Design and Analysis of a Renewable Energy Off-grid Electric Supply to Abdu Health Centre, Melume in the Democratic Republic of Congo

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I. INTRODUCTION AND ENERGY SUPPLIES

The Melume community (village), Buta, in the northern Democratic Republic of the Congo (DRC), Health Centre has no access to electricity. To ensure "good health and well-being" and to "reduce inequalities" posed by no access to good healthcare, the project aims to design renewable energy-based solutions while ensuring "affordable and clean energy" and well as offsetting carbon emissions ("climate action") in line with the Sustainable Development Goals (SDGs) as agreed by the global leaders in 2015 [1]. The health centre is located at **3^0N** Latitude ($\boldsymbol{A}+\boldsymbol{B}=1+2=\boldsymbol{3^0}$), **$24^0$E** longitude ($\boldsymbol{D}+\boldsymbol{U}=4+21=\boldsymbol{25^0}$) with location code **ABDU**.

The health centre's daily power requirement as given in [2] can be written mathematically, where D(t) represent demand in kW while D_{max} is the maximum demand (3kW). The daily amount of energy required is calculated as in equation 2 while daily average demand in kW is calculated in equation 1.

For	$t < 4$,	$D(t) = D_{max} \times 1/3$
For	$4 \le t < 8$,	$D(t) = D_{max} \times 2/3$
For	$8 \le t < 12$,	$D(t) = D_{max}$
For	$12 \le t < 16$,	$D(t) = D_{max} \times 2/3$
For	$16 \le t < 20$,	$D(t) = D_{max}$
For	$t \ge 20$,	$D(t) = D_{max} \times 1/3$

$$D_{av} = \frac{\sum_{i=0}^{23} D_i}{24} = \frac{48}{24} = 2\ kW \ldots\ldots\ldots (1)$$

$$E_{day} = \sum_{i=0}^{23} D_i = (4\times 1) + (4\times 2) + (4\times 3) + (4\times 2) + (4\times 3) + (4\times 1) = 48\ kWh \ldots\ldots\ldots (2)$$

A. Renewable Energy Resources at Abdu Health Centre, Melume, DRC

There are different types of renewable energies present at ABDU such as Solar, Wind, Hydro, biomass, green hydrogen etc. However, this report will only focus on the first three as discussed in the following subsection.

A. Wind Energy

The average annual wind speed at 50m for 2023 wind for Abdu, Melume is 1.66m/s which is quite low for wind turbine generation making wind not suitable for this location of Health Centre, Figure 1a gives a year's historical wind speed data for 2023 at Abdu, DRC while 1b gives the wind speed frequency distribution with 1 m/s intervals [3].

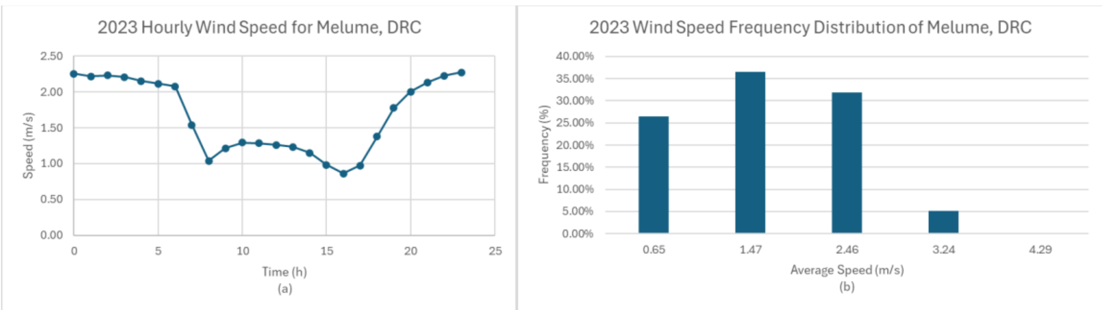

Figure 1: Historical Wind Data for Abdu, Melume, 2023 [3]

With Ryse Energy E – Series Small Wind Turbines with a cut-in speed of 2m/s, the WT can only utilise about 2% wind energy for both 5kW and 10kW, E-5 and E-10 HAWT respectively while 20kW E-20 HAWT can only utilise about 4% wind energy as shown in Figure 2a and 2b, the wind power curve for these WTs [4]. From the wind speed frequency distribution in Figure 2b, it can be seen from Table I that wind is not a suitable renewable energy source for the health centre which shows that the WT will not generate energy for 5,507 hours while only generating less than the minimum health care power demand for 3253 hours of the year 2023.

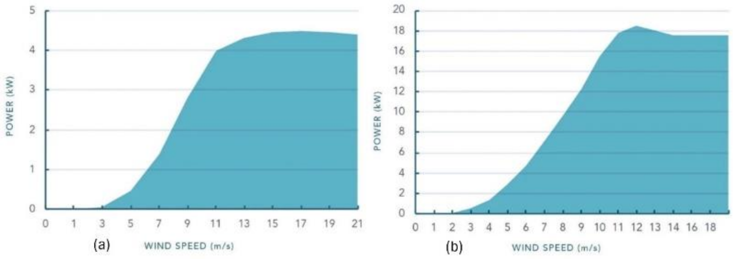

Figure 2: Wind Power Curve for (a) 5kW and 10kW Ryse Energy WTs and (b) 20kW WT [4]

Table I: Wind Power Available for Ryse Energy E - Series WT for Abdu Wind Speed at 50m for 2023 [3]

Average Speed (m/s)	Freq. (h)	5kW WT (kW)	10kW WT (kW)	20kW WT (kW)
0.65	2312	-	-	-
1.47	3195	-	-	-
2.46	2786	0.03	0.14	0.14
3.24	454	0.06	0.31	0.31
4.29	13	0.14	0.73	0.73

B. Solar Energy

There is an average 13 hours daily clear sky at the location under study with a daily irradiance of **6810.09 Wh/m²** for 2023 with an average daily power of **283.75W/m²** [3]. There is enough solar energy to supply health while excess generation during the bright day can be stored in green hydrogen (Fuel Cell Energy Storage) or Battery ESS. The daily irradiance for the location for the year 2023 is given in Figure 3. Solar has so much potential in the location under study which will require a form of storage during no sun-hours per day. However, there is a need to observe the hydro potential before selecting the type of renewable energy resource(s) to be designed for Abdu Health Centre, DRC. With an adequate selection of PV panels to harness this irradiance as presented in Figure 3, solar energy resource is a strong candidate for this design.

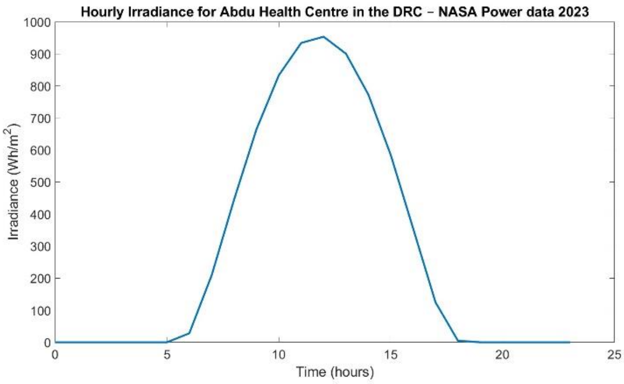

Figure 3: Hourly Irradiance for Abdu Health Centre, DRC [3] [5]

C. Hydro Energy

Hydro has great potential at the health centre location as it is located just at the upper Congo River basin and lower Uele River basin, giving micro-hydroelectric a huge potential which does not require a large construction of a reservoir before the generation of the required health centre electricity demand as will be analysed in the next section. The rainfall amount is shown in Figure 4 for Abdu Health Centre.

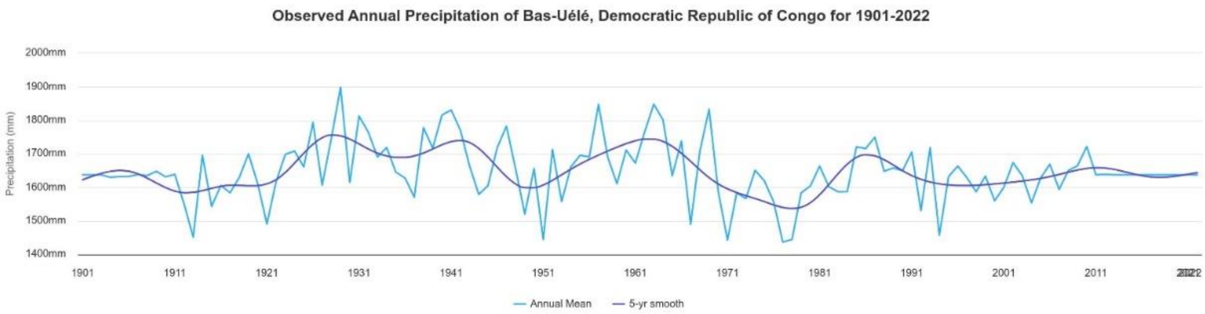

Figure 4: Annual Precipitation for the Health Centre Area from 1901 – 2022 [5]

The annual rainfall from 1991 – 2020 averaged **1501.35mm/year** [5] while rainfall for 2023 is **1932.03mm/year** [3] Table II. The evapotranspiration of the catchment area of Abdu Health Centre is 351.63mm/year [6] [7]. The average flow rate obtained in equation 3 based on the selected catchment area of **150km** as shown in Figure 5 is **7.52m³/s**. The estimated input hydropower is calculated as in equation 4 as **958.66kW**, this gives hydro-renewable energy the best RE resource for this location as this does not require an additional Battery Energy Storage System and will be available throughout the year. Table III shows the comparison between the selected hydropower and solar energy systems.

$$Q = (Rainfall - Evaporation) \times A_{catch} = \frac{(1.93203 - 0.35163) \times 150 \times 1000^2}{365 \times 24 \times 60 \times 60} = 7.52\ m^3/s \ldots\ldots\ldots (3)$$

$$P_{in} = \rho Q g H = 1000 \times 7.52 \times 9.81 \times 13 = 958.66\ kW \ldots\ldots\ldots (4)$$

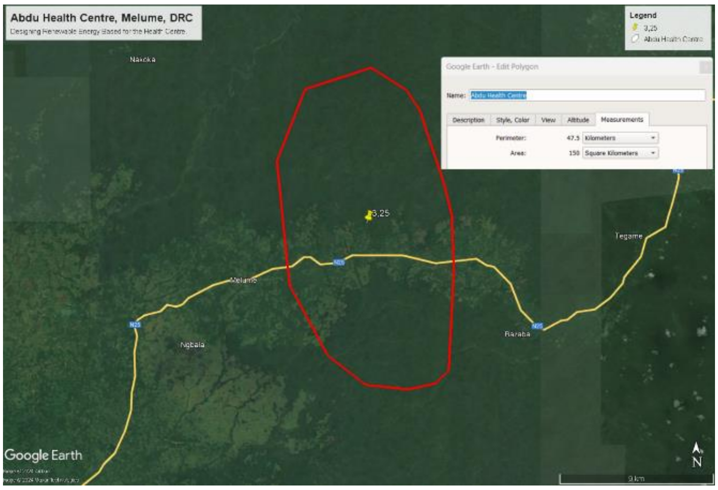

Figure 5: Catchment Area for Abdu Health Centre Hydrology – Google Earth

Table II: The Monthly Rainfall and Evapotranspiration of Abdu, Melume, DRC [3]

mm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain	12.23	17.94	125.39	148.06	126.91	146.39	174.57	189.56	134.03	294.32	427.33	135.3
Evap	30.88	31.50	30.81	24.80	35.23	24.57	33.41	30.32	25.42	24.52	29.46	30.71

Table III: Hydropower vs Solar Energy System

RE Resources	Land	Cost	Battery Storage	Availability	Green	Maintenance
Hydropower	<	>	<<<	>>>>	>>>>	>>
PV Solar	>>>>	>>>>	>>>>	>>	>>>	>

II. ENERGY CONVERSION

According to Table III, the Hydropower system is the best source of supply to the clinic based on the justifications and rationale given in Section I. The design outlines of this hydropower system will be discussed here, and the Solar PV system will also be designed as an alternative electricity supply system.

A. Design Outline of Hydropower System

The monthly mean rainfall in mm/month for 2023 is given in Table II. The peak power demand of the health centre is 3kW which is the range of a Pico/Micro hydro system. The block diagram of the energy conversion system is given in Figure 6.

Figure 6: Hydropower System Block Diagram

To account for conversion losses as shown in Figure 6, a 5kW turbine is selected for this project. The different flow rate on a different net Head is calculated for different turbine power from 3kW to 6kW in Table IV.

Table IV: Flow Rates for different Head of Turbine Input Power

P (W)	3000	4000	5000	6000
H (m)	Q (m3/s)			
5	0.061	0.082	0.102	0.122
10	0.031	0.041	0.051	0.061
15	0.020	0.027	0.034	0.041
20	0.015	0.020	0.025	0.031

25	0.012	0.016	0.020	0.024
30	0.010	0.014	0.017	0.020
35	0.009	0.012	0.015	0.017
40	0.008	0.010	0.013	0.015
45	0.007	0.009	0.011	0.014
50	0.006	0.008	0.010	0.012

For a 5kW hydro turbine, the design outlines are:

- The rated net head is 20m and the flow rate at this head is 0.025m^3/s.
- Jet velocity: $v_j = k_v\sqrt{2gH} = 0.96 \times \sqrt{2 \times 9.81 \times 20} = 19.017m/s$ where k_v is the nozzle coefficient with a value of 0.96 – 0.98 [8] [9]
- Jet diameter: $d = \sqrt{\frac{4Q}{\pi v_j}} = \sqrt{\frac{4\times0.025}{\pi\times19.017}} \times 1000 = 41.307mm$
- Peripheral velocity: $v_u = k_u\sqrt{2gH} = 0.45 \times \sqrt{2 \times 9.81 \times 20} = 8.914m/s$ where k_u is the coefficient with a value of 0.45 – 0.49 [8]
- Turbine speed: $\omega = \frac{\omega_s(gH)^{\frac{4}{5}}}{\sqrt{P/\rho}} = \frac{0.239\times(9.81\times20)^{4/5}}{\sqrt{\frac{5000}{1000}}} = 78.5rad/s$ or $N_s = 78.5 \times \frac{60}{2\pi} = 750rpm$
- Pitch cycle diameter: $D = \frac{60v_u i}{\pi N_s} = 60 \times 8.914 \times \frac{1}{\pi\times750} = 226.993mm$
- Approximate number of buckets: $z = \frac{D\pi}{2d} = 226.993 \times \frac{\pi}{2\times41.307} = 6.632$ since the minimum number of buckets is 16 [8] [9], therefore four jets are designed for this project with each discharging 1/4th of the Q
- Each jet diameter: $d = \sqrt{\frac{4Q}{\pi v_j}} = \sqrt{\frac{4\times0.0125/3}{\pi\times19.017}} = 20.456mm$
- Bucket: width $b = 2.9d = 59.62mm$; bucket height $h = 2.22d = 45.41mm$; depth $t = 0.9d = 18.4mm$
- Outside diameter of runner: $D_{out} = D + 1.2h = 226.993 + 1.2 \times 63.966 = 281.485mm$
- Approximate number of buckets: $z = \frac{D\pi}{2d} = \frac{226.993\pi}{2\times23.621} = 18$
- Assumed efficiency of pipe = 94%, turbine = 80%, generator = 92%: $\eta = \eta_{pipe} \times \eta_{turbine} \times \eta_{gen} = 0.94 \times 0.8 \times 0.92 = 0.6918\ or\ 69.18\%$
- Output power: $P_{out} = \rho QgH\eta = 1000 \times 0.025 \times 9.81 \times 20 \times 0.6918 = 3393.279W\ or\ 3.4kW$
- Daily Energy: $E = P_{out} \times 24hours = 3393.279 \times 24 = 81.439kWh$. from equation (2), the daily energy required is 48kWh, therefore this single design is sufficient to supply the health centre's daily energy requirement.

B. Energy Storage Equipment and Backup (Redundancy)

This installation provides a redundant system as a backup should one of the generators be faulty or need maintenance the other kick start without the loss of supply to the health centre. Although there is the Congo River (the longest river in the world) and river Uele close to the health centre which will provide year-on-year enough water to supply the health centre's electricity requirement, i.e. there will never be a shortage of water to power the hydro turbine. However, a 60-day storage backup reservoir is designed for January and February where the amount of rainfall is less than the evaporation as shown in Table II.

From equation (1) input power to the turbine can be calculated, and then the flow rate at that power is calculated,

$$P_{in} = \frac{D_{av}}{\eta} = \frac{2000}{0.6918} = 2891.009\ W$$

$$Q = \frac{P_{in}}{\rho gH} = \frac{2891.009}{1000 \times 9.81 \times 20} = 0.0147m^3/s$$

The volume of reservoir/tanks required is

$$V = Qt = 0.0147 \times 60 \times 60 \times 24 \times 60 = 76386.291\ m^3 \ldots\ldots\ldots (5)$$

A storage reservoir/tank of **7.64×10^{7}L** of water will be required as energy storage equipment which is completely green as it can be stored for a long time without degradation or the need for an alternate conversion chain as in Figure 6 (main conversion block) as compared to Battery Energy Storage Systems.

C. Solar Energy Systems – Option B

An LG NeON2, model LG350N1C-V5 is selected for this design with electrical properties given in Figure 7 and the datasheet is [10]. The daily energy produced by a PV panel with an area of 1.71m^2 [10] and the minimum number of PV panels required to produce the energy required in equation (2) is obtained as follows.

$$E_{PV} = Daily\ Irradiance \times 20.4\% = 1.39\ kWh/m^2$$

From Figure 3 from [3] has an average daily 8 sun-hours just enough to meet the minimum demand at that sun-hour for the year 2023, a 14-hour daily storage energy will be required. Then an additional 70% of solar energy will be required to charge the storage system to ensure a constant supply of power after daily sun-hour. The total PV panels area is.

$$PV_{area} = \frac{1.7E_{day}}{E_{PV}} = 1.7 \times \frac{48}{1.39} = 58.74m^2$$

The minimum number of PV panels required to meet energy demand and minimum charging requirements is.

$$PV_{no} = \frac{PV_{area}}{1.71} = 35\ panels$$

The total amount of daily energy production from the PV panels is given below while Figure 8 shows the graph of this energy and daily health centre demand.

$$E_{PVtotal} = PV_{no} \times E_{PV} = 35 \times 1.39 = 48.624\ kWh$$

The minimum storage energy is calculated by integrating the power demand curve in Figure 8 where PV power is less than the demand. This iteration was implemented on MATLAB code and can be found in Appendix I. Figure 9 shows the state of charge of the proposed energy storage over an average day.

$$E_{storage\_min} = \sum_{i=0}^{23} P_{PV_i} - D_i = 14.16\ kWh$$

Electrical Properties (STC*)

Model		LG350N1C-V5	LG345N1C-V5
Maximum Power (Pmax)	[W]	350	345
MPP Voltage (Vmpp)	[V]	35.3	34.9
MPP Current (Impp)	[A]	9.92	9.89
Open Circuit Voltage(Voc, ± 5%)	[V]	41.3	41.2
Short Circuit Current(Isc, ± 5%)	[A]	10.61	10.57
Module Efficiency	[%]	20.4	20.1
Power Tolerance	[%]	0 ~ +3	

* STC (Standard Test Condition): Irradiance 1000 W/m², Cell temperature 25 °C, AM 1.5

** Measurement Tolerance : ± 3%

Figure 7: Electrical Properties of LG NeON2 [10]

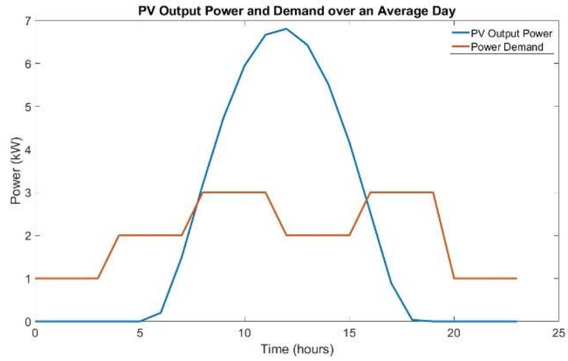

Figure 8: Daily Demand and Daily PV Power

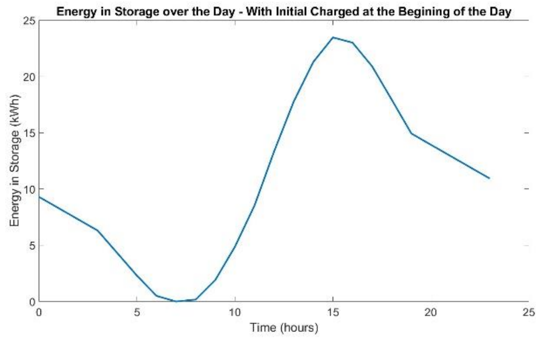

Figure 9: Charge and Discharge Cycle of the Energy Storage

Three sets of 5.12kWh rack-mounting Lithium-ion batteries from V-TAC [11] will be required which will be connected in series to give a total of **15.36kWh** storage capacity. For this location of the health centre, there is always sunlight according to [3] [5] then an additional day of battery autonomy is added to the total battery storage as **61.44kWh**.

III. COST AND EMISSIONS

A. Expected Costs of Supply Equipment

The cost of equipment for the system and its redundancy is given in Table V [12] [13].

Table V: Cost Estimate of 2x5kW Hydropower System

S/N	Item	Quantity	Price	Cost
1	Turbine	2	€ 3,200.00	€ 6,400.00
2	Induction Generator	2	€ 1,680.00	€ 3,360.00
3	Piping (PVC)	2	€ 2,500.00	€ 5,000.00
4	Intake	2	€ 1,500.00	€ 3,000.00
5	Control	2	€ 1,300.00	€ 2,600.00
6	Powerhouse	2	€ 1,200.00	€ 2,400.00
7	Installation	2	€ 1,600.00	€ 3,200.00
	Total			**€ 25,960.00**

B. Running Costs

The annual electricity energy demand of Abdu Health Centre, Melume, DRC is.

$$E_{annual} = E_{day} \times 365 = 17520\ kWh$$

The estimated operations and maintenance cost is between 1 – 4% of the installation cost [14]. The operational cost (running) is.

$$O\&M\ Cost = 25960 \times 0.04 = €1038.4$$

The lifetime of a typical hydro according to [15] is 25 years minimum, although hydro's from these manufacturers usually last as twice as much but the manufacturer needs to quote a number [15]. The estimated cost of electricity is given as.

$$Cost\ per\ kWh = \frac{Total\ Installation\ Cost + O\&M\ Cost}{E_{annual} \times 25} = €\ 0.06/kWh$$

C. Hydropower System vs Diesel Engine Generator and Emissions

Table VI: Hydropower vs Diesel Engine

Condition	Hydropower System	Diesel Engine Set
Size	Large	Small
CO_2 Emission	Very low	Extremely high
Compact	Required loose system e.g. piping	Very compact
Cost	€ 25,960.00	€ 1,800.00
Noise	Low	High
Installation cost	High	Low
Maintenance	Less	Very frequent
Running Cost	Low	Very High
Durability	Very High	Low
Lifetime	Decades of usages	A few years

An MSW MSW-AVR 5000S EURO5 Diesel generator 5000 W 16 L 240/400 V mobil AVR Euro 5 Power generator Portable power station [12] with 8 hours of operation time with 16 litres of diesel.

$$Dail\ Diesel\ Consumption = \frac{24}{8} \times 16 = 48\ litres$$

$$Vol_{annual} = 48 \times 365 = 17520\ litres$$

- CO_2 emission per litre is 2.55kgCO_2/litre [16]. The annual CO_2 emission for the diesel generator is.

$$CO_2\ Emission\ of\ Diesel\ Genset = Vol_{annual} \times Emission\ per\ litre = 17520 \times 2.55 = 44676kgCO_2/year$$

- According to [17], small run-of-river plants emit between 0.004536-0.01361kgCO_2/kWh, because this is a micro hydro and would most likely emit far below the starting value of this range, 0.013616kgCO_2/kWh was chosen on a worst-case scenario.

- Then, the emission of this hydropower design is calculated as follows.

$$CO_2\ Emission\ of\ Hydro = E_{annual} \times emission\ per\ kWh = 17520 \times 0.01361 = 238.408\ kgCO_2/year$$

- Therefore, the CO_2 savings by the use of Hydropower system renewable energy is.

$$CO_2\ Savings = Emission\ of\ Diesel\ Genset - Emission\ of\ Hydro = 44676 - 238.408 = 44437.591kgCO_2/year$$

- Percentage of CO_2 emission savings is.

$$\%CO_2\ Savings = \frac{44437.591}{44676} \times 100\% = 99.47\%$$

IV. CONCLUSION

This report explained and designed two renewable energy systems (Hydro and Solar) both providing sustainable energy to Abdul Health Centre. However, hydropower systems are more promising as they require less infrastructure to be installed with enough energy to supply the health centre from a completely renewable energy source without additional BESS. This report also demonstrates savings of 99% of CO_2 emissions this is in line with the global fight on greenhouse gas emissions.

Figure 10: A Realtime Completed Installation of a 5kW Hydro Power System

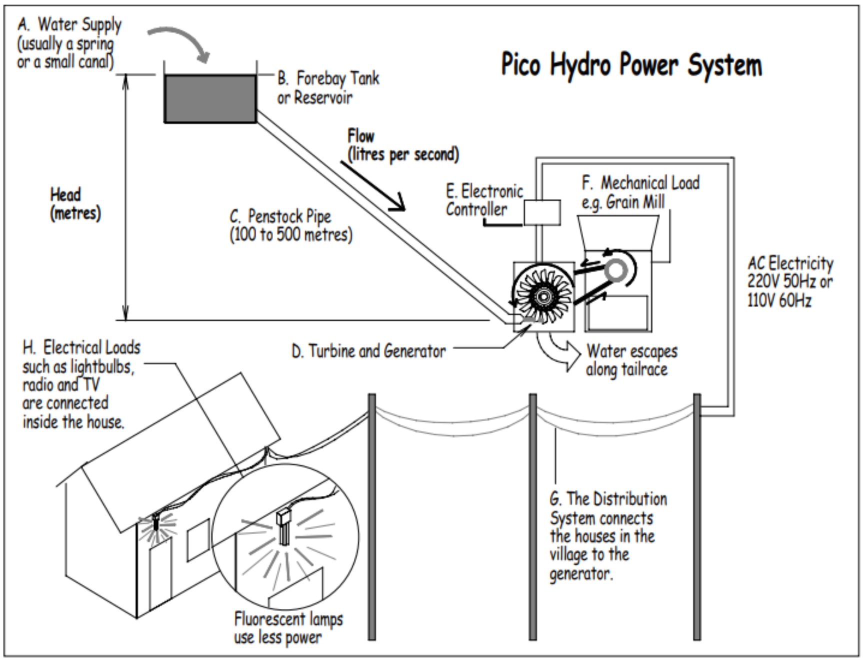

Figure 11: Schematic Diagram of a Pico/Micro Hydro Power Systems

REFERENCES

[1] T. G. Goals, *The Global Goals,* The Global Goals, 2015.

[2] D. A. WALKER, Writer, *Renewable Energy Technologies Coursework II.* [Performance]. University of Nottingham, 2024.

[3] NASA, "POWER | Data Access Viewer," 2024. [Online]. Available: https://power.larc.nasa.gov/data-access-viewer/.

[4] *Ryse Energy.* [Film]. United Kingdom: Ryse Energy, 2024.

[5] World Bank, "Climate Change Knowledge Portal," World Bank, [Online]. Available: https://climateknowledgeportal.worldbank.org/country/congo-dem-rep/climate-data-historical#:~:text=In%20the%20equatorial%20climate%20zone,mm%20and%202%2C000%20mm%20annually.. [Accessed 03 04 2024].

[6] ORNL DAAC, "Fixed Sites Subsetting and Visualization Tool," NASA. [Online]. [Accessed 03 04 2024].

[7] M. Q. Z. M. S. Running, "MOD16A2 MODIS/Terra Net Evapotranspiration 8-Day L4 Global 500m SIN Grid," NASA, 2021. [Online]. [Accessed 03 04 2024].

[8] M. Eisenring, Harnessing Water Power on a Small Scale - Micro Pelton Turbines, Niederuzwil, Switzerland: SKAT, Swiss Center for Appropriate Technology, 1991.

[9] K. Batinic, D. Golubovic, S. Simic and G. Orasann, "Design of Pico Hydropower Plants for Rural Electrification," *Springer International Publishing, AG,* pp. 397-404, 2019.

[10] LG, "LG Electronics," 2019. [Online]. Available: https://www.lg.com/global/business/download/resources/solar/Neon_2_60_BF_90812.pdf. [Accessed 29 February 2024].

[11] HDM Solar, "HDM Solar," HDM Solar, 2024. [Online]. Available: https://www.hdmsolar.co.uk/products/v-tac-5kwh-rack-mounting-lithium-ion-battery-vt-48100e-p2?currency=GBP&utm_medium=cpc&utm_source=google&utm_campaign=Google%20Shopping&stkn=bb077d4b3705&srsltid=AfmBOop3-dWc0SAz4GTwT3MlMeASrEdaLh5CtUgiz00ATd_R9doKMexJFt. [Accessed 06 March 2024].

[12] Amazon, "Amazon," [Online]. Available: https://www.amazon.co.uk/Horizontal-Hydroelectric-Generator-Voltmeter-Generators/dp/B0CRDQG7CH/ref=sr_1_6?dib=eyJ2IjoiMSJ9.2RRJxLc3EM0GpidPwdgktWTUfoPcuWKTa5466U8LyVpABdzVMa7f43E49xAcX7x_H-jH0STwzDbA3QY9dFyHHz7ZZmCIcQju7yyqIlnS41qpNWJb5fOgQxvyScOMNsBkVeuo. [Accessed 30 04 2024].

[13] Suneco Hydro, "How Much Does a 5kw Hydro Turbine Cost?," [Online]. Available: https://www.sunecohydro.com/how-much-does-a-5kw-hydro-turbine-cost/. [Accessed 13 04 2024].

[14] The International Renewable Energy Agency (IRENA), "RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES," *The International Renewable Energy Agency (IRENA),* vol. 1: Power Sector, no. 3/5, 2012.

[15] RenewableFirst, “How long do hydropower installations last?,” [Online]. Available: https://renewablesfirst.co.uk/renewable-energy-technologies/hydropower/hydropower-learning-centreold/how-long-will-hydropower-systems-last/. [Accessed 27 04 2024].

[16] A. Q. Jakhrani, A. R. H. Rigit, A.-K. Othman, S. R. Samo and S. A. Kamboh, “Estimation of carbon footprints from diesel generator emissions,” in *IEEE - 2012 International Conference on Green and Ubiquitous Technology*, Bandung, Indonesia, 2012.

[17] J. Richardson and R. Burdett-Gardiner, “Renewable Energy Hub,” 21 April 2023. [Online]. Available: https://www.renewableenergyhub.co.uk/main/hydroelectricity-information/environmental-impact-of-hydroelectricity. [Accessed 30 April 2024].

APPENDIX – MATLAB CODE FOR SOLAR DESIGN

```
clc;
% EEEE4121: Renewable Energy Technology- Coursework2
% Author: Abdulazeez Adebayo Olayinka
% Student ID: 20626477
% Program: Sustainable Transportation and Electrical Power Systems
% Last Modified: 09 - 04 - 2024
fprintf('Coursework 2 - Off Grid Power Solution for a Rural Health Center\n\n')
t = 0:23;
D = zeros(size(t));
E = zeros(size(t));
for i = 1:length(t)
    if t(i) < 4
        D(i) = 1;
        E(i) = E(i) + D(i);
    elseif t(i) < 8
        D(i) = 2;
        E(i) = E(i) + D(i);
    elseif t(i) < 12
        D(i) = 3;
        E(i) = E(i) + D(i);
    elseif t(i) < 16
        D(i) = 2;
        E(i) = E(i) + D(i);
    elseif t(i) < 20
        D(i) = 3;
        E(i) = E(i) + D(i);
    else
        D(i) = 1;
        E(i) = E(i) + D(i);
    end
end
%fprintf('Load Demand\\hour = %.2f kW\n', P)
Pavg = mean(D); %kW
E_daily = sum(E); %kWh
fprintf('Average Daily Demand = %.2f kW\n', Pavg)
fprintf('Daily Energy = %.2f kWh\n', E_daily)

%Solar PV Option
fprintf('PV Solar System Option\n\n')
%LG NeON 350W PV Panel Datasheet
Vmpp = 35.3; % V
Pmax = 350; % W
Impp = 9.92; % A
Voc = 41.3; % V
Isc = 10.61; % A
efficiency = 20.4/100; % in percentage
PVArea = (1686/1000)*(1016/1000);
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fprintf('Area of a PV Panel = %.2f m^2\n',PVArea)

%Irradiance, PV Energy and Number
Irradiance = [0 0 0 0 0 0 28.03847761 209.1564776 445.1782388 664.4200299 833.2702687
934.0622985 953.4313134 900.4069552 772.8469552 584.401791 355.1335522 124.7290746
5.012985075 0 0 0 0 0];%Wh/m^2
PV_Panel_Energy = sum(Irradiance) * efficiency / 1000; %A Panel energy generated in kWh/m^2
PV_CoverageArea = E_daily * 1.7 / PV_Panel_Energy; %PV Panel area required in m^2
PV_no = ceil(PV_CoverageArea / PVArea); %number of PV Panel required to meet energy demand
of 66.667% more of the demand to be able to have minimum energy in storage
fprintf('A PV Panel Energy = %.2f kWh/m^2\n',PV_Panel_Energy)
fprintf('Area of PV Panels = %.2f m^2\n',PV_CoverageArea)
fprintf('Number of PV Panels Required = %d\n',PV_no)
PVIrrad = Irradiance .* efficiency / 1000;
PVPout = PVIrrad .* PV_no; %Total PV Power/Energy
E_PV = sum(PVPout);
fprintf('Total Daily PV Energy = %.3f\n',E_PV)

%Hourly Irradiance Plot
figure
plot(t, Irradiance,"LineWidth",3)
xlabel('Time (hours)','FontSize',24);
ylabel('Irradiance (Wh/m^2)','FontSize',24);
title('Hourly Irradiance for Abdu Health Centre in the DRC – NASA Power data
2023','FontSize',24);

% Plot PV power and demand
figure;
plot(t, PVPout, t, D,"LineWidth",3);
xlabel('Time (hours)','FontSize',24);
ylabel('Power (kW)','FontSize',24);
legend('PV Output Power', 'Power Demand');
title('PV Output Power and Demand over an Average Day','FontSize',24);

%storage, net power, storage input and output power
Storage = zeros(size(t));
Max_Storage = 0;
Net_Power = zeros(size(t));
Input_Power = zeros(size(t));
Output_Power = zeros(size(t));
for i = 2:length(t)
    Net_Power(i) = PVPout(i) - D(i);
    Storage(i) = Storage(i - 1) + Net_Power(i);
    Max_Storage = max(Max_Storage, abs(Storage(i)));
    Input_Power(i) = max(Net_Power(i), 0);
    Output_Power(i) = max(-Net_Power(i), 0);
end

fprintf('   Minimum Energy Storage Capacity: %.2f kWh\n', Max_Storage);
fprintf('   Input Power Rating: %.2f kW\n', max(Input_Power));
fprintf('   Output Power Rating: %.2f kW\n\n', max(Output_Power));

% Plot energy in storage - Charge and discharge: Negative discharging while positive is
charging
figure;
plot(t, Storage,"LineWidth",3);
xlabel('Time (hours)','FontSize',24);
ylabel('Energy in Storage (kWh)','FontSize',24);
title('Energy in Storage over the Day - Charge and Discharge','FontSize',24);

% Adjusting the initial energy in store to not crossover to negative
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```
Storage_NonNegative = zeros(size(t));
Storage_NonNegative(1) = abs(min(Storage)); %considering the initial energy
for i = 2:length(t)
    Storage_NonNegative(i) = max(Storage_NonNegative(i - 1) + Net_Power(i), 0);
end

% Plot energy in storage with 100% roundtrip efficiency of the storage with maximum
discharged value
figure;
plot(t, Storage_NonNegative,"LineWidth",3);
xlabel('Time (hours)','FontSize',24);
ylabel('Energy in Storage (kWh)','FontSize',24);
title('Energy in Storage over the Day - With Initial Charged at the Begining of the
Day','FontSize',24);
```