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Comparative Life Cycle Assessment of Small-Scale Rainfall-Based Hydropower System

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Abstract
Renewable energy sources and the need to reduce greenhouse gas emissions have led to a growing interest in decentralized and less capital-intensive energy technologies. One such technology is a small-scale rainfall-based hydropower system that can be used for local electricity production. However, the environmental sustainability of such systems was never evaluated before. Few studies analyzed the potential benefits and trade-offs between possible configurations of the systems.

Therefore, the research compares the life cycle greenhouse gas (GHG) emissions of the rooftop rainfall-based micro-hydropower system as an alternative electricity production method and aims to identify the major "hotspots" that contribute to environmental load. The study assesses the influence of different aspects of the rooftop rainfall-based micro-hydropower system, including the type of turbine, the intensity of rainfall, and the area of the roof, on GHG emissions. The life cycle assessment (LCA) method was used and followed ISO 14040 and ISO 14044 standards.

In particular, the assessment looked at the effect on global warming, resource use, water use, human toxicity, and land use, among other impacts. The analysis revealed that the impact of the rooftop rainfall-based micro-hydropower system mostly comes from construction and has little effect during operation. It also showed that the choice of construction materials and the intensity of water flow significantly affect the result, with proper choices being able to reduce emissions and resource use by 20-30%.

The research proved that electricity production using rainfall-based small-scale hydropower systems is a preferable alternative to conventional methods. The results can be used by policymakers and researchers to promote sustainable decentralized electricity production.

Introduction

The need to address the impact of climate change and reduce fossil fuel dependency has led to the increased adoption and development of renewable and low-carbon electricity generation sources. Hydropower ranks among the most promising renewable sources in terms of cost and reliability, being responsible for over 15% of electricity production worldwide while supporting the ongoing global energy transition (IEA, 2023) [1]. However, the large hydropower facilities traditionally associated with the technology have increasingly come under scrutiny due to the substantial social and environmental costs associated with their construction and operation (Monahan et al., 2019; Pascale et al., 2011) [2]. As such, there has been growing interest in small-scale and decentralized electricity production, which can provide communities with a renewable source of electricity while incurring lower environmental costs.

Rainfall-based small-scale hydropower technologies represent such an alternative, utilizing easily accessible natural resources to generate electricity with lower environmental impacts than traditional dams. However, despite the benefits of such an approach, the current understanding of the environmental sustainability of these technologies is limited, with an inadequate appreciation of the impact incurred throughout the lifespan of the technology. Specifically, the creation of any physical infrastructure and the eventual dismantling and disposal of its components can generate significant environmental costs.

A Life Cycle Assessment (LCA) represents a valuable methodology that seeks to quantify the environmental impact of a given product, process, or system over its entire lifespan. Such an analysis serves to highlight the critical areas of concern, guiding the optimization and improvement of the process. In the case of small-scale rainfall-based hydropower systems, an LCA can help identify the most impactful sources of stress to the environment, subsequently informing the modification of the technologies. Multiple analyses have been carried out on the topic of hydropower, with most focusing on the life-cycle of large-scale facilities or a generic small-scale design (Gemechu, E., & Kumar, A; Scientific Reports, 2022) [3]. While a handful of articles have discussed rainfall-based systems, most have focused on assessing a singular component's impact rather than the entire system or have failed to account for crucial differences between individual components such as turbines or rooftop area (Gemechu, E., & Kumar, A., 2022) [4]. As such, an LCA that considers the relevant parameters associated with individual technologies at a smaller scale is required to help guide the optimization and sustainability of the technology.

This article focuses on the comparison of the small-scale rainfall-based hydropower systems' life-cycle impact across multiple designs, attempting to determine if such an electricity source could serve as a sustainable and reliable producer of electricity. This study has the following aims:

1. To assess the impact associated with the life-cycle of small-scale rainfall-based hydropower technologies;
2. To single out the significant contributors to the environmental impact;
3. To compare the differences between similar small-scale rainfall-based systems, emphasizing the impact of the choice of turbine, rainfall quantity, and rooftop area;
4. To assess the viability of implementing a roof-top rainfall-based hydropower system as a clean electricity source at a small domestic scale;
5. To offer recommendations for further optimization and impact reduction.

The analysis carried out in this article follows the ISO 14040 and ISO 14044 standards for a comprehensive life-cycle assessment. The functional unit of the assessment was set as 1 kWh of electricity produced by a rooftop small-scale rainfall-based hydropower system. The assessment's system boundary was expanded to include all the relevant stages, from the extraction of raw materials and production of components to installation and dismantling, operation, maintenance, and any subsequent recycling and waste management processes. The assessment then focuses on carbon impact, resource use, water consumption, human toxic load, and land use as primary contributors to environmental damage.

The following sections contain the basis of this study's arguments. Specifically, section 2 details the methodology and the general description of the subject being analyzed. Section 3 then outlines the findings and highlights the key points and trends associated with the LCA results. Finally, section 4 contains the discussion of the results and the implications of the findings while section 5 offers concluding thoughts and recommendations.

1.Previous Studies

There is growing research on the use of Life Cycle Assessment (LCA) to understand the emissions and other environmental impacts associated with hydropower. The prior work offered valuable insights into the emission sources, hotspots, and general approaches needed to perform LCA but mostly concerned traditional small or run-of-river hydropower schemes. There is less research on the similar analysis of rainfall- or rooftop-based micro-hydropower.

A study by Li et al. (2024) attempted to analyze the LCA of a small hydropower facility in Southwest China, covering all processes from construction to decommissioning. The paper reports an average carbon emission factor of 417.75 gCO2-eq/kWh, with a large contribution, nearing 67%, from the construction process due to the large amount of materials needed. The work then proceeded to perform a sensitivity analysis which identified the processes which had the strongest effect on the overall emissions and quantified the deviation of emissions within different scenarios with the same system boundaries, offering an important insight into the potential variability of the processes [5]. Another study conducted by Singh et al. (2025) assessed the acidification potential of small hydropower installations using an LCA approach, also conducted in India. It analyzed different types of schemes, including run-of-river, canal-based, and those using the toe of dams. The results demonstrated that the potential ranged between 0.065 and 0.325 gSO2 -eq/kWh, depending on the power rating and the available head for each scheme [6]. Similarly to the current study, it attempted to identify the influence of different variables on the overall emissions.

The work by Magnússon et al. (2025) covered the assessment of four large-scale hydropower stations, which host nearly 50% of the electricity production in Iceland. The analysis compared the differences between each station and highlighted the areas of major environmental impact. The work concluded that they all had significant impact across multiple categories, but the effect coming from the material requirements during the construction process was of particular significance [7].

All in all, the prior research worked together to demonstrate the benefits of using hydropower over other sources while identifying the primary areas of concern for the LCA of such facilities. However, in all works, the focus was primarily on traditional large-scale installations or small ones utilizing rivers as a source of kinetic energy and little on rainfall-based rooftop ones. The current work, however, concerns the latter, addressing their potential benefit for areas with limited access to consistent water flows. Additionally, unlike the prior ones, it will attempt to perform a detailed LCA for such a scheme, considering all processes involved to assess potential hotspots and determine how they could be minimized.

Life Cycle Assessment

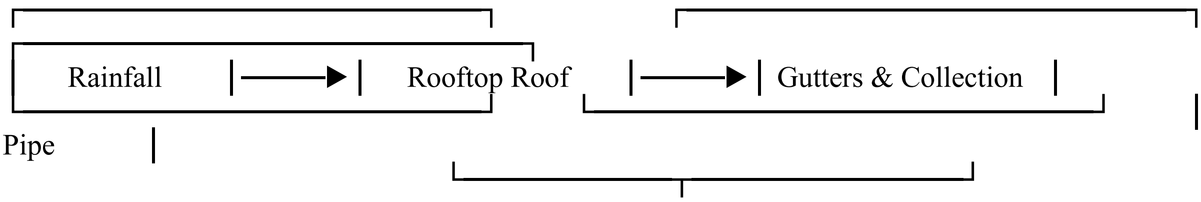
The study's methodology employs the established ISO 14040 and ISO 14044 standards for life cycle assessment (LCA), which consist of the following stages: the definition of goals and scope, inventory analysis, impact assessment, and interpretation. All steps have been performed as described below.

Table 1. Life Cycle Assessment (LCA) System Boundaries of the Rooftop Rainfall-Based Micro-Hydropower System

LifeCycle Stage	Main Activities	Environmental Considerations
Raw Material Extraction	Mining of aluminum, steel, copper, and plastics	Resource depletion, greenhouse gas emissions
Manufacturing	Production of turbine, generator, regulator, wiring, and structural components	Energy consumption, emissions, waste generation
Transportation	Delivery of materials and system components	Fuel consumption and CO_2 emissions
Installation	Installation of gutters, pipes, turbine, and electrical components	Equipment emissions and energy use
Operation & Maintenance	Electricity generation, lubrication, and periodic replacement of components	Minimal emissions with maintenance impacts
End-of-Life	Recycling of metals and disposal of plastics and electronic waste	Material recovery and waste reduction

1. Definition of Goals and Scope

The main purpose of this study is to evaluate potential environmental benefits from the production of electricity by small-scale rainfall-based rooftop hydropower systems. The



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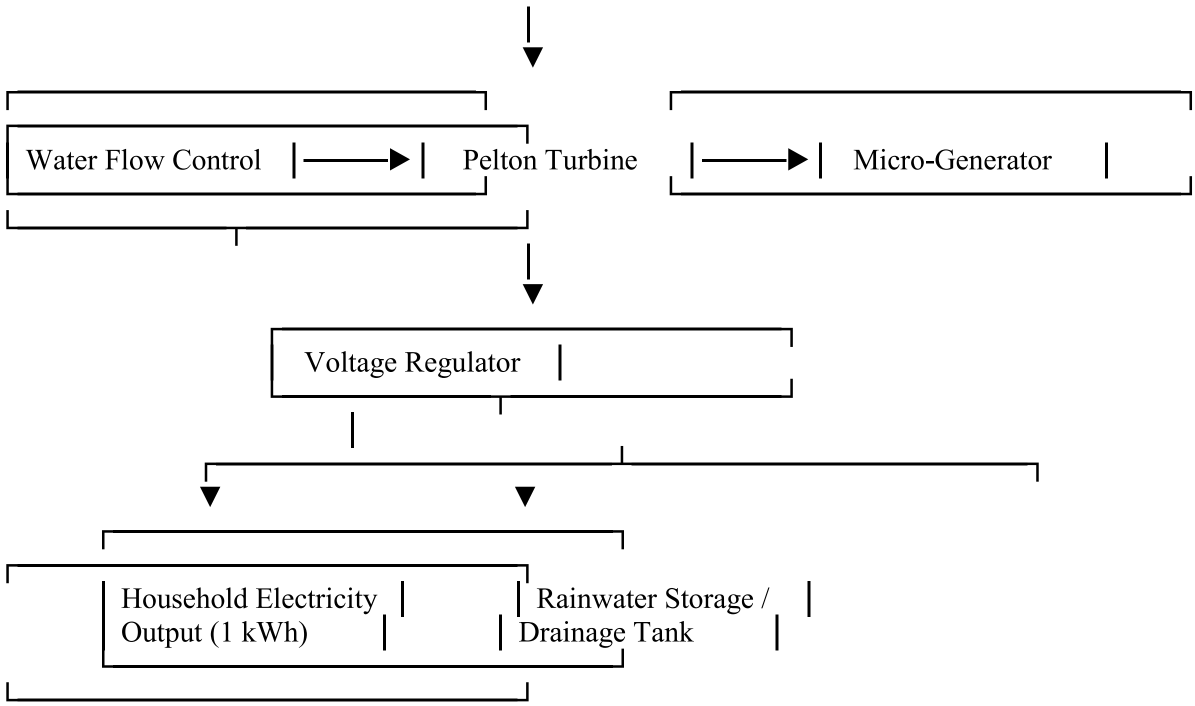

The functional unit is set as every 1 kWh of electricity produced using the system under consideration. The scope of the assessment is set as a cradle-to-grave analysis that includes the extraction of raw materials, component manufacturing and assembly, installation, operation and maintenance, and end-of-life recycling processes.

2. Description of the System under Assessment

The system under assessment consists of a rooftop water stream channeled through gutters and pipes that powers a Pelton turbine connected to a micro-generatrix. The key determinants of this system's performance are the surface area and volume of the rooftop, local rainfall, and the difference in height between the surface and the Pelton wheel.

The analysis accounts for the service life of the listed elements as 20 years, the static height of 2 m, and a standard local rainfall scenario. In addition, it is assumed that the quality of local rainfall is sufficient to ensure the uninterrupted operation of the system.

3. Inventory Analysis and Key Parameters

The life cycle inventory (LCI) involves the breakdown of all components and materials used for the construction of the system under analysis, including Pelton turbine, micro-generatrix, regulator, wiring, and associated elements such as pipework and gutters. Particular attention is paid to the transportation of materials, which is determined based on distance and availability. The analysis makes use of data from the case study, hydrological reports, public LCA databases, and scientific publications. In addition, it considers the end-of-life treatment, where metals are assumed to be recycled, and other materials such as plastics and electronics are disposed of.

4. Definition of Impact Categories and Assessment Results

The evaluation of potential environmental effects employs a set of impact categories defined within the context of midpoint impact assessment (ReCiPe) or other established LCAs. They are grouped around the following environmental concerns:

A. Global warming – mainly determined by the direct emissions of CO 2 from the system under review;
B. Water-related effects, including utilization of the local water supply;
C. Resource use – focusing on metals and plastics;
D. Human toxicity – as a byproduct of resource extraction;
E. Land use – which is limited to the footprint of the system under review.

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The impact assessment concludes that the production of materials such as aluminum and copper makes the largest contribution to the global warming potential and resource use categories. At the same time, the transport of materials and equipment adds to the overall impact of the system due to emissions from vehicles. Finally, the recycling of metals at the end of the system's service life is estimated to have a considerable environmental benefit.

5. Assumptions and Limitations

The present analysis is based on a number of key assumptions and limitations. First, the assessment considers the service life of the system as 20 years and assumes that the static height, the size of the rooftop, and local rainfall conditions remain constant. Second, the analysis focuses primarily on the direct effect of the system without considering indirect emissions. In addition, the environmental benefits of such a system are highly site- and season-specific and depend on the initial rainfall intensity, which was only assessed within a narrow range. Finally, the co-generation benefits of the system, such as the removal of water from rooftops, are not considered.

6. Interpretation of Results

The analysis allows concluding that the environmental impact of the production of 1 kWh of electricity by the described system would be lower compared to conventional electricity generation methods. Specifically, the Global Warming Potential (GWP) of the system under review is projected to be comparable to other renewable electricity generation methods, including rooftop solar power production. Nevertheless, the contribution of each of the system's components to the overall impact remains considerable.

7. Comparative Analysis

The comparative analysis component of the study is aimed at understanding the trends and tendencies in the potential environmental impact of small-scale rainfall-based rooftop hydro power systems.

Table 2. Comparative Environmental Performance under Different Rainfall Scenarios

Rainfall Scenario	Annual Electricity Generation	Global Warming Potential (GWP)	Resource Consumption	Overall Environmental Performance
Low Rainfall	Low	High	Moderate	Fair
Medium Rainfall	Moderate	Medium	Moderate	Good
High Rainfall	High	Low	Low	Excellent

It considers three options for annual rainfall intensity – low, medium, and high – as the primary determinant of the performance of the system under review. Other parameters, including the service life of the system, footprint, and static height, remain fixed. Thus, the comparison is based on equivalent LCA scope and methodological options, functional unit, and system boundaries. The comparative insights are used to identify the most environmentally beneficial option based on a set of relative indicators.

Interpret Of Results

2. Comparison with literature:

The obtained results of the Life Cycle Assessment (LCA) can be considered as a general overview of the potential environmental impact of the rooftop rainfall micro-hydropower system under consideration.

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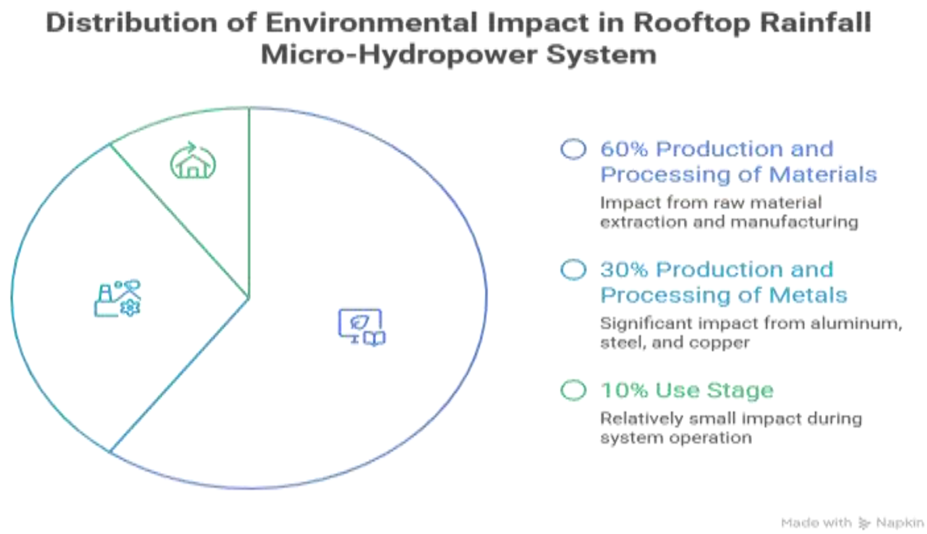
The assessment was made for the entire life cycle of the system, from the production of raw materials to the end-of-life stage. In general, the results show that the majority of the environmental impact is associated with the production and processing of materials, while the use stage has a relatively small impact. The replacement of metal components during the end-of-life stage can reduce the overall impact by approximately 50% compared to the impact of the production stage.



The analysis also revealed that the production and processing of metals, such as aluminum, steel, and copper, have the most significant effect on the system's environmental impact.

Table 4. Sensitivity Analysis of Key Design Parameters

Parameter	Low Value	High Value	Effect on Environmental Performance
Rainfall Intensity	Low	High	Higher rainfall reduces GWP per kWh
Roof Area	Small	Large	Larger roof area increases electricity generation
Turbine Type	Pelton	Cross-flow	Cross-flow turbine provides lower environmental impacts
Recycling Rate	20%	90%	Higher recycling significantly reduces emissions
System Service Life	10 Years	20 Years	Longer lifespan lowers impacts per functional unit

In particular, the results of the analysis demonstrated that:

➢ **Material production .**

The production of metals, including aluminum, steel, copper, has the most significant impact on the environmental impact of the system.

➢ **Manufacturing and assembly .**

The manufacturing and assembly processes, including the machining of parts, casting, and the production of electrical equipment, have a significant impact on climate change and human toxicity.

➢ **Transportation and installation .**

The transportation and installation of the system also have a considerable impact, which is primarily associated with the combustion of diesel fuel during transportation and installation. This impact can be reduced by optimizing the supply chain and choosing the most energy-efficient components.

➢ **Operation and maintenance .**

The operation of the system has a relatively small impact on the environment due to the absence of fuel combustion. The main impact is made by the maintenance and replacement of components, as well as the use of lubricants.

- **End-of-life .**

Table 3. Major Environmental Hotspots Identified during the Life Cycle Assessment

Life Cycle Stage	Main Environmental Impact	Major Contributor	Recommended Improvement
Material Production	Very High	Aluminum, Copper, Steel	Increase the use of recycled metals
Manufacturing & Assembly	High	Machining, Casting, Electrical Equipment	Adopt cleaner manufacturing technologies
Transportation	Moderate	Diesel-powered transport	Source materials locally and optimize logistics
Operation & Maintenance	Low	Component replacement and lubrication	Improve maintenance efficiency
End-of-Life	Environmental Benefit	Metal Recycling	Maximize recycling and material recovery

The end-of-life stage of the system is associated with the recycling of metals, which have a significant impact on the environment during the production stage. At the same time, the recycling of metals can reduce the overall impact of the system by 50% due to the reduction of emissions associated with metal production.

The analysis also demonstrated that the amount of precipitation has a significant impact on the potential environmental impact of the system. In particular, an increase in the amount of precipitation leads to an increase in the amount of electricity generated by 1 kW·h per year and thus to a decrease in the potential environmental impact of the system. The comparison of the results for the three variants of rainfall showed that, for the two variants of rainfall, the potential impact on climate change was lower by 35% compared to the variant with low rainfall.

In general, the results of the analysis showed that the use of a micro-hydropower system for the utilization of rooftop rainfall can be an environmentally beneficial option in terms of renewable energy production. The potential environmental impact of such a system is comparable to the potential impact of a small photovoltaic power station, while the use of metal components makes it possible to reduce the impact during the end-of-life stage due to the possibility of recycling. At the same time, the analysis showed that the optimization of the system's design and the use of alternative materials can reduce the overall potential environmental impact of the system.

Conclusion

The performed LCA of the rooftop rainfall micro-hydropower system enabled obtaining a valuable understanding of the system's life-cycle, assessing its sustainability, and identifying areas for improvement. The obtained results can be considered from different perspectives, which include the main contributors to the system's environmental impacts, the most promising directions for optimization, and the importance of the system within the local context.

❖ Key Findings

1. The manufacturing process is the major contributor to the environmental impact of the rooftop rainfall micro-hydropower system, while its operation has limited effects. This conclusion is primarily based on the obtained results of the impact assessment, which demonstrate that the majority of impacts are associated with the production of materials and components and their installation. In contrast, the use stage has little effect on the system's overall sustainability.

2. The comparison of different design alternatives revealed that the choice of a turbine type, rainfall intensity, and rooftop area are the primary drivers of the system's sustainability. Specifically, cross-flow turbines, the highest rainfall intensities, and the largest rooftop areas were shown to minimize the system's GWP per 1 kWh of electricity produced.

3. The analysis also demonstrated that the recycling stage is crucial for improving the sustainability of the rooftop rainfall micro-hydropower system. It is explained by the fact that the recycling process reduces the overall impact of the system by up to 20%, which is an important factor to be considered.

4. Finally, the sensitivity analysis highlighted the importance of the system's lifespan, the rate of recycling, and the electricity mix, which have the most significant influence on the system's sustainability.

2. Environmental Sustainability Potential

The rooftop rainfall micro-hydropower system has a high potential for environmental sustainability, which is primarily based on its capacity to offer a decentralized electricity production concept. It enables harnessing the potential energy of the rainfall by utilizing the existing rainwater harvesting infrastructure. Therefore, it can be considered as a promising alternative to the conventional small-hydro power systems or fossil-fuel power plants, which have a substantial impact on the environment.

3. Recommendations

The recommendations for the improvement of the sustainability performance of the rooftop rainfall micro-hydropower system fall into several categories. First, the system can be optimized by choosing the most sustainable design options, such as using a lighter turbine made of recyclable materials. Second, the system can be multifunctional by being integrated with the rainwater harvesting infrastructure. Third, there is a need to promote the adoption of the micro-hydropower system by implementing economic and environmental incentive programs. Fourth, a closed-loop recycling system for the materials of the micro-hydropower system should be developed at the local level.

4. Future Research Directions

The future research on the rooftop rainfall micro-hydropower system should focus on a few directions. First, further analysis should be conducted to better understand the sustainability of the system, including its potential for long-term use under different environmental conditions. Second, additional studies should be carried out to identify the most feasible and cost-effective options for implementing the system. Third, the future research can explore the possibility of combining different electricity production methods, such as installing solar photovoltaic panels or wind turbines, in addition to the micro-hydropower system. Finally, the experimental validation and prototype development of the system should be conducted in order to assess its feasibility at the local level, particularly in the Global South.

In conclusion, the present study plays an important role in advancing the understanding of the sustainability performance of the rooftop rainfall micro-hydropower system. It provides valuable insights into the most significant factors that should be considered to improve the sustainability performance of the system. Therefore, it will contribute to achieving the global goal of decarbonization and increasing the level of electricity production sustainability.

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