale power plants. Long-term forecasts include expansion into multiple markets, including the US, Europe, Pacific/China, CIS and Eastern European markets. Additionally, wind turbines and off-grid energy systems can be installed to meet the energy needs in rural areas of regions without grid connection [8] [9].

1.2. Geothermal Energy

Geothermal energy production has increased significantly over the last few decades; Installed capacity increased from 1300 MW in the 1970s to 10,000 MW around 2007 [10]. About 75% of the extraordinary increase of about 9000 MW comes from about 20 projects with production above 100 MW, using energy stored in hot rocks where water draws heat from these rocks and takes it to the earth. This heat is then converted into electrical energy using a turbine engine. As of 2005, average thermal energy production exceeded 28,888 MWt, which emphasizes the importance of hydroelectric energy [11]. Ongoing efforts in geothermal energy research focus on extracting heat from rocks by injecting water into hot rocks, causing the rocks to heat up and produce hot water or oil. While initially facing economic challenges, High Temperature HDR (Hot Dry Rock) technology has witnessed recent technological advances leading to commercial success. Total electrical energy resources are expected to increase significantly as HDR technology becomes more economically viable. Variants of HDR such as Hot Wet Rock (HWR) and Geothermal Systems (EGS) are increasingly sought after. A new concept has emerged in EGS that requires the use of carbon dioxide (CO₂) instead of water as the working fluid. Another important development is the use of heat recovery systems, especially in hydroelectric power plants. Popular for large installations, these systems often involve keeping hot water under pressure using electrically assisted pumps (ESP). The heat from this water phase is then converted into a binary liquid that produces electricity when burned in a special turbine [12].

1.3. Hydroelectricity

Hydropower, which uses the gravity of falling or flowing water to generate electrical energy, is a dominant and environmentally friendly form of renewable energy. This system, which utilizes the kinetic energy of water, produces electricity with low impact on the environment. It is clear that hydropower has many advantages, including no direct waste and low carbon dioxide production [13]. Worldwide, electricity has played an important role, with an installed capacity of 1010 GW in 2010, providing 16% of global electricity and 76% of electricity from renewable energy sources [14]. One of the most distinctive features of electrical energy is that it is uninterrupted, 24-hour electricity. This reliability differs from wind and solar power, which do not operate twenty-four hours a day. Sustainable and reliable electricity production with low environmental impact has an important place in the global energy environment [15].

1.4. Global Energy Landscape

The increase in global energy demand driven by population growth and rapid industrialization poses a variety of challenges that are exacerbated by pressure to reduce greenhouse gas emissions. To solve these problems, research into effective and sustainable energy becomes a priority. Renewable energy solutions derived from renewable sources such as solar power, solar energy and hydropower offer

a powerful alternative to burning fossil fuels [16]. The results not only meet energy needs, but are also compatible with environmental protection goals by reducing the negative effects of climate change. Diversifying the energy mix not only increases global energy security but also reduces dependence on scarce resources. Ongoing technological developments, especially in solar, wind and energy storage systems, contribute to the realization and challenge of renewable energy sources [17]. This transformation represents an important step in shaping the world's energy, environmental and economic dynamics. It underlines the urgent need to address problems related to population growth, industry and greenhouse gas emissions, and emphasizes the need for sustainable energy solutions.

1.5. Environmental Imperatives

The need to move away from fossil fuels stems from increasing awareness of the negative effects of the fossil fuel-based energy system on the environment. Coal, oil and natural gas, common primary energy sources, release large amounts of greenhouse gases, including carbon dioxide, into the atmosphere when burned. These processes play an important role in global warming and climate change, with significant impacts on the environment, atmosphere and oceans [18]. In this context, electrical energy is seen as a major renewable energy solution to reduce these environmental problems. Unlike fossil fuels, hydropower generation uses energy from flowing water, producing emission-free electricity. This contributes to efforts to reduce the carbon footprint associated with energy production by making electrical energy a sustainable option [19] [20]. One of the most important environmental benefits of hydroelectric energy is its role in mitigating climate change. Climate change, which occurs as a result of the accumulation of greenhouse gases in the atmosphere, traps heat and causes changes in the Earth's temperature. Hydropower helps reduce greenhouse gas emissions by providing electricity without greenhouse gas emissions and plays an important role in reducing the negative effects of climate change. Additionally, hydropower helps reduce greenhouse gas emissions in line with the global climate change initiative. Hydroelectric power plants provide clean and healthy energy by not emitting emissions, unlike traditional electricity generation based on fossil fuels. Most importantly, it is important to move away from fossil fuels due to the urgency of solving environmental problems, especially the serious consequences of climate change. Electricity is not only considered a practical energy solution, but also plays an important role in improving the environment by mitigating climate change and reducing greenhouse gas emissions, thus contributing to an increasingly better future for our world [21] [22].

1.6. Cameroon's Energy Landscape

Cameroon's energy sector has a unique history, starting with its dependence on hydropower since 1902 [23]. This historical context not only highlights the country's enduring relationship with electricity, but also paves the way for deeper

research within the scope of this study. Our analysis of Cameroon's energy sector provides insight into the development, challenges and opportunities of this sector, especially as the country combines a strong electricity history with a rapidly growing economy. Cameroon's long-standing dependence on hydropower as a major renewable energy player. This dependence reflects the abundance of electricity in the region and the direction of the strategy to use clean and sustainable energy sources. As our research progresses, an in-depth study of this historical context provides important insights into the foundations of Cameroon's energy strategy, laying the foundation for the analysis of contemporary energy projects [24]. Research into non-renewable electricity is widely used to improve the economy. Cameroon's economic growth presents challenges and opportunities in the field of sustainable energy. Renewable energy represents unused energy that, when used wisely, can lead to energy self-sufficiency and economic growth. Set in Cameroon's energy sector, this study offers a way to understand the challenges of combining historical past, current challenges, and future demands for sustainable energy development. Research on renewable and non-renewable sources of electricity is beneficial because it is compatible with the national plan to solve increasing energy problems, respecting the principles of environmental sustainability [25]. Cameroon's energy system is a natural one, combining historic power lines with existing solutions to meet energy needs as the economy grows. With this study, we aim to discover the hidden problems in this unique energy structure and shed light on ways that can lead to the sustainable and sustained development of the country.

1.7. Market Competition and Efficiency

Market competition and efficiency are critical to energy production in Cameroon, highlighting the need for business development in the face of intense competition. The dynamics of the Cameroon energy market highlight the importance of efficiency and decision-making in the development of an energy project. In this competitive environment, companies need to understand the economic potential of such projects and use resources effectively to achieve the best results [26]. Efficiency is seen as the key factor of success in a competitive energy market where many players compete for turnover and market share. Companies operating under this model need to coordinate their project development activities in order to gain a competitive advantage. This requires not only efficiency, but also following guidelines, obtaining funding, and completing projects on time. Assessing the economic feasibility of hydropower projects is a priority in this field. The company must conduct a comprehensive analysis to evaluate construction costs, expenses, potential return on investment, and sustainability of the project. This type of evaluation is important to make good decisions to ensure that selected projects are compatible with economic and environmental objectives [27]. The process becomes more complex due to the importance of developing a project quickly and efficiently. Time is a valuable tool in a competitive market and delays can impact businesses. Successful project development, combined with a deep understanding

of economic feasibility, helps companies seamlessly solve problems from obtaining permits to starting construction and bringing energy to market. Efficient distribution methods are also important. The company must use financial, human and technological strategies to maximize the success of the project in the competitive energy market. This requires a comprehensive understanding of the economic environment, including market trends, government support and potential risks. Providing practical tools ensures that companies are well-positioned to capture opportunities, adapt to market conditions, and improve the overall performance of the Cameroonian energy sector [28].

2. Literature Review

2.1. Hydropower

Hydropower, also known as hydroelectricity, constitutes an important renewable energy source by utilizing the potential energy of water at high altitudes. The flow of water in the hydrological cycle contains a lot of energy that can be used efficiently to generate electricity or for mechanical work such as grinding grain, making electricity a more efficient and sustainable option. Its two-thousand-year historical journey, from ancient Greece, demonstrates its durability and adaptability thanks to technological advances in turbine technology [29]. Hydroelectric dams are classified according to several characteristics, including operating methods, installed capacity, and operating efficiency, and hydroelectric dams regulate the flow of water throughout the construction of dams, dams, and conventional dams with pumped storage that serves as energy storage. These categories provide information on different electricity sectors and their roles in providing sustainable and reliable electricity and addressing environmental and social issues.

2.2. Hydropower in the World

The world energy market has grown rapidly due to population and industrial growth, resulting in a 70% increase in global energy consumption, with an annual increase of 2% since 1971 [30]. In 2007, hydropower was responsible for 15.6% of the world's electricity, and if you factor in pumped storage, it was 16% of the world's electricity that year [31]. This highlights the important role of electricity in the global energy mix. Hydropower plays an important role in the energy supply of 55 countries and is the only source of domestic energy in some countries [32]. However, despite its established technology and history of use, much of its potential remains untapped. Although the technical and economic potential of the global electrical energy potential is approximately 14,370 TWh/year and 8,080 TWh/year, only one-third of the economy has been developed so far [33]. The unused capacity is concentrated in Asia, Africa and South America, where water and energy are most important. While Western countries used most of their rivers to generate electricity in 1975, the distribution of electricity by continents in 2022 shows that Asia made the biggest contribution to the world, followed by North America and the South; Even Africa has a lot of untapped potential [34]. Certain

countries such as China, Russia, Canada, Brazil, the USA are seen as important contributors at the national level. Despite the decline in the overall share of electricity in total electricity production due to the rapid growth of fossil fuels, electricity still plays an important role in the global energy supply and contributes significantly to the renewed role of renewable energy. Forecasts show that electricity consumption is expected to increase, especially in non-OECD countries, with electricity consumption expected to double between 2006 and 2030. But falling technology costs and government policies are encouraging more energy. The proliferation of renewable energy in electricity is expected to make renewable energy the fastest-growing energy source in the world, impacting both OECD and non-OECD countries and reflecting the global trend towards dependence on renewable sources [35].

2.3. Energy Present Status in Cameroon

Today, Cameroon's landscape shows a mix of traditional and modern energy sources, in which biomass, oil and electricity play an important role. Biomass remains the most important energy source and accounts for a large portion of the country's energy consumption. This dependence on biomass is particularly evident in the residential sector, where biomass accounts for the majority of energy used for cooking and heating. Petroleum products, including gasoline, diesel and petroleum, are also used mainly in transportation and industry. In terms of electricity generation, Cameroon relies on a combination of hydropower, natural gas, oil and, increasingly, solar energy (PV). Hydropower is the main source of electricity for the grid, and many large power plants contribute to the country's electricity supply [36]. Natural gas and petroleum gas are used in thermal power plants to generate electricity during periods when water is scarce. Solar radiation is also increasing, although at a slower rate than other sources. Utilities such as ENEO, GLOBELEQ, ALTAAQA, SinoHydro China and AGGREKO play an important role in energy production and distribution. The national grid consists of several interconnected networks operating in different parts of the country, with plans to further connect and expand the network infrastructure to provide reliability and access to electricity in Cameroon. Overall, Cameroon's energy sector faces challenges in terms of reliability, affordability and sustainability, but efforts are being made in the country to diversify energy sources, improve infrastructure and develop renewable energy sources to meet the energy needs of the land [37].

Overview of Hydropower Development in Cameroon

Hydropower development in Cameroon has been a cornerstone of the country's energy strategy, leveraging abundant water resources to generate electricity and promote sustainable development. With an extensive network of rivers and waterways, Cameroon has untapped hydropower potential, making it a good candidate for large-scale hydropower projects [38]. In recent years, the Cameroonian government has launched various electricity projects in order to capitalize on this potential and diversify the country's energy. These plans led to the construction

of many hydroelectric power plants across the country, with important projects such as the Lom Pangar Dam, Nachtigal Hydroelectric Dam, and Song Loulou Hydroelectric Power Plant. These projects not only contribute to solving the country's electricity problems, but also position Cameroon as an important energy market in Central Africa by offering export and regional integration opportunities. Additionally, electricity development is consistent with Cameroon's renewable energy and climate change commitments, providing a clean and reliable source of electricity and reducing dependence on fossil fuels. However, electricity development in Cameroon also faces challenges, including environmental and social impacts, regulatory constraints, and financial constraints [39]. Solving these problems requires a holistic approach that balances the economic benefits of electricity with an emphasis on environmental protection and social justice. Despite the challenges, the development of electricity remains a priority in Cameroon, offering huge opportunities for sustainable energy production and social and economic development.

2.4. Analysis of Cameroon Electricity Sector

Cameroon is highly dependent on electricity, accounting for 95% of electricity. Despite the abundance of energy, including powerful electricity, only 20% of the population has access to electricity, especially in cities. Rural electrification is even lower; It is less than 15%. Low investments in alternative energy sources such as solar energy, biomass and natural gas [40]. Three major hydroelectric dams operate in the country, but constraints such as high costs, transportation problems and distribution restrictions keep people off the electricity grid for a large portion of the population. Addressing these issues is of great importance for Cameroon to use its energy efficiently and provide reliable electricity throughout the country. (Table 1)

Table 1. Analysis of Cameroon electricity sector.

Energy Sources	Hydropower dominates the electricity sector, constituting approximately 95% of the total electricity produced and sold in Cameroon. Other potential energy sources include sunlight, biomass, and natural gas reserves, but limited investments have been made to harness these resources [41].
Electricity Access	Only about 20% of the Cameroonian population has access to the grid network, with urban areas having higher access rates compared to rural areas. Rural electrification lags significantly at less than 15%, indicating a significant disparity in electricity access between urban and rural communities [42].
Major Hydropower Dams	Cameroon operates three major hydropower dams: Songloulou (387 MW), Edea (263 MW), and Lagdo River Benuje (72 MW). Additionally, there are three retaining dams (Mbakaou, Bamendjin, and Mape) strategically placed on the main tributaries of the Sanaga River to augment power generation [43].

Continued

Challenges and Issues	High production costs, transportation challenges, and distribution constraints pose significant challenges in the Cameroon electricity sector. Disconnections from the grid are common among many Cameroonians, often attributed to price increments by the energy company AES-SONEL Cameroon [44].
Potential for Improvement	Addressing challenges in production costs, transportation, and distribution infrastructure is essential to ensure reliable electricity access for both urban and rural areas. Investing in alternative energy sources such as solar, biomass, and natural gas could diversify the energy mix and reduce dependence on hydropower [45].
Government Initiatives and Policies	Implementing policies to encourage private sector investment in the electricity sector and improve regulatory frameworks can stimulate growth and development in the industry. Promoting rural electrification projects and initiatives to increase access to clean and affordable energy for all segments of the population is a priority for the government [46].

2.5. Case Studies Specific Hydropower Projects in Cameroon

Hydropower projects in Cameroon underscore the government's commitment to achieving energy self-sufficiency and driving socio-economic development. Among these projects, the Mape Dam, initiated in 1978, aims to bolster the southern interconnected network's electricity supply by regulating the Sanaga River flow during the dry season, resulting in additional electricity production and substantial water reservoir creation. Similarly, the Bamendjin Dam, constructed between 1972 and 1974, enhances the Sanaga River's flow to power existing hydroelectric plants. Another significant endeavor is the Lom Pangar Dam project, serving the dual purpose of supplying water to existing power plants and increasing production capacity [47] [48]. Despite their benefits, these projects face challenges such as financial implications, environmental concerns, and resettlement issues. Additionally, projects like the Mouséré Hydroelectric Project and the Grand Eweng Project hold strategic importance in supporting industrial processes and regional energy needs, further reflecting Cameroon's ambitious plans for hydropower development. The government's efforts to modernize existing operations and establish new power plants demonstrate a proactive approach towards enhancing the country's energy sector, albeit with challenges that require careful management and mitigation strategies.

1) Lom Pangar Hydroelectric Project: The Lom Pangar Hydroelectric Project is one of Cameroon's flagship hydropower initiatives aimed at enhancing energy security and fostering economic development. This project involves the construction of a dam on the Sanaga River, creating a reservoir with significant storage capacity. The hydropower plant utilizes the stored water to generate electricity, contributing to grid stability and reducing reliance on fossil fuels [49]. The project has faced challenges related to the resettlement of affected communities, environmental conservation, and infrastructure development. However, it represents a

significant investment in Cameroon's renewable energy sector and demonstrates the country's commitment to sustainable development.

2) Menchum Hydroelectric Project: The Menchum Hydroelectric Project is a run-of-river scheme located in the Menchum River Basin in northwest Cameroon. This project harnesses the natural flow of the Menchum River to generate electricity without the need for a large dam or reservoir [50]. By leveraging the region's abundant water resources, the Menchum Hydroelectric Project contributes to local electrification efforts and promotes rural development. However, like many hydropower initiatives, it has faced challenges related to environmental conservation, land acquisition, and community engagement. The project serves as a case study for decentralized energy production and its potential to empower local communities while mitigating environmental impacts.

3) Edea Hydroelectric Complex: The Edea Hydroelectric Complex, located on the Sanaga River near the town of Edea, is one of Cameroon's oldest and largest hydropower facilities. The complex consists of multiple generating units and dams, with a total installed capacity exceeding 700 megawatts. Initially developed to meet industrial and urban electricity demand, the Edea Hydroelectric Complex plays a crucial role in Cameroon's power sector, providing reliable and affordable electricity to industries, households, and commercial enterprises. Over the years, the complex has undergone upgrades and expansions to increase efficiency and adapt to changing energy needs. However, it also faces challenges related to sedimentation, reservoir management, and environmental conservation, highlighting the complexities of managing large-scale hydropower projects in dynamic ecosystems [51] [52].

These case studies offer valuable insights into the diverse range of hydropower projects in Cameroon, showcasing both the opportunities and challenges associated with sustainable energy development in the country. Through careful analysis and lessons learned from these projects, stakeholders can make informed decisions to promote responsible hydropower development and achieve long-term energy security and environmental sustainability.

3. Assessment of Social and Environmental Implications of Hydropower Development in Cameroon

Social and environmental assessment of electricity development in Cameroon is important to understand the different impacts of such projects on the population and the environment. This assessment examines a variety of factors to ensure the implementation and sustainability of hydropower projects, including community participation, indigenous rights and cultural heritage protection. Electricity as a renewable energy source provides environmental benefits and problems in Cameroon [53]. On the one hand, it contributes to limiting climate change by producing emission-free electricity, thus reducing carbon dioxide emissions compared to burning fossil fuels. In addition, the hydroelectric power plant acts as a carbon sink, capturing vegetables in storage and preventing them from spoiling, which

would otherwise release greenhouse gases [54]. But the environmental impacts of electricity can be significant and specific. Large-scale projects, especially reservoirs, can lead to habitat loss, degradation of ecosystems, and changes to natural processes such as fish migration and waste transport. Additionally, the construction of dams and related infrastructure can contribute to erosion, alter water quality, and affect biodiversity. Despite their limitations, run-of-river energy projects generally have less environmental impact than storage-based projects because they cause less damage to rivers and the environment. Overcoming these environmental challenges requires careful consideration of environmental impacts, ecosystem protection measures and climate change adaptation measures for the sustainable development of hydropower in Cameroon. Additionally, complying with stringent environmental regulations and encouraging community participation in decision-making processes are important to reduce environmental impacts and promote sustainable energy while protecting ecosystems and ecosystems [55]. In the social context, community participation is important so that the target community is adequately informed about the project plans and has the opportunity to participate in the decision-making process. This includes addressing issues related to land acquisition, settlement and compensation for affected communities. Additionally, the rights of indigenous peoples must be respected by recognizing the traditional land ownership and customs of indigenous peoples living in Project [56]. Environmental impact assessments include potential impacts of habitat degradation, ecosystem loss, watershed degradation, and runoff on river ecosystems. This assessment helps identify sensitive environmental areas and measures that can be taken to reduce adverse environmental impacts. Mitigation measures may include implementing sustainable land management to prevent erosion and soil erosion, as well as ecosystem restoration measures such as reforestation and habitat restoration [57]. Additionally, stakeholder consultations play an important role in solving social and environmental problems, ensuring that the voices of affected communities, non-governmental organizations and other relevant stakeholders are heard and taken into account during decision-making. By encouraging dialogue and cooperation among stakeholders, hydropower projects can be planned and implemented to maximize profits while minimizing negative impacts on people and the environment.

Economic Analysis of Hydropower Projects in Cameroon

The economic analysis of hydropower projects in Cameroon is crucial for understanding their financial viability and broader economic implications. This analysis involves several key components:

- 1) *Cost-Benefit Evaluation*: Conducting a comprehensive cost-benefit evaluation is essential to assess the economic feasibility of hydropower projects. This involves identifying and quantifying both the costs and benefits associated with project development and operation. Costs may include capital expenditures for infrastructure construction, land acquisition, environmental mitigation measures, and

ongoing operational expenses. Benefits may encompass revenue from electricity sales, avoided costs of alternative energy sources, and socio-economic benefits such as job creation and improved energy access [58].

2) *Financial Modeling*: Financial modeling plays a central role in projecting the cash flows of hydropower projects over their operational lifespan. This involves estimating revenue streams, operating expenses, depreciation, taxes, and financing costs. Various financial metrics such as the internal rate of return (IRR), net present value (NPV), and payback period are calculated to assess the project's financial performance and attractiveness to investors. Sensitivity analysis helps identify key variables and assess the project's resilience to potential changes in market conditions [59].

3) *Economic Contribution Analysis*: Evaluating the economic contribution of hydropower projects involves assessing their impact on the broader economy. This includes estimating the direct and indirect effects on GDP growth, employment generation, and income distribution. Hydropower projects create employment opportunities during construction and operation phases, stimulate local economic development, and generate revenue for the government through taxes and royalties. Furthermore, the integration of hydropower into the energy mix enhances energy security, reduces dependence on imported fuels, and promotes sustainable economic development [60].

4) *Risk Assessment*: A thorough risk assessment is essential to identify and mitigate potential financial risks associated with hydropower projects. Risks may include construction delays, cost overruns, fluctuations in electricity prices, regulatory uncertainties, and environmental and social impacts [61]. Risk management strategies such as diversification, insurance, and contingency planning are employed to minimize these risks and ensure the long-term financial sustainability of the projects.

4. RETScreen Clean Energy Analysis Software

Assessing small hydropower project feasibility and impacts requires using various tools and methods for a thorough evaluation. Developing such projects entails significant financial investment, time, and engineering expertise. Investors and developers prioritize efficient resource allocation, making tools that save time and costs highly desirable. Computer-based assessment tools, ranging from simple programs to advanced software packages, play a crucial role. Their main aim is to predict energy output for specific hydropower schemes, with some also facilitating cost estimation and financial analysis. Wilson evaluated these tools for initial project assessments, highlighting key features in **Table 2**. Utilizing these tools streamlines the assessment process, empowering developers to make informed decisions and optimize resource allocation [62].

The DSI (State Hydraulic Works) defines firm energy as the reliably deliverable energy 95% of the time [64]. The discharge exceeding this threshold hovers around 40 m³/s. It's noteworthy that the design discharge for CanmetENERG used in

Table 2. Discharge at CanmetENERG Weir [63].

Year	Discharge (m ³ /s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1986	50.1	49.5	53.5	60.3	52.8	106.5	236.6	191.2	69.9	43.6	41.2	45.2
1987	49.6	51.2	55.4	56.9	52.7	64.3	88.2	125.8	82.2	45.8	41.6	45.3
1988	51.3	51.6	58.7	57.2	53.1	74.4	460.9	313.2	97.9	44.1	42.5	46.0
1989	51.6	52.7	56.2	55.1	52.9	65.3	99.4	248.4	68.9	43.0	40.3	44.3
1990	52.1	49.7	53.7	55.8	60.0	66.0	53.1	60.9	41.9	43.0	40.6	46.6
1991	54.2	55.9	62.9	65.7	59.4	77.7	86.9	63.7	57.9	48.1	48.3	54.3
1992	62.5	65.8	53.3	30.9	33.8	79.4	120.5	76.9	64.6	46.9	46.8	50.6
1993	58.1	60.5	65.7	64.9	30.7	44.4	91.1	77.5	60.5	57.1	26.9	1.6
1994	11.2	22.9	23.9	14.7	16.0	65.4	84.4	73.5	55.9	44.1	45.0	53.2
1995	60.0	56.9	28.1	18.2	20.1	85.0	107.9	70.6	60.2	47.3	42.9	49.4
1996	57.4	59.4	66.4	55.3	26.3	78.8	82.6	81.8	59.4	41.7	39.3	43.9
1997	53.0	50.3	52.8	54.4	58.0	65.4	79.0	90.1	69.3	41.3	40.6	44.7
1998	55.0	56.8	58.3	60.8	65.5	96.5	137.1	183.2	67.2	40.8	40.9	46.8
1999	51.1	53.2	57.3	75.2	63.1	70.4	76.2	66.8	49.0	41.8	41.6	47.7
2000	54.1	60.4	58.6	59.2	56.6	87.1	82.8	195.2	51.0	42.2	39.6	43.5
2001	49.5	52.3	57.6	57.9	56.8	106.7	74.1	83.4	61.0	41.2	39.8	42.9
2002	50.7	53.2	59.1	57.6	53.8	63.8	115.9	169.2	74.9	43.1	42.9	45.8
2003	48.0	51.0	53.9	56.9	52.7	76.3	93.8	124.2	44.5	43.4	42.5	48.6
2004	52.5	60.2	62.4	62.7	57.1	71.2	75.0	61.6	46.6	38.9	42.1	46.4
2005	51.6	52.5	55.0	57.7	57.6	71.2	94.4	67.3	50.2	43.5	43.5	49.1
2006	58.7	64.2	69.2	69.6	67.8	71.8	80.7	104.5	75.5	47.8	44.5	47.8
2007	57.5	63.4	70.2	72.1	77.8	64.1	110.6	101.1	130.1	43.1	42.2	46.5
2008	50.0	56.0	66.1	54.7	54.9	89.6	224.6	343.4	170.0	50.7	41.6	45.2
2009	59.5	197.0	210.9	149.2	123.8	185.8	220.8	74.5	44.6	40.7	41.0	46.8
2010	50.8	61.7	65.2	55.5	50.4	68.8	129.4	313.1	107.8	46.2	60.7	46.4
2011	94.0	50.7	70.4	52.6	54.4	95.8	108.9	166.9	65.1	39.7	44.2	48.0
2012	55.7	60.0	78.6	57.8	53.7	73.8	114.2	139.6	91.4	51.9	53.2	62.4
2013	53.9	61.5	82.2	75.0	70.1	97.1	119.0	365.6	189.4	55.3	46.9	46.5
2014	60.3	61.2	60.0	65.3	61.2	69.4	68.3	64.8	45.7	47.2	48.3	52.0
2015	60.6	57.1	64.5	99.9	83.9	92.1	102.6	84.5	54.8	43.2	46.6	53.8
2016	58.6	66.3	70.6	65.1	56.7	71.0	87.9	333.4	64.0	45.0	45.5	54.5
2017	63.4	71.3	65.0	58.4	55.4	64.5	125.5	230.8	73.9	50.1	53.5	54.6
2018	57.7	53.6	59.9	60.4	57.2	71.4	249.2	291.0	155.7	47.6	48.6	46.2
2019	54.2	60.1	61.7	57.0	47.6	58.0	205.1	249.7	83.7	45.2	41.7	43.2
2020	49.2	57.1	49.3	55.2	52.9	64.6	164.5	182.0	59.6	49.2	44.0	49.6
2021	53.3	54.1	61.0	63.1	61.2	71.0	65.5	72.7	53.0	53.8	58.0	60.3

DSI's formulation is $60 \text{ m}^3/\text{s}$, surpassing this value approximately 40% of the time. Conventionally, design discharges for small Hydropower Plants (HEPPs) in Cameroon often correspond to discharges occurring 20% - 30% of the time. For energy computations in this study, the flow duration curve from the Feasibility Report [65]. This dataset includes monthly average discharges spanning from 1986 to 2021. However, to account for recent changes in the flow regime, monthly average discharges for 2022-2023 are also extracted from another feasibility report [47].

Table 3 presents the monthly average discharge data for the years 2022 and 2023 at CanmetENERG. The values are given in cubic meters per second (m^3/s), indicating the average flow rate of water over each month. These measurements offer insights into the variations in river discharge over different months, which are crucial for understanding the hydrological dynamics and planning water resource management strategies. The provided information suggests that adding flow data from 2022-2023 to the flow duration curve of CanmetENERG results in a slight decrease in discharge values (**Figure 1**). This decrease indicates a practical consequence: the anticipated annual energy generation is expected to decrease accordingly. This impact is reflected in **Table 2**, where the revised flow conditions lead to a noticeable shift in the expected annual energy generation.

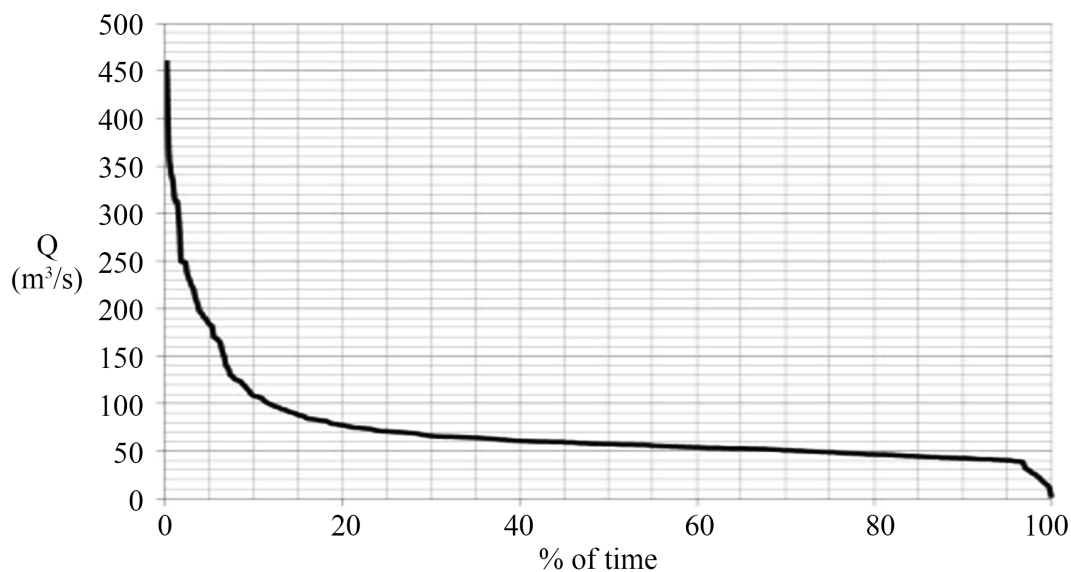


Figure 1. Flow duration curve of CanmetENERG [66].

Table 3. Monthly average discharges between 2022-2023 [67].

Year	Discharge (m^3/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	48.9	56.6	31.5	16.4	11.0	14.2	86.2	89.5	71.6	53.2	33.2	30.5
2023	25.7	18.1	21.5	35.4	27.1	87.6	77.9	67.7	62.3	43.8	43.4	52.4

Table 4. Energy production for two different flow duration curves [68].

Q (m ³ /s)	With data of 1986-2021	With data of 1986-2021	Difference %
50	204,366	200,901	-1.7
60	232,626	228,133	-1.9
70	250,874	245,619	-2.1
80	262,945	256,992	-2.3
90	271,871	265,608	-2.3
100	279,144	272,892	-2.2

Table 4 compares cumulative flow volumes derived from two different flow duration curves (FDCs) spanning the years 1986 to 2021 for several flow rates (50, 60, 70, 80, 90, 100 m³/s). Each entry in the table represents the total volume of water that equaled or exceeded a particular flow rate according to each dataset. The percentage difference column shows negative values (-1.7% to -2.3%), indicating that the first dataset generally recorded higher cumulative flow volumes compared to the second dataset across all listed flow rates. These discrepancies are essential for assessing variations in hydrological data and have implications for water management practices, hydroelectric power generation, and environmental monitoring in the studied area.

5. Possible Alternatives to DSI formulation of CanmetENERG

Exploring alternative formulations for the CanmetENERG layout in the Lom Pangar project involves considering various design aspects to optimize efficiency, environmental impact, and overall performance. Potential alternatives include:

- 1) *Conveyance System Layout*: Reevaluating the layout of the conveyance system to optimize efficiency and reduce environmental impact.
- 2) *Turbine Technologies*: Experimenting with turbine technologies beyond Francis turbines to enhance energy production.
- 3) *Water Sourcing*: Assessing alternative points for sourcing water to improve system efficiency and minimize environmental impact.
- 4) *Hydraulic Design Parameters*: Exploring variations in hydraulic design parameters, such as penstock diameter and turbine speed, to enhance energy production.

These alternatives aim to minimize environmental impact, optimize infrastructure configuration, and incorporate energy storage solutions for a more sustainable and resilient hydropower project. Community and stakeholder involvement, along with considerations for climate resilience, are crucial to ensure alignment with local needs and environmental sustainability. Thorough feasibility studies and assessments will be essential to determine the viability and appropriateness of each alternative for the unique conditions of the Lom Pangar project.

The investigation into alternative formulations for the CanmetENERG project aims to enhance energy generation efficiency while minimizing costs. This

involves evaluating alterations to key components such as the diversion weir, forebay, and powerhouse, as well as redefining the trajectory of the water conveyance system and adjusting the design discharge. Preliminary assessments using topographic maps provide insights, but on-site investigations are necessary for a comprehensive understanding. The topography of the region and the presence of upstream or downstream power plants influence the selection of component locations. While some components like the powerhouse and diversion weir locations may have limited flexibility due to topographical constraints, alterations in the water conveyance system and design discharge can still optimize energy generation [69].

The conclusion of the study underscores the pivotal role of hydropower projects in fostering sustainable development, particularly in countries like Cameroon where hydropower is positioned as a vital domestic and renewable energy resource. Hydropower projects not only offer economic benefits but also create opportunities for market growth and business development, especially in developing nations. The focus on the CanmetENERG project aligns with broader objectives of enhancing national energy security and reducing reliance on imported resources [70].

The application of the RETScreen Clean Energy Project Analysis Software in evaluating the economical feasibilities of various alternatives for the CanmetENERG project proves instrumental. However, it is important to acknowledge the software's limitations, particularly in environmental analysis and consideration of seismic, erosion, and sediment issues. Therefore, a holistic approach integrating economic, environmental, and social dimensions is essential in the planning and development of hydropower projects.

The study emphasizes the significance of considering not only economic factors but also environmental, social, and cultural aspects in project development. While economic viability is crucial, projects must align with principles of sustainable development and adhere to international standards. This necessitates proactive legislative and administrative measures to ensure responsible resource utilization, contributing to a cleaner and more resilient energy future for the nation.

Continued research and technological innovation in the field of hydropower are deemed essential to enhance project efficiency and sustainability. Collaboration between academia, industry, and policymakers is encouraged to explore cutting-edge solutions, improve project outcomes, and address emerging challenges. Additionally, community engagement and stakeholder involvement are highlighted as integral aspects of project planning and execution, promoting transparency and social responsibility [70].

The study underscores the importance of adaptive management strategies to ensure project resilience in the face of uncertainties, climate change, and evolving energy market dynamics. Hydropower development requires a holistic and forward-thinking approach that balances economic viability, environmental sustainability, and social responsibility.

Ultimately, the CanmetENERG Hydropower Project in Cameroon is envisioned as a model for responsible and sustainable hydropower development, contributing to the nation's energy security and a greener, more resilient future. The study's findings and recommendations offer broader insights into best practices for sustainable energy development, addressing the universal challenge of balancing energy security, economic viability, and ecological integrity in a rapidly evolving global energy landscape.

6. Future Study

Future research on hydropower development, specifically concerning the Canmet-ENERG Project in Cameroon, should prioritize advancements in hydraulic modeling techniques, such as incorporating AI or machine learning, to enhance the accuracy of predicting water flow patterns and optimizing design discharge. Additionally, there's a need to refine risk assessment methodologies, particularly for seismic activity and operational challenges, to improve risk mitigation and project resilience. Innovations in economic analysis methods are crucial for considering changing electricity prices and market dynamics, aiding decision-making and investment planning. Environmental impact assessment methodologies should be expanded to encompass broader ecological considerations, including sustainable practices and biodiversity conservation. Leveraging big data analytics can provide more nuanced insights into project feasibility and environmental impacts. Lastly, emphasizing community engagement and stakeholder involvement in future research is essential for developing effective strategies for inclusive decision-making and addressing local concerns about hydropower projects.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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