Renewable Energy for Rural Electrification of Sub-Saharan Africa: Why it matters (SDG7)

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Abstract

For over five decades, electricity grids in many Sub-Saharan African countries have been limited to urban areas, leaving the rural communities with no electricity. This is why it matters to have a paradigm shift from centralized urban grids to standalone micro-grids powered by renewable resources from rural localities. This paper describes an approach to designing such standalone systems. The approach, which is based on the concept of Renewable Energy Map, has been applied to the South-West Region of Cameroon. The Map, which identifies the locations of Renewable Resources and quantifies the electricity generation potential of each resource, has been used to design a Rural Electrification Master Plan for 480 villages of the South-West Region. As part of the Master Plan, 54 Renewable Power Generators have been designed. These include 18 Biomass Generators powered by Empty-Palm-Fruit Bunches, 16 Run-of-River Mini-Hydro Power Generators driven by fast flowing streams and rivers, 8 Waterfall-driven Mini-Hydro Power Generators and 12 standalone Solar Generators. The project is the fruit of a partnership between the University of Buea and the thirty-one Councils (Local Governments) of the South-West Region of Cameroon.

Keywords: Renewable Energy Map; Rural Electrification Master Plan; Empty Palm Fruit Bunches; Run-of-river Scheme

Introduction

95% of people with no access to electricity live in Sub-Saharan Africa and Asia, and 80% of these energy-deprived people live in the rural areas (IEA, 2017). For these rural inhabitants, the Sustainable Development Goal Number 7, which requires all citizens of the world to have access to affordable, reliable and sustainable energy, remains an unattainable luxury. According to 2014 World Bank Statistics, rural access to electricity is as low as 0.4% in the Democratic Republic of Congo, 3.09% in Central African Republic and 4.53% in Chad. This is why it matters to develop a sustainable rural electrification strategy for Sub-Saharan Africa.

Rural communities, which are the most affected by poverty, in the economic sense, are further affected by Energy Poverty, in the context of access to energy. According to the 2021 Energy Progress Report, about 759 million people in the world still lack access to electricity and only 46% of the population in Sub-Saharan Africa has access to electrical energy (IEA et al.,2017).

While technology and industrialization are growing at a fast pace, the means of providing clean electrical energy to the world’s population, at a relatively low cost, remains a challenging task (Rehman,2021).

If the problem of rural electrification is not addressed, the African Union Agenda 2063 vision of a prosperous Africa in which citizens drive their own development will remain a hollow dream. The African Union has long recognized the fact that Agenda 2063 cannot be achieved without developments in Science, Technology and Innovation. This is why the STISA-2024 (Science, Technology and Innovation Strategy for Africa) was designed. STISA-2024 has five priory areas (Clusters), one of which is Energy. This is why it matters to solve the problem of rural electrification in Sub-Saharan Africa, to make a contribution to the realization of both Agenda 2063 and STISA-2024.

The project reported in this paper is based on the use of a Renewable Energy Map in developing a sustainable rural electrification master plan for four hundred and eighty (480) villages in thirty-one Councils (Local Governments) of the South-West region of Cameroon. The project provides a model which can be leveraged and replicated in other Sub-Saharan African countries, especially countries of the Equatorial Rain Forest which are endowed with renewable resources similar to those in Cameroon.

The replication of this rural electrification model in many Sub-Saharan African countries will impact several Sustainable Development Goals (SDGs), since SDG7 is the epicenter of the system of SDGs. Energy impacts every economic or developmental activity. The Sustainable Development Goal Number 7 is at the epicenter of all Sustainable Development Goals, since it impacts many other SDGs. This dependence of other SDGs on energy is illustrated in figure 1.

Figure 1: Energy as the epicenter of Sustainable Development Goals

Energy directly or indirectly facilitates the attainment of at least 8 other Sustainable Development Goals (SDGs), including SDG 1, to end poverty, SDG 3, to ensure healthy lives and promote well-being; SDG 4, access to quality education; SDG 8, to promote sustained, inclusive and sustainable economic growth; SDG 9, to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; SDG 13, to combat climate change; SDG 15, to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt biodiversity loss.

The availability of electricity to both rural and urban populations provides a lever to poverty alleviation, improves the well-being of the population, facilitates inclusive economic growth through the creation of enterprises, facilitates industrialization and fosters innovation. It also combats climate change by reducing the pressure on forest exploitation to provide firewood for rural populations, combats desertification and halts biodiversity loss which is a consequence of the depletion of forests resulting in the loss of the natural habitat of wildlife. Energy impacts most of the Sustainable Development Goals. This is why it matters to solve the problem of rural electrification in Sub-Saharan Africa.

The authors' research shows that absence of electricity is the epicenter of the underdevelopment matrix of Sub-Saharan Africa, as illustrated in figure 2. The lack of electricity is deadweight on the development of Sub-Saharan Africa. The replication of this model of rural electrification in other countries of the region will remove this deadweight and reverse the phenomena highlighted in figure 2.

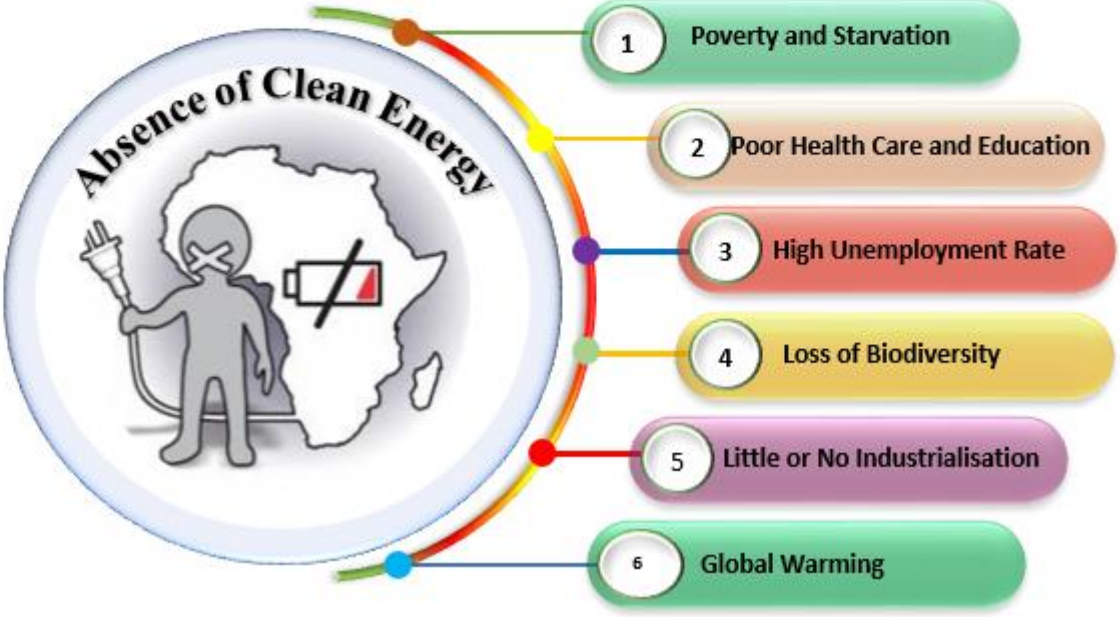

Figure 2: Lack of Energy and the Underdevelopment Matrix of Sub-Saharan Africa (From the Author's Research and Analysis)

Why It Matters

The national grids in many Sub-Saharan African countries distribute electricity from hydro-electric power stations. In Cameroon, for example, there are three hydro-electric stations: Edea, Songloulou and Lagdo. Edea and Songloulou supply the more populous southern part of the country while Lagdo supplies the north. This dependence on hydro-electric stations built many decades ago is the same in many countries.

The electricity grids supplied by these hydro-electric stations are limited to urban centers for two main reasons:

- The power output of the hydro-electric stations is not sufficient to meet the needs of the urban and rural populations
- The rural areas cover wide geographical areas and huge power losses would be incurred if the grids were extended to these localities

These two factors have been the greatest impediment to the expansion of the national grids to the rural areas. For over five decades, many Sub-Saharan African countries have not overcome the problem of grid limitation. One solution is to build more hydro-electric stations but very few new stations have been built. The situation is further compounded by demographic factors such as the rapid population increase, both in the urban and rural areas.

It is now clear that the paradigm of centralized electricity distribution from hydro-electric power stations does not provide a solution to the problem of rural electrification. This approach to electricity distribution has not solved the problem of rural electrification for over five decades and from all indications, it will not solve the problem even in the next five decades.

This is why it matters to have a paradigm shift to decentralized standalone micro-grids powered by renewable resources from many localities.

Methodology

A four-step methodology is used in the project:

- Development of the Renewable Energy Map of the South-West Region
- Design of a Power Generation Schedule for 480 villages which lack electricity in the region
- Design of Power Generators to supply the villages
- Development of Partnerships for Project Consolidation, Implementation and Replication

Development of the Renewable Energy Map of the South-West Region of Cameroon

The concept of Renewable Energy Map is used to identify the locations of renewable resources in a specified geographical area and to quantify the electricity generation potential and sustainability of each of the resources.

The potential of Renewable Energy in providing electricity to all inhabitants of rural communities has long been recognized by many researchers (Rehman, 2021) but the slow pace of tapping this great potential is due to the absence of strategies which address sustainability of resources, high initial cost and resource mobilization. The concept of Renewable Energy Map is a model of sustainability modeling and a tool for the design of low-cost electrification systems.

The application of the concept to the South-West Region of Cameroon revealed an abundance of four types of renewable resources:

- Biomass from Empty Palm Fruit Bunches: Palm oil is produced on a massive scale by two big Agro-Industries located in the South-West Region of Cameroon: Cameroon Development Corporation (C.D.C.) and PAMOL. The Empty Palm Fruit Bunches, which are residue from palm oil production, are mainly dumped as organic waste. In addition to these two agro-industries, thousands of small-scale farmers also produce palm oil and dump tons of Empty Palm Fruit Bunches.

- Fast Flowing Streams and Rivers: The South-West Region is endowed with 16 fast flowing streams and rivers with great hydro potential.
- Waterfalls: The region also has 8 waterfalls with significant hydraulic head.
- Solar Energy: There is an abundance of solar energy everywhere in the region, but this resource is assigned the lowest priority in the Rural Electrification Master Plan because of the high cost of community-scale solar systems, compared to other options. Solar Energy is used only in villages which do not have any of the other resources (Empty Palm Fruit Bunches, Fast Flowing streams or rivers, Waterfalls).

Power Generation Schedule for 480 Villages

From the analysis of the data provided by the Renewable Energy Map, a total of 54 power generators are required to supply 480 villages which are without electricity in the region. These include 18 Empty-Palm-Fruit-Bunch Biomass generators, 16 run-of-river mini-hydro power generators driven by fast flowing streams or rivers, 8 Mini-hydro power generators driven by waterfalls and 12 standalone solar power generators. The allocation of these generators to the villages is shown in table 1.

The data used in constructing the Renewable Energy Map was collected by a team of Engineers from the Faculty of Engineering and Technology of the University of Buea. The data acquisition process was facilitated by Project Liaison Officers from the 31 Councils (Local Governments) of the South-West Region of Cameroon. The Project Liaison Officers were designated by the Mayors of the Councils (1 per Council). The Liaison Officers selected Local Guides from the communities to show the team of Engineers the locations of renewable resources such as waterfalls, dumps of empty-palm-fruit bunches, fast-flowing streams and rivers.

The Engineers then measured the Hydraulic Heads of the waterfalls and Flow rates of the fast-flowing streams and rivers, in order to determine their mini-hydro potentials. From the dumps of empty-palm-fruit bunches in each location, the Engineers estimated monthly averages of this resource in order to quantify the electricity generation potential and sustainability. The Engineers also carried out energy audits of the villages to determine the number of villages which can be supplied from each of the power generators.

The information in table 1 is a synthesis of the data collected by the team of Engineers. The study shows that twelve villages are not located near fast-flowing streams or rivers and do not produce palm oil. The only sustainable resource for the 12 villages is solar energy.

Table 1: Power Generation Schedule for the Villages

No.	Type of Generator	Number of Generators	Number of Villages
1	Empty-Palm-Fruit-Bunch Biomass	18	206
2	Run-of-river Mini-hydro driven by fast flowing streams or rivers	16	172
3	Waterfall-driven Mini-hydro	8	90
4	Solar	12	12
Total		**54**	**480**

Design of Power Generators to Supply the Villages

The objective is to design power generators to facilitate the construction of 54 turn-key power stations. Apart from the solar stations which are autonomous systems in each of the 12 villages, each of the other generators is designed to supply a group of villages.

Design of the Empty-Palm-Fruit-Bunch Biomass Generators

Each of the 18 biomass power generators was designed to incorporate 3 subsystems:

- Pelletizer
- Power Generator
- Micro-grid

Design of the Pelletizers

Pelletization reduces the Empty-Palm-Fruit-Bunch biomass to pellets which are suitable for combustion in the power generation.

After the collection of the Empty Palm Fruit Bunches, unwanted impurities are manually removed and the sizes of the bunches are reduced to facilitate drying. The drying is done to reduce the moisture content. After the drying process, the pellets are then produced using the pelletization machine. Because of the heat involved during this process, they are cooled and then stored for usage. These final pellets are the fuel which is fed to the generator.

Cameroon is endowed with a huge potential of palm biomass. The country produces an estimated 300,000 tons/year (Rosalien Jezeer and Nick Pasiecznik, 2019).

Palm trees are rich in biomass and produce seven different types of biomass products (Onoja et al., 2018). Only one of these biomass products, the Empty Palm Fruit Bunches (**EPFB**), is used in this project. The EPFB accounts for about 23% of the weight of fresh cones of palm nuts. The fresh cones and residual Empty Palm Fruit Bunches are shown in figure 3.

Figure 3: Oil Palm Cones and Residual Empty Palm Fruit Bunches

Pelletization reduces the Empty Palm Fruit Bunches into pellets which are suitable for combustion in the power generator. Figure 4 shows the pelletization process and figure 5 shows the Pellets.

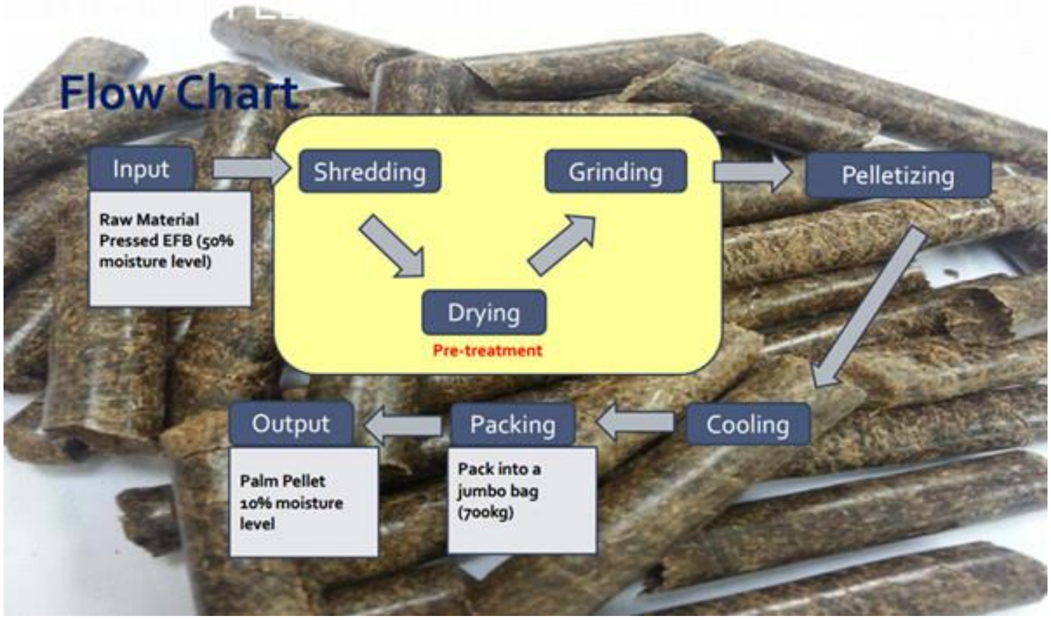

Figure 4: EPFB Pellet Making Process

Figure 5: EPFB Pellets

Design of the Power Generators

Conversion of large quantities of pelletized Empty Palm Fruit Bunches to electricity is done by combustion of the pellets in a furnace, to generate high-pressure steam. The operational principle is shown in figure 6.

When the pellets are fed into the combustor, in the presence of excess air, they are burnt in the combustor to produce heat. Water is then pumped from the condenser to the combustor using a high-pressure pump transforming it into high pressure steam which rotates the steam turbine blades. The turbine is mechanically coupled to a generator through a high-speed rotating shaft. When the shaft rotates, it causes the rotor of the generator to rotate, cutting the flux of the stator and generating electricity. The hot air from the combustor goes through the cyclone where tar is separated from the air. The solid slag is recycled back into the combustor for combustion. The solid free air then runs through a scrubber where it is purified by removing toxic gases and dust, making the air environmentally friendly and ready for discharge into the atmosphere through the chimney.

One of the smallest generators was designed to supply a village of 200 households requiring 11 KW of power. The quantity of pellets required to produce this power, for a plant efficiency of 35%, operating 24 hours a day was calculated from equation 1 (Olisa & Kotingo, 2014).

$$P = \frac{MQe}{t} \qquad (1)$$

Where P is the electrical power (kW), M is the quantity of pellets in (kg), Q is the net heating value of the pellets in (MJ/kg), t is the operational time (hours), and e is the plant efficiency.

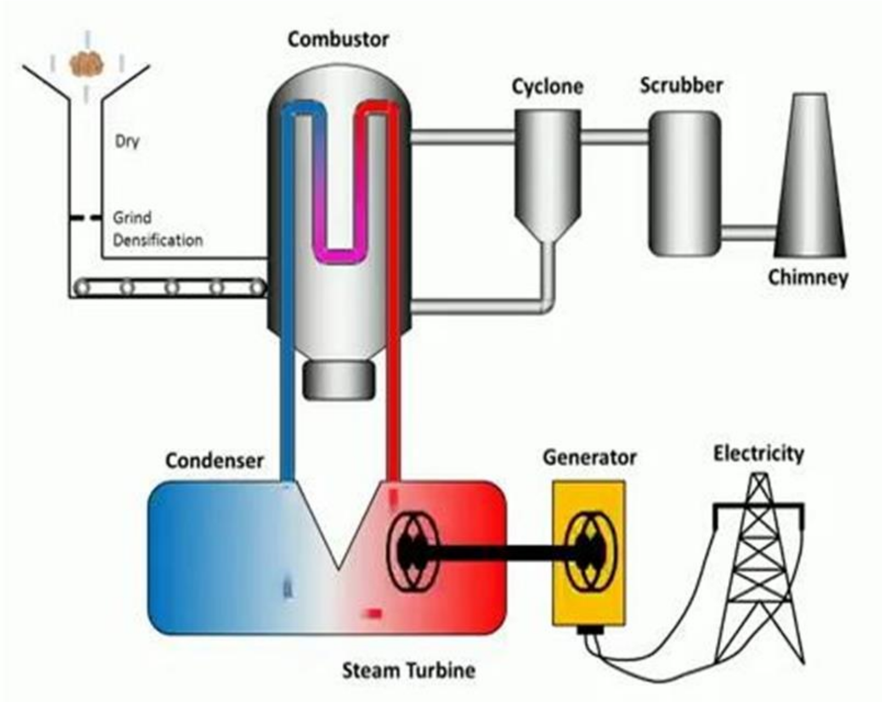

Figure 6: Operational Principle of the Biomass Power Generator

Design of the Micro-grid

Each of the 18 Empty-Palm-Fruit-Bunch biomass generators was sized, based on estimates of the biomass available to feed the generators. The sizing provided an estimate of power output and this was used to determine the number of villages which could be supplied by each generator. A micro-grid was then designed to transport power to the target villages. 14 of the generators were sized to supply several villages. Only 4 were sized to supply only one village each.

Design of Run-of-river Mini-hydro Generators Driven by Fast Flowing Streams or Rivers

All of the 16 Mini-hydro generators, driven by fast flowing streams and rivers, were designed as run-of-river diversion schemes. These are low-cost schemes since they do not incorporate reservoirs or dams. The scheme is shown in figure 7.

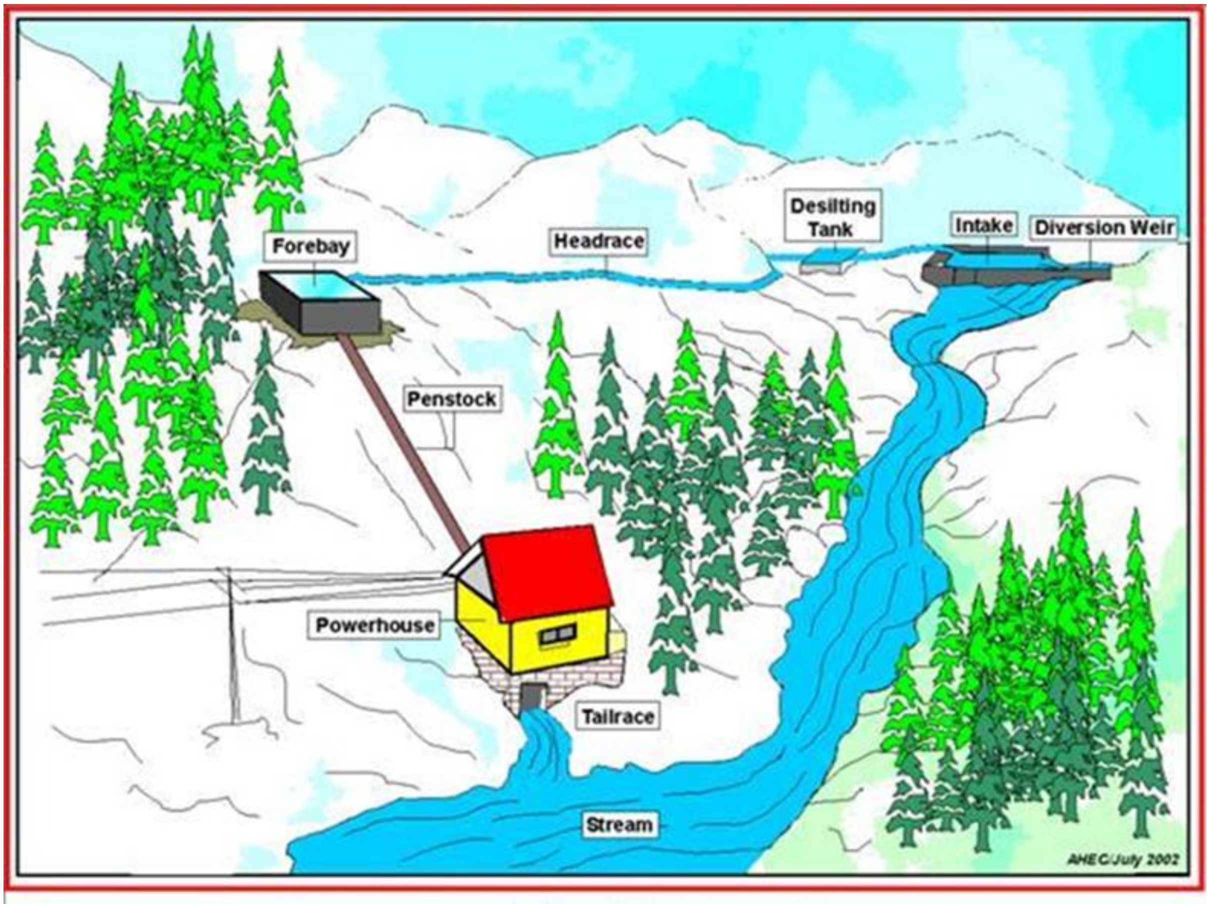

Figure 7: Run-of-River Diversion Scheme

Water is diverted from the main stream or river to create a hydraulic head which is passed through the penstock with high energy. The pressurized water in the penstock rotates the turbine which spins the shaft coupled to the generator. The subsystems of the scheme include the intake from the river or stream, Desilting tank, Power Canal (headrace), Forebay, Penstock, Power House and Tailrace Canal.

The nominal power of the hydro system $\boldsymbol{P_{\mathrm{hyd}}}$ is the power produced by the hydro turbine. It is a function of Hydraulic Head and Flow Rate. The computation includes the efficiency of the hydro turbine but not the pipe head loss. The nominal hydro power is given by equation 2.

$$P_{hyd.nom} = \frac{\eta_{hyd} . \rho_{water} . g.h.\dot{Q}_{design}}{1{,}000{,}000 W / MW} \qquad (2)$$

Where:

$P_{hyd,nom}$ is the nominal hydro power output of the hydro turbine (MW)

h_{hyd} is the hydro turbine efficiency (%)

ρ_{water} is the density of water (1000kg/m^3)

g is the acceleration due to gravity (9.81 m/s^2)

h_{net} is the effective water head (10m)

Q_{design} is the hydro turbine flow rate (15m^3/s and 20m^3/s)

The application of equation 1 to one of the diversion schemes with a Head of 10m and Flow rate of 15m^3/s resulted in a numerical value of 1.1772 MW, obtained from:

$$P_{hyd.nom} = \frac{0.8 \times 1000 \times 9.81 \times 10 \times 15}{1,000,000} = 1.1772MW$$

The application to a second scheme with a Head of 10m and flow rate of 20m^3/s resulted in a numerical value of 1.596 MW, obtained from:

$$P_{hyd.nom} = \frac{0.8 \times 1000 \times 9.81 \times 10 \times 20}{1,000,000} = 1.5696MW$$

The calculated $\boldsymbol{P_{hyd}}$ values for each of the 18 Mini-hydro Power Generators were used to determine the number of villages which could be connected to the micro-grids transporting power from the generator to the villages.

Design of Waterfall-driven Mini-hydro Power Generators

All of the 8 Waterfall-driven Mini-Hydro Power Generators were designed as Diversion Schemes, but the diversions were from the base of each of the waterfalls (ground level). This design option maximizes the Hydraulic Head impacting the turbines. The diversions are very short, compared with run-of-river schemes.

Apart from this structural difference, the technology used in Waterfall-driven Mini-Hydro plants is exactly the same as that used in the run-of-river plants (Figure 7).

A two-step methodology was used for each of the Waterfall-driven mini-hydro power plants:

- Dimensioning and configuration of the Hydraulic System
- MATLAB Simulation for design of system parameters and testing of system stability and robustness to faults

Dimensioning and Configuration of the Hydraulic System

Table 2 shows the design parameters for one of the waterfalls with a Head of 30m and a flow rate of 2m^3/s.

Table 2 Dimensioning of the Hydraulic System for a Waterfall with a Head of 30m

Intake	Area of intake	1m^2
	Flowrate	2 m^2/s
	Velocity	2 m/s
Settling Basin	Width	2m
	Length	10 m
	Depth	1.66 m
Head race	Width	1.33 m
Forebay	Storage volume	18 m^3/m
	Thrashrack height	1m
Penstock	Length	71m
	Diameter	0.76m
	Thickness	2.47mm
	Head loss	1.21m
	Net head	28.79m
Turbine-Generator	Turbine type	Francis turbine
	Nominal speed	500 rpm
	Turbine dimension (m)	D_3=0.65; D_1=D_2=0.64
	Generator type	Synchronous
	Generator apparent power	584 kVA
	Combined efficiency	0.6
	Generator current	850A
	Generator frequency	50 Hz
	Generator poles	12
	Active power generated	467 kW
	Capacity factor	0.6
Transformer	Rating	700 kVA
	Primary voltage	400 V
	Secondary voltage	15 kV
	Number of phases	3

MATLAB Simulation for Design of System Parameters and Testing of System Stability and Robustness to Faults

The “Powergui” tool in MATLAB was used to automatically calculate the load flows.

A three-phase line-to-ground fault was introduced at 0.3s and removed at 0.4s. The simulated results from the generator, exciter and turbine showed that the response of the system was acceptable. The configuration of the system, obtained from the simulation is shown in table 3.

From the simulation, five graphs were plotted: the turbine speed characteristics; the generator output voltage characteristics; the generator excitation voltage characteristics; field current characteristics; and the stator current were all plotted with respect to time.

The plant's ability to overcome faults rapidly and effectively was tested by the introduction of a fault. The fault type used was the three-phase line-to-ground fault, which is the most common in practice. The fault was initiated at 0.3s and lasted for a period of 0.1s. The following observations were made:

- During the duration of the fault, the generated output voltage V_a dropped significantly from the nominal 1 pu to 0.15pu where stabilised for the duration of the fault.

- The stator current I_{abc} increased from 1pu to 12 pu and even after the fault was cleared at 0.4s, the current transients lasted for approximately 0.1s more.

- The excitation voltage, V_f increased from its initial values of 1 pu to 3.5pu during the fault and took 0.3s to return to the initial state.

- The machine speed dropped from the initial value of 1 pu to 0.885 pu and then rose to 1.118 pu at the start of the fault. The system took approximately 0.3s to attain equilibrium.

Table 3: System Configuration generated from the MATLAB Simulation

System Parameter	**Value of Parameter**
Power and Voltage Rating of Synchronous Machine	584 kVA 400V
Nominal Power and Root-mean-Square Voltage	584 kVA 400 V rms
Bus Type	P & V generator
Voltage of first Phase of Generator, Uan	400 Vrms [1 pu] -30.15°
Voltage of second Phase of Generator, Uab	400 Vrms [1 pu] -0.15°
Voltage of third Phase of Generator , Ubc	400 Vrms [1 pu] -120.15°
Current of first phase of Generator, Ia	675.77 Arms [0.8017 pu] -34.24°
Current of second phase of Generator, Ib	675.77 Arms [0.8017 pu] -154.24°
Current of third phase of Generator, Ic	675.78 Arms [0.8017 pu] 85.76°

Power	4.67e+05 W [0.7997 pu]
Mechanical Power, Pmec	4.7282e+05 W [0.8096 pu]
Torque	3010 N.m [0.8096 pu]
Excitation Voltage, Vf:	2.3892 pu

However, there was an abnormality in the generator excitation response graph. From the literature review, it was expected that excitation voltage would be constant (nominal value) at the start, then increase during the fault and then return to normal after the fault. The observed response was different. This was a consequence of the excitation signal from Simulink.

The response of the system to the simulated fault was consistent with the theoretical prediction. The voltage induced in a machine is a function of both the Flux linking the machine and the synchronous speed of the machine. Consequently, the increase in the excitation voltage during the fault increases the induced flux.

The machine speed which was expected to increase by the same order of magnitude as the excitation voltage, only increased by around 0.012 pu. This is explained by the fact that the speed is limited by the maximum flow rate which is only $2m^3/s$. The Governor controls the position of the Wicket Gates, but the flow rate depends on the availability of flowing water. Furthermore, after the fault was removed, at 0.4s, the stator current and speed both oscillated down to their initial values before the fault with the latter oscillating for about 0.4s (0.3-0.7) just around the pre-set condition and took longer to stabilize with a possible explanation being the rate of opening or closing of the wicket gates by the governor.

Design of Solar Power Generators

The solar power generators for the 12 villages shown on table 1 were all designed as standalone (off-grid) systems. Each system was designed in a three-step process which included:

- Energy Audit of the households in the village
- Sizing of the battery bank
- Sizing of the PV Array, Charge Controller and Inverter

The design process for one of the villages with 200 households is presented.

Energy Audit

The Energy Audit for the village with 200 households is shown in table 4.

Table 4: Energy Audit of a Village with 200 households

Average Daily Energy Consumption per household	1.315 KWh
Daily Consumption for the community of 200 households	263 KWh
Power required to supply the energy	10.96 KW

Sizing of the Battery Bank

Considering a 240V system, then the Ah rating (Q) of the battery will be given by equation (3).

$$Q = \frac{Eac}{240} = \frac{292000}{240} = 1218\ Ah \tag{3}$$

This calculation is done considering one day of autonomy. If a 70% **Depth of Discharge** (**DOD**) is considered (Jäger et al., 2014), then the new system battery capacity becomes

$$Q = 1218 \div 0.7 = 1740\ Ah. \tag{4}$$

Using 200 Ah, 12V batteries, the total number of batteries (n_{Bat}) required are computed from equation 5.

$$n_{Bat} = 1740 \div 200 = 9 \tag{5}$$

We obtained 9 batteries in parrallel and 20 batteries to be connected in series to give 240V as the system voltage since each battery outputs 12V. Therefore the total number of batteries (N_{Bat}) is

$$N_{Bat} = 9 \times 20 = 180 \tag{6}$$

The sizing of the battery bank is summarized in table 5.

Table 5: Sizing of the Battery Bank

Power Rating of Battery	1740 Ah
Number of batteries	180
Number of rows of batteries	9
Number of batteries connected in series in each row	20

Sizing of the PV Array, Charge Controller and Inverter

Considering a battery efficiency of 90%, 5% manufacturer's tolerance and 3% cable losses [5], then the PV array current (I_{PV}) requirement is given by equation (7).

$$I_{PV}(Ah) = 1740 \div 0.9 \div 0.97 = 1993Ah \tag{7}$$

Considering the worst months in the wet season with daily peak sun hours of 4.5 hours, then the current requirement of the PV array will be

$$I_{PV}(A) = 1993 \div 4.5 = 1136.38 \div 4.5 = 443A \tag{8}$$

Using the PV module of table 4, the current can be modified to

$$I_{PV\_module} = 9.16 \times 0.95 \times 0.95 = 8.27A$$

Therefore the number of modules (n_{PV_Module}) to be connected in parallel is

$$n_{PV\_Module} = 443 \div 8.27 = 54 \tag{8}$$

The number of modules to be connected in series is 10, to give an input voltage of 240V to the charge controller since each module has a nominal voltage of 24V.

The total number of modulesN_{PV_Module}

$$N_{PV\_Module} = 54 \times 10 = 540 \tag{9}$$

Table 6: Sizing of the PV Array, Charge Controller and Inverter

Subsystem	**Characteristics**	**Value**
PV Array	Technology	Silicon-Crystalline
	Rated Power	300 Watts
	Nominal Voltage	30.2 Volts
	Nominal Current	9.6 Amperes
	Short Circuit Current	9.6 Amperes
	Open Circuit Voltage	40.1 Volts
	Number of Panels connected in parallel	54
	Number of modules connected in series	10
	Total Number of Panels	540
Charge Controller	Rating	100 A
	Charge Controller Current	554 A
Inverter	Rating	15 KW

The charge controller current ($I_{Controller}$) is evaluated by equation (10)

$$I_{Controller} = 1.25 \times 443 = 554A. \tag{10}$$

The factor 1.25 (Ammar Alkhalidi, 2017) provides a margin of safety which protects the charge controller. Using a 100A charge controller, 6 charge controllers are needed.

The Inverter was also sized to withstand the load demand. Considering the 10.958 kW which is the required output power to produce energy for 24 hours, the inverter size is calculated from equation (11).

$$P_{Inverter} = 11 \times 1.25 = 13.75KW \qquad (11)$$

This implies that an inverter rated at 15kW is suitable for the system.

Development of Partnerships for Project Consolidation, Implementation and Replication

Partnership for Project Implementation

The project has now reached the construction phase. According to the Memorandum of Understanding between the University of Buea and the thirty-one Councils of the South-West Region of Cameroon, the responsibility for the construction of the Rural Electrification Systems is jointly shared by the thirty-one Councils and the Faculty of Engineering and Technology of the University of Buea.

The role of the thirty-one Councils is resource mobilization. The Councils are presently sourcing for financial resources for the construction of the 54 Power Plants. Each Council will finance the construction of the plants within its Council area.

The role of the Faculty of Engineering and Technology is the construction of the plants. In return, the Faculty will be paid consultancy fees by the Councils. An agreement has already been reached on the amount of fees to be paid by each Council. This will significantly empower the Faculty to embark on other outreach activities. The resource mobilization by each Council will raise enough funds to cover both the procurement of equipment and payment of consultancy fees to the Faculty.

Development of a Triple Helix Partnership for Extension of the Project to Other Parts of Cameroon

Many Mayors from Councils of other Regions of Cameroon have expressed interest in the Rural Electrification Project between the University of Buea and the thirty-one Councils of the South-West Region. This has caused the University of Buea to lobby several Government Line Ministries as well as Electricity Companies operating in Cameroon, to initiate a Triple Helix Partnership between Universities, Government and Power Industries. The purpose of the partnership is to provide a framework for extending the Rural Electrification Project to the other Regions of Cameroon. The Government Line Ministries solicited for this partnership include the Ministry of Water and Energy; Ministry of Higher Education; Ministry of Scientific Research and Innovation; Ministry of Industrial Development; Ministry of Finance; Ministry of Economy and Plan.

The broad outline of the Partnership has been elaborated. One University will be selected from each Region of Cameroon to develop the Renewable Energy Map of the Region and the Rural Electrification Master Plan for the Region. The University of Buea will coordinate and supervise the work of all the Universities involved in the project.

The Electricity companies will build the Power Plants which are designed by the Universities.
The Central Government will give tax exemption to the Electricity Companies for a period of five years, to enable them devote their resources to investment in the power plants.

Partnerships for Capacity Building and Replication of the Project in other Countries of Sub-Saharan Africa

The University of Buea has developed partnerships with seven African Universities to build capacity in Renewable Energy on the African continent. These partnerships are within the framework of two European Union Intra-Africa Mobility Projects, funded in the 2019 round of projects.

One project, MASTET (**M**obility of **A**frican **S**cholars for **T**ransformative **E**ngineering **T**raining), is implemented by a Consortium of five African Universities, including the University of Buea, in Cameroon, Makerere University, in Uganda, Stellenbosch University, in South Africa, Abomey Calavi University, in Benin, and Botswana University of Agriculture and Natural Resources. Twenty-four African Scholars from 20 countries are currently being trained in Masters and PhD programmes offered by the Partner Universities. By the time the MASTET project ends, a total of thirty-four African scholars will have been trained.

The second project, MIRET (**M**obility for **I**nnovative **R**enewable **E**nergy **T**echnologies), is implemented by another Consortium of five Universities, including the University of Buea, Moi University, in Kenya, Makerere University, University of Sfax, in Tunisia and the University of Zambia. Thirty students are currently being trained at the Masters and PhD levels in programmes in the domain of Renewable Energy. By the time the MIRET project ends, a total of forty African scholars will have been trained.

Many of the MASTET and MIRET students are currently doing their research projects on various Rural Electrification thematic areas. This is a concrete strategy to build capacity across Africa. The Partner Universities share their expertise and experience in various Renewable Energy Technologies.

The project reported in this paper is already shared with other Partner Universities and is widely regarded as one of the best practices in the continental rural electrification drive. It can, therefore, be expected that many other countries will leverage and replicate the project.

Results

The results of the project are six-fold:

i. A Renewable Energy Map of the South-West Region of Cameroon has been developed.

ii. The Renewable Energy Map has been used to develop a Rural Electrification Master Plan for the Region.

iii. The Master Plan includes the Design of 54 Power Plants to supply electricity to 480 villages. The Power Plants include 18 Empty-Palm-Fruit-Bunch Biomass Generators; 16 Run-of-River Mini-Hydro Power Stations, driven by fast flowing rivers and streams; 8 Waterfall-driven Mini-Hydro Power plants and 12 Solar Power Plants.

iv. The Renewable Energy Map provides an innovative model of sustainability management and a tool for low-cost design of rural electrification systems.

v. The project is an innovative case study which can be leveraged and replicated in other Sub-Saharan African countries to accelerate the attainment of SDG7, in particular, and other energy-dependent SDGs, in general. The replication of the project in other parts of Sub-Saharan Africa will also impact the continental visions of Agenda 2063 and STISA-2024.

vi. The project is a concrete example of University/Local Government Partnership

The impact of the project will be measured by three indicators:

- The number of power generators built in the South-West Region
- % increase in access to electricity by rural populations of the region
- Number of regions which replicate the project in Cameroon

Conclusions

Five conclusions are drawn from the project:

i. Renewable Energy Maps serve a dual purpose as a paradigm for sustainability modelling and a tool for the design of low-cost Rural Electrification Master Plans.

ii. The application of the paradigm to the South-West Region of Cameroon has facilitated the identification of the renewable resources of the Region and quantification of the electricity generation potential of each of the resources. The Renewable Energy Map of the Region has revealed an abundance of four types of renewable resources: Empty-Palm-Fruit-Bunch Biomass; Fast Flowing rivers and streams; Waterfalls and Solar Energy

iii. The Renewable Energy Map developed for the South-West Region of Cameroon has also facilitated the development of a Rural Electrification Master Plan for the Region. One deliverable in the Master Plan is a Power Generation Schedule which assigns 54 Power Generators to 480 villages, based on the renewable resources which are closest to each of the villages.

iv. The project, which is the fruit of a partnership between the University of Buea and the thirty-one Councils of the South-West Region of Cameroon, is a concrete example of how University/Local Government partnership can be used to positively impact the attainment of SDGs

v. The project is a concrete case study which can be replicated across Sub-Saharan Africa, to accelerate the attainment of SDG7, in particular, and energy-dependent SDGs, in general.

The project opens several perspectives for further work. These include:

- Construction of the Power Plants by the Faculty of Engineering and Technology of the University of Buea, in collaboration with the thirty-one Councils of the Soth-West Region which are currently involved in the resource mobilization drive.

- Future recruitment of Power Systems Engineers trained by the Faculty of Engineering and Technology to serve as Power Plant Operators in the newly constructed plants.

- Extension of the project to other Regions of Cameroon on the basis of numerous requests from the Mayors of the other Regions

- Operationalising the Triple Helix Partnership between the Cameroon Government, the Universities and the Electricity Companies operating in Cameroon, to provide a framework for extending the project to every Region of Cameroon

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References

Abanda, F., 2012. Renewable energy sources in Cameroon: Potentials, benefits and enabling environment. Renewable and Sustainable Energy Reviews 16, 4557–4562.

Al Dulaimi, N.H., 2017. Design of an Off-Grid Solar PV System for a Rural Shelter. German Jordanian University.

Antonio Castellano, Adam Kendall, Mikhail Nikomarov, Tarryn Swemmer, 2015. Brighter Africa: The growth potential of the Sub-Saharan electricity sector. McKinsey & Company.

An Introduction to hydropower Concepts and planning [WWW Document], n.d. . Guide Hydro Power. URL http://www.canyonhydro.com/guide/Guide%20to%20Hydropower.pdf. (accessed 3.23.22).

Asan, V., Abdullahi, A., Salman,A. , Razeman,M., Ruzairi, A., and Abu, B., 2015. Renewable Energy potentials in cameroon: Prospects and Challenges. *Renewable Energy,* 75 (2014), 560-565.

Azimoh, C.L., Klintenberg, P., Wallin, F., Karlsson, B., Mbohwa, C., 2016. Electricity for development: Mini-grid solution for rural electrification in South Africa. Energy Convers. Manag. 110, 268–277. https://doi.org/10.1016/j.enconman.2015.12.015

Basnyat, D., 2006. Fundamentals of Small Hydro Power Technologies - Training BACKGROUND MATERIAL [WWW Document]. URL ttps://www.researchgate.net/publication/331132575_Fundamentals_of_Small_Hydro_Power_Technologies_-_Training_BACKGROUND_MATERIAL (accessed 3.23.22).

British Hydropower Association, 2012. A GUIDE TO UK MINI-HYDRO DEVELOPMENTS [WWW Document]. URL https://www.british-hydro.org/wp-content/uploads/2018/03/A-Guide-to-UK-mini-hydro-development-v3.pdf

Canyon Hydro, n.d. Guide to Hydropower: An introduction to hydropower concepts and planning. Canyon Industries. Inc.

Chhetri, A.B., Pokharel, G.R., Islam, M.R., 2009. Sustainability of micro-hydro systems -a case study. Energy Env. 20.

Colorado Energy Office, 2012. Colorado Small hydropower Handbook. The Colorado Energy Office.

Duane Castaldi, Eric Chastain, Morgan Windram, Lauren Ziatyk, 2003. A Study of Hydroelectric Power: From a Global Perspective to a Local Application. College of Earth and Mineral Sciences The Pennsylvania State University.

FICHTNER, n.d. Hydroelectric Power A Guide for Developers and Investors [WWW Document]. URL https://www.ifc.org/wps/wcm/connect/906fa13c-2f47-4476-9476-

75320e08e5f3/Hydropower_Report.pdf?MOD=AJPERES&CVID=kJQl35z. (accessed 3.23.22).

Friedrich Sick, Thomas Erge, 1996. Photovoltaics in Buildings: A Design Handbook for Architects and Engineers, 1st ed. Routledge.

Gaelle, D., Xicang, Z., 2018. Current Status of Renewable Energy in Cameroon. North American Academic Research.

Gebrehiwot, K., Mondal, M. A. H., Ringler, C., & Gebremeskel, A. G., 2019. Optimization and cost-benefit assessment of hybrid power systems for off-grid rural electrification in Ethiopia. Energy, 177, 234–246. https://doi.org/10.1016/j.energy.2019.04.095

GTZ, 2010. Policy and regulatory framework conditions for small hydro power in Sub-Saharan Africa [WWW Document]. Eur. Union Energy Initiat. Euei. URL http://kerea.org/wp-content/uploads/2012/12/Policy-and-regulatory-framework-conditions-for-small-hydro-power-in-Sub-Saharan-Africa.pdf (accessed 3.23.22).

Jäger, K., Isabella, O., Smets, A., Swaaij, R.A., Zeman, M., 2014. Solar Energy Fundamentals, Technology, and Systems. Delft University of Technology, Delft.

Kalitsi, E.A.K., n.d. Hydropower Development in Africa [WWW Document]. URL https://sdgs.un.org/sites/default/files/statements/3209nepadkalitsi_ppt.pdf (accessed 3.16.22).

Kenfack, J., Neirac, F.P., Tatietse, T.T., Mayer, D., Fogue, M., Lejeune, A., 2009. Microhydro-PV-hybrid system: Sizing a small hydro-PV-hybrid system for rural electrification in developing countries. Renew. Energy 34, 2259–2263. https://doi.org/10.1016/j.renene.2008.12.038

Kenfack, J., Bossou, O. V., Voufo, J., Djom, S., & Crettenand, N., 2016. New Renewable Energy Promotion Approach for Rural Electrification in Cameroon. II. https://doi.org/10.1007/978-3-319-18215-5

khurana, S., Kumar, A., 2011. Small hydropower, A Review. International Journal of Engineering, Science and Metallurgy 1, 278–282.

Lombardi, V., 1990. A Practical Guide to Solar Power System Design For Homeowners, Solar Power 101. Virginia Tech.

Muh, E., Amara, S., & Tabet, F., 2018. Sustainable energy policies in Cameroon: A holistic overview. Renewable and Sustainable Energy Reviews, 82, 3420–3429. https://doi.org/10.1016/j.rser.2017.10.049

Muh, E., & Tabet, F., 2017. Sustainable energy policies in Cameroon : A holistic overview. https://doi.org/10.1016/j.rser.2017.10.049

Muh, E., & Tabet, F., 2019. Comparative analysis of hybrid renewable energy systems for off-grid applications in Southern Cameroons. Renewable Energy, 135, 41–54. https://doi.org/10.1016/j.renene.2018.11.105

Murugaperumal, K., Srinivasn, S., & Satya Prasad, G. R. K. D., 2020. Optimum design of hybrid renewable energy system through load forecasting and different operating strategies for rural electrification. Sustainable Energy Technologies and Assessments, 37, 100613. https://doi.org/10.1016/j.seta.2019.100613

Nafu, Y. R., Foba-tendo, J., Njeugna, E., Oliver, G., & Cooke, K. O., 2015. Extraction and Characterization of Fibres from the Stalk and Spikelets of Empty Fruit Bunch. Journal of Applied Chemistry, 2015, 1–10.

Nasir, B.A., 2013.Design of micro-hydro electric power station . IJEAT 2, 39–47.

Naveen, R., Revankar, P. P., & Rajanna, S., 2020. Integration of renewable energy systems for optimal energy needs-a review. International Journal of Renewable Energy Research, 10(2), 727–742.

Nasir, B., 2018.Matlab Simulation Procedure for Design of Micro-Hydro Electric power Plant. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE),* 13(4), 31-45.

Olisa, Y. P., & Kotingo, K. W., 2014. Utilization of palm empty fruit bunch (pefb) as solid fuel for steam boiler. European Journal of Engineering and Technology, 2(2), 1–7.

Onoja, E., Chandren, S., Ilyana, F., Razak, A., Arafat, N., & Wahab, R. A., 2018. Oil Palm (Elaeis guineensis) Biomass in Malaysia : The Present and Future Prospects. Waste and Biomass Valorization, 0(0), 0. https://doi.org/10.1007/s12649-018-0258-1

Pacific Northwest, 2009. Washington State University Extension Energy Program: Solar Electric System Design, Operation and Installation. An Overview for Builders in the U.S [WWW Document]. Dir. Organ. URL (accessed 3.17.22).

Pal, A.M., Das, S., Raju, N.B., 2015. Designing of a standalone Photovoltaic System for a Residential Building in Gurgaon, India. Sustainable energy 2, 14–24.

Panhwar, I., Sahito, A.R., Dursun, S., 2017. Designing Off-Grid and On-Grid Renewable Energy Systems Using HOMER Pro Software 12, 7.

Pasalli, Y.R., Rehiara, A.B., 2014. Design Planning of Micro-hydro Power Plant in Hink River | Elsevier Enhanced Reader. Procedia Environmental Sciences 20, 55–63. https://doi.org/10.1016/j.proenv.2014.03.009

Patel, 2015. Generating Equipment, in: International Conference on Hydropower for Sustainable Development. Dehradun, India.

Penche, C., 1998. Layman's Guidebook on How to Develop a Small Hydro Site. European Small Hydropower Association (ESHA).

Power Africa., 2019. Off-Grid Solar Market Assessment Cameroon.

Ramos, H., Belfast, N., 2000. Guidelines for Design of Small Hydropower Plants. WREAN (Western Regional Energy Agency and Network) 205.

Rehman, S., 2021. Hybrid power systems – Sizes, efficiencies, and economics. Energy Exploration and Exploitation, 39(1), 3–43. https://doi.org/10.1177/0144598720965022

Rosalien Jezeer, Nick Pasiecznik, 2019. Exploring inclusive palm oil production. ETFRN News 59.

Saleh, U., Haruna, Y.S., Onuigbo, F.I., 2015. Design and Procedure for Stand-Alone Photovoltaic Power System for Ozone Monitor Laboratory at Anyigba, North Central Nigeria. International Journal of Engineering Science and Innovative Technology (IJSIT) 6, 41–52.

ScienceDirect, n.d. Hydro Power [WWW Document]. URL https://www.sciencedirect.com/topics/engineering/hydro-power (accessed 3.16.22).

Suarez, R.A., Toscano, P., Siri, R., Muse, P., Abal, G., 2012. Recent advances in solar resource assessment in Uruguay, in: 2012 Sixth IEEE/PES Transmission and Distribution: Latin America Conference and Exposition (T&D-LA). Uruguay.

United Nations., 2015. Sustainable Development Goals.

United Nations., 2020. The Sustainable Development Goals Report 2020. https://doi.org/https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

World Bank, 2015. Evaluation of Rural Electrification Concessions in Sub-Saharan Africa. Detailed Case Study:Cameroon [WWW Document]. URL http://documents1.worldbank.org/curated/en/361311498151364762/pdf/116642-WP-PUBLIC-P150241-20p-Detailed-Case-Study-Cameroon-20151204-No-Logo.pdf (accessed 3.23.22).