Microgrid Implementation on Teaching Hospital in Gisenyi, Rwanda

Adrian Jonathan Yosua
Energy Science, Technology and Policy
Carnegie Mellon University
Pittsburgh, PA
ayosua@andrew.cmu.edu

James Hayes
Civil and Environmental Engineering
Carnegie Mellon University
Pittsburgh, PA
jameshay@andrew.cmu.edu

Nick Cooper
Energy Science, Technology and Policy
Carnegie Mellon University
Pittsburgh, PA
ncooper2@andrew.cmu.edu

Martin Japheth Semwanga
Energy Science, Technology and Policy
Carnegie Mellon University
Pittsburgh, PA
msemwang@andrew.cmu.edu

***Abstract*—Microgrids offer flexibility, reliability, and sustainability in energy supply, catering to diverse needs across different locations and scenarios. In this paper, microgrid feasibility is analyzed in building a new teaching hospital in Giesenyi, Rwanda. The analysis was carried out by building a Microgrid model on Xendee, a Microgrid Decision Support Platform. The electricity and heating profiles of the model were obtained from typical teaching hospitals. Various configurations were investigated, including Solar PV, Hydro, and no grid connection cases. Optimization results for cost, emissions, and resiliency were generated, and the required technology capacities needed to fulfill load demands throughout the project lifetime were also determined. NPV, IRR, and LCOE analysis for the various optimization results were conducted to consider the feasibility of different microgrid configurations. The optimization results show a feasible model with low LCOE for scenarios that include both Solar PV and Hydropower. Including both these technologies and a grid connection to keep LCOE low is recommended. Without a grid connection, immense solar capacity and area are required, which is not feasible for this project. Furthermore, depending on whether costs or emissions are more important to the user, the capacity of solar and batteries can be varied.**

Keywords*—*Microgrid, Rwanda, Hospital, LCOE, Distributed Energy Resources

I. Introduction

Rwanda, a landlocked country in Central Africa, encounters a moderate climate featuring two rainy seasons and occasional frost and snow in its mountainous regions. As of 2021, approximately 48.7% of Rwanda's population had access to electricity, with rural areas lagging at 38.1% compared to 97.9% in urban regions [1]. By September 2023, the country achieved a cumulative connectivity rate of 74.40%, with 54.19% of households connected to the national grid, marking a significant increase in on-grid connections over the past two decades [2]. In terms of energy sources, biomass, and waste comprised 74% of Rwanda's primary energy, followed by oil products at 20% in 2019, while natural gas, hydroelectric, and other sources contributed to the remaining mix [3]. Rwanda has made considerable strides in electrification, targeting universal access by 2030, backed by an annual access growth rate surpassing 3 percentage points [3]. Hydropower dominates the country's electricity production, accounting for 43.9% of the 332.6 MW capacity, with thermal sources including methane, diesel, biomass, and solar contributing the remaining 51% [4, 5]. In 2019, Rwanda's total carbon dioxide emissions stood at 1.189 million metric tons [3].

Rwanda, in partnership with global entities, has improved healthcare through community-based approaches, decentralized services, and technology investments [6]. The Ministry of Health focuses on boosting human resources and upgrading hospitals as part of its strategy for healthcare enhancement [7]. Despite a skilled healthcare worker ratio of 1.09 per 1000 individuals in 2021 (below the WHO recommendation), Rwanda aims to address this by transforming nine hospitals into teaching facilities to expand healthcare worker training by 2030 [8].

In Rwanda, there are 2,139 health facilities, mainly concentrated in Healthcare Centers and Posts, totaling around 1.6 facilities per 1000 individuals across five regions [9]. These facilities range from national hospitals to local healthcare posts, with grid connectivity for all facilities above posts and 74% of posts themselves [9]. Among the 326 non-grid-connected facilities, 30% utilize solar power (including 11 mini-grids), 57% rely on diesel generators, and 13% lack any electricity, accounting for a total of 44 facilities.

Establishing a teaching hospital in Gisenyi, the urban hub of Rubavu District in Rwanda's Western Province, holds strategic importance due to its higher population density and current infrastructure connectivity. Gisenyi, housing the district's capital, has a substantial portion already connected to the grid, with Gisenyi Hospital catering to most of the city's medical needs through its 28 doctors [10]. However, with a doctor-to-patient ratio of 1:3,082 in Gisenyi, the introduction of a teaching hospital is pivotal. This initiative aims to augment healthcare professional numbers, ultimately reducing the doctor-to-patient ratio and enhancing medical accessibility for the local population. In this paper, a teaching hospital in Gisenyi paired with a microgrid is proposed.

II. Microgrid Systems for Hospitals

A. Hospital Energy Load Case Studies

Managing a hospital building is intricate due to its diverse engineering systems and operational demands. Strategies predominantly involve engineering solutions like enhancing HVAC systems, optimizing lighting efficiency, and addressing building orientation alongside effective operation and maintenance practices [11]. For designing a hospital in a climate such as Rwanda, energy is mainly used for electricity and heating. Most of the electricity is used for air conditioning.

A case study on Hospital Canselor Tuanku Muhriz UKM (HCTM), previously known as Hospital Universiti Kebangsaan Malaysia, showcases a prominent specialist healthcare facility and a respected teaching hospital in Malaysia [12]. The hospital was chosen because of the similar climate between Malaysia and Rwanda, which is a tropical climate. Data gathered from the electricity usage reveals that the cooling system accounts for 62% of the building's total consumption, followed by lighting (21%), plug loads (16%), and lifts (1%) [12]. This pattern of electricity usage mirrors that of hospitals in Malaysia and tropical countries like Rwanda. HCTM's substantial energy use stems from extensive cooling system utilization, including Air-Handling Units (AHUs), Fan Coil Units (FCUs), and Air-conditioning Split Units (ACSUs). Notably, plug loads, especially from medical devices like Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) scanners in the Radiology Department, nearly match the energy consumption of the lighting system [11]. The below figure is the daily electricity consumption in a given hospital in 2011.

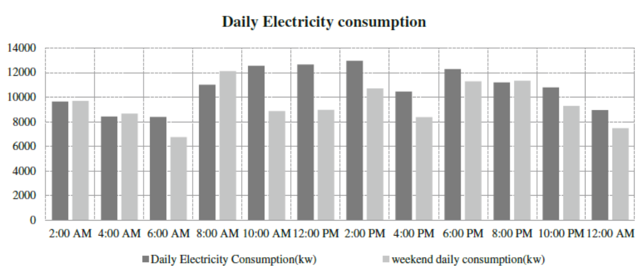

Figure 1. Daily Energy Consumption for HCTM hospital.

The hospital registers its highest energy usage between 8 a.m. and 2 p.m. on both weekdays and weekends, driven by increased activity in clinical and medical imaging departments like MRI and radiology. This period marks the peak demand. Conversely, energy consumption drops during nighttime, from 2 a.m. to 6 a.m., exhibiting a one-third reduction compared to peak hours. The smaller-than-expected fluctuation between day and night electricity usage is attributed to two key factors. Firstly, a considerable portion, accounting for 63.3% of the hospital's total area, remains operational throughout the night. Secondly, the hospital employs ice storage for air conditioning, generating, and storing ice during the night to fulfill daytime cooling requirements. This approach results in a 30% difference in consumption between night and day, lower than the norm for typical buildings. Additionally, specific hospital sections such as laboratories, wards, emergency, and on-call offices operate during weekends and holidays, contributing to about 88% of the energy consumption observed on workdays [12]. The Malaysian hospital's total energy consumption in 2011 is given in the table below. An annual projected energy growth of 1% per year was assumed, and the values to 2023 are to be put on this study.

Table 1. Total Energy Consumption

Energy Source	Energy Consumption in 2011 (kWh)	Energy Consumption in 2023 (kWh)
Electricity	41,379,113	46,627,020
Heating	15,926,293	17,946,146

The projected 2023 values in Figure 1 will be used for modeling electrical and heating loads for the proposed teaching hospital in Gisenyi, Rwanda.

B. *Case Study: Solar Thermal Heating in Hospitals*

A case study of energy potential for solar thermal heating in South African hospitals was analyzed to understand how it can be implemented as a heat technology. It also provided a daily heat demand load shape on a typical sunny day which helped us validate our heating load shape.

In the case study, a unique approach was adopted to understand the heat demand of hospitals. The heat demand profile was derived hourly and then represented as a percentage of the total demand for a single day. It was plotted alongside the typical hourly GHI (W/m^2) over a single sunny day in Cape Town as shown in Figure 2.

As most hospitals serve a common purpose, it is expected that most large hospitals that operate on a 24-hour basis throughout the year will exhibit daily heat demand profiles very similar to those depicted in Figure 2 [13].

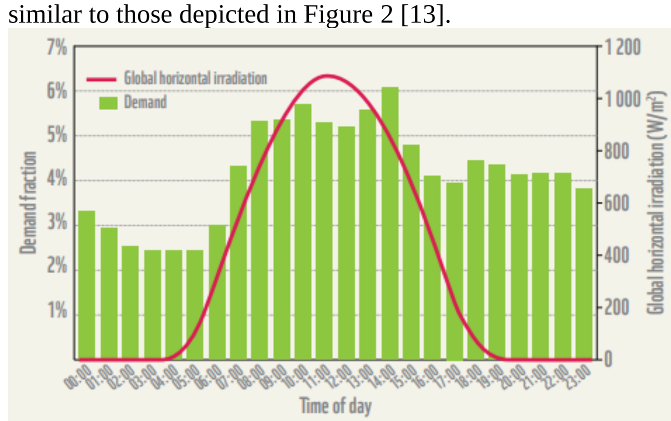

Figure 2. Daily demand profile of a provincial hospital and the hourly GHI in Cape Town [13]

As shown in Figure 2, a factor that favors the implementation of solar thermal solutions at hospitals is the increase in the diurnal heat demand, during periods when the solar thermal technologies operate most efficiently. With the correct sizing of collector areas and thermal storage capacity, solar water-heating systems can also supply the heat demand of hospitals during overnight periods when needed. This allows these technologies to effectively contribute to the hot water demand of hospitals and achieve high solar fractions and financial savings in applications where they are used to offset the use of electric boilers. Based on the findings of this study, it can be realistically assumed that hospitals can feasibly increase their overall solar thermal capacities to compensate for

20 to 40% of their combined annual thermal energy needs [13]. In the modeling of the Gisenyi Teaching Hospital microgrid, the solar thermal solution would contribute to a reduction in emissions that would otherwise result from the use of diesel boilers.

C. Hospital Microgrid Case Study: Kaiser Permanente

Kaiser Permanente's Richmond Medical Center, a hospital in California, installed a microgrid in 2019 [14, 15]. This included 250 kW of Solar PV and a 1 MWh, 1 MW battery storage unit. The batteries were designed to provide 3 hours of backup of power. The facility also had pre-existing backup diesel generators.

As a result of the microgrid, the Medical Center saved 2.63 MWh of energy every year, corresponding to annual savings of \$394,000. This is relative to the \$4.77M grant from the California Energy Commission used to fund the project. The microgrid also reduces greenhouse gas emissions by 263 tons of CO_2eq per year. Moreover, according to Kaiser Permanente, their Richmond Facility is now net zero.

Additionally, the microgrid was paired with a smart controller, which helped to reduce demand by 140 kW, corresponding to a 20-25% decrease in peak demand.

This case study emphasizes the practical and economic feasibility of implementing microgrids for medical facilities.

III. Design Model

A. Xendee Optimization

Both electricity and heating loads were considered for the simulation. Cooling loads were assumed to all be included in the electricity demand by way of electric air conditioners and chillers. The total annual load and peak load were input into the NREL Load Builder, and Houston was selected because of its similar tropical climate to Gisenyi. A new hospital construction was selected in the load builder. The electricity and heating loads for weekdays and weekends are shown in Figures 3 and 4.

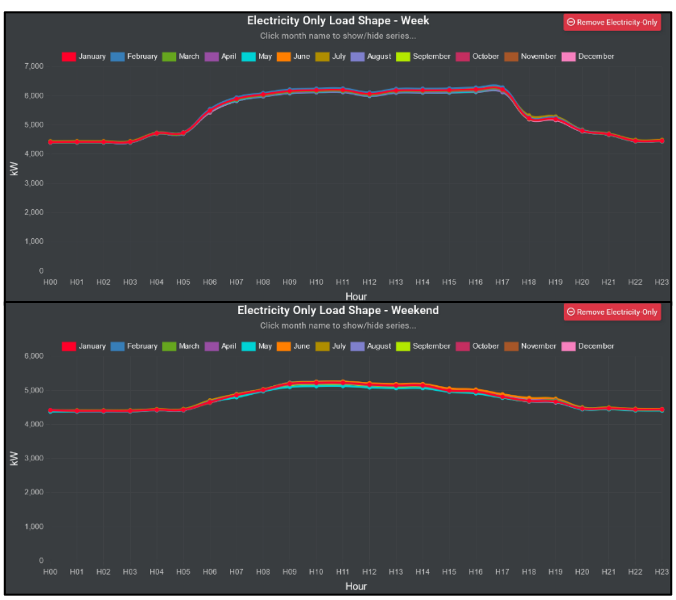

Figure 3. Xendee Electricity Load Shape of Hospital for the Weekday and Weekend by Month and Hour of Day.

The electrical load tends to have a subtle plateau around 6 am to 5 pm where the load was about 6 MW, but for the rest of the day, it was closer to 4 MW. This is similar to the load for the case study considered in Figure 1. The weekend loads also tended to be lower than the weekday loads by about 12%. The variation from month to month in electricity demand is also not that great. However, this was not the case for the heating load.

The heat demand load shape from Xendee was compared with the one from the previously mentioned case study in Figure 2. The similarities between the two confirmed its validity.

The heating load varies quite a bit from month to month, but it generally peaks from 9 am to 5 pm regardless of the time of year. The heating load tends to be less in January and February (only peaking around 2 MWth) and more in June through August. (peaking around 3 MWth).

The critical load of the facility was set to be 40% of the total load, meaning that 60% of the load could be shed in an emergency. The microgrid was set up to be connected to the grid in Gisenyi, where the electricity tariff for hospitals is \$0.1488/kWh [16]. No district heating system is available, so the microgrid will need to generate the entire heating load for the hospital.

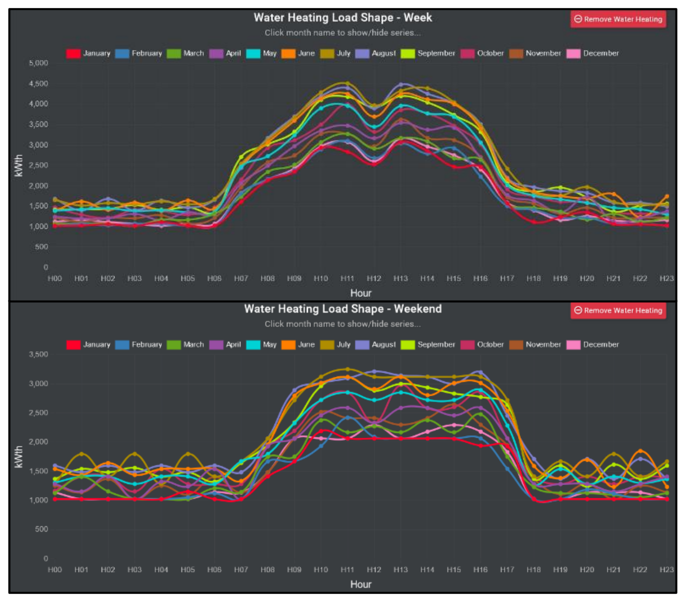

Figure 4. Xendee Heating Load Shape of Hospital for the Weekday and Weekend by Month and Hour of Day

Rwanda's health sector benefits from financial aid through its collaborations with several organizations, such as The Global Fund, the World Bank, the US Government through PEPFAR, Enabel, the GAVI Alliance, and ONE UN [9]. Given these existing funding opportunities, an upfront cash purchase to finance the project was selected. A discount rate of 7% and a project lifespan of 20 years were considered.

B. System Design

A variety of technologies have been considered for the microgrid to meet both the electrical and heating loads, which are summarized in Table 2 and Figure 5.

Table 2. Electricity, heat generation, and energy storage technologies considered for microgrid systems in Xendee analysis.

Type	Technology
Electricity Generation	Solar PV
	Run of River Hydropower
	Diesel Generator Backup
Energy Storage	Battery Energy Storage
Heat Generation	Solar Thermal
	Diesel Boiler

Figure 5. Technologies included in Xendee Simulation for Microgrid

Wind energy was not considered for this microgrid simulation due to the wind potential being very low in Rwanda according to the Global Wind Atlas, with capacity factors of only a few percent [17].

C. Solar PV and Solar Thermal

Rwanda has favorable solar energy resources due to its climate and latitude. According to the Global Solar Atlas (2023) [18], the average irradiance in Gisenyi is:

$$1810.5\ \frac{kWh}{m^2 yr}\frac{8760\ hr}{yr}\frac{1000\ W}{1\ kW} = 206.7\ W/m^2 \qquad (1)$$

This irradiation suggests solar is a viable source of electricity generation in Rwanda; the average capacity factor for solar is about 16%. Moreover, about 30% of off-grid healthcare facilities in Rwanda already using solar power [9]. Therefore, both solar PV and solar thermal have been considered for the microgrid. The performance of solar PV and solar thermal in Gisenyi is shown in Figures 6 and 7.

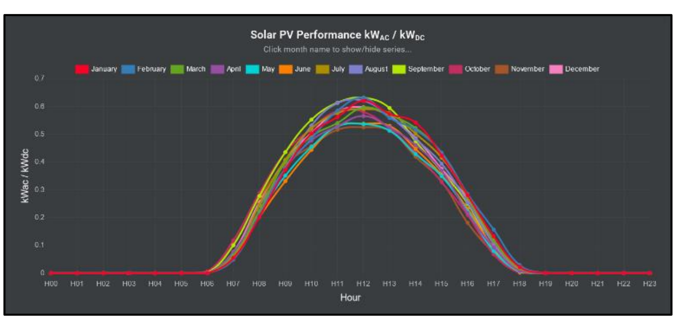

Figure 6. Solar PV Performance and Solar Thermal Insolation in Gisenyi, Rwanda

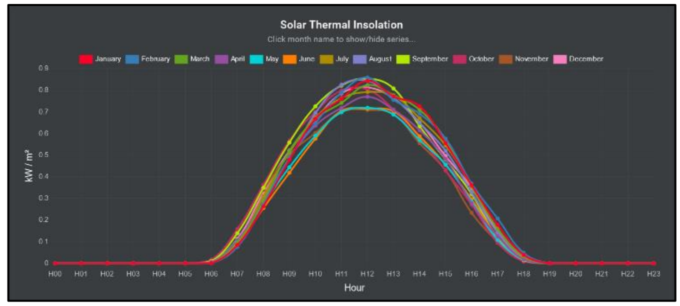

Figure 7. Solar Thermal Insolation in Gisenyi, Rwanda

These figures show that Rwanda has very consistent solar resources. Regardless of the time of year, it peaks around noon. There is also very little variation from month to month, due to its proximity to the equator.

Based on the map in Figure 5, an area of about 40,000 m^2 could be available for these technologies. Of this area, 30,000 m$_2$ was allowed to be reserved for solar PV and the rest for solar thermal. The specifications for these systems input to the Xendee simulation are shown in Table 3.

Table 3. Specifications for Solar PV and Solar Thermal Systems.

Technology	Process Specification	Value
Solar PV	Efficiency (%)	19
	Capacity Per Panel (W)	400
	Tilt Angle (degrees North)	2
	Max Capacity if All Area Used (MW)	5.7
Solar Thermal	First Order Heat Transfer Coefficient (W/m^{2}K)	5.16
	Zero Order Heat Transfer Coefficient (W/m^{2}K)	0.82
	Water Heating Temperature (°C)	60
	Tilt Angle (degrees North)	2
	Max Capacity if All Area Used (MW)	8.2

The cost specifications of the Solar PV and Solar Thermal systems input to Xendee are shown in Appendix Table A1. Typical values were chosen from Xendee base models for PV panel specifications and the solar thermal system.

D. Sebeya River Hydropower

The Sebeya River which runs through Gisenyi, Rwanda provides a great opportunity for baseload electricity production. There is currently one existing hydroelectric facility on this river, named the Keya Hydropower Plant. It is a run-of-the-river facility constructed in 2011 in the Nyundo Sector, Rubavu District of Western Province of Rwanda. It has a rated capacity of 2.2MW but typically produces closer to 900 kW due to sediment issues. It uses a crossflow turbine and has a net head of approximately 87.6m [19, 20]

For the microgrid, the possibility of including a run of river hydroelectricity facility in Gisenyi was considered. Data on stream flow for the Sebeya River was taken from the Rwanda Water Portal [21]. The data for 2022 was organized into 1-hour intervals and was used as input into the Xendee simulation. The results are shown in Figure 8.

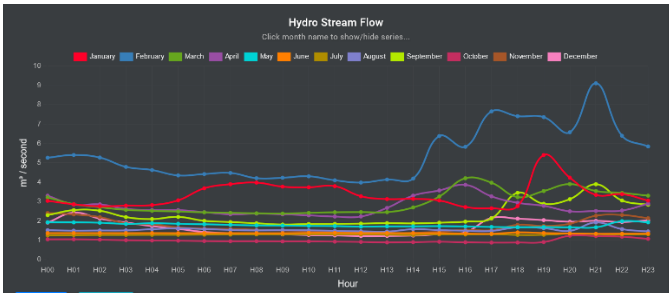

Figure 8. Hydro Stream Flow for Sebeya River by month and hour of day.

This figure suggests that there are flooding events in February and January. However, for most of the year, the flow rate usually stays around 2 m^3/s. For every month except January and February, the flow is less than 3 m^3/s for most of the day. Therefore, a rated capacity of 3 m^3/s is selected. The other specifications of this facility are summarized in Table 4.

Table 4. Specifications of Sebeya River Run of the River Hydro Plant in Gisenyi.

Process Specification	**Value**
Design Flow Rate (m^3/s)	3
Design Head (m)	70
Head Loss (%)	10
Efficiency (%)	70
Rated Capacity (MW)	1.3

A head of 70 m was used, which is within the range seen in the literature for this river. A head loss of 10% is assumed, and the efficiency of the system is taken to be 70%, which is typical for small hydro systems [22]. This corresponds to a rated capacity of 1.3 MW.

The cost assumptions for the facility are summarized in appendix Table A2 and were determined using typical values for a run of river hydro plant [23, 24].

E. Diesel Generators and Boiler

A diesel generator in the simulation was added to serve as backup electricity generation and was set to be backup only. A diesel boiler is included to meet the heating load when solar thermal alone cannot. A typical diesel price in Rwanda of \$1.313/L is used [25]. The specifications of the diesel-powered units are summarized in Table 5. A model from Generac was selected to represent a typical generator [26].

Table 5. Specifications of Diesel-powered Generator and Boiler.

Technology	**Process Specification**	**Value**
Diesel Generator	Capacity per Unit (kW)	150
	Efficiency (%)	30
	Max Number	3
Boiler	Efficiency (%)	80

The cost specifications of the generator and boiler input to Xendee are shown in Appendix Table A3.

F. Battery Storage System

A battery energy storage system was selected for the microgrid's electrical energy storage. Batteries are scalable, have good energy density, and unlike pumped hydro do not require extensive construction [27]. Therefore, they are the best choice for energy storage for buildings like hospitals. In the Xendee simulation, an upper bound for a battery storage capacity of 10 MWh was set. However, this limitation was removed for several scenarios to avoid issues with meeting demand during emergency load periods. Other specifications of the battery energy storage system are shown in Table 6.

Table 6. Specifications of Battery Energy Storage Technology.

Process Specification	**Value**
Charging Efficiency (%)	90
Discharge Efficiency (%)	90
Charging Rate (% Total capacity/hour)	30
Discharging Rate (% Total capacity/hour)	30
Max SoC (%)	100
Min SoC (%)	5

The cost specifications for the battery energy storage system input to Xendee are summarized in Table A4.

G. Capacity Factors

The capacity factors of the different technologies considered for the microgrid in Xendee are shown in Table 7.

Table 7. Capacity Factors of Generating Technologies in Xendee

Technology	Capacity Factor (%)
Boiler	42.19
Solar Thermal	16.74
Solar PV	17.04
Run of River Hydro	66.05
Diesel Generator	Depends on Optimization

H. Financial Parameters

We considered four different economic measures for our Xendee analysis.

Net Present Value (NPV) is a financial metric that compares the current value of incoming cash with outgoing cash within a specified timeframe. It's a crucial tool in assessing the potential profitability of an investment or project, often used in decision-making for capital budgeting and investment planning [28].

LCOE stands for Levelized Cost of Energy, and it's a key metric used in the energy industry, especially in comparing different sources of energy generation like solar, wind, coal, natural gas, etc. It's a way to measure the cost of generating electricity over the entire lifetime of a particular energy-producing asset.

The internal rate of return (IRR) was also considered in this analysis. This is the discount rate necessary for the NPV to go to zero. A higher IRR is an indicator that a project is more profitable because even if the future cash flows are heavily discounted, the NPV still goes to zero. On the other hand, a very low IRR shows that even with little discounting it is difficult to achieve a positive NPV.

The payback period is a measure of how long it takes to reach an NPV of 0. Generally, the longer it takes to reach this point, the less attractive the investment is unless the potential returns could be very high over the entire project lifespan.

IV. Project Analysis

Several optimizations of microgrid systems were completed in Xendee as shown in Figure 9, including the grid as the only source of electricity, no grid connection, both hydro and solar for generation, and only solar for generation.

A. *Optimization Scenarios*

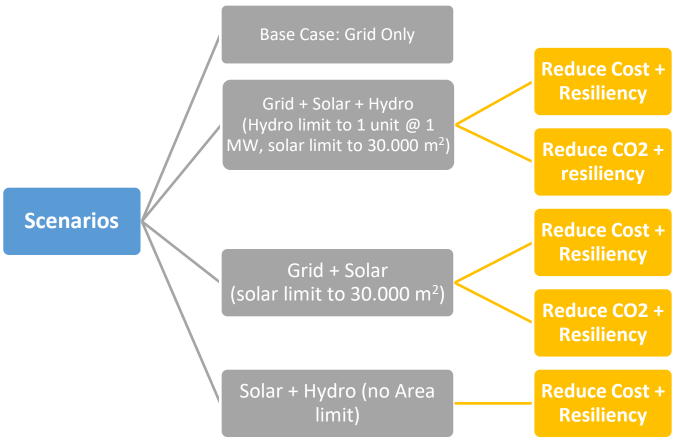

Figure 9. Optimization Scenarios for Microgrid

B. *Grid Connected Only*

As a reference case, a scenario where all the hospital's electricity comes from the grid was considered. However, since there is no district heating, boilers and solar thermal would still be installed on-site to provide the heating load. In this base case, CO_2 emissions all came from the grid and diesel boilers. In 2022, the amount of electricity generated from fossil fuel generation in Rwanda is 527 GWh [29]. With total emissions of around 1 million tons, that constitutes around 0.188 metric ton CO_2/MWh. That number is inserted to Xendee for Microgrid Optimization considering reducing CO_2 emissions.

A cost optimization was run on the microgrid including only these two technologies. This was then used as the reference case for all future optimizations in Xendee. It should be noted that no NPV, IRR, or payback period could be determined for this scenario since it is the reference case itself.

1) *Electricity*

This scenario served as a baseline for comparison with other scenarios. It represented the traditional electricity system where power was supplied solely through the grid. While this setup might have been cost-effective (lowest LCOE), it had the highest CO_2 emissions, reflecting a higher environmental impact. By comparing this scenario with others, improvements in cost and environmental impact that alternative setups could offer were assessed.

2) *Heating*

Throughout the various scenarios, the optimal heating technologies remained constant, even when the optimal electricity-producing or storage technologies changed. After optimization, the heat technology split that resulted is shown

Figure 10. Electricity Dispatch for Grid + Solar. Optimized for CO_2 scenario.

Technology	**Capacity**	**Initial Equipment Cost (in thousands of dollars)**	**Heat Demand Split (%kWhth)**
Solar Thermal	3546m^2	\$1,420	23.7%
Diesel Boiler	3.73MWth	\$933	76.3%

below in Table 8.

The results indicate that a boiler is required to meet the base heating load, which constitutes approximately 76% of the total heat demand. On the other hand, solar thermal energy can address the peak demand that occurs in the middle of the day, accounting for about 23.7% of the total heat demand.

Table 8. Optimal Heating Technology Specifications for All Scenarios.

Optimizing for Cost versus optimizing for CO_2 does not change the results since both optimizations involve maximizing solar thermal energy use and minimizing diesel boiler use. This result makes sense given the fact that solar thermal energy use has lower operational costs post-installation and zero CO_2 emissions compared to diesel boilers. Also, solar thermal makes economic sense in the context of Rwanda's good solar energy resource.

C. *Grid Connected with Solar (G+S)*

This scenario introduced a renewable energy source (Solar) into the microgrid, while still connecting to the grid which was optimized for both cost and CO_2 emissions. In each case, a 3-day outage from February 8th to 10th was also optimized for resilience. Solar power, a clean and renewable energy source, can generate electricity without producing CO_2 emissions. By optimizing for cost (G+S For Cost) or CO_2 reduction (G+S For CO_2), this setup achieved a balance between economic feasibility and environmental sustainability.

Table 9 describes the calculated feasible installed energy technologies for Grid Connected with Solar, optimizing for cost, or optimizing for CO_2.

Table 9. Grid + Solar Optimized Capacity

Technologies	**Optimize Cost**	**Optimize CO_2**
Boiler	3.73 MW_{th}	3.73 MW_{th}
Solar Thermal	3,546 m^2	3,546 m^2
Solar PV	5.53 MW	5.7 MW
Hydro	-	-
Battery	21.5 MWh	55.4 MWh
Diesel Generator	450 kW	-

In terms of daily energy use, in Figure 10 below, it’s shown that solar PV can generate up to half of the hospital’s electricity demand depending on the time of day. Battery is not used to power the hospital, because the grid is cheaper to use in this scenario except during emergencies.

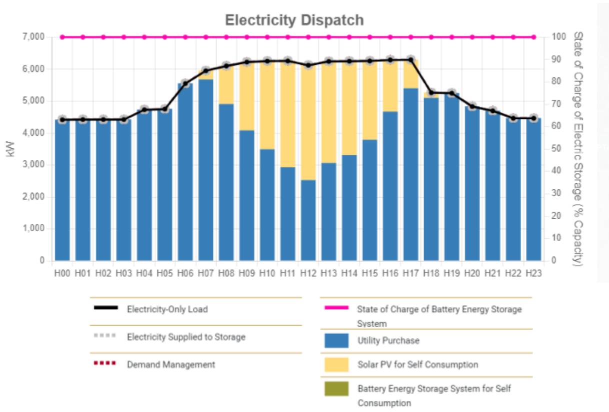

Figure 10. G+S Electricity Dispatch. Optimized for CO_2 scenario.

D. Grid Connected with Solar and Hydro (G+S+H)

This scenario further diversified the energy mix by adding another renewable source (Run of River Hydro). Hydropower, a reliable (high-capacity factor) and renewable source of energy, complemented the intermittent nature of solar power. Like the G+S scenarios, this setup was optimized for cost (G+S+H For Cost) or CO_2 reduction (G+S+H For CO_2). Both optimizations also included resiliency with a 3-day outage similar to the G+S optimizations.

Table 10 describes the optimized feasible installed energy technologies for the Grid Connected with Solar and Hydro, optimizing for cost, or optimizing for CO_2.

Table 10. Grid+Solar+Hydro Optimized Capacity

Technologies	**Optimize Cost**	**Optimize CO_2**
Boiler	3.73 MW_{th}	3.73 MW_{th}
Solar Thermal	3,546 m^2	3,546 m^2
Solar PV	135 kW	5.7 MW
Hydro	1.3 MW	1.3 MW
Battery	-	1.36 MWh
Diesel Generator	450 kW	450 kW

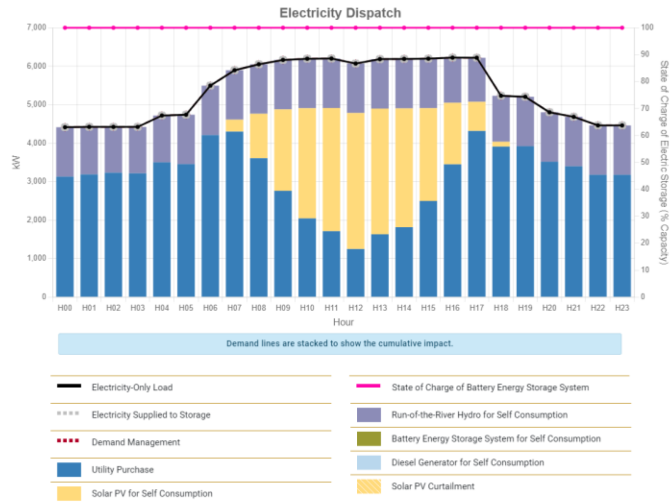

Figure 11. G+S+H Electricity Dispatch. Optimized for CO_2 scenario.

Figure 11 highlights that the inclusion of hydropower enhanced the system’s reliability, allowing for less utility electricity usage. In fact, during the middle of the day, most of the electricity consumed is also generated on site.

E. No Grid Connection

This scenario represented a grid-independent fully renewable microgrid (except for the potential backup diesel generators) with cost and resiliency being optimized for this scenario, and not CO_2, since the only emitting technology that could be used, is the backup diesel generators and boiler. Limits on the capacity of solar and battery storage were also removed for this scenario.

It had the highest LCOE of \$0.2192/kWh, a high upfront cost of \$75.8 million, and an NPV at the end of the project of negative \$59.8 million. However, this scenario has the lowest CO_2 emissions, with a total reduction of 66.6% from the reference scenario indicating a low environmental impact.

This optimization gave a total of over 35 MW of solar PV, and 72.4 MWh of battery storage needed, which is completely unrealistic for this system. Over 87 thousand units of solar would have to be installed to reach this capacity, leading to 69% of the cost stemming from the solar installation. It would also require about 185,000 m^2 of land area to install this solar capacity, which is well beyond what would be available in this location.

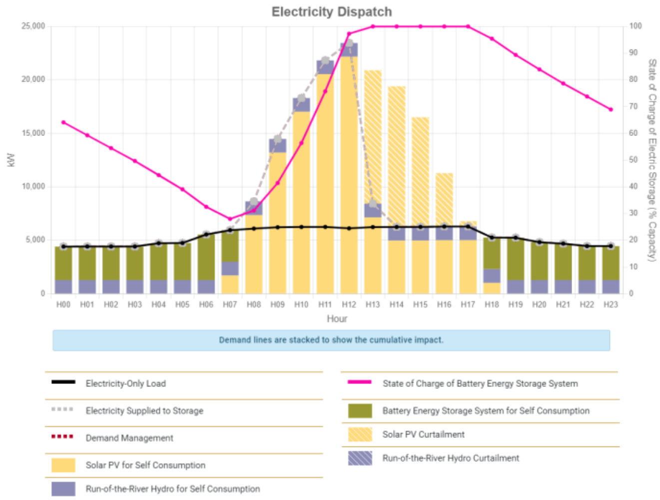

Figure 12. Microgrid (Solar+Hydro) Electricity Dispatch

From Figure 12 above, battery storage will supply energy to the system during the night until early morning. After sunrise, the solar PV will operate in full power, and charge the battery storage. The battery itself will be charged from 35% to 100% in around 5 hours. The solar PV energy will be curtailed from there on, just operating to fulfill the hospital energy demand, until the evening when the sun sets. Since in this case, Hydropower is limited to 1.3 MW, it operates as the base load constantly to reduce the amount of energy needed from other renewable sources. Overall, this power system configuration could support the hospital load operations but is not practically feasible.

F. *Comparison between Scenarios*

Table 11 presents the comparison of the mentioned scenarios, each optimized for cost or CO_2 reduction. The scenarios include Grid Only Grid + Solar (G+S) For Cost, G+S For CO_2, Grid + Solar + Hydro (G+S+H) For Cost, G+S+H For CO_2, and No Grid.

Some of the cases, which include G+S For Cost, G+S For CO_2, and No Grid Connection, have negative NPV and IRR, and a payback period of more than 20 years. This suggests that the initial investment may not be recouped within the project's lifetime. In other words, the future cost savings from the microgrid over the project's lifespan are not enough to justify the capital investment.

On the other hand, the G+S+H For Cost and G+S+H For CO_2 optimizations, which integrate Solar and Hydro with the Grid, have positive NPV and IRR, and a payback period of less than 10 years. This indicates that the savings received over the project's lifetime exceed the initial investment; the project's returns exceed its cost of capital, and the initial investment can be recouped relatively quickly. These are all desirable outcomes for any energy project. These results also suggest that the inclusion of a Run of River Hydro Power Plant is necessary to reduce the LCOE enough to have a positive project NPV. This makes sense given that hydro is a baseload electricity generator. The significant variability of solar and the need for storage to pair with it do not lend themselves to an economical microgrid system on their own.

The No Grid scenario has the lowest CO_2 emissions but also the highest LCOE, indicating a trade-off between environmental impact and cost. The Grid Only scenario has the lowest LCOE and highest CO_2 emissions, suggesting that while it may be the most cost-effective, it is also the least environmentally friendly. A balance is needed between the two cases. There should be a grid connection to keep costs down, but significant renewable generation in the microgrid to reduce emissions.

In summary, the scenarios optimized for cost have higher NPVs and IRRs, but also higher CO_2 emissions compared to the scenarios optimized for CO_2 reduction. This indicates a trade-off between environmental impact and cost. However, integrating Solar and Hydro with the Grid and optimizing for either cost or CO_2 reduction can result in a financially feasible and environmentally friendly microgrid setup.

Table 11. Comparison between different scenarios by key parameters

Scenario	**LCOE ($/kWh)**	**NPV (dollars in thousands)**	**IRR (%)**	**Pay Back Period**	**CO_2 (metric tons)**
Grid Only	0.145	-	-	-	12,925
G+S For Cost	0.1638	($12,314)	-7.70%	>20 years	11,327
G+S For CO2	0.1829	($25,156)	- 12.90%	>20 years	11,258
G+S+H For Cost	0.1351	$7,005	22.80%	4 years	11,428
G+S+H For CO2	0.1421	$2,305	9.10%	9 years	9,845
No Grid	0.2192	($59,804)	-6%	>20 years	4,314

The share in electricity produced by the microgrid system versus imported from the grid varied between the scenarios. Table 12 summarizes the breakdown of energy sources.

Table 12. Comparison between different scenarios by electricity production breakdown

Scenario	**On-Site Renewables (MWh/yr)**	**On-Site Diesel Generation (MWh/yr)**	**Electricity Purchase (MWh/yr)**
Grid Only	-	-	45,633
G+S For Cost	8,325	32.40	37,022
G+S For CO_2	8,583	-	36,799
G+S+H For Cost	7,733	18.56	37,620
G+S+H For CO_2	16,064	0.103	29,309
No Grid	49,813	-	-

The grid-only case and no grid connection case unsurprisingly have very different profiles. Interestingly, the total electrical energy is more for the no-grid connection case than the grid-only case. This can be explained by losses due to overproduction of solar energy and when discharging/charging the battery energy storage system. This means more energy must be produced overall in the no-grid connection case.

The other scenarios have similar electricity source breakdowns with about 8,000 MWh/yr produced on-site. The one exception is the G+S+H for CO_2 optimization, which produces nearly double this. This can be explained by this scenario being the only one that includes both the maximum amount of hydro and solar when using area limits.

Diesel power generation was small in all the scenarios. It is larger in the cost optimizations than the CO_2 optimizations, likely because the LCOE of diesel generators is less than batteries or solar.

G. Sensitivity Analysis – Solar PV Installation Cost and Load Variation

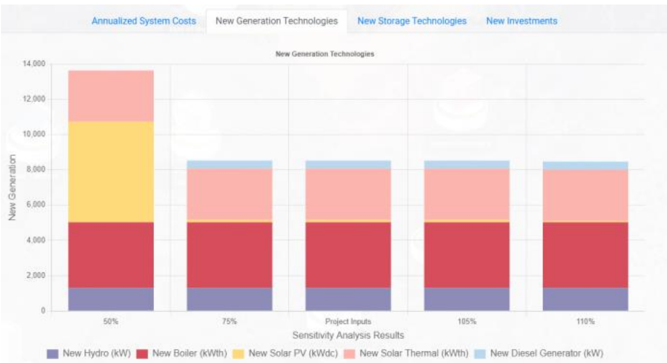

Figure 13. Sensitivity Analysis results after varying Solar installation costs between -50% and +10%

Figure 13 presents an analysis of the feasibility of Solar PV under varying installation costs, ranging from a decrease of 50% to an increase of 10%. The scenario considered for this analysis is the Grid, Solar, and Hydropower case, optimized for cost, with a Solar PV capacity of 135 kW.

The key insight from the figure is the significant increase in the utilization of solar PV when the installation costs are reduced by 50%. This reduction in costs makes the deployment of Solar PV more economically viable, leading to its increased usage. In contrast, smaller percentage changes in the installation costs do not have as substantial an impact on the usage of solar PV.

Therefore, if the installation costs of Solar PV can be reduced by 50%, it becomes feasible to use Solar PV as the primary energy source in the microgrid system. This finding underscores the importance of reducing installation costs in promoting the adoption of renewable energy sources like Solar PV.

V. Conclusion

The implementation of a microgrid system for a teaching hospital in Gisenyi, Rwanda, necessitates a nuanced approach that factors in the indispensability of a grid connection, the pivotal role of hydroelectric power, and the adaptability to scale battery and PV use for specific needs like cost, resilience, or emissions reduction. Various configurations were evaluated using Xendee, finding the significance of integrating both solar PV and hydropower alongside a grid connection for optimal outcomes.

Solar thermal heating emerges as a promising technology, demonstrating potential in offsetting thermal energy demands in hospitals and contributing to emissions reduction. The findings suggest the feasibility of augmenting solar thermal systems to fulfill a substantial portion of hospitals' thermal energy requirements, emphasizing its role in decreasing reliance on diesel boilers, thereby reducing emissions.

The Xendee optimization model simulated diverse scenarios incorporating solar PV, solar thermal, run-of-river hydropower, diesel generators, and battery storage to fulfill both electricity and heating loads. The results emphasize the significance of integrating solar PV and hydropower in conjunction with the grid to achieve economically feasible and environmentally sustainable microgrid setups.

A balanced approach is needed in this case. While scenarios optimized for cost exhibit higher financial metrics such as NPV and IRR, they tend to result in higher CO_2 emissions. Conversely, scenarios optimized for CO_2 reduction demonstrate lower environmental impact but may have slightly lower financial metrics.

The sensitivity analysis further underscores the importance of cost fluctuations, particularly in solar PV installation, revealing that a substantial reduction in solar PV costs could significantly influence the feasibility of utilizing solar energy as the primary microgrid source.

VI. References

[1] Central Intelligence Agency, "Rwanda," 2023. [Online]. Available: https://www.cia.gov/the-world-factbook/countries/rwanda/#energy.

[2] Rwanda Energy Group (REG), "Ongrid," 2023. [Online]. Available: https://www.reg.rw/what-we-do/access/ongrid/.

[3] IEA, "Rwanda-Countries & Regions," 2023. [Online]. Available: https://www.iea.org/countries/rwanda.

[4] Rwanda Energy Group (REG), "Generation," 2023. [Online]. Available: https://www.reg.rw/what-we-do/generation/.

[5] Rwanda Energy Group (REG), "Hydro Power in Rwanda," [Online]. Available: https://www.reg.rw/what-we-do/generation/hydro-power/.

[6] O. Uwishema, " Rwanda's health-care transformation: a case study for war-torn countries," *The Lancet,* p. 1076–1077, 2023.

[7] L. Adrian, M. Karangwa and M. Cardenas, "Rwanda Health System Strengthening Design Team Summary Report," USAID/Rwanda Mission, Kigali, 2013.

[8] W. Buningwire, "Gov't Upgrade Nine Hospitals to Teaching Hospitals," 19 August 2022. [Online]. Available: https://www.ktpress.rw/2022/08/govt-upgrade-nine-hospitals-to-teaching-hospitals/.

[9] Sustainable Energy for All & Power Africa, "Powering Healthcare in Rwanda: Market Assessment and Roadmap for Healthcare Facilities".

[10] Gisenyi Hospital, "Doctors," 2023. [Online]. Available: https://www.gisenyihospital.gov.rw/doctors.

[11] N. M. H. A. K. K. M. A. R. N. R. G. C. J. &. I. I. N. Yenita Dahlan, "Energy Star based benchmarking model for Malaysian Government hospitals - A qualitative and quantitative approach to assess energy performances," *Journal of Building Engineering,* pp. 145-155, 2022.

[12] S. A. F. M. S. L. C. S. E. &. S. K. Moghimi, "Building energy index and end-use energy analysis in large-scale hospitals—case study in Malaysia," *Energy Efficiency,* pp. 243-256, 2014.

[13] A. Buckley, D. Fitzgerald and U. Terblanc, "Energy Potential for solar thermal heating in South African hospitals," WWF, 2018.

[14] "Kaiser Permanente Pioneers California's First Medical Center Microgrid," Better Buildings US Department of Energy, [Online]. Available: https://betterbuildingssolutioncenter.energy.gov/implementation-models/kaiser-permanente-pioneers-californias-first-medical-center-microgrid. [Accessed 4 December 2023].

[15] "A Novel, Renewable Energy Microgrid for a California Healthcare Facility," California Energy Comission, [Online]. Available: https://www.energy.ca.gov/publications/2019/novel-renewable-energy-microgrid-california-healthcare-facility. [Accessed 4 December 2023].

[16] "Tariffs," Rwanda Energy Group (REG), [Online]. Available: https://www.reg.rw/customer-service/tariffs/. [Accessed 4 December 2023].

[17] Technical University of Denmark, [Online]. Available: https://globalwindatlas.info. [Accessed 2023].

[18] Technical University of Denmark, [Online]. Available: https://globalsolaratlas.info. [Accessed 2023].

[19] O. M. F. M. S. &. H. E. Munyaneza, "Performance evaluation of sediment basins: Case study of Keya hydropower plant in Rwanda," *Journal of Water Resource and Protection,* p. 1387–1398, 2015.

[20] G. S. A. N. E. &. Z. D. Gasore, "Sizing of small hydropower plants for highly variable flows in tropical run-of-river installations: A case study of the sebeya river," *Energies,* Vols. 16(3), 1304, no. https://doi.org/10.3390/en16031, 2023.

[21] "Real Time Data," Rwanda Water Portal, [Online]. Available: https://waterportal.rwb.rw/data/real_time_data. [Accessed 4 December 2023].

[22] "Planning a Microhydropower System," US Department of Energy, [Online]. Available: https://www.energy.gov/energysaver/planning-microhydropower-system. [Accessed 12 December 2023].

[23] "Hydropower installation cost worldwide 2022," Statistica, [Online]. Available: Hydropower installation cost worldwide 2022. (n.d.). Stahttps://www.statista.com/statistics/799341/global-hydropower-installation-cost/. [Accessed 4 December 2023].

[24] "US Hydroelectric Power Plant Operating Expenses Since 1998," Statistica, [Online]. Available: https://www.statista.com/statistics/195828/us-hydroelectric-power-plant-operating-expense-since-1998/. [Accessed 4 December 2023].

[25] "Rwanda Diesel Prices," GlobalPetrolPrices.com, [Online]. Available: https://www.globalpetrolprices.com/Rwanda/diesel_prices/. [Accessed 4 December 2023].

[26] "Generac qt15068anac kilowatts—150kw engine—6. 8 liter engine 120/240 1 nat gas al encl catalyst equip—Scqmd | crawford electric supply.," [Online]. Available: https://www.crawfordelectricsupply.com/product/detail/358989/generac-power-systems-inc-qt15068anac?utm_source=google&utm_medium=surfaces&utm_campaign=shopping%20feed&utm_content=free%20google%20shopping%20clicks. [Accessed 6 December 2023].

[27] "Batteries or Supercapacitors? Why Not Both?," Capacitech Energy, [Online]. Available: https://www.capacitechenergy.com/blog/batteries-or-supercapacitors-why-not-both. [Accessed 4 December 2023].

[28] J. Fernando, "Net Present Value," Investopedia, 24 May 2023. [Online]. Available: https://www.investopedia.com/terms/n/npv.asp.

[29] Climatescope, Bloomberg, 2023. [Online]. Available: https://www.global-climatescope.org/markets/rw/.

[30] M. T. A. I. T. &. S. M. M. Munsamy, "Hospital energy demand forecasting for prioritization during periods of constrained supply," *Journal of Industrial Engineering and Management,* pp. 131-149, 2023.

[31] A. E. v. A. B. J. C. A. D. v. W. M. M. D. M. &. M. S. Laher, "“Getting out of the dark”: Implications of load shedding on healthcare in South Africa and strategies to enhance preparedness," *SAMJ: South African Medical Journal,* pp. 899-901, 2019.

[32] Better Buildings Initiave, US Department of Energy, "Kaiser Permanente Pioneers California’s First Medical Center Microgrid".

[33] WorldData.info, "Rwanda," WorldData.info, 2021. [Online]. Available: https://www.worlddata.info/africa/rwanda/energy-consumption.php. [Accessed 12 December 2023].

APPENDIX

Table A1. Costs and Lifetime of Solar PV and Solar Thermal.

Technology	**Specification**	**Value**
Solar PV	Installation Cost ($/kW)	1,000
	Fixed Install Fees ($)	2,000
	Variable Maintenance ($/kWh)	0.10
	Monthly Fixed Maintenance ($/kW month)	0.30
	Lifetime (Years)	20
Inverter	Installation Cost ($/kW)	250
	Lifetime (Years)	10
Solar Thermal	Installation Cost ($/m2)	400
	Fixed Install Fees ($)	2,000
	Variable Maintenance ($/kWh)	0.01
	Monthly Fixed Maintenance ($/m2 month)	0.02
	Lifetime (Years)	20

Table A2. Costs and Lifetime of Run of River Hydro Plant.

Specification	**Value**
Installation Cost ($M)	4.5
Variable Maintenance ($/kWh)	0.0025
Monthly Fixed Maintenance ($/month)	2,000
Lifetime (Years)	20

Table A3. Costs and Lifetime of Diesel Generator and Boilers.

Technology	**Specification**	**Value**
Diesel Generator	Per Unit Install Cost ($)	30,000
	Variable Maintenance ($/kWh)	0.12
	Annual Fixed Maintenance ($/kW yr)	0
	Lifetime (Years)	15
Boiler	Installation Cost ($/kW)	250
	Fixed Install Fees ($)	0
	Variable Maintenance ($/kWh)	0
	Monthly Fixed Maintenance ($/m^2 month)	1.13
	Lifetime (Years)	20

Table A4. Costs and Lifetime of Solar PV and Solar Thermal.

Technology	**Specification**	**Value**
Solar PV	Installation Cost ($/kWh)	150
	Fixed Install Fees ($)	150
	Variable Maintenance ($/kWh)	0.001
	Monthly Fixed Maintenance ($/kWh month)	0.001
	Lifetime (Years)	10
Inverter	Installation Cost ($/kW)	250
	Lifetime (Years)	10