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DESIGN METHODOLOGY OF A HYBRID RENEWABLE ENERGY MICROGRID FOR AN ISOLATED RURAL COMMUNITY. APPLICATION CASE IN ZAMBIA

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ABSTRACT:

This article proposes a methodology for designing off-grid electricity systems based on renewable energies in rural communities of developing countries that never consumed electricity.

The state of the art is reviewed and the methodology aggregates proposals from multiple previous works. It is divided into phases: Data Collection, Assessment, Planning/Modelling, and Execution. The main actors and their responsibilities are explained. Rarely considered stages such as co-design with the beneficiary community or the creation of a renewable energy community are included.

The application of the methodology is illustrated with the first results from a case study in Mumbeji, Zambia, Africa. The project stakeholders, the results of demand curve estimation, power generation curves, available resources, engineering costs, and microgrid design modeling are presented.

Keywords: *Hybrid renewable energy systems; Rural electrification; Off-grid rural communities.*

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1. INTRODUCTION

There are different ways of supplying electricity to remote areas, these can be classified as Grid extension, Off-grid, and a combination of both. Off-grid normally includes Stand-Alone Power Systems (SAPS) and/or Hybrid Renewable Energy Systems (HRES). Grid extensions are not always viable due to long connection distances, low population density, and low ability to pay for the nonelectrified population. SAPS are mostly limited to one household/institution, while HRES are often the optimal solution for electrifying areas with some concentration of people and energy uses [1]. The literature review did not yield any publications on HRES design methodology for rural communities isolated from the electricity grid, that never consumed electricity in developing countries. Various publications on HRES simulation have been found see Table 1. However, few of the documents reviewed holistically address the project in all its complexity. The table includes activities that are poorly covered such as i) the integration and active participation of the beneficiaries in the different stages of the project, ii) the description of the actors and their responsibilities, or, very importantly, iii) a program of affordable tariffs for the community (see more in [2], [3]).

All reviewed references propose how to size HRES using different tools and methods1, with some authors using a combination of tools to complement their simulations and optimisations [4], [5]. For the problem of not having a previous electricity consumption pattern, most proposals include a deterministic model to forecast the demand curve (FDC, read more in [6]). To power the HRES, solar photovoltaic power (PV) is the preferred technology (used in almost all case studies), while hydro turbines (HT) are used as the baseline technology in some projects. The HT productivity can vary appreciably depending on several factors such as distance to loads and local natural resources [7]. Wind turbines (WT) are the second most chosen technology due to their maturity and performance [8], [9]. Biomass (BM) is highly recommended to replace diesel generators (DG) as a backup system if there are enough local natural resources (wet or dry biomass) [10].

Regarding storage capacities, battery energy systems (BES) are included in most off-grid HRES cases due to their important role in improving the performance of the entire system [11]. The kind of energy storage system preferred is related to the size of the amount of energy demand: electrochemical batteries are associated with small and medium systems, while pumped storage seems to be suitable for large systems [12].

The aim of this research is to propose an HRES design methodology for off-grid rural communities that have never consumed electricity in developing countries. The main innovation, in addition to addressing the difficulties of such contexts, is completing previous proposals with: holistic concept of energy supply, co-design with the beneficiaries and creation of a renewable energy community. To the knowledge of the authors, neither the few publications on HRES design methodologies, nor the abundant publications on HRES simulation and optimization, have such an up-to-date and complete proposal. To illustrate the application of the methodology, a case study in Mumbeji, Zambia is presented.

2. - METHODOLOGY

The methodology, as can be seen in Figure 1, is arranged in a matrix of 4 columns indicating the stages, and 3 rows showing the leading actors.

2.1. BASE LINE AND ANALYSIS OF THE ACCESS TO ELECTRICITY.

All projects must start by establishing the baseline situation of the community and whether it is ready for the efforts and the profound transformation that the arrival of electricity will bring. This work is the responsibility of the stakeholders, usually the beneficiaries together with one or more external agents who start the analysis process: public officers and non-profit organizations, among others.

A multi-tier framework assessment is performed to classify the current access to electricity, determining if the community has access to electricity in terms of power and quantity, its availability during the day, frequency of disruption, voltage problems, affordability (% of household's incomes), ways of payments and health and safety [27]. A target of ensuring "Tier 3 or more" access should be set to achieve a meaningful development outcome (see box 2 of page 6 in [27]).

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[1] Tools and methods: GA (Genetic Algorithm), PSO (Particle Swarm Optimization), PIO (Piegon Inspired Algorithm), Homer (Hybrid Optimization Of Multiple Energy Resources), ANNBP (Artificial Neural Network), LM (Levenberg-Marguardt), DDSM (Monte-Carlo Simulation), SO (Stochastic Optimization), MD (Mathematical Definition), GWO (Grey Wolf Optimizer), AOA (Arithmetic Optimization Algorithm), WHO (Wild Horse Optimizer).

Table 1 Literature review

Ref	Tools	Actors Tasks	Base Line.	Initial Assess	Community Integration	Stochastic FDC	Type Sol.	Simu-lation	Optimi zation	Sensitivity Analysis	Project Viability	Tariff Program	Execu tion	Control/ Monitoring
[13]	Homer		✓				✓	✓	✓	✓				
[5]	GA, PSO			✓				✓	✓	✓				
[10]	Homer						✓	✓	✓	✓				
[14]	Matlab, Simulink	✓	✓					✓	✓	✓				✓
[15]	PSO		✓					✓	✓	✓				
[16]	GA, PSO			✓	✓			✓	✓	✓				
[17]	PIO, Matlab		✓					✓	✓	✓				
[18]	PSO		✓					✓	✓		✓			
[2]	AOA, Homer, Matlab		✓	✓			✓	✓	✓	✓				
[19]	GA, Homer						✓	✓	✓	✓				
[4]	ANNBP, LM, Homer		✓				✓	✓	✓	✓				
[20]	DDSM	✓	✓					✓	✓	✓			✓	
[21]	Matlab, GA		✓					✓	✓	✓				
[22]	Homer						✓	✓	✓	✓				
[23]	Homer			✓			✓	✓	✓	✓				
[24]	MD		✓		✓			✓	✓					✓
[25]	Energy Fuzzy-On		✓					✓	✓	✓	✓			
[11]	GWO, SO, GA, WHO		✓			✓		✓	✓	✓			✓	
[7]	PSO, Homer			✓			✓	✓	✓	✓				
[9]	Homer		✓			✓	✓	✓	✓	✓		✓		
[8]	RETScreen		✓	✓				✓	✓	✓	✓			✓
[26]	TRNSYS18		✓		✓			✓	✓	✓				

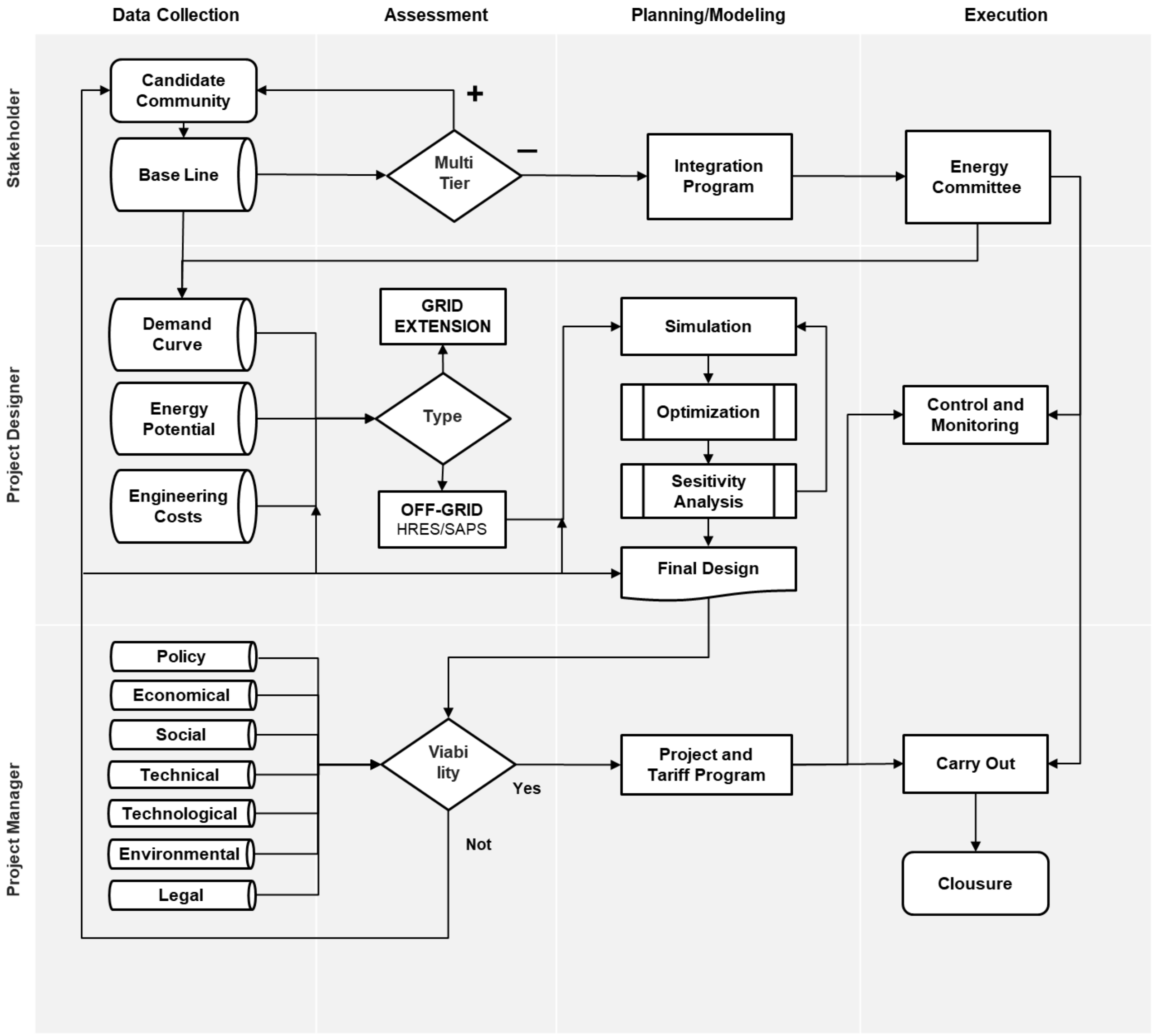

Figure 1 Proposed project design methodology including Actors and Responsibilities

2.2. INTEGRATION PROGRAM AND ENERGY COMMITTEE.

For integrating the technology into the community it is necessary to shorten communication barriers, especially for vulnerable groups. Other key activities are to sensibilize to climate change and gender equality, to educate in economic and administrative management, to train in technical operation and maintenance activities, and to engage them to participate in the construction and start-up of the power plant. One of the expected outcomes is the forming an energy committee capable of responding to any situation.

2.3. ENERGY CHARACTERIZATION AND DATA COLLECTION.

The Project Designer: a team of experts, engineers, etc. lead the data collection, involving fieldwork, literature review and consulting experts and suppliers. The main goals are to determine the FDC, the energy resources potential, and the preliminary engineering costs. For FDC there are two main models, deterministic and stochastic. The first one requires less information and mathematical processing but generates less accurate results.The second consumes more resources but gives more realistic results for correct design. Therefore, both can be useful and can be combined [6].

Also, the availability of natural renewable energy sources is determined, typically: Solar, Eolic, Hydro, and Biomass (dry or wet). The engineering cost include costs of technology, installation on-site, operation & maintenance, replacement, land or building.

2.4. GRID EXTENSIÓN vs OFF-GRID AND OPTIMIZATION OF THE DESIGN.

The Project Designer decides on the type of solution (grid-extension, off-grid, or hybrid) according to key parameters. The design team should also consider multi-criteria decision-making to optimize trade-offs among economic, environmental, institutional, social/ethical, and technical criteria [1], [3], [28]. If an off-grid solution is opted, the project designer chooses between HRES and/or SAPS according to geographical conditions such as climate, vegetation, topography (plain/hilly), population dispertion, etc.

The simulation process starts by adding the input information, setting the system boundaries, and continues with an optimization and sensitivity analysis. An iterative loop process starts modifying the inputs until an optimal output is found..

2.5. OTHER VIABILITY ANALYSIS.

Usually, the project management team performs a technical feasibility analysis. For this, information like the following is considered: regulatory framework and administrative, financial mechanisms, tax exemption, willingness and capacity to pay, social acceptance, changes in the land-use, noise, waste, visual impact, etc. [29]. The viability assessment may influence the process to the point of changing the design, and even the candidate community (feedback mechanism in Figure 1).

2.6. ELECTRICITY TARIFF SYSTEM.

For the operation and maintenance of the HRES, a tariff plan must be included comprising the mode of payment and the frequency. It will depend on the community and its ability to pay. Social inequality and energy poverty should be foreseen in advance. Hourly electricity price discrimination could be applied in the case of installing smart meters in each household. All this should be done by the local energy committee.

2.7. CASE STUDY

This case study aims to illustrate the application of the methodology to an on going project. The HRES to be designed will electrify an off-grid rural community in Mumbeji, Zambia. The overall access to electricity is 6% in rural areas [30]. The rural community of Mumbeji is located to the North-West of Zambia, in one of thirteen wards of the Kabompo district. Based on their participation in the project tasks, the number of beneficiaries and households was finally set at 144 households in 8 nodes and 13 clusters (see figure 5), for a total 778 inhabitants..

3.RESULTS

The main results of the application of the methodology are presented below.

3.1. BASE LINE

Currently, there is no electricity in the community and households cope with the situation by using candles, kerosene lamps, or dry-cell-battery-powered devices (flashlights or radios). This means a “Tier-0” classification according to the multi-tier framework [27], that has to be imporved to Tier-3.

The local stakeholders are manyfold, but the main ones are: i) the neighborhood association, ii) the local development agent in Solwezi (regional capital), iii) a representative of the Rural Electrification Authority (REA), iv) the non-profit organization Joint Country Programme Zambia, and v) an electrical company in Kabompo (the nearest town).

3.2. INTEGRATION OF THE PROJECT, ENERGY COMMITTEE.

The community is to have an energy committee (EC) incorporating the women who have been most involved in its implementation. The EC is to be trained in the administration and management of tariff setting, i.e.wether payment will be in i) Kwacha, the local currency, ii) in working hours or iii) in species (kg of cassava residue). Also, the EC sets the electricity price, charges for electricity consumption, calculates the depreciation of equipment and saves money for repairs and replacements. Four young men and women are to be trained in the operation and maintenance of the power plant and the electricity grid. Kabompo's electrical company is familiar with the project and will be involved in the physical implementation.

3.3. DEMAND CURVE

To forecast the demand, a deterministic model was initially chosen [6]. The community’s demand was divided into household demand, community demand, and commercial demand. Calculations of the number of units per household (HH), average wattage per device, and total wattage can be seen in Table 2. Also the aggregated hourly profile of the domestic load curve was determined, see Figure 2. As a result, the daily expected electricity consumption per household is 1.52 kWh, and the total domestic demand is 219.04 kWh/day.

Household Consumption	Units per HH	Total Units	Power (W)	Total power (W)
Lighting	3.00	432.0	20	8,640
TV	0.3	43.2	150	6,480
Radio	0.75	108.0	20	2,160
Phone	2.00	288.0	10	2,880
Fan	0.40	57.6	50	2,880
Fridge	0.05	7.2	180	1,296
DVD player	0.10	14.4	43	619
Internet routers	1.00	144.0	6	864
Computer and laptops	0.30	43.2	175	7,560
Other appliances	0.05	7.2	1,600	11,520

Table 2 household consumption

The communal buildings or services include one school, a health care center, a church, and a town/police office. In addition, it was assumed 3 street lights for each of the 13 residential clusters, 39 street lights in total. A load of a wood chipper for the gasifier is also included. The aggregated communal demand is calculated based on similar buildings and their foreseen activity, amounting to 67.67 kWh/day.

The community has two general stores and two food shops stores with electric appliances. The total demand of electricity for commerce is thus 17.39 kWh/day. Figure 2 shows the three demand profiles and the resulting total demand.

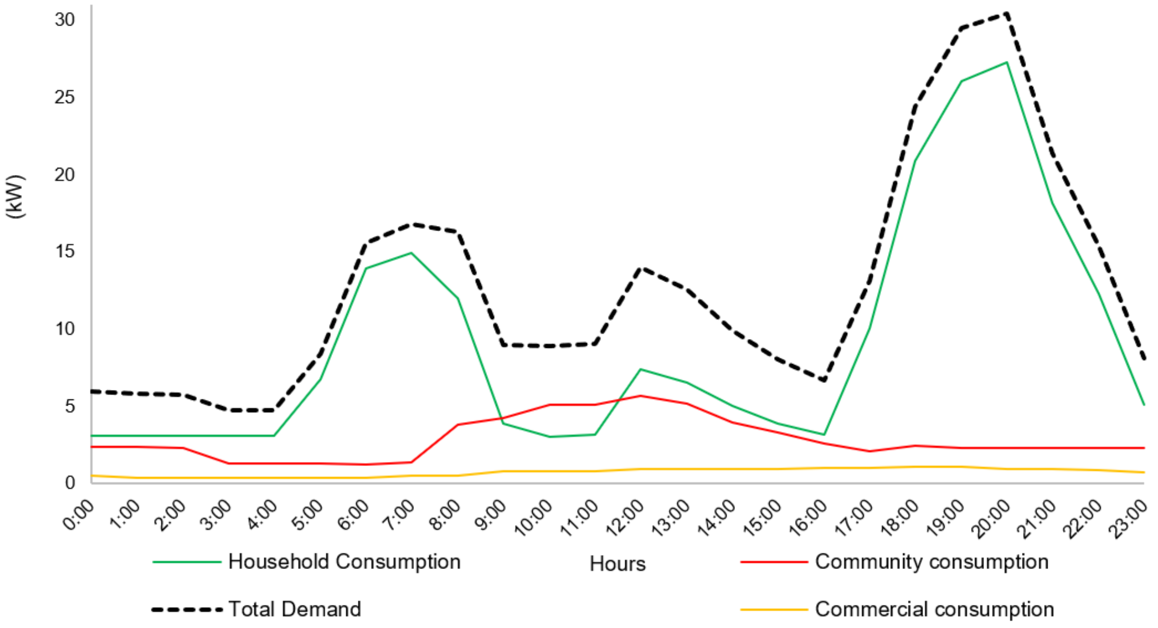

Figure 2 total community demand load in Mumbeji's community.

3.4. GRID EXTENSION vs OFF-GRID.

The community is located 140 km away from the nearest electric grid. A study showed the electric distance limit (EDL) for a stand-alone generation system to be preferred to connecting to the grid resulted in if the power system is for biomass 82.0 km, and 92.7 km for PV [1], [31]. The population is relatively concentrated in housing nodes and clusters within 200 m of each other (see figure 5).

Based on the above, it is decided that a HRES is more economically and environmentally efficient than a SAPS, or connecting to the grid.

3.5. LOCAL, RENEWABLE AND CLEAN ENERGETIC RESOURCES

At the Mumbeji location, there is a great potential for solar energy, around 5.5 kWh/m2/day. There is a creek running alongside the community but it is dry in the long hot season and it has been discarded. Wind power is not good either, with the average annual wind speed being 3.2 m/s at 10 m height [30], [31].

Cassava waste is a suitable option for biomass, as it represents approximately 60% of the agricultural yields and does not require additional land use. In addition, cassava has a lower heating value of around 16 MJ/kg [32]. The available biomass in Mumbeji fluctuates with an annual average of 0.365 tonnes per day [30], [31]. The final dry biomass potential is 0.13 ton/day based on data regarding the ratio of the waste to useful crop: 36% according to [32], [33].

Since solar energy is highly intermittent it is necessary to add electricity storage to the system to be able to meet the demand. Lead-acid batteries were chosen for this project because they are the most common and economically competitive option for off-grid applications in developing countries.

3.6.ENGINEERING COSTS

The main engineering costs are the following. Capital costs include transport, installation, etc, and are based on local suppliers and the literature [30], [31], [34]:

- PV modules 3 USD/Wp
- Batteries: 10.55 USD/kWh
- Iverters and other electronic equipment: 2.2 USD/Wp .
- Gasifier is 2 USD/Wp
- Grid extension (as an alternative): 6,000 USD/km

In every case, the replacement cost was estimated to be 10% lower than capital costs. The annual operation and maintenance (O&M) cost is 1% of capital costs, except for the gasifier, which is 0.18 USD/hr based on the manufacturer's data (All Power Labs). The biomass feedstock cost is set at 50 USD/ton from local sources. For grid extension, O&M cost is 160 USD/km/year. The grid electricity price is heavily subsidized (households: 0,027 USD/kWh if less than 100 kWh/month, as in this case, business: 0.042 USD/kWh) [31], [35]

3.7.SIMULATION, OPTIMIZATION AND SENSITIVITY ANALYSIS

HOMER Pro® was chosen, the simulations were done by first introducing the data obtained from the fieldwork and the literature. This resulted in a first model of the HRES that was further evaluated, optimized, and modified by sensitivity analyses. For optimisation, Homer calculates all possible combinations of equipment in the system, increasing or decreasing their power at predefined intervals. For all these alternative systems it calculates the key performance indicators (KPIs) in this case: annual energy generation per component, net present cost (NPC), levelized cost of energy (LCOE), maximum annual capacity shortage (MACS), and annual GHG emissions.

3.7.1. Input data

The main input data were load curves, solar radiation (from PVGIS-SARAH®) and biomass production, as well as the characteristics of the equipment.

- PV panels: lifetime 25 years, derating factor 85%, slope 13.89º the same as the latitude, azimuth of 180º to face North, ground reflectance 20%, and overall efficiency 15.8%.
- Batteries: 1,500 Ah/unit, capacity 3 kWh per set, lifespan 1,500 life cycles, nominal voltage 2 V, 24 batteries in each string of 48 V per string.

In addition, a procedure for enabling gasifiers simulation in HOMER was followed [36]. The downdraft gasifier with a capacity of 25 kW was chosen. The fuel consumption is 1.2 kg biomass per kWh of generated electricity. The minimum load ratio is 20%. The lower heating value of syngas is 4 MJ/kg. Other technical parameters included the schedule of the gasifier, the dispatch strategy, maintenance requirements, etc.

3.7.2. System simulation, optimization and sensitivity analysis

If all the KPIs have to be minimum, except the generated energy, the optimized HRES for the community in Mumbeji has to have 80 kW of PV panels, a 25 kW gasifier, 120 batteries of 3 kWh each, for a total capacity storage of 360 kWh, one inverter of 80 kW, a multicluster box and 6 smart grid managers of 10kW each. Figure 3 shows the power plant configuration in AC-coupling.

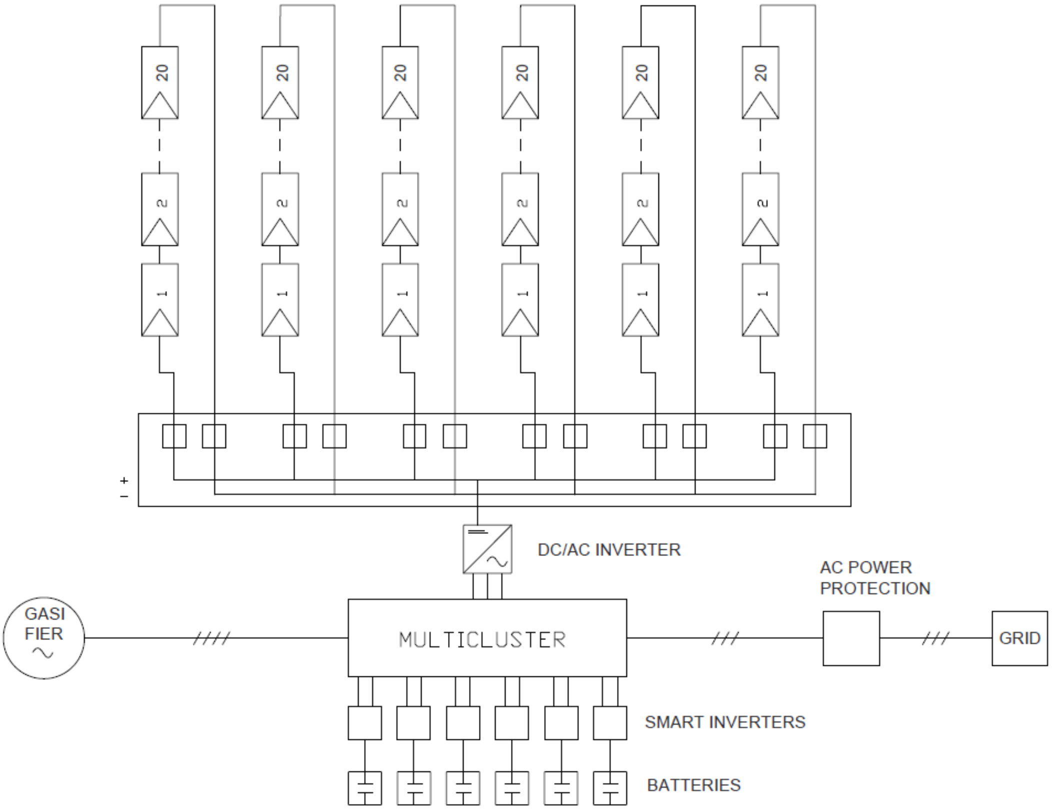

Figure 3 System design based on the optimization results

On the other hand, Homer provides the performance results like the rated power/capacity of the components, the NPC, LCOE, emissions, hourly performance data, etc. The sentivity analysis to obtain this final configuration included changing the dispatch strategy from cycle charging to following the load, which was selected. Also to run the simulation & optimization varying up and down:

1. The electricity demand by a 20%
2. The availability of biomass for the gasifier by a 50%
3. Equipmen costs by 20%
4. Equipment durability, by 20%.

3.7.3. Performance of the Hybrid Renewable Energy System

After optimization, the designed HRES can supply up to 250,000 kWh/year although, to meet the average demand, it will annually produce 155,693 kWh of electricity (there is a loss of up to 9% in the plant, and 6% in the electricity distribution network). The PV modules stand for 95.7% of the yearly production and the gasifier 4.3%, although the share changes over the season. Some performance parameters such as the PV output, the syngas generator output, and the batteries state of charge (SOC), hourly and daily in a year, can be seen in Figure 4. The gasifier has a yearly fuel consumption of 5.37 tonnes resulting in 14.7 kg/day, safely below the 130 kg/day of waste production advanced in section 4.6.

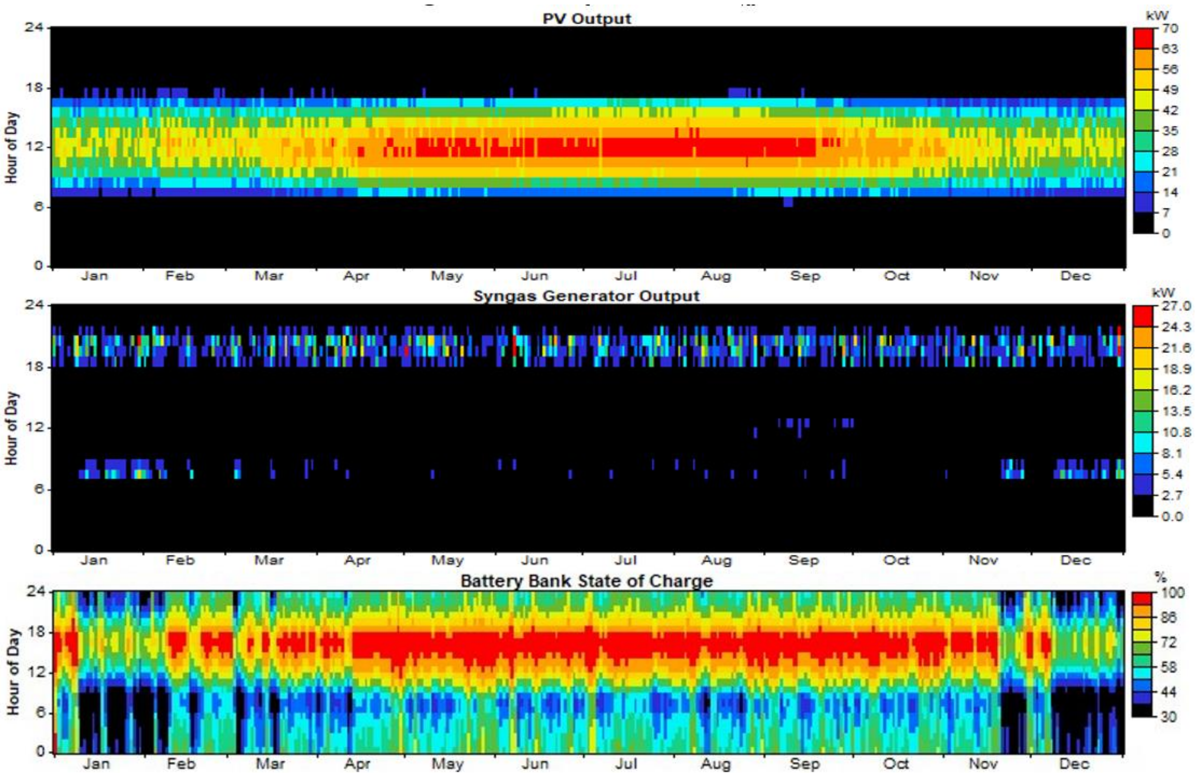

Figure 4 yearly plant performance: PV output in kW, Syngas output in kW and batteries SOC (%)

3.7.4. Electricity distribution microgrid.

The distribution network is conventional, with transformers to elevate the voltage and distribute the electricity to each node, where a transformer reduces it to the consumption voltage: 230 V (see figure 5). Protections will be installed at the power plant, at the nodes and at the dwellings. Smart meters will make it possible to know and manage individual energy consumption.

Cluster Nr	Number of HH	Line	Length (m)
Main line	-	-	1300
1	10-12	A	160
2	8-14	B	80
3	3-7	C	90
4	20-24	-	-
5	15-20	D	120
6	10	E	60
7	12-15	F	210
8	10-14	G	175
9	5-8	G	-
10	3-6	H	95
11	10-12	I	160
12	8-10	I	-
13	10-12	J	90
Total	124-164	-	2540

Figure 5. Proposed distribution line.

3.8. SYSTEM VIABILITY.

After the multiple viability analyses, the project follows the laws of the Ministry of Energy, in collaboration with the REA. The proposal is candidate to the Rural Electrification Fund.

Regarding economic viability, the summary of the NPC for 20 years can be seen in Table 3. The highest expenditures are for capital costs in year 0, and the replacement costs in years 9, 15, and 17. In addition, the LCOE in 20 years is a high 0.485 USD/kWh. However, based on the simulations and the average prices for electric grid extension in Zambia (see section 3.7.), the EDL of this case study is 70.2 km, which is clearly less than the 140 km distance to the closest grid line. Hence, the HRES is the most economic way of electrifying the community.

Component	Capital (USD)	Replacement (USD)	O&M (USD)	Fuel (USD)	Salvage (USD)	Total (USD)

PV	240,000	0	25,619	0	0	265,619
Gasifier	54,000	14,450	1,787	11,475	-3,285	78,427
Batteries	76,000	60,502	6,405	0	-372	142,535
Converter	59,400	18,725	2,882	0	-2,891	78,116
System	429,400	93,677	36,693	11,475	-6,548	564,697

Table 3. Net Present Cost (20 years) by component and type of cost.

The environmental study shows that the business-as-usual scenario emits 3.48 tonnes of CO$_2$eq/year, but if a diesel generator is used: 91.6 tCO2eq/year. Consuming electricity from the national grid would produce 0.39 tonnes of CO2eq per year, being the option with the lowest impact on global warming.

4. DISCUSSION AND CONCLUSION

The results presented here are a small summary of the multiplicity and quantity of data that has been generated. The case study started in 2019 and has taken 2 years to identify (baseline) and formulate (project objectives). The co-design has taken another two years and now the project actors are looking for funding.

Under Zambia's pricing system, no alternative for electrifying rural communities is cost-effective. However, HRES are better alternatives than extending the grid in this case. The investment is lower and the positive social impact on the beneficiary community is higher. Among the positive impacts is that the community is engaged and trained to take care of the installation. This training improves the employability of its members. In addition, HRES services are more resilient to changes in the grid prices (or community incomes), power shortages due to drought, sabotage or grid failures, etc.

The high NPC is partly due to using a gasifier as a backup, which is too expensive for the little use it has. In addition, the biomass is simulated to be paid for, but the energy committee will probably decide that the biomass will be given in payment for electricity. On the other hand, as the population and consumption is expected to grow, the gasifier will be more of a complementary energy source than a backup (it can cover up to 30% more of the total expected energy).

This methodology allows, firstly, to meet the objectives of energy autonomy, but it also does so with the flexibility and agility necessary to adapt to the high uncertainty and variability of the design conditions. Effectively, systems provide flexibility: the gasifier can operate with a wide variety of biomass types, the distribution network allows more buildings to be connected, there are several ways of organising and paying for energy, etc. Furthermore, the beneficiaries, as co-designers, become aware of the importance of respecting the intended use of the system, and the need to reach agreements between users if uses change.

In conclusion, the methodology fulfils it goals despite all the difficulties. The proposals of various authors are collected, aggregated and combined in a procedure that balances social, technical, administrative and economic aspects. As future lines of research, authors are working on a better formulation of the project's objectives and goals, a very difficult task since beneficiaries often cannot forecast the change that electricity will bring to their agendas.

Finally, the electrification of rural communities that have not consumed electricity before is gaining an increasing interest and new strategies and tools are continuously proposed that will have to be evaluated and, where appropriate, incorporated into the methodology.

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