UNIVERSITY of RWANDA

SUSTAINABILITY OF SMALL-SCALE HYDROPOWER WITH CASE EVIDENCE FROM RWANDA

By

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A PhD thesis submitted towards partial fulfillment for the requirements for the degree of doctor of philosophy in renewable energy

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CO-SUPERVISOR: Senior researcher. Daniel Zimmerle

October, 2024

DECLARATION

I GASORE Geoffrey hereby declare that the dissertation entitled "**SUSTAINABILITY OF SMALL-SCALE HYDROPOWER WITH CASE EVIDENCE FROM RWANDA**" to be submitted for the degree of doctor of philosophy in renewable energy is my original work and the dissertation has not formed the basis for the award of any degree, diploma, associateship or fellowship of similar other titles. It has not been submitted to any other university or institution for the award of any degree or diploma.

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This thesis was possible because of your academic, moral and financial sport.

DEDICATION

To my wife Mutesi, my four daughters Mukundwa, Kundwa, Ikamba, Ishya Jayla and my parents Uzanyinyana and late Kayinamura

ABSTRACT

Climate change is increasingly affecting run-of-river power plants especially rivers in tropical regions with high variable flows and this raises their sustainability concerns. This study examines the sustainability factors of small hydropower plants using Rwanda as case study. It addresses the following specific research questions. First, the challenges and opportunities around small-scale hydropower plants. Secondary, which factors affecting sustainability of small-scale hydropower plants. Third, how to design the best size of a powerplant fed by run-of-river systems in tropical highlands. The study employs a nested methodological framework starting with descriptive analysis about opportunities and challenges around small-scale hydropower plants in Rwanda. A field survey was conducted to examine sustainability factors affecting small hydropower on 24 powerplants in Rwanda using structured questionnaire and field visit observations. A case study was applied at Sebeya river, and machine learning was used to predict the river flow, whereby energy generation of different turbines and levelized cost of energy at different sizes were estimated using a stochastic modeling. Lastly, experimental analysis using simulation for different sizes of a hydropower plants for different flow conditions was developed as a reference for stainability.

The study finds indicated that the major positive factors for sustainability of small hydropower power plants in Rwanda are; selling electricity to the national grid, adequate yearly rainfall and appropriate topography for run-of-river hydropower plants structure. The major negative factors affecting the sustainability of small hydropower plants are; (a) reduction in river discharge during the dry season due to decrease in rainfall intensity, (b) high volume of sediments in rainy season resulting from soil erosion which increases maintenance requirements and shortens turbine lifetime, (c) unplanned outages caused by grid problems.

Furthermore, the study finds that plants designed substantially above the ‘knee’ in the flow exceedance curve shown (Figure 16) produced a significantly higher LCOE. Investors are advised to design Run-of River plants at, or just below, the ‘knee’ in the flow exceedance curve in similar conditions with Sebeya river.

Additionally, some turbines such as propeller performs poorly in Sebeya flow conditions and similar climatic conditions. The findings and methods used can guide future investments in small hydropower plants designed on rivers in tropical conditions.

Keywords: Small hydropower, tropical rivers, variable flows, machine learning, sustainability

CONTENTS

ABBREVIATIONS

EIA	Environmental impact assessment.
ICT	Information and communications technology.
EDPRS	Economic development and poverty reduction strategy.
GIZ	German corporation for international cooperation.
DFID	UK department for international development.
IPPs	Independent power producers
REG	Rwanda Energy Group.
ROR	Run of-rivers
IPCC	Intergovernmental panel on climate change
NST	National strategy for transformation
LCOE	Levelized cost of electricity
ACE-ESD	African center of excellence in energy for sustainable development
RDB	Rwanda development board
EnDev	Energising development
DFID	UK department for international development
GDP	Gross domestic product.
ROR	Run-of-Rivers

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CHAPTER I. GENERAL INTRODUCTION

This thesis is derived from compilation of published papers and the following papers respond to the specific objective of this study, which complete the doctorate work of Gasore. Chapters are derived from specific research papers which were published by Gasore as part of his Ph.D. work.

Gasore is the principal author of the first three papers which constitutes the chapter II, III and IV while the last conference paper, he is the co-author and contributed in repairing of the plant and development of the paper. This paper is appendix A

1.1 Study Background

In the wake of changes in climate, governments and international communities are adapting policies to mitigate the effect of climate change. The situation. The Paris agreement [1], which is a result of UN climate climate change conference (COP 21) in Paris was adopted as a global solution to climate change threat. The Paris agreement is aiming at limiting global average temperature increase below 2 °C, achieving carbon neutral by 2050 and financing both greenhouse gas emission reduction and climate-resilient development[1]. However, the IPCC climate change report of 2022 on mitigation of climate change, finds that greenhouse gas emissions over the last decade were at the highest levels in human history. The report suggests that if no immediate actions and deep emissions reductions across all sectors are made, then limiting global warming to the state goal of 1.5 °C will likely not succeed, as that threshold is likely to be reached, and then exceeded, by a substantial amount in the next decades [2].

Africa has huge unexploited renewable energy potential which can be used in achieving energy access for all and inspire social and economic development at the same time reducing greenhouse gas emissions [3]. In Africa the major contributor of electricity from renewable energy sources is hydropower, with an installed capacity is 37 GW by end of 2021, and the highest untapped hydropower potential in the whole world[4]. Continued increase in the global temperature rise will alter river basins especially in ROR hydropower plants. Tropical ROR hydropower production will be much vulnerable because seasonality is a dominant feature of most tropical rivers. Tropical rivers have few reservoirs, mostly ROR projects, and the wet/dry season extremes are therefore important to power production. One impact of climate change is more extremes in precipitation[5], impacting the viability of hydropower systems. This will reduce annually average hydropower production resulting from heavy rainfall in rainy seasons and reduced rainfall and hydropower production in dry seasons[6][7].

1.2 Problem Statement

Access to a reliable, affordable and sustainable source of electricity is a basic need for any community. However, according to African Energy outlook 2019, the electricity access in Sub-Saharan Africa by population was 45% in 2018. The same report recommended small-scale hydropower (1-10 MW) and mini-hydro power (0.1-1 MW) as a solution for rural electrification in some areas of sub-Saharan Africa[3].

In accelerating electricity access to all, the government of Rwanda has established a 7-year Government Programme: NST1[8], which targets 100% electricity access for population by 2024 where current electricity access is 61.0% according to Rwanda 5th population and housing census of August 2022. The country possesses many small rivers with hydropower potential throughout the country. Given the size of water resources and topography of the country, most existing hydropower plants are small-scale. While previous studies from the region, as well as from other parts of the world where socioeconomic conditions are similar, have identified factors influencing the sustainability of small-scale hydropower, Rwanda is a somewhat unique case in that almost all systems connected to the national grid. As Rwanda being in tropical region where rivers experience high variable flows, have some many deployed run-of-rivers, study to discuss the sustainability of installed small-scale hydropower plants and optimal design of small hydropower plants is highly needed.

1.3 General Objective

The general objective of this research work was to study the small-scale hydropower systems and develop an understanding of whether, or what fraction of power plants should be designed differently to best implement small run-of-river, hydropower production required in Rwanda's tropical highlands.

1.4 Specific Objectives

(i) Present a status of small-scale hydropower plants development trends, opportunities, and challenges in Rwanda.

(ii) Determine factors affecting operation and sustainability of small-scale hydropower plants.

(iii) Develop sustainability framework for small scale hydro energy technology deployment, including the following proposed components:

a) A techno-economic model of the turbine choice and integration into Rwanda river flows.
b) Understanding of whether, or what fraction of, power plants should be designed differently to be best implement the run-of-river systems required for tropical highlands.

1.5 Research Questions

i) What are the challenges and opportunities around small-scall hydropower plants in Rwanda.
ii) Which Factors affecting the sustainability of small-scale hydropower plants in Rwanda.
iii) How to design the best size of a powerplant fed by a run-of-river system in tropical highlands.

1.6 Contribution to Scholarly Work.

This thesis contributed to the methodology used for analyzing run-of-river hydropower plants in a tropical climate in situation where river flow rate is undocumented or poorly documented. Machine learning method was used to estimate Sebeya flow rate where a combination of Sebeya daily precipitation of 2019 and Sebeya historic flow rate of 2017 were used to predict Sebeya 2019 flowrate. The model was trained on historic Sebeya flow rate of May to December 2017 using scaled conjugate gradient (SCG) method. Power generated per turbine type were calculated based on power formula with varying Sebeya flow rate and turbine efficiency variation as a result of flow rate variation.

A simplified cost model was utilized for plant sizing and costs, to provide general information on the tradeoffs between plant sizes, as is appropriate for the early planning stages. Levelized cost of energy were computed using the 1000 Monte Carlo iterations.

Furthermore, the study contributed on existing literature on design of optimal hydropower on Sebeya river in Rwanda which may be used by other countries with similar context where plants designed substantially above the 'knee' in the flow exceedance curve shown in Figure 16, right panel, produced a significantly higher LCOE than plants sized below the knee. Through this methodology, we observed that investors interested in small hydropower development ought to invest in river monitoring as a catalyst to development.

1.7 Methodology

The methodology used to achieve the overall objective is summarized in table 1

Table 1: Technique and mode of collecting, measuring and analyzing specific data

s/n	Objectives	Specific research questions	Modes of data collection	Methods of analysis
1	Present a status of small-scale hydropower plants development trends, opportunities, and challenges in Rwanda.	To identify the challenges and opportunities of small-scall hydropower plants	Review of the relevant literature	Content analysis analyzing opportunities and challenges of small-hydro power plants in Rwanda based on the frequency on which they were articulated in the desk review.
2	Determine factors affecting operation and sustainability of small-scale hydropower plants.	Which Factors affecting the sustainability of small-scale hydropower plants in Rwanda.	Structured questionnaire, field photos and observations were used.	After conducting interview, all responses from respondents were coded in an excel sheet and Sustainability factors were analyzed based on the frequency by which each factor occurred in responses.
	Develop sustainability framework for small scale hydro energy technology deployment, including the following proposed components: i. A techno-economic	how to design the best size of a powerplant fed by a run-of-river system in tropical highlands.	Both primary and secondary data collection were used. Primary data were collected from Sebaya River. The river flow was recorded from different visits,	In the sizing of small hydropower plant, flow time series data are needed. However, the Sebaya river which was used as case study had no times series data of flow rate. The only available date were daily precipitation and flow rate of date from 1st may 2017 to 31st December 2017 Therefore, Machine learning

	model of the turbine choice and integration into Rwanda river flows. j. Understanding of whether, or what fraction of, power plants should be designed differently to be best implement the run-of-river systems required for tropical highlands.		both in dry and rainy seasons respectively in 2019. The flow measurement was collected using floating method. Secondary data were collected from recorded precipitation of 2019 and historical flow rate in Sebaya region	method was used to estimate Sebeya flow rate where a combination of Sebeya field visit flow rate measurements, daily precipitation of 2019 and Sebeya historic flow rate of 2017 were used to predict Sebeya 2019 flowrate. The model was trained on Historic Sebeya flow rate of May to December 2017 using scaled conjugate gradient (SCG) method. Power generated per turbine type were calculated based on power formula with varying Sebeya flow rate and turbine efficiency variation as a result of flow rate variation. A simplified cost model was utilized for plant sizing and costs, to provide general information on the tradeoffs between plant sizes, as is appropriate for the early planning stages. Levelized cost of energy were computed using the 1000 Monte Carlo iterations.

1.8 Limitation

The study does not include the effects plants may have on the natural environment and river system. It focuses only on the ways in which environmental factors affect the plants. Due to limited data for civil or mechanical construction costs and availability of, and innovations in, turbines for small-scale hydropower, all cost simulations are based upon a limited set of data from constructed plants. Changes in significant cost items or equipment availability could change results substantially.

1.9 The Structure of the Thesis

Chapter 1 outlines study background, problem statement, general objectives, specific objectives, summary early work, scope and limitation. Chapter 2 discusses the general understanding of small hydropower plants in in Rwanda. Chapter 3 discusses suitability factors affecting sustainability of small small hydropower plants in Rwanda. Chapter 4 discusses the sizing of small hydropower plants for highly variable flows in tropical run-of-river installations. Chapter 5 draws conclusion with sustainability framework. Appendix is supplementally information on sustainability factors affecting small hydropower plants in Rwanda.

CHAPTER 2. SMALL HYDROPOWER DEVELOPMENT IN RWANDA: TRENDS, OPPORTUNITIES AND CHALLENGES.

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2.1. Introduction.

Globally, the most-used definition of small hydropower is hydropower units with a rated capacity of 10 MW or less, but many countries define their own classification to meet local needs[9]. The sector guidelines for environmental impact assessment (EIA) for hydroelectricity development in Rwanda by Rwanda environmental management authority, classified small hydropower plants by their capacity as: mini hydro ranging from 500 kW-10 MW, micro hydro 5-500 kW and Pico hydro which is less than 5 kW[10]. Small hydro power plants can also be classified according to head where ultra-low head of less than 3 m, low-head of 3-40 m head; and medium-to-high head with more than 40 m head[11]. A recent government study estimates that Rwanda has 333 potential sites for small hydropower development and recommends medium-to high-head pico-and micro-hydro, using run-of-river plant designs[12]. According to hydropower atlas of 2007[13], the majority of Rwanda potential hydropower sites have a capacity of 50-1000 kW of electrical production. Figure 1 illustrates a small run-of-river hydropower facility designed for 300 kW. This type of facility is typical of both the location and architecture expected for many hydropower facilities in Rwanda. An upper catchment (left panel) slows the stream flow and allows some portion of the entrained silt to settle out. Design and maintenance of the silting basins are of paramount importance in Rwanda, new to the high silt load in many streams. Water is conveyed through an open channel (upper left in left photo) for some distance (approximately 2 km in this example) along the valley wall before emptying into 0.5 m diameter penstock that drops 30 m to the turbine house. Impulse or cross-flow turbine types are frequently utilized for the heads seen in Rwanda. The example turbine is a gated cross-flow type (blue, right photo) driving a constant-speed synchronous generator (orange). Generation is governed by gating water flow (gray valve arms). Ingestion of silt into the turbine equipment presents significant issues for small Rwandan hydropower facilities, and may cause significant wear on both turbine blades and bearing seals.

(a) Upper holding reservoir and silt removal basin.

(b) Penstock (green), control gate (black), cross flow turbine (blue), and generator (orange).

Figure 1. Example of small run-of-river hydropower facility in Rwanda.

Hydropower is the main source of electricity generation in Rwanda. in 2017, out of energy generation capacity of 210 MW, renewable resources represent 53.7% of the total energy generation and hydro power contributes 48%[14]. Figure 2 illustrates the domestic electricity generation in Rwanda.

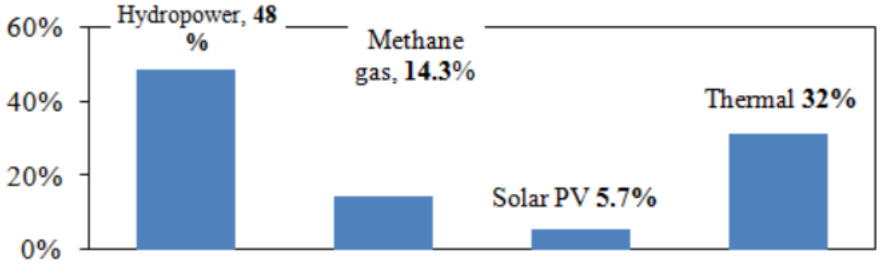


Figure 2. Resource mix for Rwandan current energy generation.

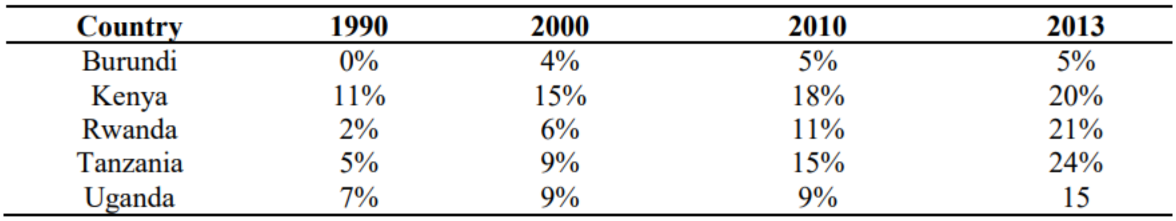
In Rwanda’s electrification strategy targets 512 MW installed power generation capacity by 2023/24 and universal access to electricity for all households by 2023/24[15][16]. Current electrification data indicate that electrification has reached 40.5% of the population, of which 29.5% are grid connected and 11% are serviced by off-grid systems[18]. Under Rwanda rural electrification strategy, mini-grids will be developed by the private sector with government assistance in identifying potential sites and establishing framework through which they can become financially viable investments. Given the distributed nature of hydropower locations, the high targets for off-grid development will likely encourage small hydropower development. In Rwanda rural electrification strategy, the levels of access are defined in five multi-tiers as illustrated in Table 1. The government plans to finance rural electrification in partnership with private sector.

Table 2. Energy usage levels in Rwanda grouped in tiers.

Level	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Energy usage	Household lighting, Radio and phone charging	Household lighting, Radio, phone charging and basic appliances (TV or fan)	Household lighting, Radio, phone charging, basic appliances (TV or fan), medium appliance such as low power refrigeration	Household lighting, Radio, phone charging, basic appliances (TV or fan), medium appliance such as low power refrigeration, high power appliances such as pumping.	High power suited to commercial and industrial uses.

Source[15]

Table 3. Comparison of Electrification rate for the five East-African Countries.

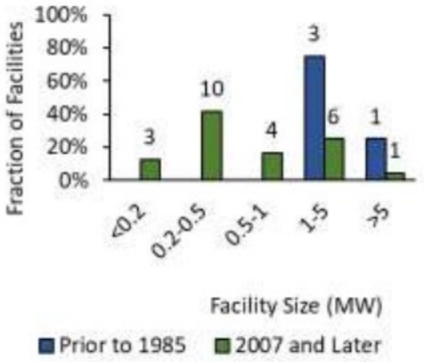


Country	1990	2000	2010	2013
Burundi	0%	4%	5%	5%
Kenya	11%	15%	18%	20%
Rwanda	2%	6%	11%	21%
Tanzania	5%	9%	15%	24%
Uganda	7%	9%	9%	15

Source[17]

2.2. Small Hydropower Development Trends in Rwanda.

There has been rapid development in small hydropower in Rwanda since 2007. A full list of operational small hydropower facilities, at least as known to the government, is provided in Appendix 1. These facilities account for an installed capacity of 47.5 MW. No small hydropower facilities were built between 1985 and 2006. Facilities built prior to 1985 were more traditional developments, larger – averaging 16.5 MW/plant – and fewer – 4 facilities – than recent development (Fig 3)



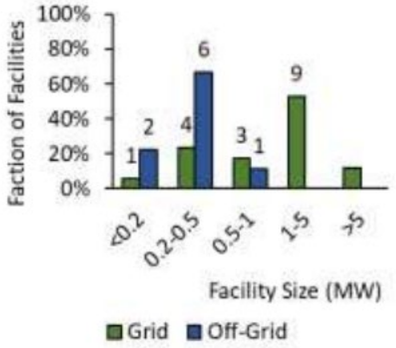


Figure 3. Small hydropower facility size by construction date. Larger facilities were built prior to 1985 than subsequently.

Figure 4. Grid connection status of small hydropower facilities. Larger facilities tend to be grid connected, while a substantial fraction of small facilities power off-grid systems. Following policy changes to encourage development of generation sources, 24 facilities / 31 MW of capacity were commissioned since 2007. These facilities are smaller – averaging 1.3 MW/plant. A third of these new facilities are connected to off-grid power systems (Fig 4) in contrast to facilities built prior to 1985, which were all grid-connected. In addition, off-grid facilities tend to be smaller – averaging 0.2 MW – than on-grid facilities – average

2.3. Opportunities.

The combination of topology and hydrology make Rwanda an excellent location for small hydropower, while population density and other constraints likely would not encourage larger hydropower development that requires significant flooding of major valleys. As indicated earlier, many sites with power-producing potential remain undeveloped. The distributed nature of these sites could be complimentary to micro-grids, including off-grid power systems, as small hydropower facilities could be integrated into these facilities to provide 24/7 generation to compliment photovoltaic generation sources. An upper bound on the potential for small hydropower can be estimated with several assumptions. First, of 333 identified sites, 28 have already been developed and we assume that 25% will prove unsuitable for environmental or other reasons. For example, some sites are likely to be in areas with sensitive plants or animals, or are in areas that are restricted from development, such as national parks or military installations. This leaves a total of 229 possible locations for development. If we further assume that new facilities will average 75% of the size of sites developed since 2007, potential generation capacity can be estimated as shown in Table 5. We assume 63%, or 143 facilities, would be grid-connected and average 1.5 MW, while 38% or 86 facilities, would be connected to off-grid systems and average 150 kW. Obviously, actual construction may deviate significantly from these assumptions, but they serve to scope the potential of small hydropower as guide to policy discussions. Given that Rwanda seeks to add approximately 300 MW of generation (from current 210 MW to 512 MW), potential generation from small hydropower sources could represent a non-trivial fraction of the solution – up to 60% of the desired increase in generation. Further, the distributed nature of the sites could support development of off-grid electrification, and thus not require extension of grid distribution systems. Producing energy domestically also provides a strategic advantage to Rwanda, as it does not require foreign currency reserves to pay for imported power in the case of electricity imports, or for fossil fuels, in the case of diesel-fueled generation. Finally, the site survey[13] indicated that most small hydropower sites could be developed utilizing run-of-river methods. These methods do not require large dams to impound water – expensive and environmentally challenging construction projects**.**

2.4. Development potential.

Based upon the survey data mentioned above, only a small fraction – 28 or 8% -- of potential small hydropower sites in Rwanda have been developed (Figure 4). Therefore, a substantial number of possible development sites exist, for both on- and off-grid development. However, the survey data did not include an evaluation of potential cost or environmental conditions which might eliminate some sites from consideration. These could include sensitive watersheds, poor access to grid or population centers, or intermittent water flow.

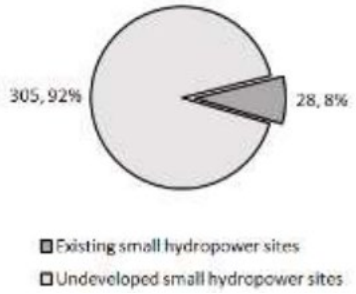
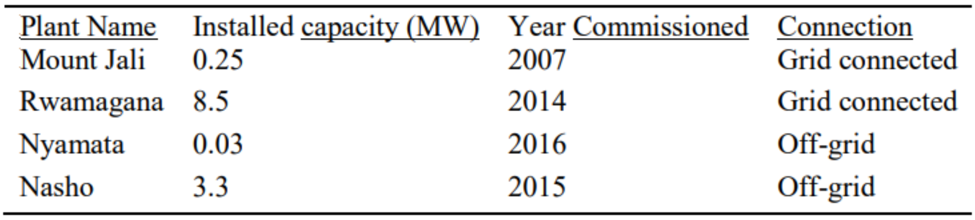


Figure 4. Comparison of developed small hydropower sites in Rwanda relative to a recent survey of locations with small hydropower potential.

Table 4. Small solar power plants in Rwanda.



Plant Name	Installed capacity (MW)	Year Commissioned	Connection
Mount Jali	0.25	2007	Grid connected
Rwamagana	8.5	2014	Grid connected
Nyamata	0.03	2016	Off-grid
Nasho	3.3	2015	Off-grid

Source [16,17].

Comparing solar and hydropower development rate, both are developing at a high rate, but small hydropower is developing somewhat faster, due to a larger number of facilities and the relatively larger size of hydropower facilities.

2.5. Causes of Rapid Development in Small Hydropower.

There has been rapid economic growth in sub-Saharan Africa, resulting in increased energy demand. This has pressured governments to explore all solutions to increase domestic energy supply[19].

2.5.1 Rwandan development incentives.

Rwandan economy has performed well since 2000, with an average annual growth rate of nearly 8%[20]. The government has also identified several growth strategies, including development of the tourism and information and communications technology (ICT) sectors. Both sectors place a high priority on reliable and competitively priced energy, driving a substantial need to improve energy capacity and infrastructure[21]. Also, EDPRS II acknowledges that Rwanda’s current energy system creates challenges for development. The plan articulates strategic areas of improvement in the energy sector. These include rapid expansion of energy supply capacity through grid and off-grid technologies[22]. To support development of energy sources, Rwanda has established laws meant to promote private sector involvement in energy development. The country has developed regulations including a renewable energy feed-in tariff for hydropower between 50 kW and 10 MW[23] and a simplified licensing method which exempts generation facilities of less than 50 kW from most licensing requirements[24]. Additionally, the government has initiated a privatization of public services, including the main electricity utility. Benefits are provided to foreign investors, including tax holidays, import tariff reductions, assistance to access water and electricity, and assistance with obtaining visas and work permits[25]. Finally, the RDB has launched a program to assist with business registration, licensing and obtaining tax incentives. Stakeholder support promoting private sector involvement in energy sector investments has boosted power generation. An example is GIZ which promotes private investment in the energy sector through the EnDev fund. Results-based financing was introduced into Rwanda by the DFID and implemented by EnDev in several countries, including Rwanda. The idea behind the approach is to reward companies for their previously-agreed and delivered results. For off-grid electrification, results-based financing provides companies incentives in form of subsidies for either in increasing sales of small electric systems (typically small PV systems) or in developing isolated village grids.

powered by renewable energy sources. Financing mechanisms are implemented by Urwego opportunity bank on behalf of EnDev Rwanda[26].

2.6. Challenges

Small hydropower in Rwanda also faces several non-trivial challenges. First, the mountainous topology in Rwanda makes transmission and distribution relatively expensive. Mountain ranges up to 3,000 m in height run across the country. Therefore, not all larger sites with multi-megawatt potential can be cost-effectively connected to Rwanda's transmission system, shown schematically in Figure 5. Few vendors provide equipment for small hydropower sites, and significant custom engineering is required for each facility. A 2012 study of hydropower in Colorado, USA, irrigation systems indicated that, while equipment existed, manufacturers for key components were few, were internationally-dispersed, and often required custom engineering for each installation[27][28][29]. As a result, installation engineering, and post-installation maintenance expertise and spare parts, present a challenge for Rwandan hydropower developers. Rwanda is a landlocked country, increasing transportation costs for all imports, and particularly for heavy equipment. Since most hydropower plant components are manufactured outside of Africa, this increases the cost of hydropower plant investments. For example, of hydropower investment cost is estimated at 4000 US$/kW in Rwanda compared to 3829 US$/kW in Kenya[30][31]. The integration and control of many small hydropower facilities into the national grid may present control challenges. Assuming a high penetration of small hydropower sites, the national grid control center may need automated mechanisms to dispatch small hydropower facilities. These mechanisms are not currently in place. Finally, it is expected that climate change may reduce precipitation and flow Rwanda's from interconnect lakes, leading to a decline of electricity generation from small hydropower plants[32]

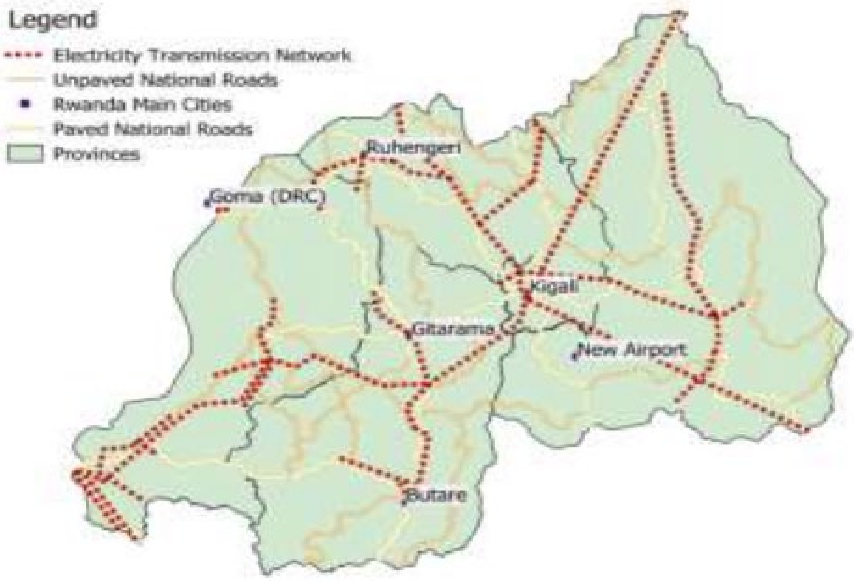


Figure 5. Approximate location of electricity transmission lines in Rwanda, 2012 data

2.7 Conclusions and Policy Recommendations

Strong evidence indicates that small hydropower could contribute significant electricity production in Rwanda. The government actively encourages development, in contrast to many countries with more developed electricity systems. Many promising sites exist, distributed throughout the country. Considering the need for energy development and available hydropower resources, our analysis suggests several possible policy recommendations:

1. Due to the difficulty of building energy transmission in Rwanda, it is advisable to encourage small hydropower use in off-grid systems;
2. Investments should be made to develop the necessary support expertise for small hydropower technologies, including expertise for community-based micro-grids and training for plant maintenance to reduce operational cost.
3. Small hydropower remains a niche business worldwide. Policies should be considered to attract investors willing to design and manufacture some hydropower plant components in Rwanda. This would allow solutions to be customized for Rwandan conditions, including:
    a) Standardizing designs for run-of-river systems.
    b) Improving designs to deal with high silt loads in Rwandan streams.
    c) Providing local expertise, repair, and spare part service.

CHAPTER 3. PROGRESS FOR ON-GRID RENEWABLE ENERGY SYSTEMS: IDENTIFICATION OF SUSTAINABILITY FACTORS FOR SMALL-SCALE HYDROPOWER IN RWANDA.

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3.1. Introduction.

Africa has large untapped renewable energy potential that can help achieve energy access for all and catalyze social and economic development while keeping greenhouse gas emissions at low levels. However, rapid urbanization with an expected additional 500 million people moving to cities will incur a great demand for transport and building construction, while higher temperatures increase the need for cooling services. The continent's increasing demand for electricity, fuel, and construction materials led the International Energy Agency[3] to state that the energy pathway chosen by African countries will have a global impact and significantly influence the time it takes to achieve a carbon-neutral energy sector worldwide. While the responsibility for reducing emissions of greenhouse gases rest heavily on industrialized nations, the effects of increasing average temperatures are already affecting life and well-being on the continent.

This research deals with the current development and sustainability factors for small scale hydropower plants in Rwanda, an East African country with high hydropower resource potential, ambitious national targets, and a strong development of the hydropower sector. Rwanda is unique in the East African context in that most current small-scale hydropower systems are connected to the national grid, supplying additional generation capacity at a guaranteed price. Rwanda possesses 333 potential sites for hydropower, the majority being at the scale of micro and mini—i.e., with potential generation capacity below 5 MW. Rwanda may develop a country-wide integrated network of distributed generation. In combination with rapid development in solar, a vision of 100 percent renewable energy-based electricity generation is within reach. However, small-scale hydropower plants face contextual challenges that negatively affect the sustainability of such systems. This study investigates both positive and negative factors affecting the sustainability of Rwanda's small-scale hydropower plants from a utility perspective, providing the hitherto most comprehensive study of on-grid small hydro in the East African region.

The majority of rivers in Rwanda have relatively low flow rates: 0.05 m^3/s to 7.14 m^3/s in the rainy season, with a high degree of flow variability between wet and dry seasons (typically >50 percent decrease in the dry season). Globally, the most often used definition of small scale hydropower plants is hydropower units with a rated capacity of 10 MW or less, but many countries have their own classification reflecting the local situation[9]. In Rwanda, there is no established country definition for the limit of small scale hydropower plants[33]. In this study, we define small scale hydropower plants as plants with as plants with < 5 MW in capacity. These can be further subdivided in Pico (<10 kW), micro (10-100 kW), mini (100-1000 kW) and small (1000-5000 kW). The 5 MW limit on small-scale hydropower plants is based on the low flow rate of most rivers. The majority of existing hydropower plants are below 5 MW, with a few larger plants between 9.5-28 MW. Table 4 summarizes data on the country's 30 deployed hydropower plants by 2019, with installed capacity, type of ownership, year of commission, storage type, and supply model[34][35].

Table 5. Characteristics of deployed hydropower plants in Rwanda for both small and big plants.

s/n	Plant Name	Installed Capacity (MW)	Year Commissioned	Storage Type	Ownership	Grid/Off-Grid
1	Nyabarongo I	28	2014	Reservoir	Government	Grid
2	Mukungwa I	12	1982	Reservoir	Government	Grid
3	Rusizi II	12	1984	Reservoir	Regional	Grid
4	Ntaruka	11.25	1959	Reservoir	Government	Grid
5	Rukarara I	9.5	2010	Reservoir	Private	Grid
6	Giciye I	4	2013	Run-off	Private	Grid
7	Giciye II	4	2016	Run-off	Private	Grid
8	Rugezi	2.6	2011	Run-off	Private	Grid
9	Rwaza Muko	2.6	2018	Run-off	Private	Grid
10	Mukungwa II	2.5	2013	Run-off	Private	Grid
11	Keya	2.2	2011	Run-off	Private	Grid
12	Rukarara II	2.2	2013	Run-off	Private	Grid
13	Gihira	1.8	1984	Run-off	Private	Grid
14	Gisenyi	1.2	1957	Run-off	Private	Grid
15	Nkora	0.68	2011	Run-off	Private	Grid
16	Gaseke	0.582	2017	Run-off	Private	Grid
17	Mazimeru	0.5	2012	Run-off	Private	Grid
18	Nyirabuhom-bohombo	0.5	2013	Run-off	Private	Grid
19	Musarara	0.45	2013	Run-off	Private	Grid
20	Nshili I	0.4	2012	Run-off	Government	Grid
21	Cyimbili	0.3	2011	Run-off	Private	Grid
22	Agatobwe	0.2	2010	Run-off	Private	Grid
23	Mutobo	0.2	2009	Run-off	Private	Grid
24	Nyabahanga I	0.2	2012	Run-off	Government	Grid
25	Gashashi	0.2	2013	Run-off	Private	Grid
26	Janja	0.2	2012	Run-off	Private	Grid
27	Murunda	0.1	2010	Run-off	Private	Grid
28	Nyamyotsi I	0.1	2011	Run-off	Private	Grid
29	Nyamyotse II	0.1	2011	Run-off	Private	Grid
30	Ecos	0.011	2016	Run-off	Private	Off-Grid

Most existing small-scale hydropower plants are implemented as ROR plants. ROR hydropower plants generate electricity by the immediate use of the inflows and have little or no reservoir storage capacity[9]. Therefore, run-of-river hydropower plants are subjected to weather and seasonal variations, resulting in seasonal variation in power generation. The steepness of the terrain leading to small and heavily populated valleys makes large storage reservoirs difficult to implement. Some evidence[9] indicates that this type of plant is very cost-effective and has few negative impacts on the environment and river ecosystem compared to larger hydropower with dam infrastructure that floods a large area. Additionally, these systems require relatively small investments, involve fewer construction activities, and need less maintenance. Further, Table 1 shows that the development of privately-owned plants is notably strong in the last decade. This coincides with good economic performance (with an average GDP growth rate of around 8 percent per year from 2000 to 2015), and the introduction of policies to encourage private sector involvement and the leasing of government-owned hydropower plants to private power developers[12][20][23]. In addition, the country has set an ambitious energy development agenda to meet a 100 percent electrification target by 2024, and the rate of development has been rapid in the last 10 years. National access was estimated at 10 percent in 2009 and reached 52 percent in 2019, while generation capacity grew from 88 MW in 2010 to 221 MW in 2019 [36][37][38].

This rapid increase in electricity access is a result of government initiatives and new energy policies, such as the energy sector strategic plan (2015), the rural electrification strategy (2016), and the national strategy for transformation (2017), establishing the target of 100 percent electricity access by 2024. This is suggested to be achieved with 52 percent of the population reached by the national grid and 48 percent being supplied with off-grid services. A renewable energy feed-in tariff for small and mini-hydropower was issued in February 2012[8][15][23][39].This regulation attracted many independent power producers (IPPs) leading to growth in the sector.

The objective of this research is to first, identify environmental, technical, economic, institutional, and social factors affecting the operation and sustainability of deployed small-scale hydropower plants in Rwanda. Secondly, it describes the interconnection with the national grid and analyses the consequences thereof. The scope of the study includes both positive and negative factors affecting system operation. Potential factors were identified based on literature review and investigated through site observation and interviews with plant operators and company technical directors. Since almost all the plants are grid-connected, users receive electric services from REG through the national grid and not from the plants directly, except for off-grid plants. This study is thus limited to investigating operational issues from the plant operator's point of view, excluding the perspectives of users. Another limitation of the study is the exclusion of effects that plants may have on the natural environment and river system, focusing instead on the ways in which environmental factors affect the plants.

The sustainability factors of small-scale hydropower plants have been discussed in previous literature, with examples from all over the world. This section focuses primarily on literature discussing small scale hydropower in rural and poor community contexts. Our understanding of sustainability builds, for this study, on work and previous definitions of sustainability, as applied to small-scale electric power plants in a developing economy context. The UN commission on sustainable development describes sustainability in five dimensions: technical, economic, social, environmental, and institutional[40]. Building on these, Ilskog et al. [41] evaluate the sustainability of rural electrification systems as follows: technical sustainability, which relates to maintaining the energy service at a certain quality through its lifetime of the investment; economic sustainability, which focuses on the survival of the service beyond the economic lifetime of the initial investment; social sustainability, which focuses on equitable distribution of the benefits offered by electrification; environmental sustainability, mainly focused on the conservation of natural resources and minimizing negative environmental impact; institutional sustainability, involving the survival of the organization and its ability to maintain adequate performance with respect to other dimensions of sustainability[41].Based on these five dimensions of sustainability, we can notice that three of them (technical, economic, and institutional) focus on the sustainability of the electric power system as such. Social and environmental dimensions are considering the effects of the power production and distribution on society and nature, which are outside of the scope of this study. We are, however, interested in the effects that the natural environment may have on the technical system, in terms of environmental factors affecting technical, economic, and institutional sustainability of the plant and utility organization. We may also expect that social and cultural factors influence the economic and institutional sustainability of hydropower. In the following, we include only factors that affect the system over its lifetime, while we exclude for example financial, social, or institutional barriers that prevent construction of new infrastructure.

The review of previous literature was carried out based on searches in Google Scholar and Scopus, using the following key words combined using Boolean operators into different search strings: hydro potential; hydropower AND small scale OR small OR mini OR micro OR Pico; sustainability AND issues OR drivers OR factors OR barriers; developing countries; Africa OR Sub-Saharan Africa OR East Africa OR Rwanda; operational OR performance OR viability OR reliability OR profitability. 77 published resources were reviewed including: scientific articles on small-scale hydropower in low- and middle-income countries (26 articles); scientific articles with broader focus on distributed generation (23 articles); and relevant but not peer-reviewed literature (28 publications, including reports and conference proceedings). The list of papers is provided in Supplementary Materials.

Previous literature identifies a range of factors affecting the technical sustainability of plants. These are commonly linked to resource potential, design, technical reliability, or managerial capacity. Singh et al[42]. identified head, river discharge, turbines, and generators as the major parameters that affect the operation of hydropower plants. Negative factors are negligence in the construction of mini hydropower plants, low plant capacity factor[43], overestimation of plant capacity resulting from low quality of pre-studies, and limited capacity in plant construction and design[44]. During operation, challenges include long breakdown periods, low efficiency, carelessness, and inefficient operation[43]. Besides the importance of feasibility studies and good technical design, Didik et al.[45] mention the availability of operation and maintenance funds, and good managerial capacity. Many studies point to the generic importance of the availability of adequate technical knowledge and skills, and well as access to spare parts[41][46][47].

Environmental factors relate primarily to water discharge and sediment levels. For example, Luis et al.[48] identify increasing inflow of sediment year after year as a sustainability challenge. Thakur et al. [49] find that silt in river water is among the key factors that cause rapid wear and premature failure of turbines. Similarly, the authors argue that wear by silt affects turbine performance, with variations in erosive wear depending on silt concentration, silt size, stream velocity, and working time.

Previous studies identify economic barriers to both investment and operation of small-scale plants, with a major hurdle being a weak customer base (especially in off-grid rural areas with customers of low purchasing power) which affect utility income in both short and long-term perspectives[50]. Economic issues are interlinked with institutional issues, as utility income affect managerial capacity and organizational development and vice versa. Ahlborg and Sjöstedt[51] note the importance of coupling energy programs with complementary activities such as education and agricultural processing while identifying negative factors such as lack of local managerial capacity and business skills as threats to the sustainability of rural micro-grids. Institutional sustainability factors are considered very important[51] for long-term functioning of utility organizations, with type of ownership, decision-making, and mechanisms for community participation making a difference for ability to handle challenges such as free riding and the risk of elite capture. Likewise, Terrapon-Pfaff et al.[46] mention importance of network connections and the commitment of the implementing organization. The question of local participation is brought up in many studies as a social and institutional factor that can work either as driver or barrier to sustainability, however, many previous studies concern off-grid hydropower systems with distribution to local customers[51][52] whereas on-grid systems in Rwanda do not sell to local customers. There is a lack of studies comparing on and off-grid hydropower and it is thus an open question if on-grid systems face the same challenges or not.

There are very few scientific studies of small-scale hydropower plants in Rwanda, with most of the previous literature composed of consultancy reports, government reports, single case studies, master theses, and conference papers. For example, Maurice et al.[53] examine private sector participation in micro-hydropower plants development in Rwanda. The study suggests proper institutional arrangements, local participation at all levels and in all project phases, and good collaboration between local people and firms in both private and financial sectors as sustainability solutions. The study does not consider technical and environmental factors affecting sustainability of small-scale hydropower plants. Geoffrey et al.[54] describe development trends of small-scale hydropower plants in Rwanda, identifying causes of the rapid development happening since 2007 and available opportunities and challenges. The same study does not, however, consider factors influencing the sustainability of existing plants. Bensch et al. [38] examine social-economic impacts of rural electrification in Rwanda but do not analyze the sustainability of generation systems. The review shows that the current base of evidence regarding factors influencing sustainability of small-scale hydropower plants in the East African region is limited and not strong enough to support effective policy or sector advice. The knowledge gap for Rwanda is even more pronounced and no studies to date investigate the sustainability of on-grid small-scale hydropower plants development in the region. Most studies are still focused on technical and economic factors, with less attention given to social or institutional factors. Some studies concern environmental factors related to soil erosion, discussing effects on the technical system [55][56].

This study aims to contribute to improved understanding of what role hydropower currently plays and can play in the future for Rwanda's energy system. This is the first study to evaluate the sustainability of the deployed small-scale hydropower plants in Rwanda. Taking stock of the current situation is necessary to plan for future development of the resource potential, some of which would be on-grid and some of which would be off-grid.

We apply a sociotechnical approach based on previous work by Ahlborg[51] and see electric power systems as interacting with the local context in a complex process involving humans, nature, and technology. This involves seeing the different dimensions of sustainability as systemic and to consider how interactions change over time and with place. Factors are also cross-scale which means that factors originating at higher levels (regional climate patterns, national legislation, international programs for financing renewable energy, etc.) can have very direct, localized effects. A systems analysis explicitly considers what multi- and cross-scalar relations imply for preconditions and sustainability outcomes for a specific electric power system. Rather than considering sustainability "indicators" as analytically separate which is the case in e.g., Ilskog et al. [41], we thus expect that there will be connections between them: trade-offs, contradictions, synergies, and sequential relations. The extent to which such dynamics are captured in the data is highlighted in the result section and discussion.

The significance of this research is that it presents results from a comprehensive empirical study of existing small-scale hydropower plants in Rwanda, assessing the main factors affecting their operation and prospects for working sustainably their entire technical system lifetime, with data from 17 out of the country's 25 plants. Undertaken in connection to a technical assessment of silt and sediment levels in rivers and the effect on turbine functioning, this qualitative study investigates the relative importance of sustainability factors, from the perspective of utility companies. This study targets energy developers, scholars, and energy sector stakeholders in Rwanda and the wider sub-Saharan region.

3.2. Methods

Rwanda is located in the eastern part of Africa with an area of 26,338 km^2 and an average altitude of about 1700 m. The population is estimated to be around 12.8 million as of February 2020[57]. Precipitation ranges from 1000 to 1400 mm (40 to 55 inches) per year depending on the area[58]. Rwanda is among the fastest-growing economies in sub-Saharan Africa (SSA), with a GDP amounting to 10 billion USD and a GDP growth of 8.6 percent in 2018 (World Bank, 2019). The service sector is the leading contributor to the GDP (49 percent), followed by agriculture (27 percent) and industry (17 percent), with 7 percent attributed to adjustment in taxes and subsidies on products[37].

Using a mixed-methods approach, we identified factors currently affecting the operation of studied plants. The study design sought to include all of the existing 25 small-scale hydropower plants in the country. This purposive method for sample determination allowed flexibility for working with those who were willing to respond and allowed us to select respondents with specific skills.

Secondary data[34] were used to identify and preliminarily classify existing small-scale hydropower plants. The majority are located in western Rwanda, an area with higher precipitation, more rivers, and larger elevation changes than in eastern Rwanda as seen. The first author approached all hydropower plant owners countrywide for permission to survey their assets. Owners of 17 of 25 hydropower plants agreed. The plants' geographical distribution is shown in Figure 6.

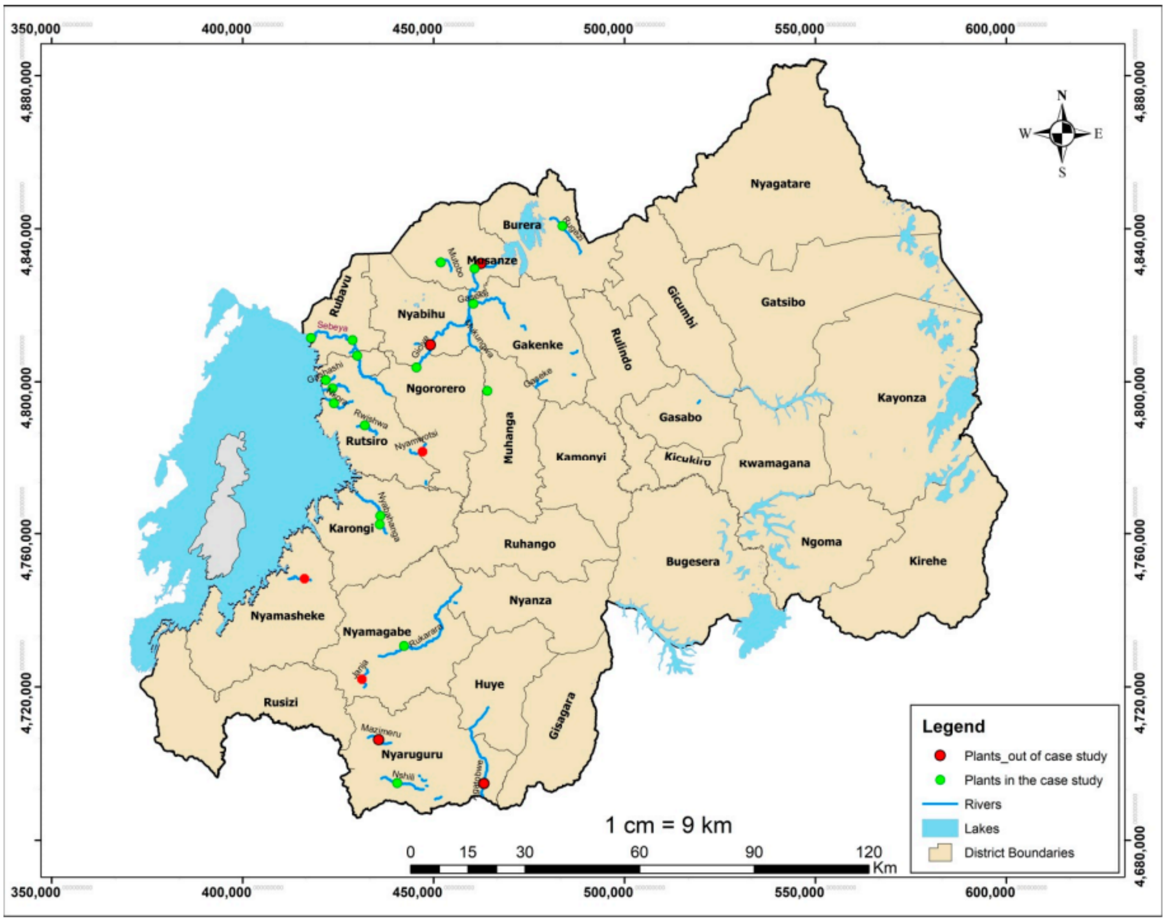


Figure 6. Map showing deployed small-scale hydropower plants included in the sample study and plants not included in the study.

The first author conducted two rounds of interviews, first in meetings with each company technical director. Interviews were carried out using a printed questionnaire in English, with respondents answering in Kinyarwanda. The first author took notes and afterwards translated notes to English. While interviewees answered many questions during the first interview, some required technical data that was not available or not known to the interviewee. To complete the technical questions, the questionnaire was sent to each company by email, asking respondents to return answers by email. While all respondents replied, answers were short and incomplete.

The first author then scheduled visits at all 17 hydropower plants. Each plant was visited two times, once each in dry and rainy seasons. During the visit, the first author conducted interviews with technical staff on site to validate and clarify the previous answers. The questionnaire included mostly open-ended questions in a semi-structured format, and the interviewer posed follow-up questions to probe any new issues that emerged during the interviews. This allowed for further explanations and possibility to follow up on issues not included in the questionnaire. The following themes were covered in these interviews on site: plant technical characteristics and current status, maintenance, technical problems (including reasons for these), repair activities, other sustainability problems (including issues outside the control of operators), and sediment questions (including infrastructural design to reduce sediment levels in the turbine). The respondents were also asked to compare the importance of silt wear in comparison to other technical problems. The interview questionnaire used is included in the Supplementary Materials. The information on policy/regulations for IPPs and small-scale hydropower plants comes from secondary data.

Twenty-six respondents participated in in-person interviews and visits; eight were managerial personnel at the level of technical director or company manager who were interviewed in corporate offices, 14 were technicians assigned to plant operations who interacted during field visits, two were owners of the company, and two were managers in the generation division of the REG. (Note that some companies own more than two plants and interviews with technical directors or managers may cover multiple plants.)

In connection to interviews, the first author used field observation at the powerhouse and intake to complement interview responses with photos, notes, and open-ended discussion with the plant managers and technicians. This auxiliary documentation and supplemental discussion were used to validate questionnaire responses and improve the first author’s understanding of each plant’s characteristics and issues. Following the field visits, responses were further clarified through follow up questions by phone or email, as required. Additionally, at seven sites additional time was spent conducting technical measurements of river discharge.

The one-day plant visits took place in April–May 2019 (rainy season) and June-August 2019 (dry season). The first author also spent one month (October 2019) as a guest at one micro-hydropower plant, following daily operation to fully understand the effect of flow rate variation and grid issues on plant operation. In total, 90 days were spent in the field for data collection during 2019. Finally, the data was also reviewed with experts at the REG, with specific attention paid to operational challenges related to grid integration discovered during field visits.

The analysis is based on a content analysis approach to interview data collected in field work[59]. The interview responses were coded using an excel sheet, where we organized all answers thematically, question by question, and according to respondent. The answers were summarized for each question and together the authors scrutinized the meaning and interpretation of all answers. Sustainability factors are analyzed based on the frequency by which a factor occurred in responses, and the importance attributed to them by respondents. Factors are also analyzed in terms of their origin and effect when such explanation was given by respondents. Some sustainability dimensions are interlinked and feedback between them shape outcomes over time. For example, the choice of turbine and design of the intake influence the degree of maintenance needed, with consequences for both costs and required local technical expertise. System dynamics are context-specific and change over time, which means that in-depth case assessments require the collection of significant amounts of data at multiple points in time[51]. Given the broad scope with 17 hydropower plants, it is not feasible to provide in-depth analysis for each case and sustainability dimension. The use of qualitative interviews has some advantages in this situation, as questions and answers can address the current situation and development over time and retrospectively discuss causes and effects. There may still be issues that were overlooked, misunderstood, or not understood in enough depth. Another limitation has to do with documentation of interviews where it was not possible to record the interviews, which limits original data to notes and photos taken by the first author. The site visits at most plants were also relatively short, limiting time for interviews and observation to a few hours.

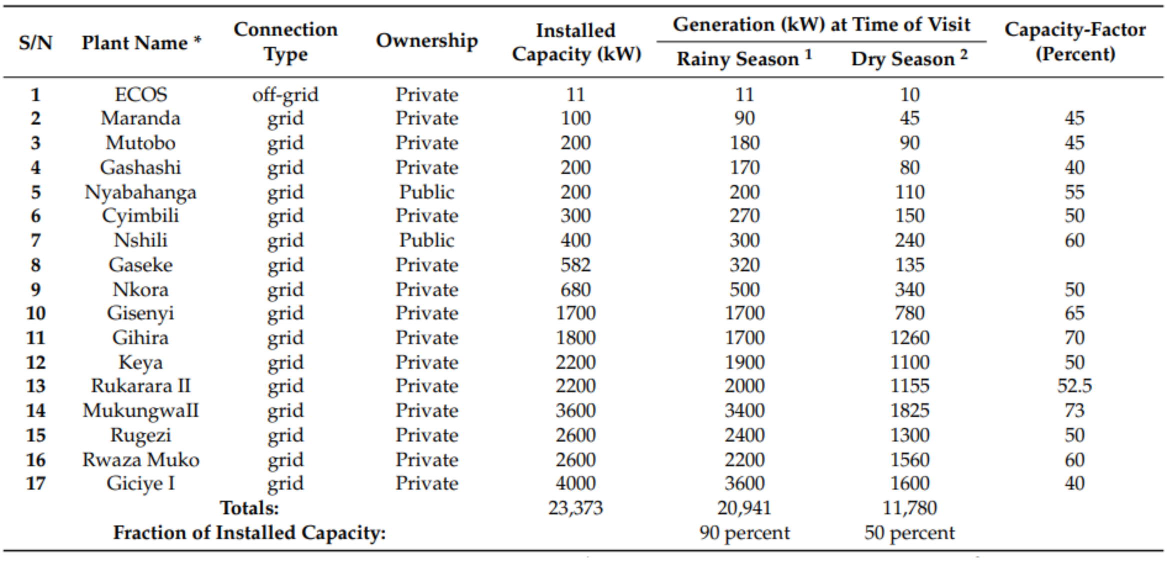
3.3. Results

To capture the system interactions between human, technological, and environmental components, we organized results schematically, considering the hydropower plant itself as the main system, which is connected to two other physical systems that are largely outside the control of local operators and plant owners; the upstream river system and the ‘electrically downstream’ national grid. In the following sections, we provide a description of the plants’ technical characteristics and then discuss factors originating with the river system and their impact on plant infrastructure and operations; factors originating in the hydropower plant itself, and last; factors related to the plant’s grid connection. Economic and institutional factors are cross-cutting, sometimes cross-scale, and highlighted throughout.

3.3.1. Plant technical characteristics

The first characterization of the studied plants shows that a majority are privately owned and were developed in the last ten years. Table 5 shows that all seventeen (17) plants are run-of-river type and sixteen (16) out of seventeen (17) plants are grid-connected. Notably, the figures on generation capacity show that there is a considerable decrease in river discharge leading to a 40 percent decrease, on average, in generation during the dry season, and a corresponding decrease in the annualized plant capacity factor.

Table 6. Plants in the sample study technical characteristics and current status.



S/N	Plant Name *	Connection Type	Ownership	Installed Capacity (kW)	Generation (kW) at Time of Visit		Capacity-Factor (Percent)
					Rainy Season [1]	Dry Season [2]	
1	ECOS	off-grid	Private	11	11	10	
2	Maranda	grid	Private	100	90	45	45
3	Mutobo	grid	Private	200	180	90	45
4	Gashashi	grid	Private	200	170	80	40
5	Nyabahanga	grid	Public	200	200	110	55
6	Cyimbili	grid	Private	300	270	150	50
7	Nshili	grid	Public	400	300	240	60
8	Gaseke	grid	Private	582	320	135	
9	Nkora	grid	Private	680	500	340	50
10	Gisenyi	grid	Private	1700	1700	780	65
11	Gihira	grid	Private	1800	1700	1260	70
12	Keya	grid	Private	2200	1900	1100	50
13	Rukarara II	grid	Private	2200	2000	1155	52.5
14	MukungwaII	grid	Private	3600	3400	1825	73
15	Rugezi	grid	Private	2600	2400	1300	50
16	Rwaza Muko	grid	Private	2600	2200	1560	60
17	Giciye I	grid	Private	4000	3600	1600	40
		Totals:		23,373	20,941	11,780	
		Fraction of Installed Capacity:			90 percent	50 percent	

note: * All plants are run-of-river designs with no storage reservoir. 1. Rainy season visits happened in April and May. 2. Dry season visits happened in Jun and August. Plant capacity factor data are from secondary data since it can't be calculated from the field visits data [59].

3.3.2. Effects of the river system on hydropower plant performance

The interviews with technical directors and plant managers revealed the importance of water-related factors that are partly or fully outside of the control of local plant operators and owners of the plants. These factors are conveniently divided into two subclassifications: (a) environmental conditions which impact seasonal river flows, and (b) the socio-economic context which impacts human activities near the river, upstream of the plant.

First, environmental conditions pose challenges that are mostly seasonal. Most importantly, low river discharge during the dry season and solid waste (e.g., tree branches) in the river during rainy season are major causes of poor plant performance. The importance of these problems can be seen from interviewees' answers in figure 7 regarding problems caused by factors that operators cannot control, as well as in figure 8 showing pictures taken during field observation.

Big drop in discharge during dry season, grid issues, and soil erosion (heavy garbage and sediments) are the most significant factors affecting negatively the sustainability of small-scale hydropower plants in Rwanda. Although water competition was not reported to be a big issue to the sustainability of small-scale hydropower plants, it is likely to be a big issue in the near future since all hydropower plants were designed for available maximum discharge. There is a reasonable increase in water use by municipalities for domestic use and such use is a priority for river water usage in Rwanda[60].

These problems are not easily solved through design measures but can be mitigated. Among positive environmental factors, the results indicate sufficient annual average rainfall and suitable head for run-of-river systems. For instance, the data indicate that plants are designed for maximum annual flows; on average the 17 hydropower plants in the study produce 90 percent of design capacity during the wet season visit. Since run-of-river hydropower plants have no water storage, river flow depends on direct runoff and limited groundwater injections into the river, resulting in a dry season generation capacity that is approximately half the capacity during the wet season. Due to the large decrease in river flow during the dry season, plants often cannot run continuously and must stop periodically to allow the forebay to fill. This reduces the dry season capacity factor further.

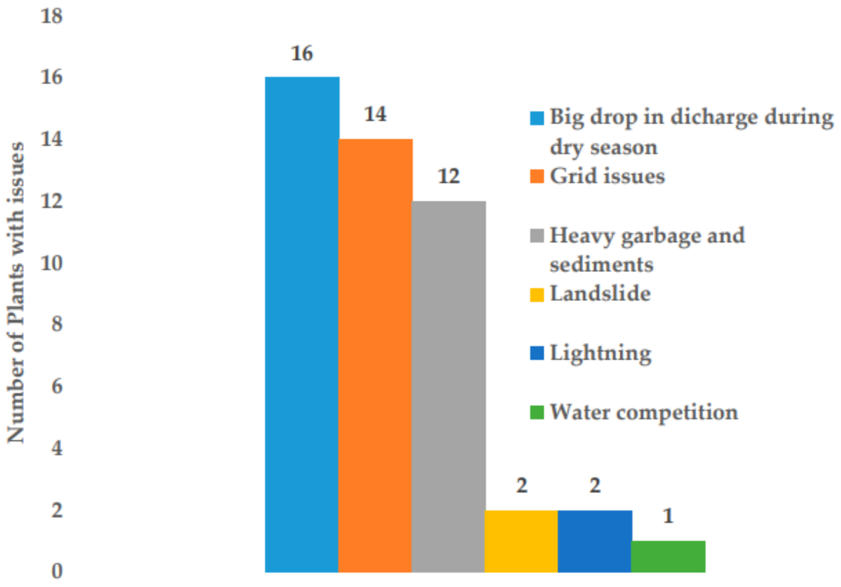


Figure 7. Interview results on factors outside operator’s control. Figure 2 reports the answers to the question: Did you have any problems with the plant or the grid caused by factors that you/the operator could not control? Respondents could give multiple answers and follow-up questions were also asked to ensure a wider set of factors were considered.

Figure 8. Field observation on soil erosion, sediments, and turbine wear. Clockwise from upper left: an upstream catchment filled with sediments and soil erosion during one rainy season, turbine runner wear due to waterborne sediment after 1.5 years in operation, heavy equipment removing sediments from another upstream catchment, and a sediment basin filled by sediments over three days during rainy season.

Second, human activities upstream of hydropower plants result mainly from the main economic activity of farming. According to Rwanda law, human activities are forbidden within 50 m of rivers, but in practice, land next to rivers is commonly used for farming and animal grazing. More than 80 percent of Small-scale hydropower plants are located in the northern and western part of Rwanda where many districts are classified as soil erosion risk zones, due to hilly topography, steep slopes, and high annual rainfall which combines to erode soil that is not covered by dense vegetation[61].

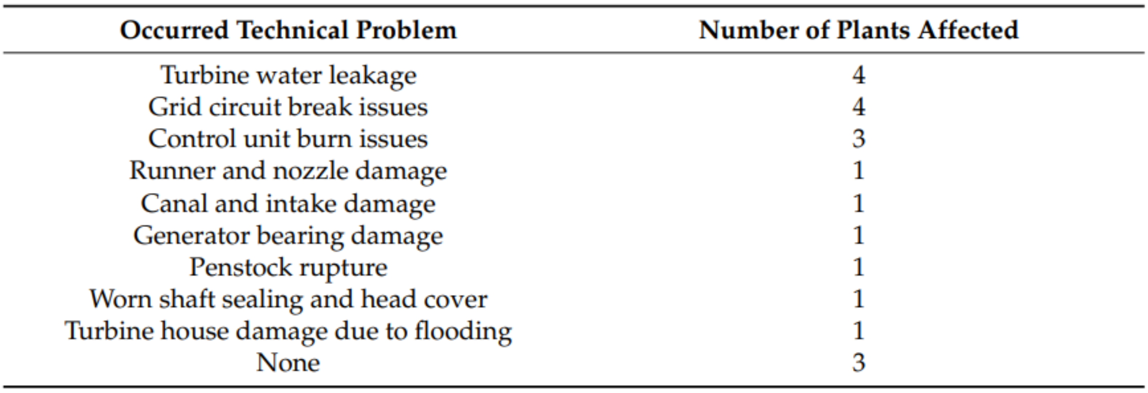
As described by Karamage et al[62], current human farming activities without erosion mitigation practices are causing high sediments loads in the rivers and, in areas where vegetation cover is cleared and the soil parent material is prone to sliding (the lithology type being gneiss or schists), heavy rains provoke the occurrence of landslides[58]. Two respondents stated that landslides increased repair costs during their plant's operation.

High sediments levels in the river are a problem in all seasons. Observations support that many technical problems are a result of high levels of sediments. Sediments fill the upstream catchment and block the intake and channel, hence reducing water flow and plant generation capacity. This causes lower production and thus lower income, and incurs cost for removing the sediments, as shown in figure 3. During field visits, the first author observed soil erosion and sediments negatively impacting upstream catchment storage capacity at ten plants. Interviewees were asked to compare the importance of sedimentation to other sustainability factors 11 out of 17 plants reported that sediment-related problems were the most important factor negatively affecting the plant operation and sustainability.

Sediments also cause wear on mechanical seals that result in turbine water leakage and damage to the runner and nozzles. Interviewee also stated that soil erosion and flooding cause damage to structures, such as the turbine house, the channel, and intake.

Table 6 shows these water-system related technical problems dealt with by respondents in 2018.

Table 7. Specific technical problems or damages reported to have occurred in 2018 at different power plants. Respondents could specify more than one type of problem. Three respondents answered that there had been no technical problem in the last year.



Occurred Technical Problem	Number of Plants Affected
Turbine water leakage	4
Grid circuit break issues	4
Control unit burn issues	3
Runner and nozzle damage	1
Canal and intake damage	1
Generator bearing damage	1
Penstock rupture	1
Worn shaft sealing and head cover	1
Turbine house damage due to flooding	1
None	3

While water level variations depend primarily on rainfall, upstream water diversions are also a factor. In interviews, only one company identified water competition as an issue, which suggests that water competition was not a critical issue for most plants. However, observation indicates that water competition may increase as the rivers are increasingly used for domestic needs in nearby villages and cities for irrigation activities or for mining. According to Rwanda water laws of 2018, domestic usage has highest priority, followed by environmental protection, and, finally, economic activities[63]. Many companies designed plants using maximum available river discharge without considering the possible emergence of competitive uses of the river flow.

3.3.3. Sustainability factors for electric power system.

Plant operators and technical directors also indicated several technical factors that are within their control. More well-known aspects have been considered in the design of infrastructure or are dealt with through regular maintenance.

For most plants, the majority of maintenance work is performed by local workers (respondents indicated that in 14 of 17 hydropower plants, their maintenance work is done by company staff only whereas in three out of 17 hydropower plants it is done by company staff except in some cases). The use of local staff reduces the cost of repair and maintenance. These workers were typically trained by equipment suppliers and through on-the-job training while working at the plant. Some companies operate multiple plants and have a team providing technical service. The level of technical skills is thus largely sufficient to correct common problems (respondents indicated that in 15 of 17 plants, their staff received training from suppliers and on-the-job experience whereas in two of 17 plants, their staff received professional training and on-the-job training). However, there is a shortage of domestic experts who can carry out plant automation and control during plant operation and upgrading (respondents indicated that in nine of 17 plants, their staff has enough knowledge to carry out operation, maintenance, and upgrading whereas in eight of 17 plants, their staff doesn’t have enough knowledge in plant automation and control). Ten respondents also stated a lack of in-country capacity building to keep pace with rapid international technology development. It was also observed that there are no in-country or in-region spare part suppliers and almost all respondents bought spare parts from overseas suppliers. Many companies maintain their own stock of spare parts, leading to premature—in worst case unnecessary—investment. Despite these issues, all respondents indicated that they can cover maintenance, operation, and equipment replacement costs through income from electricity sales.

Fifteen of the plants are privately owned. For these, interviewees bring up positive institutional factors: high commitment and ownership, simple procurement processes, and guaranteed sale of all electricity generated. Respondents perceive these as major contributors to the sustainability of their power plants.

3.3.4. Consequences of interconnection with national grid

To understand the positive economic situation, a closer look at the institutional setting is necessary. Out of the 17 surveyed plants, 16 are connected to the national grid and operate under a 25-year power purchase agreement (PPA) that sets the purchase price of the power produced by the plant. The PPAs are ‘all production’ agreements, meaning that the national grid will buy all electricity produced by the plants. The PPAs provide a key benefit to these plants: a stable sales price for all produced power. Therefore, income depends only upon how much electricity a plant can produce. Prices established by the PPAs are sufficient to cover operational and capital costs—in 16 of 17 of power plants, owners report positive net income on their plants.

Grid-connected, small-scale hydropower plants in Rwanda are typically connected to medium voltage (distribution systems are 25 kV in most cases, with a few exceptions for short distances in high population areas) distribution circuits. Synchronous generators at the plant are connected to the grid through switches and a step-up transformer. During normal operation, plant generators are synchronous with the grid, which controls the generator speed. During blackouts (local or national), the generator loses synchronization and protection controls perform an emergency stop on water flow into the turbine to avoid a destructive over-speed condition. Emergency stops produce high stresses on equipment— both rotating equipment and gates—as well as high currents and voltages in electrical components. These loads accelerate wear and failure rates of those components.

Distribution circuits in western Rwanda are often in heavily wooded areas. During high winds, vegetation may contact distribution wires, causes phase-to-ground and interphase faults. Protection devices on the distribution circuit sense these events and disconnect the circuit from the transmission system, causing a loss of voltage (a local ‘blackout’), and a plant shutdown.

While a grid connection provides a stable sales price for produced power, connection to the national grid also subjects plant equipment to frequent shutdowns due to local blackouts. Twelve interviewees identified grid integration issues as an important technical problem (see Figure 2). The issue was further investigated through observations during the one-day plant field visits in rainy and dry seasons, and during the one-month field observation at one hydropower plant.

Figure 4 shows the results of monitoring one plant for one month. Unplanned plant stops due to grid problems occurred most frequently in the rainy season—on average, three times a day. Most stops last a few seconds to two minutes—typical outage times for ground faults—and it takes a plant three to six minutes to reconnect to the grid. Faults are often caused by weather conditions; windy conditions may cause tree branches to contact power lines or lightning may trigger protection circuits. In both cases, faults may be cleared quickly by an auto-recloser, or may take longer if crews must repair damage or remove tree branches. The institutional responsibility for maintaining distribution grids and clearing line corridors lies with REG, not the IPP. Equipment problems may also cause faults. Poor insulation or water seals may cause power lines to short circuit during heavy rains, or ground faults may occur due to poor ground protection at the plant.

The outage pattern is shown in the bottom left of Figure 9. We find that blackouts were caused by a variety of factors, including external causes mentioned above, poor maintenance of some power lines, and noncompliance of small-scale power plants to grid protection standards.

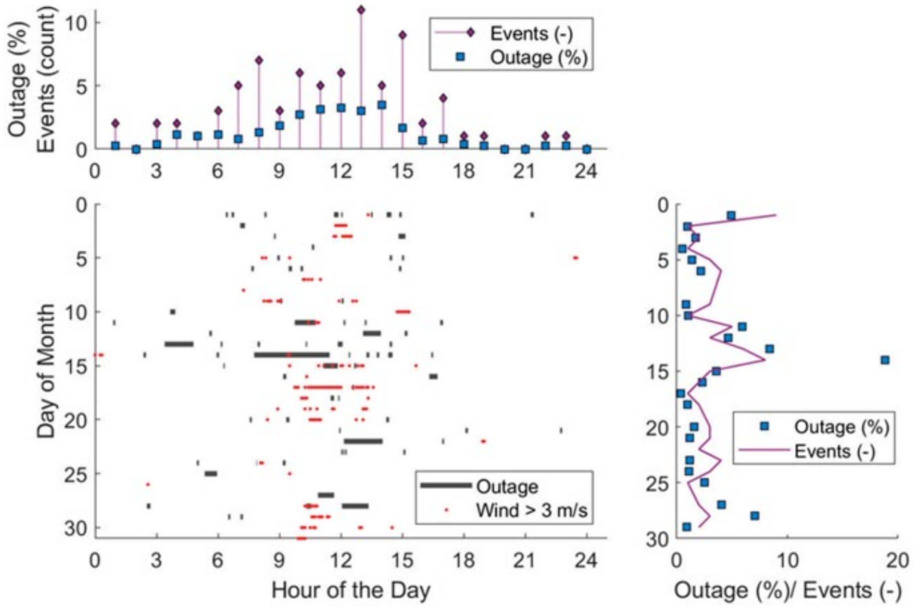


Figure 9. Data collected in the one-month field observation on unplanned plant stops due to grid tripping. Upper panel: Outage pattern by time of day—outages are more likely to occur during mid-day. Bottom left: One month of recorded outage data, overlaid with wind speed—windier times align with outage times. Right: Outage pattern by day of month—outages are random by day, but occur on 25 of 31 days.

3.4. Discussion.

In light of previous research on small- scale hydropower plants in developing economy contexts, this study indicates that Rwanda is unique for its uncharacteristically high-level grid integration and prevalence of private companies involved in the sector. Two other key features are very high sediment load in rivers and the large seasonal change river flow.

The individuals interviewed, most of whom work for private sector companies, presented a positive attitude towards the current development of the sector, as evidenced by their ability to cover costs, including capital retirement. The favorable institutional and regulatory conditions seen to have enabled the development and, in particular, the promises of economic stability offered by current PPAs for grid-integrated system[9][35]. Previous literature typically lists low income among the threats to sustainability, with difficulties in funding maintenance, repair, and re-investments as key issues [50][64][65]. Among the country's 25 small scale hydropower plants, 24 are grid connected and are not facing demand risks. Additional, REG has not had the payment problems experienced with other national utility operators in East Africa.

So far, literature on small-scale hydropower plants for the sub-Saharan region has not dealt with the issue of whether on-or off-grid operation is preferable. When off-grid generation is needed to support energy provision in remote locations, a small hydropower plant is often considered a good choice[66]. However, our study finds that access to grid connection hs attracted many IPPs to the development of small hydro, which increase private investment, freeing government capital for other public priorities. This development has been possible in Rwanda but, so far, has not happened to the same degree in neighboring countries or elsewhere in developing economies[44][65]. Strong development in Rwanda is likely a result of existing favorable policies, particularly feed-in-tariff regulation and stable PPAs, and existing ICT infrastructures in all parts of the country.

Our findings also indicate that studied plants have sufficient technical expertise to deal with most situation, whereas other studies of small-scale electric power systems in the east Africa region (on and off-grid) often mention a lack of technical skills as reasons why systems fail to operate through their design life[47]. Multiple companies involved also operate more than one plant and can afford to employ skilled staff to service their systems.

3.5. Conclusions.

This study has identified factors affecting the sustainability of 17 small-scale hydropower plants currently operating in Rwanda. Distinguishing between factors that are outside the control of plant owners and operators, and factors that they can control, we find the major positive factors to be: favorable existing regulations and policies, technical expertise among local staff to carry out plant operation and maintenance, and access to grid connection ensuring the economic viability of plants. However, river discharge drops in dry season, sediment load and soil erosion (especially in rainy season), and unplanned plant stops due to grid blackouts are the major negative factors affecting the sustainability of plants. These factors shorten the lifetime of turbines, reduce electricity production, and increase maintenance costs.

Based on these results, we conclude that the grid integration under the current institutional arrangements come with important benefits. Although there are technical issues that need further investigation and corrective actions, we recommend that the government of Rwanda maintains the conducive regulations to encourage IPPs to expand their production. To address the frequent shutdowns that are caused by grid tripping, we suggest IPPs should design plants with protection systems that comply with grid protection standards. There is a need for sector stakeholders to engage in a dialogue on how to ensure the regular maintenance of transmission lines and feeder lines from plants to grid, as well as clearing vegetation underlines to minimize grounding faults during rainy and windy weather.

The study indicates that water level is currently not a major challenge, but the seasonal drop in discharge and plant capacity factor raises questions about the suitable design of plants. We see the need for further research on the best plant designs to cope with seasonal variation and increased future water use for domestic, agricultural, and industrial needs. In addition, as increasing temperatures impact rainfall patterns, there will be a need to balance competing claims for water. The IPPs cannot control upstream activities leading to soil erosion, as erosion control is under the jurisdiction of the government of Rwanda. We suggest that there is a need for further research on upstream mitigation measures in dialogue with local farmers, and on design solutions to either reduce the amount of silt entering the plant, or the silt's effect on equipment and operation.

CHAPTER 4. SIZING OF SMALL HYDROPOWER PLANTS FOR HIGHLY VARIABLE FLOWS IN TROPICAL RUN-OF-RIVER INSTALLATIONS: A CASE STUDY OF THE SEBEYA RIVER

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4.1. Introduction

There is an increasing need for reliable technical information to inform or act as a reference for investors in hydropower development in tropical run-off rivers especially in developing countries where there is a scarcity of time series data on river flow rates and a lack of published feasibility studies on plants. Hydropower is a widely deployed renewable energy technology, reliable, and in most cases, considered an inexpensive renewable energy source, with LCOE ranging from 0.05–0.10 US $/kWh[67]. This is reinforced by prior analyses (Panwar et al.; 2011; Chu and Majumdar, 2012; Jiang et al., 2018, as cited in [68] indicating that hydropower is an affordable, reliable and the most deployed renewable energy technology.

Renewable energy are energy sources which are refilled at a higher rate compared to the rate of consumption and produce lower emissions in comparison to fossil fuels. Examples of renewable energy are solar energy, wind energy, geothermal energy, hydropower, ocean energy and bioenergy[69].

In Africa, hydropower is the most developed renewable energy source, with a total installed capacity of 53 GW or approximately 63% of the total deployed renewable energy. However, Africa needs additional generation as a catalyst for economic development, while simultaneously controlling greenhouse emissions. As of this writing, the continent has developed only 11% of its hydropower potential[4].

Hydropower plants are classified based on different factors such as water inflow regulation available, size of installed plant capacity, and type of load being supplied. Regarding water inflow regulation, hydropower power plants are classified into three categories: (1) Reservoir plants, which have a dam and reservoir that stores water and regulates water inflow; (2) (ROR) plants, which have minimal reservoir capacity—typically a small diversion dam and catchment—and the water supply is mainly determined by the current river flow; and (3) pumped storage plants, which have both upper and lower reservoirs. During low-power demand, pumped storage uses electricity to pump water from the lower to the upper reservoir, and uses water from the upper reservoir for electricity generation during high demand [67].

Hydropower power can also be classified as large or small depending on the plant's generation capacity. Small hydropower plants have a generation capacity up to 10 MW but specific definitions vary between countries[70]. There are three other commonly accepted classes of hydropower plants: mini (100–1000 kW), micro (10–100 kW) and Pico (< 10 kW).

Plants of these sizes are sometimes classified independently or included in the small hydropower plant category.

In Rwanda, the total installed capacity, by rated power, for all energy sources is 238 MW, of which renewable energy accounts for 55%. Total capacity, in descending order is: 44% hydropower, 25% thermal (primarily marine diesel), 8 % methane gas (harvested from Lake Kivu), 8% imported and shared resources with neighboring countries, 6% peat fired thermal plants and 5% solar photovoltaic[71]. Small-scale hydropower includes 44 plants [6], all of which are RoR. The country is characterized by a tropical climate with dry season river flows that are 50% or less than wet season flows [72] .Rwanda is commonly characterized as having four seasons: A short rainy season (from September to November), a long rainy season (between March to May), a short dry season (between December to February) and a long dry season (from June to August). Recent climatic data indicates that rainy seasons are becoming shorter but with higher intensity rainfall events[73]. This change is likely to increase the variability in river flows[74].

Sebeya river is located in the western part of Rwanda and is the largest catchment in the region. The Sebeya originates in high elevation mountains along the edge of Nile– Congo divide in the Rutsiro district. The river runs through Gishwati national park and discharges into lake Kivu with a length of 110 km[75]. The whole region of East-Central Africa has experienced an average temperature increase of 0.29 ◦C from 1985 to 2015, and Rwanda in particular has experienced large fluctuations in annual rainfall over the 55-year period from 1961 to 2016[76].

The plants which are the focus of this study—small ROR hydropower plants—have minimal reservoir capacity and use immediate river flows for electricity generation[67]. As a result, these plants are sensitive to seasonal weather variations that impact river flow. In particular, this study deals with sizing a hydropower plant in these highly variable flow conditions, proposing a methodology for analysis and suggests general conclusions on the optimal design flow rate and turbine type for cost-effective electricity generation. This analysis is of interest to future investors in the run-of-river hydropower plants in similar climatic conditions.

Hydro turbines are classified into two types: impulse and reaction turbines. In reaction turbines, water flows over runner blades and energy production results from the pressure caused by changes in direction of the moving water. Reaction turbine types include Francis, Kaplan and propeller turbines. In impulse turbines runner buckets redirect a jet of water impacting a runner's curved buckets, creating a change in momentum and resulting force[77]. Impulse turbine types include Pelton, crossflow and Turgo turbines.

In turbine selection, there is a set of requirements and specifications which include either site conditions (head and flow rate) and/or output power requirements[78]. In general, turbine selection is based on the available head and flow conditions in comparison to standard charts during initial sizing, while detailed design includes additional analysis to consider technical, social, environmental, and economic factors[79]. The work performed here is focused on the initial design phase, when a developer is primarily interested in the initial sizing to estimate the cost of civil works, permitting, land-access costs, and similar preparatory steps, prior to detailed design.

The previous literature identified several technical parameters considered in the sizing of hydropower plants and predicting energy generation. In the design process, sizing of a hydropower plant size is primarily determined by head, reservoir size, minimum downstream flow rate, and river seasonal inflow[76]. A study by Fairuz et al.[80] on factors affecting mini hydropower production efficiency concluded that humidity and rainfall have a significant effect on the power generation in mini hydropower plants and can be used to predict energy generation. A study by Singh et al. [42] concluded that head, discharge, and generator parameters affect the operation of ROR hydropower plants. A study by Aggidis et al. [81] on the costs of small-scale hydropower production concluded that the cost of manufacturing mini hydropower turbines is determined by the hydraulic characteristics of the hydro resource available and changes with turbine size and type.

It also defined the LCOE and identified parameters considered in computing LCOE of different renewable energy technologies. LCOE is a measure used in estimating the cost of generating electricity over a lifetime of any generation technology. It can also be used to determine the cost-effectiveness of electricity generation of any technology without taking in account the assumptions of price at which generated electricity is sold to both the end user and the grid. Again, from the LCOE one can determine whether a technology is profitable or not. If the LCOE is lower than the price at which the generated electricity is sold, it is profitable and when the LCOE is greater than the price at which the generated electricity is sold it is unprofitable

[82]. Different studies have identified different important parameters to be considered in calculating the LCOE of different technologies. A study by Patro et al.[83]on clean development projects in India found that in recent years many developers of small hydropower plants conduct life cycle costing studies without ignoring any costs which were used before operating and maintaining the plant, replacement, certified emission and others. A review of the LCOE of solar photovoltaics by Branker et al. [84] on how to get the correct LCOE of solar photovoltaics concluded that due to the highly variable LCOE inputs of solar technology, to get correct LCOE outcome, almost all costs associated with solar electricity generation should be included. A study by Ouyang et al. [85] on the LCOE of renewable energies and required subsidies in China found the accurate cost estimations of renewable energies were urgently needed to accelerate renewable energy development. The study recommended that the existing feed–in–tariff (FIT) be improved and adjusted based on the LCOE and to provide subsidies in the short-term to reduce the high-cost of renewable energy.

Additionally, previous work has identified that low-quality pre- and full-feasibility studies contributed to project failure [44], and a study by Fairuz recommended the use of machine learning to improve predictions of energy generation [80]. In Rwanda, there is no similar published work, and, unfortunately, there is little time series data for river flow (discharge rates). Therefore, to systematically size mini-hydropower plants for Rwandan rivers, such as the Sebeya, it is necessary to both estimate the river flows and to use those flows to estimate the optimal sizing of the power plant. Thus, the Sebeya flows were predicted using a neural network (scaled conjugate gradient or SGC method) by inputting both secondary data (using precipitation and flow rate) and primary data (collected flow rate at the Sebeya river).

4.2. Materials and Methods.

4.2.1. Flow rate estimation

To size a small ROR hydropower plant for any river, a time series flow rate of the river is needed. However, the only available historical consistent flow rate of the Sebeya from a Rwanda water resource board was from 2017. By 2019, historical flow rate data was inconsistent or missing for the Sebeya river. There the report from 2017 was the best method for predicting, given that the lack of data is a real issue for other sites. Machine learning is being used in different approaches to help forecast energy generation, and improve the operation, design, and maintenance of hydropower plants. Among other applications, it has been implemented in the optimal dispatch of hydropower plants based on head and river flow [86], to assess hydropower reliability due to climate change[87][88], reservoir water level forecasts[89], and to help mitigate silt erosion in the hydro-mechanical components of the plant [90]. Yang et al. used a deep learning method to predict hydropower generation at small plants based on historical precipitation data provided by weather stations with 93% accuracy, [91]. However, access to reliable and consistent data often remains a challenge in such studies[92] This study used the Sebeya 2019 precipitation from the Rwanda Meteorology Agency, available Sebeya flow rates from 2017 (provided by the Rwanda water resources board) since there were no historical consistent flow rates of the Sebeya for 2019, and Sebeya field visit measurements conducted in 2019 (19 April 2019, 17 May 2019, 29 June 2019 and 20 August 2019). Using these data, machine learning was used to predict the Sebeya flow for the observed weather conditions in 2019, a timeframe where near-continuous meteorological data was available for the watershed area of the river. The methodology used is shown in Figure 10.

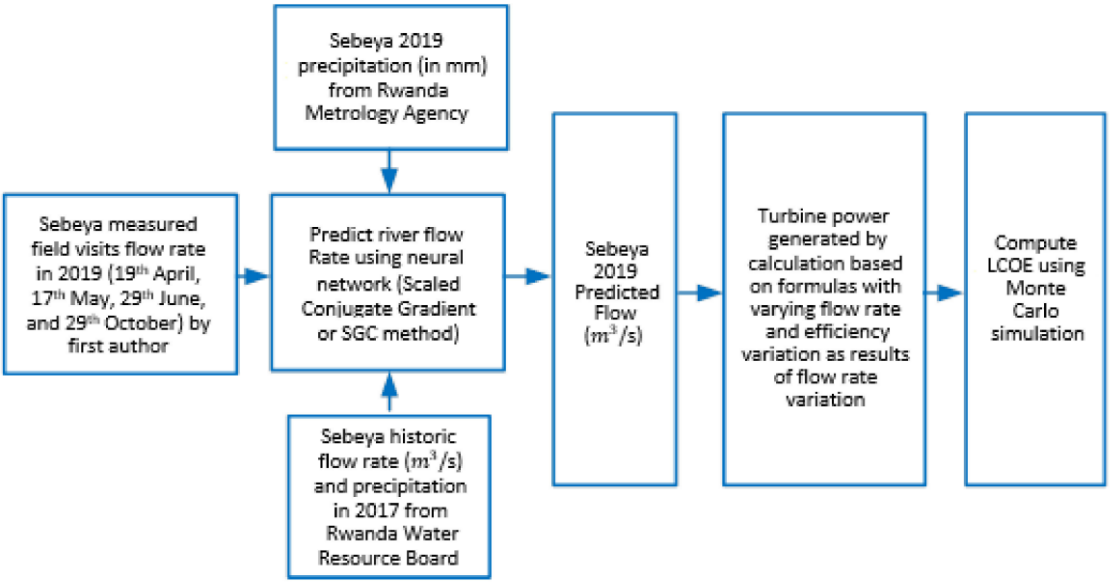

Figure 10. Methodology for estimating river flow rates.

The machine learning method estimated river flow data for 2019, using daily precipitation in the Sebeya river watershed during 2019 after being trained on the available Sebeya flow rate data from 1 May 2017 to 31 December 2017. The training data represented the longest period of near-continuous flow rate data available—200 days of data, spanning wet and dry seasons, with coincident records for both precipitation and river flow. In contrast, only precipitation was available for 2019, the year when the study was conducted. Therefore, data from 2017 was utilized to train a neural network (NNET), and the trained model took as its input precipitation, and predicted the river flow.

Training used the scaled conjugate gradient (SCG) method. SCG is a supervised learning algorithm that minimizes the error between its results and a target variable, using a defined error function [93]. The advantage of this method in comparison with others, like Adam and scaled gradient descent, is that it does not need a learning rate and therefore is less dependent on user inputs, making it effective for large-scale problems [94].

According to the US geological survey[95] and US rivers, basin lag time—the difference between peak rainfall and peak discharge of the river—varies from 0–105 h. To accommodate this lag, the model uses the 10 previous days of precipitation, approximately two times the estimated basin lag time.

The Sebeya river flows are characterized by high flow rate events shortly after heavy rain in the watershed of the river. Therefore, special precautions were taken to assure that predicted river flow rates—in practice, 1000 Monte Carlo iterations of the model—reflected the nature and magnitude of these events.

First, error was calculated using mean absolute error (MAE), rather than root mean squared error, as MAE assigns less weight to the large errors. This allows the fitted model to better retain points that deviated substantially from the norm, i.e., to better model high rainfall events. Figure 2 provides an example. The middle plot compares the training data to the predicted data for one iteration of the model. From index 25 to 80, the river flow is nearly constant as this is the dry season, with few rainfall events. Later indices indicate the start of the rainy season, characterized by periodic rain events and a higher variation in river flow rate.

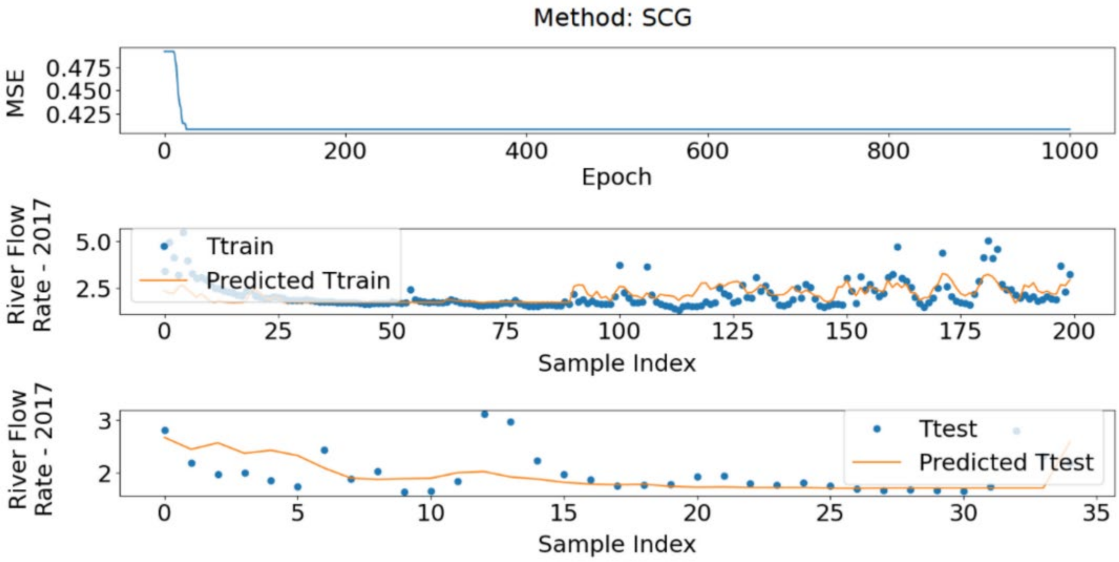

Figure 11. Machine learning results. The upper panel shows the error function over the training generations, the middle panel compares the predicted output with the training data, and the lower panel tests data with the predicted data.

The training and error functions were selected to retain the extreme flow events, which are observed on the river following major rainstorms. One example of a predicted river flow rate is shown for 2019 in figure 3.

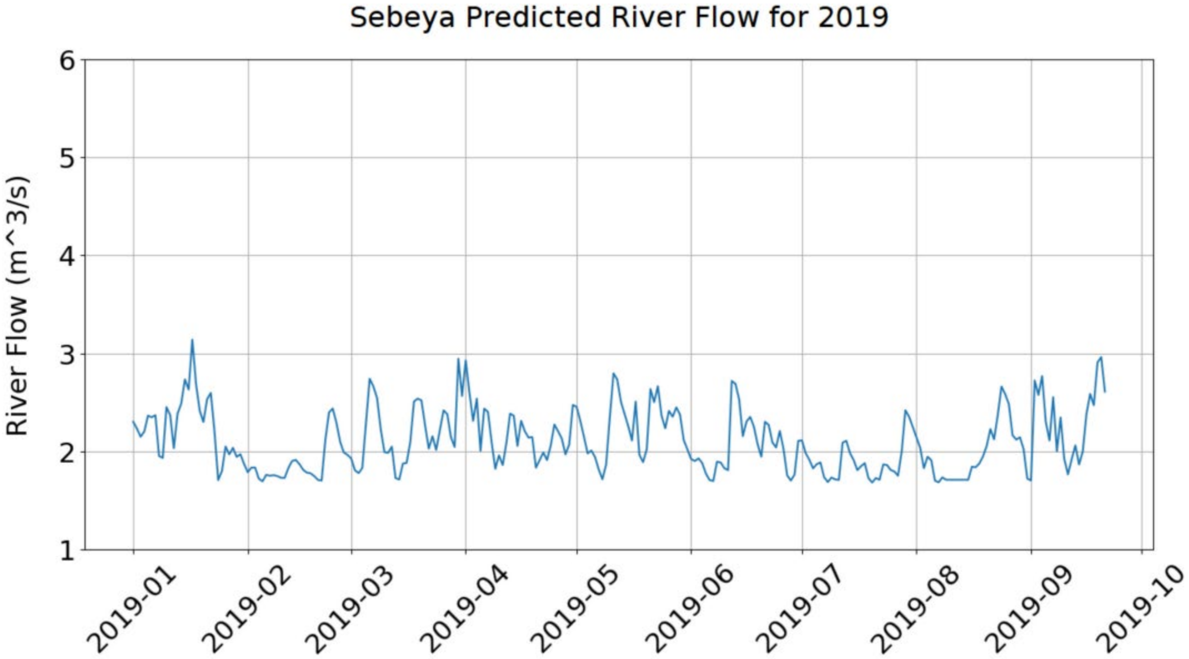

Figure 12. River flow prediction for 2019, prior to capturing high flow events.

From figure 11, during the period with high variability in the rainy season river flow (index 80 onwards), the model output does not capture high variations in the river flow seen in the training data, i.e., from actual flow measurements. This is characteristic of machine learning models for this type of application. To add this high variability back into the model results, the predicted flow was adjusted by adding in the deviation between the neural network (NNET) prediction and the training data observations of the actual flow. The method used was as follows: NNET outputs were binned at 0.1 m^3/s intervals; an error distribution between the NNET prediction and the training data was calculated for each bin; the NNET prediction for 2019 was adjusted by randomly adding a deviation drawn from the error distribution of the correspondent NNET bin. Adding these adjustments further restores extreme river flow events to the smoothed NNET results.

Each run of the trained NNET results in a different prediction of the river flow rate. This process was performed 1000 times, creating a family of 1000 plausible daily average river flow rate predictions for the Sebeya in 2019, see Figure 13.

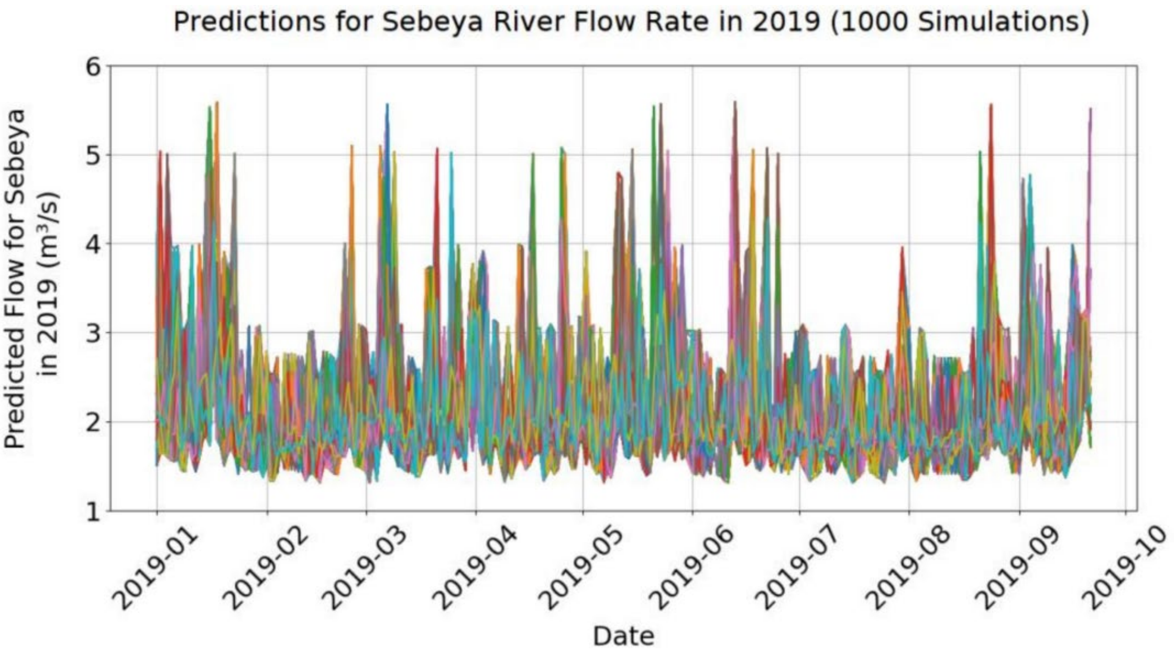

Figure 13. Adjusted predictions for the Sebeya river flow in 2019. In the chart, each of the one thousand simulations performed is represented by a line in a different color. All 1000 iterations are overlaid in the figure. Vertical width on any time step illustrates the randomized range of the river flow rate for each time step.

As noted earlier, limited river flow rate data was available, and the data available had substantial periods with no, or suspect, flow readings. Therefore, to provide a limited 'spot check' of the model, the first author measured the river flow at a power plant located on the river on four dates: 19 April 2019, 17 May 2019, 29 June 2019, and 20 August 2019, resulting in measurements of 4.24 m^3/s, 3.3 m^3/s, 1.96 m^3/s, 1.61 m^3/s, respectively. A simple measurement process was performed: Timing the movement of a float on the surface of the river, measuring the cross-sectional depth of the river, and applying appropriate hydraulic calculations. We compared these data to the distribution of results for the measurement days, as shown in figure 14.

Two measurements were well within the inner quartile of the predicted flows, while the other two measurements were within the outer quartile and within the range of the outlier data, respectively. It should be noted that Rwanda was in drought conditions in 2017, while 2019 was considered a rainy year. While limited in scope, these measurements indicate that the model produces values, including outliers, which are representative of the observed conditions.

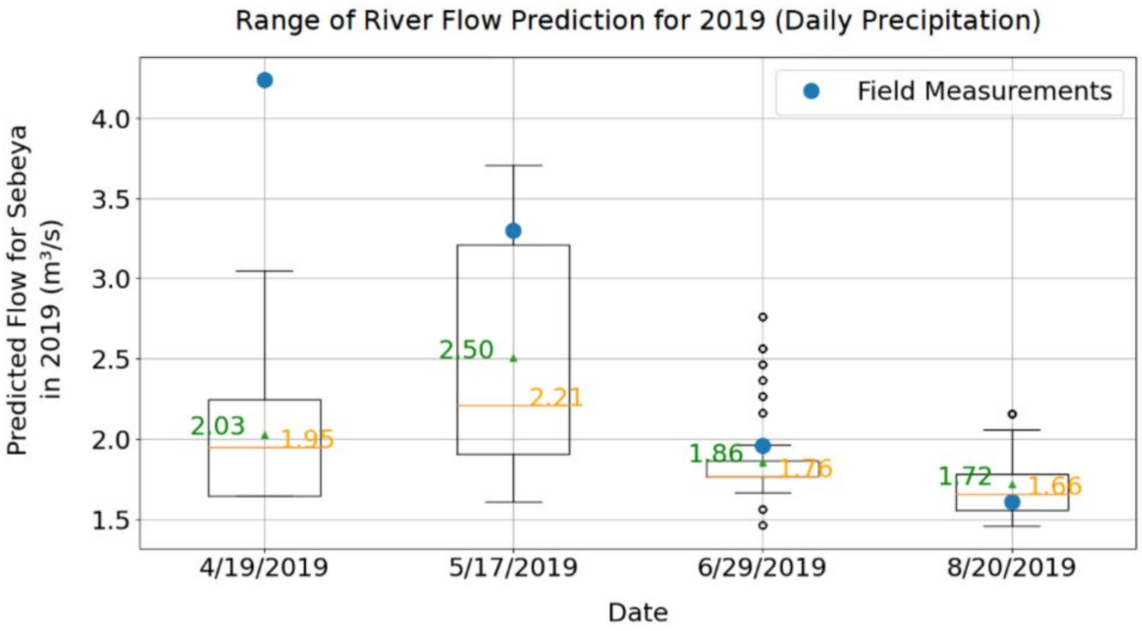

Figure 14. Predicted and measured river flow rate. Boxplots represent the inner and outer quartiles and outliers. Blue points are measured river flow rates.

4. 2.2. Power production estimation

The analysis utilized here develops a first-order simulation of the turbine performance, using the 1000 Monte Carlo iterations predicting the river flow rate. Turbine produced power,

is:

$$P_W = \frac{1000*9.81*h}{1000} = 9.81 * q_d * h \qquad (1)$$

$$P = \quad n_m \rho q_d g h \qquad (2)$$

where g is the acceleration of gravity (m^3/s), qd is the flow rate of the river in m ^{3}/s used to select the turbine and design the power plant ('designed flow rate'), h is the working head of the river net of friction losses in the penstock and head gates (m), ηm is the efficiency of the turbine at the designed flow rate, and ρ is the water density 1000 kg/m^3. For this study, we assumed the plant was designed such that the efficiency is maximized at the designed flow rate, i.e., ηm is the maximum efficiency of the turbine, typically at or near full load.

For the Sebeya River, the flow rate (qd) varies between 1.3 m^3/s and 5.5 m^3/s under non-flood conditions. In this study all plants were designed for flows below 3.5 m^3/s. Water above this flow rate would be directed around the turbine via spillway gates and not contribute to power production.

For conditions away from the designed flow rate, Equation (1) can be considered as a general function of the river flow rate and efficiency, since all other parameters remain fixed after the plant is designed. Further, efficiency is also a function of the deviation of the current flow rate from the designed flow rate, resulting in:

$$P = \quad F(q, \eta) = F\big(q, G(q)\big) \tag{3}$$

where F and G are arbitrary, typically discretized functions of flow rate. Flow rate q is determined by the analysis in the previous section for all times considered in the study, and, in general, $\eta = G(q)$ is the result of empirical testing of the selected turbine; see below. In practice the analysis utilizes normalized calculation throughputs, where performance of the hydropower plant is expressed as fractional power output calculated at the given flow rate, relative to the designed flow rate. Fractional flow rate is:

$$Fq = \frac{q_p}{q_d} \tag{4}$$

where Fq, is the fraction of designed flow, in percent, q_d is the designed flow rate, and q_p is the predicted flow rate of the river.

Turbine efficiency for each turbine type was estimated by digitizing a generic turbine efficiency chart[96] that provided the efficiency at flow rates relative to the designed flow rate of the turbine. Data is valid from 5–100% of the designed flow rate, and digitization was conducted at an interval of 5%, see figure 15.

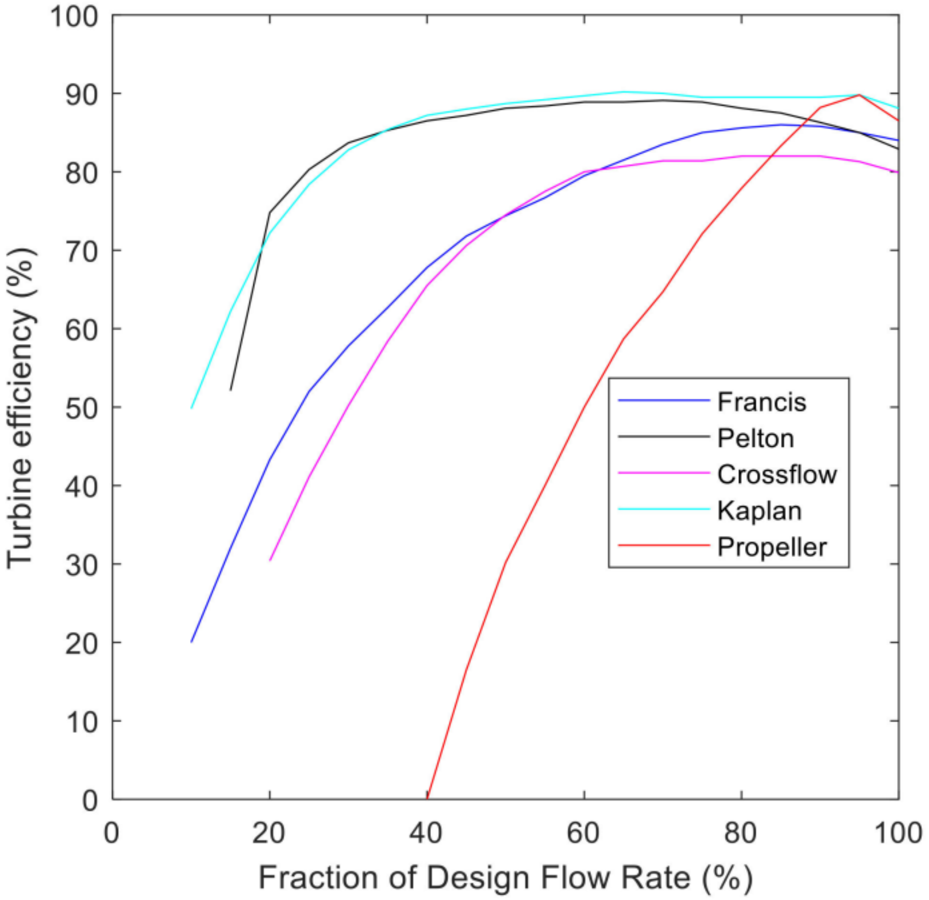

Figure 15. Summary plot of the turbine efficiencies relative to the designed flow rate.

Energy produced per turbine type was constrained to 100% of the designed flow rate, resulting in:

$$E_i = \left\{ \begin{matrix} F_{qi} & q \leq q_d \\ 100 & q > q_d \end{matrix} \right\} * \eta_i \Delta t \qquad (5)$$

Where Ei is energy produced relative to the designed conditions during one time step i, Δt is the time step of the simulation—1 day in this analysis—and Fq and η are calculated for each time step. Using the predicted flow rate, turbine net efficiency for the simulated time period is:

$$Ne = \frac{1}{n} \sum_{i=1}^{n} E\mathrm{i} \qquad (6)$$

where Ne is the net turbine efficiency relative to the power produced, across all Monte Carlo simulations, for a given turbine, sized for a selected designed flow rate. The number of periods used to simulate Ne, n, is the product of the length of the simulated river flow (262 days) and the number of Monte Carlo iterations, 1000. The designed flow rate of the powerplant, qd , was simulated for 1 m^3/s to 3.5 m^3/s. In practice, any duration of river flow rates, at any available time step, could be substituted providing peak and trough flow events, and are statistically represented in the simulation.

To compute the total energy produced for the purpose of computing the levelized cost of energy (LCOE), power in the water at the designed flow rate, as per equation (1), is multiplied by net efficiency, Ne, and annualized to one year:

$$Et = 8760 P_w N_e \tag{7}$$

where E_t is the electricity generated in one simulated year.

4.2.3. Levelized Cost of Electricity (LCOE) Generated

A simplified cost model was utilized for plant sizing and costs, to provide general information on the tradeoffs between plant sizes, as is appropriate for the early planning stages simulated here.

The head is assumed for reasonable locations on the Sebeya river, and the type of turbine being used; a typical maximum gross head is 80 m. Costs can be broken into two components. The first component is an up-front investment in non-reoccurring engineering costs, permitting, legal fees, loan applications and processing fees, supervision cost, studies, etc. This value is uncertain, but for practical implementations in Rwanda, a reasonable range is between 250,000–500,000 USD for a small hydropower plant. Lacking any information about the distribution of these costs, we assumed uniform distribution.

The second component scales with the size of the plant. Using confidential data from two hydropower developers operating in Rwanda, the study assumed a required investment uniformly distributed between 2500–3000/kW USD. Using the renewable energy technologies cost analysis series report[97] and estimates from hydropower owners in Rwanda, the study assumed the operation and maintenance (OM) cost per $ capital cost uniformly distributed between 0.025–0.03 $/$ capital investment.

To assume plant operating uptime and lifetime, owners of existing power plants were asked to estimate both parameters; resulting in an operating uptime of 0.85 and a plant design life of 18 years. Similarly, to assume a discounted rate, several banks in Rwanda were interviewed, resulting in a discounted rate of 12%. Given the above assumptions, the LCOE for renewable energy is calculated as;

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n_t} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n_t} \frac{E_t}{(1+r)^t}} \tag{8}$$

where LCOE is the average levelized cost of electricity generated, it is investment expenditures in the year t, Mt is operation and maintenance expenditures in the year t, Ft is fuel expenditures in the year t, Et is the electricity generated in year t, r is the discount and nt is the economic life of the system.

4.2.4. Return on Investment (ROI)

Return on investors is a measure of business project profitability.

ROI

$$ROI = \frac{N_g}{C_i} \tag{9}$$

where ROI is the return on investment, Ng is net gain and Ci is cost of investment. From return on investors, one can tell whether a business project is profitable or not [89]. A positive return on an investment means a profitable business while a negative return on an investment means an unprofitable business.

4.3. Results

4.3.1. Best Turbine Type and Designed Flow Rate at Sebeya

The primary metric of interest to evaluate the design of the plant is the capacity factor, defined as:

$$CF = \frac{24 * N_e * N_t}{E_t * 8760} = \frac{N_e}{365} \tag{10}$$

Where CF, the plant capacity factor, is the ratio of actual energy generated by the plant to the maximum energy that could generated by the plant working at full capacity over a period of time.

Energy generated by the plant per year (kWh/year) is mainly influenced by the available river flow rate over a year. Variation in the river flow rate affects turbine efficiency for multiple turbines as reflected in the turbine efficiency chart[77] and Equation (3). A designed flow rate with the highest capacity factor for any given turbine type harvests the maximum power from the water flow, given the characteristics of the river.

Capacity factor simulation results in Figure 16 indicates that Francis, Kaplan, Pelton and crossflow turbines operate across a wide range of flow rates at relatively high-capacity factors, while the capacity factor of propeller turbines is only near maximum over a narrow range of flow rates. This drop-off in efficiency of propeller turbines typically makes them unsuitable for the highly variable flows in tropical RoR plants. Therefore, this type of turbine is not considered further in this study.

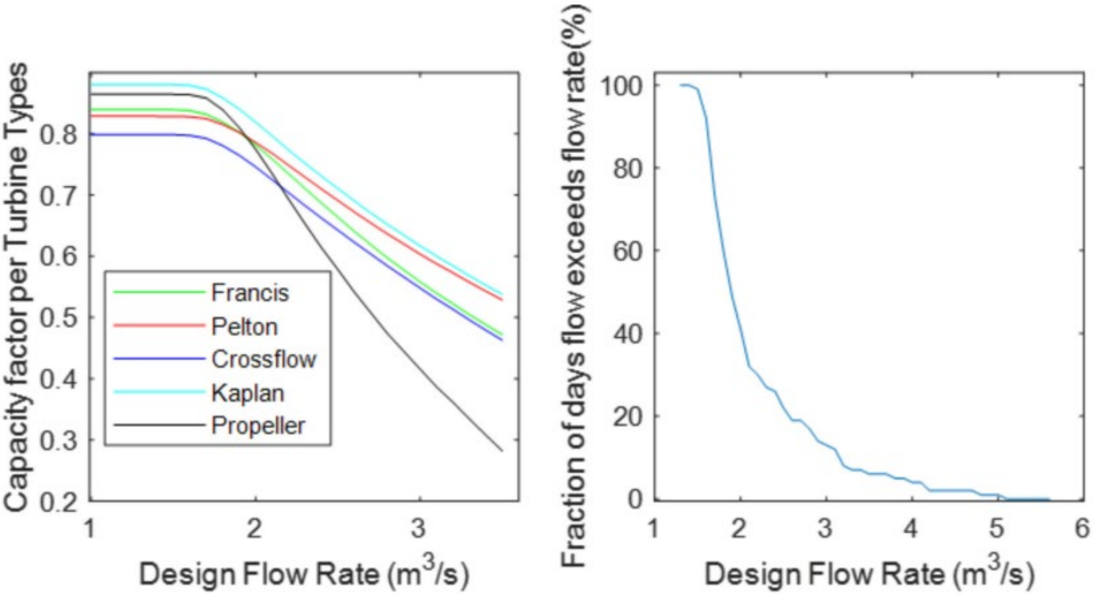

Figure 16. Capacity factor as a function of the river flow rate. Left panel: plant capacity factor for several common turbine types, as a function of the designed flow rate of the hydropower plant. Right panel: River flow exceedance curve.

It is also observed that the capacity factor for all the turbines is flat up to 1.7 m^3/s because there is an increasing power in the water flow at near-constant turbine net efficiency, which maintains the power produced at the designed power plant capacity. In contrast, the capacity factor drops at designed flow rates above 1.7 m^3/s as the number of days with available water at the designed flow rate drops off rapidly above 1.7 m^3/s —as shown by the right panel in the figure—and the plant is operating below the designed capacity, and at reduced efficiency, for an increasing number of days per year as the designed flow rate increases. As can be seen from the figure, the drop in the capacity factor is closely aligned with the knee in the flow exceedance curve. Therefore, it is reasonable to expect the optimal LCOE at or near that flow range.

Given the tight grouping of the capacity factor curves, for subsequent analysis, the study focused on the most commonly utilized impulse turbine type (Pelton), and one type of reaction turbine commonly utilized in small hydropower applications (Francis). Other turbine types were calculated but are not shown here for clarity.

4.3.2. Calculation of Annual Energy Produce (kWh) Per Turbine Type

From equation (3), the power generated is a function of the designed flow rate and turbine efficiency, which is dependent on the turbine type[98]. This variation in turbine efficiency will affect the total power generated as per Equation (7).

From figure 17, for both turbines the annual average energy produced from the designed flows of 1.7 m^3/s to 2.9 m^3/s increases monotonically as a result of the increasing water flow rate at similar high-operating efficiencies. Above a designed flow of 2.9 m^3/s, the annual average energy produced by the Francis flattens and then decreases as the increased power in the water flow cannot make up for the decreased turbine efficiency— the turbine is operating below its designed flow rate for substantial fraction of the year. The Pelton turbine, in contrast, continues to increase as it has a flatter efficiency curve resulting in a flatter power production.

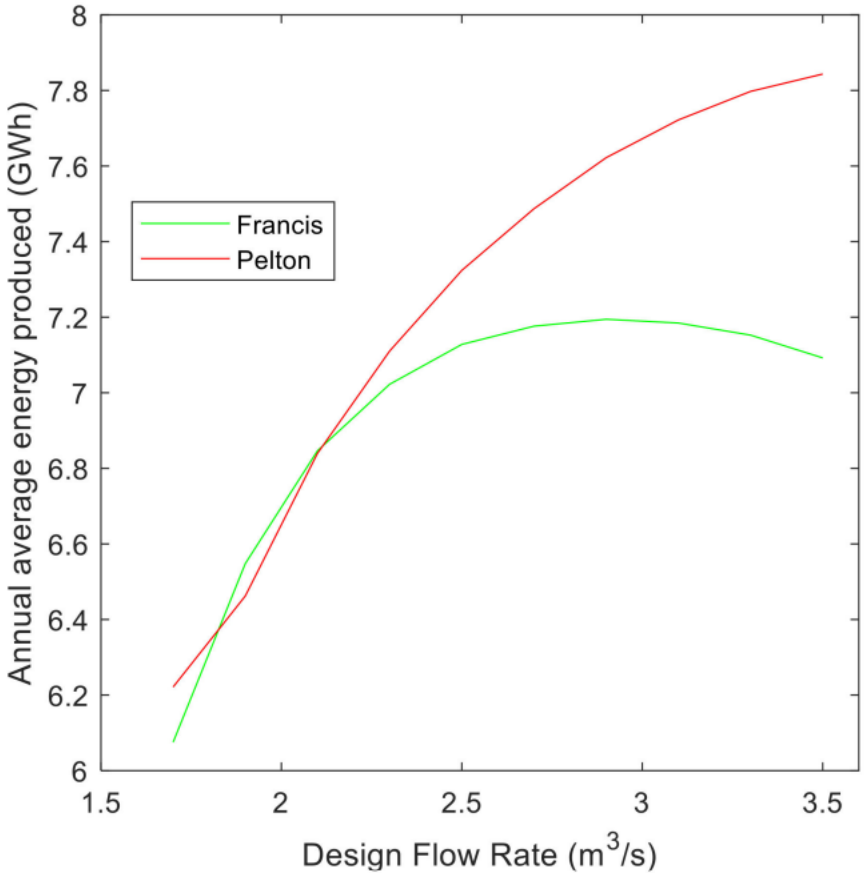

Figure 17. Annual average energy produced (GWh) at varying designed flow rates at a constant head of 70 m for the Francis and Pelton turbines.

4.3.3. Plant LCOE for the Francis and Pelton Turbine Performance at a Constant Head and Varying Designed Flow Rate.

Different turbine types perform better in different head ranges, Pelton performs better in the high head range (h = 100 m), Crossflow and Francis perform better in the medium head range (30 m < h < 100 m), while Kaplan perform better in the low head range (h < 30). Figure 18 shows the LCOE curves of Francis and Pelton at a constant head and varying river flow rate. The LCOE sets the acceptable contract price for generated electricity in most power purchase agreements.

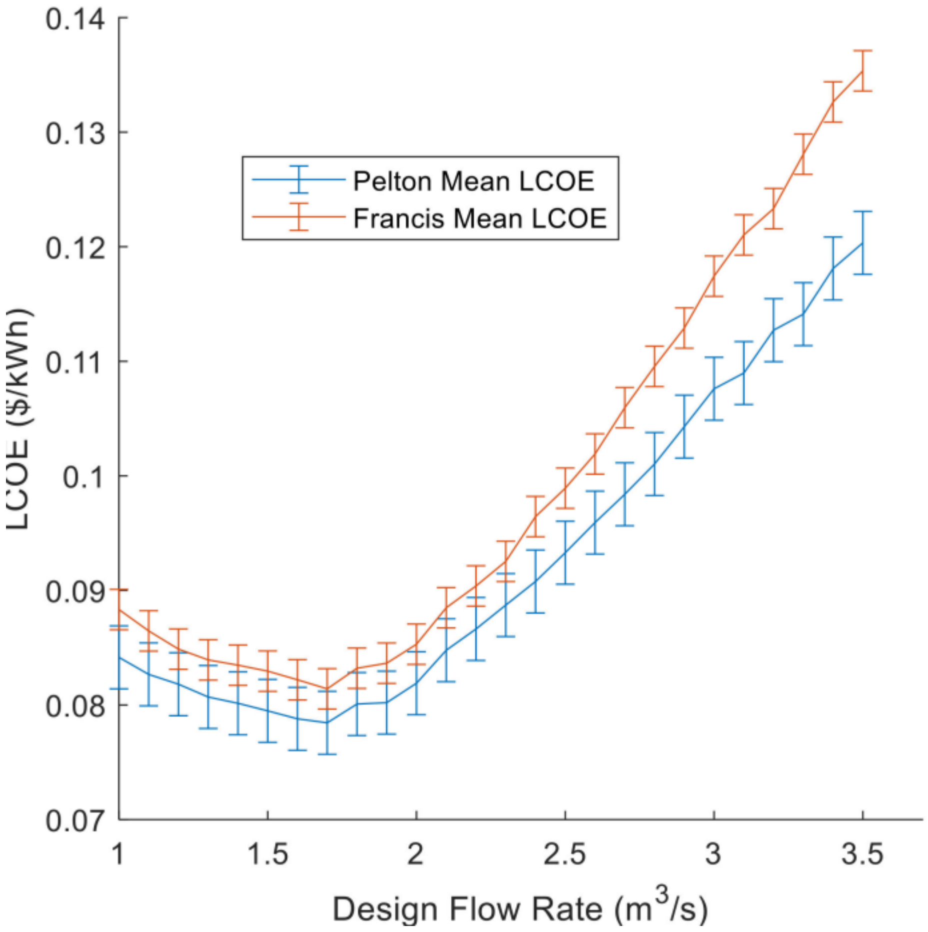

Figure 18. The LCOE ($/kWh) for Francis and Pelton at varying designed flow rate (m^3/s) and a constant head of 70 m. Error bars indicate 95% confidence intervals for each simulated LCOE point.

From figure 18 and table 7, including uncertainty, the range of the equivalent minimum LCOE, accounting for uncertainty, occurs near the knee in the flow exceedance curve, indicating that the capacity factor has the dominant influence on the LCOE, overwhelm-ing the other factors simulated in this analysis. Given the current electrical pricing in Rwanda, plants designed at the minimum LCOE would likely be cost effective, although power purchase agreements should be negotiated to include the downside uncertainty— approximately \$0.01 \$US/kWh.

Table 8. The Francis and Pelton minimum LCOE and range of the equivalent minimum LCOE including uncertainty at a net head of 70 m.

Turbine Type	Minimum LCOE ($/kwh) Including Uncertainty		Designed Flow Rate (m^3/s) that Produced the Minimum Cost
	Minimum LCOE	**Uncertainty**	
Francis	0.082	−0.011/+0.009	1.6 and 1.7
Pelton	0.082	−0.011/+0.009	1.6, 1.7 and 1.8

Return on investment (ROI) for plant with Francis turbine

$$\mathrm{ROI} = \frac{(\text{Price of selling electricity to grid}(\$/\text{kwh}) * \text{Average operating load}) - \text{LCOE} * \text{plant size}}{\text{LCOE}*\text{plant size}} * 100$$

$$\mathrm{ROI} = \frac{(0.1205 * 1023) - 0.082 * 1442}{0.082 * 1442} * 100 = 4.252\%$$

4.4 Conclusion.

This study illustrates a methodology for analyzing RoR hydropower plants in a tropical climate where rivers are characterized by highly variable flows, which are undocumented or poorly documented. This method allows for the analysis of RoR plants by using realistic flow distributions, rather than relying on reservoir assumptions that smooth river flow rates or single-point estimates based upon assumed ‘average flows. Indeed, assuming average flow—a common reservoir assumption—will often over-size a small hydropower plant, producing an unexpectedly high LCOE in operational conditions. Additionally, an oversized plant may wear more quickly than one that is properly size, an issue often seen in the field in Rwanda.

The study found that a relatively simple neural network model, trained across two complete hydrological seasons, produced a similar flow behavior to the available river flow rate measurements. While not ideal, this type of extrapolation is valuable for early planning decisions, when flow data is not available, and common average flow assumptions are not valid for ROR plants.

Finally, using a Monte Carlo analysis approach provides a template to capture the uncertainty in inputs for first-order analyses of small power plants. The approach requires reasonable up-front engineering effort and easily captures variability in values for many key variables. The LCOE results coupled with the uncertainty estimates provides the analyst with both a specific target LCOE for decision-making, and guidance on the confidence to place in that number.

Finally, absent any similar analyses, investors are advised to design ROR plants at, or just below, the ‘knee’ in the flow exceedance curve. The Sebeya river is typical of tropical conditions, and plants designed substantially above that knee produced a significantly higher LCOE. This observation also illustrates that time series of daily river flow—and corrections to those flows for expected withdrawals over the life of the plant—are a critical input to investment decisions. Jurisdictions interested in small hydropower development are therefore encouraged to invest in river monitoring as a catalyst to development.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATION

This study examines the sustainability of small-scale hydropower plants taking Rwanda as a case study. The study addresses three specific research questions. First, the thesis analyzes the challenges and opportunities of small-scale hydropower plants. Second, the thesis analyzes factors affecting sustainability of small-scale hydropower plants. Thirdly, the thesis analyzes the best size of a powerplant fed by a run-of-river system in tropical highlands. The study describes a method for performing preliminary design of such a system, focusing in on the choice of turbine type and sizing of the system for Rwanda's rivers, which are primarily fed by short-term run-off from seasonal rains.

Based on desktop review, the thesis highlighted the opportunities and challenge which formed the basis for studying the sustainability factors especially in development of study tools such as structured questionnaire. The major opportunities were found to be;

(1) existing small-scale hydro potential site. It was found that Rwanda has more than 333 potential sites for small-scale hydropower plants and distributed country wide. This was described as a big opportunity in building off-grid electrification which would reduce the cost of grid extension and accelerates the electricity access.

(2) country population density. Rwanda being a densely populated country with population density of 571 per Km^2 by 2023, would not encourage the construction of big hydropower systems which needs big valley for flooding solutions. This makes Rwanda a good place for development of small-scall hydropower facilities as an opportunity and flooding solutions which would have been caused by development bid dams for big facilities.

The major challenges were found to be;

(1) Hilly topology. Rwanda is characterized by high hills and mountains across the country with a range of 3000 m in height. This makes transmission and distribution of generated electricity to the end user very expensive especially when it is grid connected. It also incurs high cost in transportation of equipment and spare parts during plant development and operation.

Based on conducted survey using structured questionnaire and field observations, the thesis identified sustainability factors of small-scale hydropower plant and identified factors and was used as a basis of in developing a simulation model that answered research question 3.

The major identified negative factors were;

(1) High discharge drop. It was found that Rwandan rivers are experiencing a big discharge drop especially in dry seasons while the majority of the visited hydropower plants were producing 90 percent of the design capacity in the rainy season. A big drop in discharge occurs in dry season and plants don't work continuously instead are on and off. It is off in allowing forebay to be filled and restart again. This is causing loss to electricity sales to the grid and wear of machines as a result of working at reduced discharge and continuous on and off.

(2) High sediment volumes in rainy seasons. It was found that the hydropower plants weirs are being filled by sediments in rainy seasons. This is incurring high cost in removing filled sediments with in weirs. Also, sediments pathing through desilting systems and reaching turbines are causing early wear of turbines. For example, it was found on one river in western region called Giciye river with three cascaded plants, runners were edging in three years instead of working for twenty years.

(3) Grid blackout issues. It was found that majority of the plants connected to national grids and sometimes experiences suddenly stop caused by grid especially in rainy and windy times. These Emergency stops cause high stresses on rotating equipment and gate due to the water flow into the turbine in trying to avoid ever speeding conditions. It is also affecting the electrical equipment as a result of high voltages and currents. This is causing early wear of equipment and electricity loses which would have been sold to the grid.

The major identified positive factors were;

(1) Electricity sells to the grid. Rwanda is a unique where majority of deployed small-scale hydropower power plants sells their electricity production to the national grid and enjoys a stable market.

Finally, the study developed a simulation model from which different plants sizes on different turbine types was subjected to Sebeya flows and their levelized cos of energy was computed. From computed levelized cost of energy, it was observed that the best design flow rate occurs significantly below the ‘knee’ in the flow exceedance curve shown in figure 16. The plants designed significantly below the ‘knee’ in the flow exceedance curve produced lower LCOE compared to plants designed significantly above. The best levelized cost of energy at Sebeya river occurs at designed flow rate near 1.8 m^3/s and is around 0.08 $/kwh with an uncertainty of −0.011/+0.009 $/kW.

The method used and the findings from this thesis can be used by investors during plants designs in un documents or poorly documented river flow rates and similar climatic conductions.

Therefore, the findings of this study conclude with the sustainability framework as **recommendations** as follows;

1. ***A reduction in discharge due to reduction in rainfall intensity which affects electricity production.***
    - (i) In designing of Run-of-rivers plants for better plant performance, plant should be designed at significantly below the ‘knee’ in the flow exceedance curve.
    - (ii) Best plant designs for run-of-river systems should be based on recorded time series data of river flow patterns and should consider variability in the river flow, caused by rivers flow variations.
    - (iii) In rivers where there is no available historical river flow data, machine learning can be a solution in prediction of river flow rate.
    - (iv) Responsible institution and investors in hydropower plants are advised to constantly record river flow rate for future investments development of run-of-rivers plants at Sebeya river or similar tropical rivers.
2. ***sediment in river during rainy season caused by soil erosion which increases maintenance requirements and shortens turbine lifetime.***

    Silt, which causes accelerated wear of turbine runners, can be controlled by;
    - (i) Reducing soil erosion through adapting national policy on best mining practice, planting trees country wide and specifically planting bamboo and grasses along the riverbanks.

(ii) It also be controlled by improving cultivation practices country wide and specifically the surrounding hills by practices such as cultivating along the contour lines to decrease the speed of water flow down the slopes and practicing terrace cultivation on slopes to decrease erosion.

(iii) The plant owners should build efficient desilting systems where the water will first settle before entering forebay tank These methods would reduce silt, improve water quality, and create less wear on hydropower plants.

3. ***unplanned outages caused by grid problems.***

Rugular maintenance on transmission lines and feeder lines from plants to the national grid should be done to minimize ground faults during windy and rainy times. An automated mechanisms to dispatch the integrated many small scall hydropower plants should be upgraded because the existing one is not handling well rainy and windy times.

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Appendix 1: Supplementary paper on sustainability issues of small scall hydropower plants.

D. Zimmerle, A. F. B. Santos, G. Gasore, and J. Ntaganda, “Learning from Failure: A Case Study of Repairing a Pico-hydropower System in Rwanda,” *2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020*, 2020, doi: 10.1109/PowerAfrica49420.2020.9219807.

Abstract

In November 2019, a joint team from Colorado State University and the University of Rwanda intervened to repair a failed pico-hydropower plant in southwestern Rwanda. In a common outside-intervention model, the plant had been constructed by U.S. university team that later, for unknown reasons, couldn’t provide additional intervention. The system had failed in 2016 after three years of operation. The qualitative analysis completed during the repair visit identified three primary issues which led to system failure: shortage of local management and technical skills resulting in poor maintenance and no financial reserves, poor local availability of common materials and tools needed for maintenance, and lack of community education to manage the plant. The analysis also includes an assessment of progress on these issues. While immediate technical issues have been resolved and training improved, fundamental operational processes require substantial additional work. The objective of this paper is to highlight, as is too infrequently the case, a failed village electrification project. Only by illuminating what isn’t working can the development community learn the best practices.

Index Terms—Rural electrification, microgrid, hydropower, local challenges, sustainability.

I. INTRODUCTION.

While nearly 600 million people in sub-Saharan Africa (SSA) have no access to electricity [1], [2], access is increasing rapidly. Half of 10 East African countries have exceeded 25% compound annual growth rates for electricity over the last five years and three (Ethiopia, Kenya and Rwanda) have exceeded 50%. [3] However, rural electrification is typically half that of urban areas. Decentralized, off-grid systems are increasingly seen as the low-cost solution for rural electrification in SSA. [4] and off-grid electrification is expanding rapidly, ranging from solar home systems to village minigrids with central generation and local distribution systems. An intermediate between these home and village solutions are systems that use portable batteries to distribute power from a central charging location to customer homes [5], [6].

Results from off-grid electrification have been mixed. While positive benefits have been frequently reported [7], [8], there are also many anecdotes, but few published reports, of off-grid systems that have failed soon after implementation. Typically, as in Zahnd et al. [9], reports are one sentence mentions in an otherwise positive account of rural electrification:it is RIDS-Nepal's experience that a majority of the [micro hydropower] systems in the region within 3–12 months ... are either inoperable due to premature equipment breakage, inappropriate operation, and absent maintenance or they provide far less than the expected power output." Since failed systems are often not reported, and receive no analysis on why they failed, there is essentially no public feedback mechanism to correct future problems.

Previous studies have identified failure causes, including lack of sufficient maintenance reserves [10], poor staff training and lack of access to backup technical support personnel, and a shortage of management structures that minimize political interference from local authorities and influential villagers [11]. This case study originated with a chance encounter between the lead author and a local resident who felt personal ownership for a failed hydropower system in rural Rwanda. Interaction with the local village champion, residents, and the plant staff provided insights into the chain of events leading up to its failure, steps required to refurbish the plant, and lessons for future interventions.

Section II-V provides a system history, overview of the repair and operation of the plant, and a qualitative failure analysis. Remaining sections describe the status of the plant today, and lessons for future installations.

II. HISTORY OF THE BANDA SYSTEM

History: Between 2008 and 2013, a team from Dartmouth Humanitarian Engineering serially installed three versions of a small hydropower solution in Banda cell, an administrative unit in southwestern Rwanda. The plant is named "Nyiragasigo Hydropower Plant" for the stream on which it is located.

The 2008 installation was based upon a locally constructed turbine and failed for "significant inefficiencies related to its design." It was replaced in 2011 by an improved design developed by an engineering class at Dartmouth [12]. Publications do not indicate the power production or availability of the first two turbine designs (2008-2013), but recollections of village residents indicated that failures occurred and the system was not functional for extended periods. In 2013, the Dartmouth team replaced the second turbine with a commercial product from Eco Innovation. Village residents assisted with civil works that accompanied these upgrades, a significant I n-kind investment from the community. The third turbine failed in 2016. For unknown reasons, the Dartmouth program was unable to provide additional repair parts or complete repairs.

During a chance meeting In July 2019, a former Banda resident and the first operational manager at the plants, “RM,” described the failed turbine system to the first a uthor (DZ). DZ connected RM to one of his graduate students, AS (2nd author), who was planning a visit to Rwanda for other projects. Prior to AS’s trip, RM provided the turbine model number, pictures and videos of the current status of the plant. Data indicated a complete bearing system failure, resulting in unknown damage to the turbine. EcoInnovation recommended replacement of entire turbine bearing assembly, rotor and stator. AS arranged to purchase key parts, and Eco Innovation donated other components needed for the single on-site visit planned by the team (Table I).

In November 2019, AS, RM and the other authors (GG and JN) visited Banda and repaired the turbine. This case study is based upon qualitative observations the team made during the repair visit and follow-up communications.

Banda Electricity Systems: The Nyiragasigo plant is located approximately 4 km from Gahira Village, the largest village in the Banda Cell (Nyamasheke District, southwestern Rwanda). Gahira village is a commercial center with businesses that use electricity, including stores, pubs, and dressmakers. The nearby, smaller, village of Rutiritiri, which lies closer to Nyiragasigo, had also relied Nyiragasigo as a primary source of energy, mostly for residential purposes such as lighting, phone charging and radios.

In November 2019, there were three potential sources of electricity serving Gahira. The first was a solar power plant installed in 2017 by a private donor. The solar plant included a distribution system, and most shops in the village relied on it for power. However, approximately a week prior to the repair visit, the system was struck by lightning and failed. Local residents requested assistance with repairs during the visit, but the team did not have time to evaluate the damage. It is unclear if local operators had or have contacts with the installer or the financial r eserves t o m ake repairs.

The remaining two sources of power were the inoperable Nyiragasigo plant, and another pico hydropower site (Kigogo Station), also installed by Dartmouth program in 2008. Kigogo is also located in the Banda cell, approximately 3 km from Gahira village. Both hydropower systems utilize 12V automotive batteries to distribute power to homes. At the time of the visit, the small Kigogo plant was unable to keep up with the batteries that required charging, creating a substantial backlog of uncharged batteries. Battery charging observations for this study were collected at the Kigogo plant.

Routine Operations: Since no distribution system connects either hydropower site to the nearby villages, residents charge 12V automotive batteries at the site. Individual users own their batteries, which vary in exterior dimensions, capacity, and age. Customers bring the batteries to the plant, local staff charge them, and customers retrieve the batteries when charging is completed. Customers often use low-cost inverters to power AC appliances from the batteries, likely resulting in overall poor efficiency from generation to end use [13].

fig. 1. Path to Nyiragasigo plant. Photo shows local labor hired to transport equipment and repair parts to the plant, and illustrates the type of path used by residents to carry batteries to and from the plant.

Besides the Gahira village center, houses are dispersed in several small villages across Banda. The area, which is just outside Nyungwe National Park, consists of high, rolling hills, with slopes ranging from 5-20%. Roads and trails are typically dirt tracks and difficult to traverse in wet weather, as shown in Figure 1. Despite these transport challenges, villagers carry heavy batteries on their shoulders round trip between the site and their homes.

Three operators staff the plants in multiple shifts. The operators support customers and operate battery charging stations. Local operators also pursue other employment, and their availability depends upon agricultural seasons and other personal matters. Charging costs between 250 to 1200 Rwandan francs (RWF) depending upon the battery capacity (Table II).

III. SYSTEM OPERATION AND REPAIRS

The Nyiragasigo power plant is built around a PowerSpout^{TM} PLT 14 Pelton turbine (PS2186-0E9DFE9D and PS2185-358B2F0A). The turbine has a head of 12 m with a 20 m penstock, 100 mm in diameter, producing a typical flow rate of 7 lps. Prior to the repair visit, the manufacturer suggested replacing both rotor and stator with a new design that produced 38 mV/rpm. At the rated speed of 570 rpm, the generator produces 14 V and 29 A, or 405 W. Since there was unknown damage to the generator components and the site was remote, the team decided to replace all key generator components, which also brought the plant up-to-date with current designs. Pre-trip diagnostics indicated a catastrophic failure of the bearings and likely damage to the shaft, so these were also replaced. EcoInnovation donated a bearing set, a rectifier, new glazing, a refillable auto greaser and tube fittings, and a repair kit to replace items that were likely lost since installation. Costs for donated items are included in the Table I, as they represent real repair costs.

Banda is located approximately 8 driving hours from the capital city, Kigali. The day before the visit, the team traveled to a local commercial center, Tyazo, located along the nearest main highway. The following morning, they traveled to the

Fig. 2. Damaged parts and water quality. Left: Damaged bearing and housing. The bearing is completely missing (rusted opening below the thrust nut). Right: Water quality when cleaning the turbine inlet. Although the water got clearer after a while, silt concentration is typical of most streams in Rwanda.

plant using a 4-wheel drive vehicle and motorbikes arranged by RM. The majority of the work was completed during one day and the team stayed at Tyazo the following night. RM returned to the site two weeks after the repair visit to connect the dump load, which could not be connected during the visit, and to start the turbine. None of the author team or RM was paid for their time.

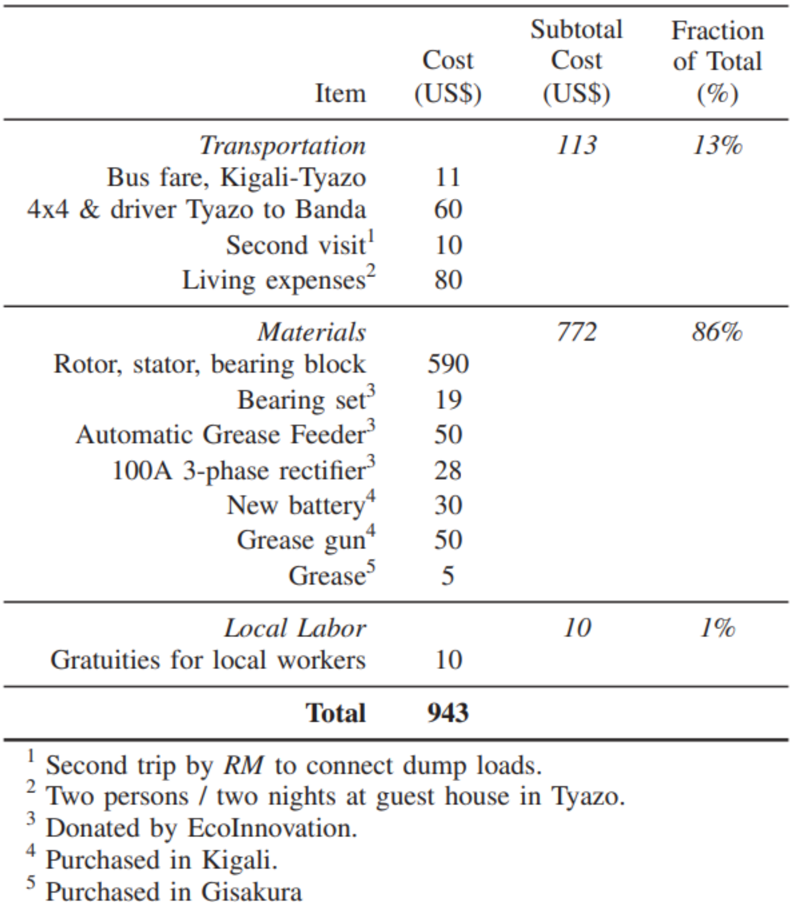
Upon inspection, the stator and rotor were in operational condition, although the rotor had minor damage to its magnets, likely due to impact during the bearing failure or wear from debris that entered the turbine through a missing upstream screen. As planned, both the rotor and the stator were replaced by new components and the old parts were kept as spares. Primary damage was to the bearing, bearing housing and primary turbine shaft, as shown in Fig. 2. The bearings had failed entirely, the shaft was rusted and had sustained damage during rotation after the bearing failure. Bearings in these units are normally protected by grease that is regularly pumped into the bearing housing and migrates through the bearings and out through shaft seals. Routine greasing had not been performed, resulting in damage from water and silt intrusion.

Total costs for the repairs are listed in Table I. Several items are of note. First, even though bearings and many other small parts, such as grease fittings, are standard sizes and widely available, these could not be located in Kigali – a supply aspect that must be considered for similar projects. Second, transportation and housing were minimalist affairs, including regional bus and guest house accommodations, that would likely be unacceptable to foreign technicians. Due to travel times to the village, a full day and two nights of local lodging would be required to dispatch a technician for repair. Roads near the village were passable only via motorbike, a mode of transportation often expressly forbidden by foreign companies sending employees to the developing world. As a result, these costs are likely as low as could likely be achieved using incountry labor for a similar repair at a similar facility.

IV. ESTIMATED PLANT ECONOMICS

Given time constraints during the repair process, data was not collected on the number and type of batteries being

ABLE I ECONOMICS OF THE NYIRAGASIGO POWER PLANT



Item	Cost (US$)	Subtotal Cost (US$)	Fraction of Total (%)
Transportation		*113*	*13%*
Bus fare, Kigali-Tyazo	11		
4x4 & driver Tyazo to Banda	60		
Second visit[1]	10		
Living expenses[2]	80		
Materials		*772*	*86%*
Rotor, stator, bearing block	590		
Bearing set[3]	19		
Automatic Grease Feeder[3]	50		
100A 3-phase rectifier[3]	28		
New battery[4]	30		
Grease gun[4]	50		
Grease[5]	5		
Local Labor		*10*	*1%*
Gratuities for local workers	10		
Total	**943**		

[1] Second trip by *RM* to connect dump loads.
[2] Two persons / two nights at guest house in Tyazo.
[3] Donated by EcoInnovation.
[4] Purchased in Kigali.
[5] Purchased in Gisakura

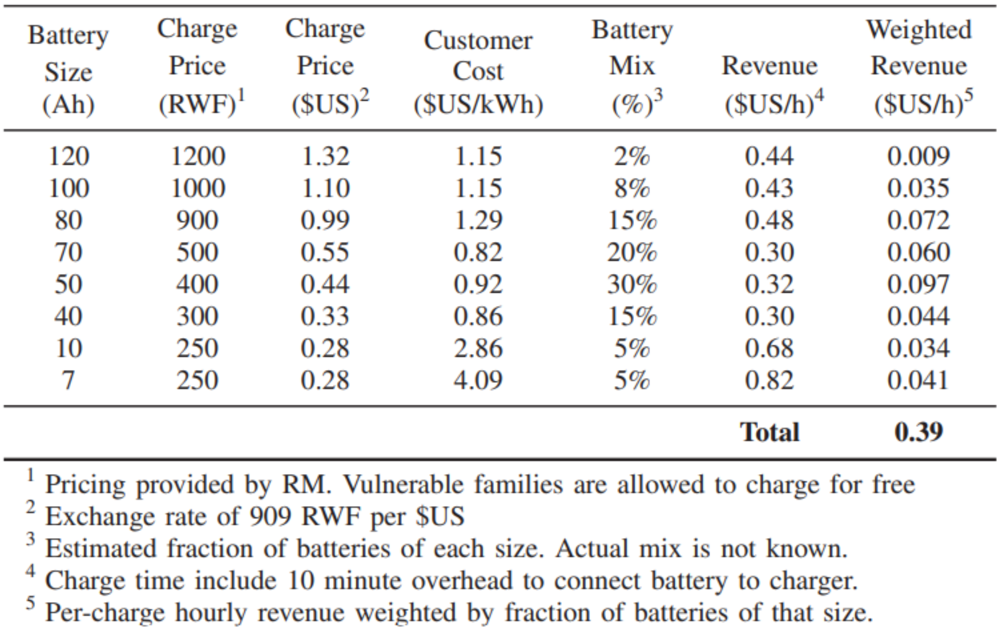
Charged at the Kigogo facility, or, by analogy, the refurbished Nyiragasigo plant. However, sufficient information was collected to develop a rough financial model for the facility, shown in Table II. The model assumes full-load operation of the turbine given the available water supply, derated by 10%, an estimate that may be optimistic given seasonal variation in river flows [14]. We also assume that batteries are 80% discharged when brought to the plant for charging. This assumption bundles both the depth-of-discharge and the battery degradation. Finally, we assume there is a 10-minute overhead between charges to connect the battery to a charger.

The pricing schedule, established by RM when he was a Banda resident and running the facilities, is also shown in Table II. While the mix of batteries is unknown, a reasonable assumption is shown in the table. Since most residents purchase used vehicle batteries, the model assumes battery size will be typical of those in sedans or light trucks – 40- 80 Ah (mean of 58 Ah). Using the battery size mix, charging time, and revenue per hour for each battery type, the weighted hourly revenue is estimated as ≈0.39 US$ per hour.

If the plant is staffed and operates at full capacity at a long-term average of 16 hours per day, 25 days per month, total revenue is approximately 156 US$ per month. The team recommended a 20% reserve for maintenance and repairs – 5% for consumables (e.g., grease) and 15% for repair reserve. At that reserve level, 40 months of full-time operation would be required to cover the material cost of repairs completed in this study. In comparison, the turbine had operated for less than three years before failure.

Table II also illustrates that, despite the low plant revenue, customers pay substantially more than the current Rwanda grid tariffs of 0.098-0.231 $US/kWh for residential customers: 0.82 to 1.29 $US/kWh for typical automotive batteries, and up to 4.00 $US/kWh for small batteries.

TABLE II ESTIMATED ECONOMICS OF THE NYIRAGASIGO POWER PLANT



Battery Size (Ah)	Charge Price (RWF)[1]	Charge Price ($US)[2]	Customer Cost ($US/kWh)	Battery Mix (%)[3]	Revenue ($US/h)[4]	Weighted Revenue ($US/h)[5]
120	1200	1.32	1.15	2%	0.44	0.009
100	1000	1.10	1.15	8%	0.43	0.035
80	900	0.99	1.29	15%	0.48	0.072
70	500	0.55	0.82	20%	0.30	0.060
50	400	0.44	0.92	30%	0.32	0.097
40	300	0.33	0.86	15%	0.30	0.044
10	250	0.28	2.86	5%	0.68	0.034
7	250	0.28	4.09	5%	0.82	0.041
					Total	**0.39**

[1] Pricing provided by RM. Vulnerable families are allowed to charge for free

[2] Exchange rate of 909 RWF per $US

[3] Estimated fraction of batteries of each size. Actual mix is not known.

[4] Charge time include 10 minute overhead to connect battery to charger.

[5] Per-charge hourly revenue weighted by fraction of batteries of that size.

V. FAILURE ANALYSIS

After the 2013 installation of a commercial turbine, evidence suggests that technical issues at Nyiragasigo had been substantially resolved. The system worked. Therefore, the failure of the turbine within three years is primarily due to business and sociological issues. The qualitative analysis completed during the repair visit identified three primary issues: shortage of local management and technical skills leading to poor maintenance and financial reserves, poor local availability of materials, and lack of community education to manage the plants.

Skills and Management: A large technical knowledge gap was identified: Local operators did not have the skills to identify problems and take the necessary corrective measures. The two hydropower plants have three local operators who staff the sites in multiple shifts. However, operating the turbine is not their only employment, and the turbines are not staffed at times. The site also lacks a regular maintenance schedule or maintenance instructions translated into the local language to remind staff of required maintenance activities.

During construction, the university group provided both financial and technical support to the plants, including the visits described earlier. After 2013, contact dropped off for unknown reasons, a pattern that is often seen when groups from industrialized countries provide assistance in the developing world. The university did not have local partners, and neither the university or local officials created a long-term support apparatus. At visit time, no clear management plan was in evidence at either Nyiragasigo or Kigogo, especially with respect to the accumulation of a maintenance and repair reserve. Therefore, when the turbine failed in 2016, no reserves were available to attempt repairs.

Due to these two problems, maintenance was not being performed on either turbine. While the installation team trained the local operators to some degree, certain aspects of the maintenance schedule were not adequately communicated. For example, neither RM (the first operational manager) nor the operators were aware of the need to regularly grease the bearings – an absolutely critical maintenance item for this type of turbine. At visit time, the Kigogo turbine was still operational, but its bearings were not greased, and appeared to have lacked grease for some time. Since the Nyiragasigo plant failed primarily due to seal and bearing failure, lack of protective grease is likely a problem at Kigogo as well. The Nyiragasigo also lacked an inlet screen, which had either decayed or been removed at some point. As a result, rocks had entered the turbine case and had likely caused some of the visible damage to the rotor.

Complicating things further, RM no longer resides in Banda and can no longer provide day-to-day assistance. As operations manager, RM had provided a bridge to suppliers and outside assistance. He speaks several languages fluently (rare in a village context) and is in regular contact with international travelers through his work as a tour guide.

Evidence therefore suggests that (a) maintenance training performed at installation was inadequate, (b) infrequent and intermittent contact with the install team meant key operational problems were neither identified nor corrected, and (c) training and communication was heavily dependent upon a rare individual with both the communication skills and contacts to maintain exchanges beyond the village.

Material Availability: Hydropower systems have moving parts that require regular maintenance, including cleaning screens, greasing bearings, and regular disassembly for inspection. The tools and materials required for these operations are not available locally.

Standard commercial components, such as bearings, grease, grease fittings, and tools, are difficult-toimpossible to find in nearby regional centers. For example, none of our contacts in the Banda area recognized a grease gun from the multiple pictures sent to them. AS purchased one in Kigali, along with grease, before the repair visit.

Commercial interactions between Banda and the main commercial centers are difficult, with long and expensive drives or even longer bus trips: Kigali (6-7 h), Musanze (4-6 h), or Butare (3-5 h). The operational team lacked a tool kit (or it had been lost) for minor repairs, and did not have the tools or skills to perform regular tear-down inspections. Our observations liken maintenance planning for these systems to the planning required for a long-distance sea voyage; tools and components for all but the most catastrophic failures must be kitted and available on site.

Small changes in system design can also reduce the likelihood of maintenance failures. To reduce future greasing issues, the team installed an automatic grease feeder, a spring-loaded external reservoir that feeds grease slowly into the bearing housing over several weeks. The feeder can be reloaded with a standard grease gun. This type of part is not available locally, and may be difficult to find anywhere in Rwanda. Reusable parts for the turbine were also left with the operators for future use.

In addition, just like Kigogo, the system had no operational charge controllers. The controllers acquired earlier had failed, and, as with other failures, no financial resources are available to replace broken units (The repair team was unaware of this issue prior to the trip and therefore brought no replacements.) At Kigogo, operators often charged batteries continuously for up to 24 hours without charging control. This likely reduces the life of the batteries, and could cause batteries to overheat and fail catastrophically if the turbine voltage became too high [15].

VI. STATUS TODAY

While the intervention by our team restored the Nyiragasigo to operating conditions, a key question remains: Have we corrected the business and sociological issues identified at the site? The sad answer is: No. Our intervention was a chance occurrence and relied on other planned travel to reduce the cost of intervention. This is obviously not a sustainable model. However, we have taken some corrective action and are looking for ways to monitor and improve operations over time.

For skill development, the repair work was completed in the presence of RM and the local operators. RM, a self-taught engineer, paid close attention to the repair steps and translated instructions for local operators and the community members who gathered to watch the repair. The team was careful to describe not only what was being done, but also the reasons behind the repair actions. For the issues that were clearly diagnosed (greasing and clearing inlet screens) maintenance instructions were communicated to the local team. Being involved with repairs also provided a clear illustration why that maintenance was important.

Considering all actions, several key sustainability issues are outstanding:

- Management processes are still uncertain, and while local leaders understand the need for a maintenance reserve, is unclear that banking and management processes exist to create it.
- Sustainable communications have not been achieved. RM remains involved on a intermittent, volunteer basis, but is too busy with other tasks to be the primary communication conduit.

- While local operators are now better trained and equipped, they likely lack sufficient knowledge to proactively identify major problems or perform major inspection or repair tasks, and likely lack a clear decision criterion of when – and possibly how – to ask for outside help.

VII. CONCLUSION

The purpose of this small and qualitative case study is to highlight the need for transparency on sustainability challenges for village electrification projects. While no public body of knowledge exists to classify this case study as ‘common,’ anecdotal evidence suggest that this type of failure falls into an all-too-common pattern – a well-meaning, but distant, group assists a village with energy access. Over time, the costs of interaction combined with personnel and priority changes of the group decrease interaction with the community. Lacking local infrastructure, financial reserves, and expertise, local leaders are unable to maintain complex technology and the system fails.

In the case of the Banda hydropower sites, we have essentially swapped one well-meaning but easily distracted university team for another well-meaning but easily distracted university team. The problem has not been solved, either specifically or in general. However, we feel that the first step to breaking this pattern is to understand it, and the first step towards understanding is to illuminate on-the-ground failures with as much vigor as we, the development community, apply to illuminate successes.

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Appendix 2. used questionnaire

Survey interview number

Plant Name and size:
PROVINCE NAME:
DISTRICT NAME:

DATE AND TIME OF interview :

A. INFORMED CONSENT

Greetings, My names are ______________________________. I am PhD student under African Center of Excellence in Energy and Sustainable Development. This survey is a part of My research study on sustainability of small hydro power plants in Rwanda. I would like to ask you few questions. All of your answers will be kept confidential, and will be used for research purposes only. You can stop the interview at any time and ask me for clarifications or repeat the question as many times as you need.

Do you have any questions for me now?

The time the interview started is: _______ hour: _________

minutes____________: Date: ____________

Title of the contributor in the company ----------------------------

Signed by the contributor:_____

A. Plant type	
1. What is the Generation type of plant	1. Run-of-river 2. type of reservoir
2. What is the type of plant turbine	1. Reaction turbine (Francis, Kaplan, Propeller) 2. Impulse turbine (Pelton,Turgo Wheel, Cross Flow)
3. Is generated directly connected to grid or there is inverter	
4. Is there a gearbox between shaft turbine and shaft of generator	
5. What is the plant head (m)	
6. What is the flow rate of the river in rainy season	
7. What is the flow rate of the river in dry season	
B. Plant current status	
1. What is the turbine designed speed?	-------------------------------
2. What is the current turbine speed?	--------------------------------
3. Is the plant working or shut down?	
4. If shut down what factors contributed to shut down?	
5. What is the plant installed generation capacity?	

6. Is it generating at its full capacity?	Yes no
7. If not, what is the cause?	
C. Maintenance Questions	
1. Do you have Maintenance Manual	
2. Do you have technical training for technicians/plant operators?	
3. How did you learn to take care of the plant?	
4. How often do you inspect the interior of the turbine?	
5. Who maintains the equipment?	
D. Technical problems	
1. What technical problems have you had in the last year?	
2. How often do you have to shut down/restart the machine?	
3. Do you have planned stops?	
4. Do you have problems with unplanned blackouts?	

5. What is the longest blackout you have experienced?	
6. What are causing these?	
7. Are there economic reasons why the plant stopped working/ is not working all the time?	
E. Repair questions	
1. Have you ever repaired the turbine?	
2. How many times you have repaired turbine since its operation?	
3. When was the last time you needed repair parts?	
4. Is there enough income from the users/customers to cover the cost of operation? To save for repair/reinvestments?	
5. If you need to make a large repair /replace components, where do you get the money?	
6. Where do you buy spare parts?	In country or oversea
F. Other sustainability problems	

1. Did you have any problems with the plant or the grid caused by factors that you/the operator could not control, like:	Examples: a) drought, wind, termites, lightning? b) Theft or sabotage? c) Social or political conflicts d) Regulations? e) Anything else?
2. How important is the problem of silt wear on the turbine in relation to these other problems?	
3. Do you consider yourself to have enough knowledge about how to operate, maintain, and repair? If no: what training do you need?	
4. Did you need to bring in external technicians to assist with the repair?	
5. Sediment questions	
1. Does the plant have sediment basin systems?	Yes/no
2. If yes which type and size (m^3)	------------------------------ --------------------------------------
3. What is the length of headrace channel (canal) (m)	

4. Do you think sediments in the river water are causing malfunctioning of plant turbine?	
5. Have you/others tried to address the problem of silt (soil erosion) in any way? What have you/they done and what was the result? Is there anything else you could do?	