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Microgrid design for disadvantaged people living in remote areas as tool in speeding up electricity access in Rwanda

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ABSTRACT

Across many developing nations, such as Rwanda, the absence of electricity has significantly reduced the economic impact of rural communities. A common practice in some locations is to process farm products using locally fabricated machines, which diminishes the quality and quantity of production while simultaneously increasing the danger of illness. Recent studies suggest that hybrid power systems, such as those based on renewable energy sources, could support the development of a climate change adaption and low-emission economy in a post-pandemic future. According to this study, the current electrification rate and the variables that restrict electricity access speed are investigated, and some solutions to overcome these issues are proposed. According to the findings of this study, the connection of rural areas is delayed by the presence of remote and low-density villages, because the access to the utility transmission lines is both expensive and complex. For this reason, the study proposes a novel microgrid design where it suggests an installed solar PV mobile mini-grid that can provide a group of households with energy, so enabling them to obtain economical and environmentally friendly energy. Results have proven that the proposed model is an adjustable and expandable generation and distributed storage. To a greater extent, the installation of a single device at a residence can even result in the establishment of an expandable DC microgrid, which then can develop in a cost-efficient manner when additional neighbors are joined to the grid. Eventually, the microgrid will be able to alter the way in which processing equipment is utilized. The solution is also expected to contribute to the advancement of clean technology in the pursuit of universal electrification.

1. Introduction

It has been reported that the number of individuals without access to power on the African continent has been progressively reducing since 2013. This was due to improvements made in nations such as Kenya, Senegal, Rwanda, and Ghana, which implemented robust energy access legislation and supported off-grid activities. However, the pandemic has reversed this progress, with the number of Africans without electricity climbing to more than 590 million in 2020, an increase of 13 million people, or 2%, from last year, according to data in the World Energy Outlook 2020 [1].

According to the literature, improved socioeconomic conditions are dependent on access to power in countries in the process of development as it affects important living condition factors such as education, money, health, and the environment [2]. In terms of remote places, in Ref. [3] it has been demonstrated that the largest obstacle to economic growth is living without access to electricity. Authors in Ref. [4] said that as the power is one of the most needed for production activity a high correlation exist between electricity availability and living conditions improvement in rural areas. Panel data and two identification procedures, such as the instrumental variables strategy and the fixed effects approach, were used by the author in Ref. [5] to determine that there is a beneficial influence of electricity access on female employment. She also showed that new electrification-based infrastructure improves working

Abbreviations: MV, Medium Voltage; LED, Light Emitting Diode; REG, Rwanda Energy Group; PID, Potential Induced Degradation; REM, Residential Energy Management; PAR, Peak-to-Average Rate; MPPT, Maximum Power Point Track; MDL, Maximum Demand Limit; COE, Cost of Energy; VEMS, Village Energy Management Systems; MINL, Mixed Integer Nonlinear; NPV, Net Present Value.

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hours for men or women, leading to greater income. In addition, she noted that if access to electricity is achieved by using clean energy, it will help rural home conditions further. Additional research on the effects of various power projects in rural Africa was also looked into in Ref. [5].

As for Rwanda, different programs to improve energy availability have been implemented, as presented in Table 1.

Project 1 scope extended the grid by constructing medium voltage (MV) lines of length equals approximately 216 km, and low voltage lines totaling about 398 km. In addition, about 14,150 households were connected. It was also to increase the reliability of the electricity grid through grid strengthening and harmonized standards. This was performed on 8.4 km of MV, 41 km of LV, and 2737 connections. Through the intervention's pilot operations, the cost effectiveness of grid energy access was also enhanced. The second project's scope was to strengthen the electricity sector capacity by developing and installing a management information system, creating a metering control centre, acquiring meter data management software and training of staff in its use and supplying, and installing metering infrastructure for targeted customers. Another scope was to increase the access to electricity services where electricity access was accelerated (about 72,000 households were connected, giving access to electricity to about 324,000 people where 50% among them are female). For the project number three, the scope was to extend the national grid by 221.4 km of MV distribution lines and 393.15 km of LV distribution lines [6].

Although the above-mentioned projects were to support in the increased electrification rate, numbers still show a low access to electricity especially in rural areas. As of June 2021, Rwanda had a 65% access rate to electricity, with 47.2% of the population using the national grid and 17.8% using off-grid power (mostly solar PV). The system typically runs 4 to 5 LED lights, a radio, a TV, and a mobile phone charging device for a typical household and can be extended with options that include fans, stereos, irons, fridge, as well as small business solutions (village cinema, barber shop) [7,8]. This demonstrates that access to electricity in rural areas is still limited, as evidenced by the fact that in these areas, houses are connected to electrical energy through a majority of off-grid sources, with only 17.8% of rural homes being connected to off-grid sources, as previously stated. This does not imply that all residents of rural areas are connected through off-grid, but it does imply that the rate of on-grid connections is low as well. The extensive deliberations on this assumption are completed in subsection 2 paragraph 2.

Therefore, more analysis and investigations on the causes of this low electrification rate are needed in order to arrive at possible solutions. This study examines Rwanda's rural electrification difficulties, and some practical solutions are thoroughly researched where the study revealed that the future with renewables could be different.

Table 1
Electricity access scale up projects.

Number	Category	Name	Donor/Funder	Start	End
1	On grid	Increasing access rate to reliable Grid-connected Electricity supply for homes but prioritising public institutions BE1EARP	Government of Rwanda & Belgian Kingdom	2014	2020
2	On grid	Strengthening electricity sector in Rwanda	World Bank IDA	2016	2021
3	On grid	Remote areas electrification in Nyagatare and Burera districts	Arab Bank for Economic Development in Africa	2014	2020

2. Problem formulation and literature presentation

During the development of the Economic Development and Poverty Reduction (EDPRS) II, the Rwandan government made a clear policy choice to diversify electricity sources beyond the traditional dominating grid, including off-grid connections. As a result, households located outside of the intended areas with national grid presence have been advised to make advantage of alternative, less expensive connections. Mini-grids and solar photovoltaic (PVs) are examples of connectivity to minimize their electricity costs. Nethereless there has been effort to increase electricity access rate, according to statistics from June 2021, the access rate to electricity was 65% in Rwanda, with 47.2% per cent using the national grid and 17.8% using off-grid power (mostly solar PV). The current access targets state that by the year 2024, everyone should have electrical access with no exceptions, and businesses should be entirely linked by the year 2022. To meet this goal, Rwanda Energy Group (REG) wants to add approximately 500,000 new electrifications each year, including approximately 200,000 on-grid and around 300,000 off-grid [7] The country of Rwanda is divided into four administrative provinces [9], each of which is made up of 30 districts and 416 sectors. There are at least two sectors in each of the 30 districts that are located in rural areas, which is why the electrification percentage is still low.

An access percentage of less than 65% is recorded in nine districts (30%), according to the findings. Only one district, accounting for 3.3% of the total, has an electricity rate greater than 90%. In addition, only three districts, or 10%, have an electricity rate greater than 70%, while the remaining districts, or 40%, have an access rate of less than 50% [7]. As seen on the map, the districts with the lowest rate of energy availability are in rural places, making it difficult to connect to the national grid. This is always owing to the high expense of distributing grid electricity in sparsely populated mountainous areas with high usage. Another truth is that the majority of people in rural areas have poor salaries, which can make energy costs tough.

It has been observed that projects to enhance electricity generation in order to accelerate electrification are primarily on-grid connection-based, which is consistent with the goal of accelerating electrification. In contrast, as seen in Ref. [10], the majority of on-grid power plant building projects resulted in a low available capacity when compared to their total installed capacity. This system, which has been constructed as a result of the rapid expansion in energy generation, has serious flaws. According to current projections, the country will produce significantly more electricity than it will need in the next years, with existing generation capacity far exceeding anticipated consumption.

As a result of these circumstances, the country's energy output could become prohibitively expensive, especially in the perspective of the African continent. As a result, additional generation will not be able to enhance the financial accessibility of electricity, while tying the country into high energy costs for the foreseeable future. The example is the currently 12.230 MW (MW) of installed capacity of solar energy, which comes from five solar power plants: the Jali power plant, with 0.25MW, the Rwamagana Gigawatt, with 8.5 MW, the Ndera Solar power plant, with 0.15MW, and the Nasho Solar plant, with 3.3 MW (MW). However, in terms of available power, Jali has only 0.035MW, Rwamagana Gigawatt generates 1.19MW, and Nasho Solar has only 1.155MW of installed capacity, according to Ref. [10].

In addition to solar, the government has launched a large-scale micro hydro development program to offer electricity to rural villages and cities. The projects are performed in collaboration with many donor partners. There are a total of 23 government-initiated projects with an overall goal of delivering an additional 41.3 MW of electricity. However, because they are on-grid and their production is low in comparison to their installed capacity, the same problem persists. As the total installed capacity of 19.89MW is identified, it is seen that the production of many of these generation power plants is less than 50% of the installed capacity. According to Ref. [11], the water quality was shown to be one of the most significant contributors to this poor production. With regard to solar PV systems, the author did not have access to data and was unable to determine the root causes of the systems' low production levels. There are, however, a variety of causes. Within the first 10 years of operation, the likelihood of a PV system failing to produce at its maximum capacity is roughly 10%. Inverters and other electronic components are responsible for 85% of all failures in photovoltaic systems. The most common failure modes are: environmental conditions that exceed the equipment's rating, hot cells caused by excessive current flow in a de-energized state, potential induced degradation (PID) caused by leakage currents to earth ground, low cell conversion rate caused by cell cracks, delamination caused by extreme heat and humidity, and current loss caused by shorts (shunting) between cells where the module substrate is damaged by wind, dust, or other natural forces [12–14].

Alternative solutions to the challenges outlined above can be found in locally renewable energy-based power generation that is situated near to the load and does not require the use of transmission lines. Furthermore, in order to keep prices as cheap as possible, components can be kept to a bare minimum and capacities can be kept to a bare minimum, primarily servicing small DC appliances for lighting and communication. It may be possible to implement a realistic solution based on electricity mini grids, which can generate electricity at the local level through the use of village-wide distribution networks. They will be able to supply capacity for both domestic appliances and small enterprises in the surrounding area, and they have the potential to become one of the most powerful technological options for accelerating rural electrification.

A number of studies have demonstrated that mini grids can provide an uninterrupted and reliable electricity supply that is comparable to (and sometimes even better than) the electricity supplied to grid users in developing countries. As well as meeting modern home necessities (lighting, communication, refrigeration, and water supply), they also contribute to the development of public services (such as health clinics and schools) and the growth of a local economy. In summary, the installation of mini grids has demonstrated that it has a beneficial social impact by nurturing and developing local governance structures through the participation of the community in the decision-making process associated with the electricity grid. On top of being a good, isolated solution, mini grids have two additional advantages: they can be easily scaled up when demand increases due to the modularity of their generation components, and they can be connected to the national grid and used as additional generation capacity if the need arises [15,16].

Some solar PV-based rural electrification architectures have been proposed in the literature. Authors in Refs. [17–21], proposed a centralized generation and centralized battery storage (also known as "central storage"). The central generation with distributed storage setup in Refs. [22–24] is another proposed option. From a control aspect, centralization of resources is generally preferable since it allows for reliable monitoring of total power produced and reserve levels (battery charging). Nevertheless, increased distribution losses and future growth stiffness arise because of this.

Another PV-based ad hoc DC microgrid architecture for rural electrification was developed in Ref. [25]. This looks at how much electricity is needed for up to 20 customers and combines it as a single power unit. As the total voltage is 48 V due to higher energy losses, this makes the system inappropriate for the needs of large families or community loads [19]. presented a centralized photovoltaic plant and battery as a reserve system Although local energy storage improves efficiency over this system, it is inefficient in two respects, which is still the case: a) It is more expensive to generate electricity from central PV systems up front because a big nominal output for the solar panels is needed at the beginning, creating a financial barrier. b) The substantial system losses are associated with the distribution of power to distant dwellings. For the microgrid to function properly, there is many surveillances, detection, and interaction. This adds to the complexness and expense of the microgrid which is why it would be an unwise investment for rural electrification [22,26,27].

In [28], a robust Residential Energy Management (REM) technique capable of monitoring and controlling residential loads within a smart home was proposed. A distributed multi-agent framework based on the cloud layer computing architecture was developed for real-time microgrid economic dispatch and monitoring. In addition [29], proposed an adaptive energy management system for islanded mode and grid-connected mode. In this paper, a hybrid system that includes distribution electric grid, photovoltaics, and batteries were employed as energy sources in the residential of the consumer in order to meet the demand. The proposed system was found to permit coordinated operation of distributed energy resources to concede necessary active power and additional service whenever required. Even though, the authors used home energy management system which switches between the distributed energy (which solar and battery) and the grid power sources, they considered an isolated house which makes this system very expensive and hence unaffordable for some poor families.

In [30], the authors introduced a method for residential load control with energy resources integrated. To this end, an input and optimization algorithm was employed to control and schedule residential charges for cost savings, consumer inconvenience, and peak-to-average rate savings (PAR) purposes, including real-time electricity costs, energy demand, user expectations, and renewable energy parameters. Moreover [31], established an advanced demand management system that depends on the consensus algorithm-based coalition game theory method for multi-agents for a smart microgrid. In addition, the work in Ref. [32] intended to serve as a preliminary basis for quantifying the environmental and social benefits resulting from microgrid implementation. The authors presented a cooperative controller for coordinating the multi renewable energy resources operation using the IEEE 9 test feeder as the basis and with major modifications.

The suggested control scheme defines the data exchange within, and among, a multi agent system to enable MG's flexible control in Internet of Energy. The proposed control objectives are achieved with the evaluation of the stability considering network latency. In Ref. [33] also, a novel robust smart energy management system and demand reduction for smart homes based on internet of energy is proposed. The paper also uses energy sources to access the intelligent framework, followed by a strategy on optimization of time intervals with two different satisfaction functions. The method is based on Wi-Fi wireless technology. However, the authors overlooked that in future the lifestyle style of individuals living in the region where this microgrid is located will improve and will require an expansion for grid connection. If this concern is not taken into consideration, more work and technical considerations will be required in future and even the microgrid can be deemed incompatible and be removed. As a complement to the above proposed models, the work in the manuscript proposes a novel microgrid design. It suggests an installed solar PV mobile mini-grid that can provide a group of households with energy, so enabling them to obtain economical and environmentally friendly energy.

3. Research elaboration

Due to the limitations of the previously mentioned, we propose a solar PV-based adjustable and expandable generation and distributed storage configuration using the use of control method. According to the suggested model, to a greater extent, the installation of a single device at a residence (a solar panel, an energy processing unit, and a rechargeable batteries) can result in the establishment of an expandable DC microgrid, which then can develop in a cost - efficient manner when additional neighbors are joined to the grid. Fig. 1 depicts the model that we are proposing. The study proposes a micro-grid made up of a group of families with households that can be expanded to connect with other nearby villages until they are eventually connected to the national grid, pending improvements in living conditions.

Ideally, the power supplied from the solar panels plant should be in

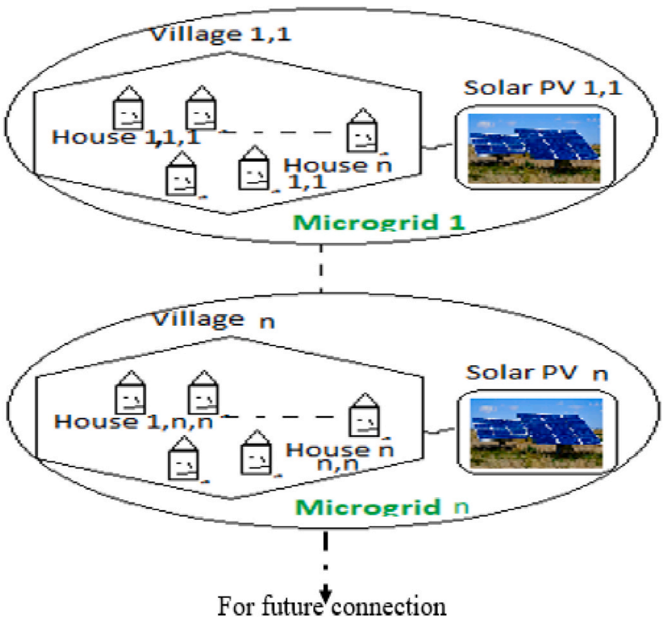

Fig. 1. Proposed mini grid for rural area.

direct current (DC) (its efficiency to be evaluated and compared with AC power transmission for a given village). When it comes to the distribution side, each group of families will either have a converter or will not have one, depending on their preference and whether their living situations allow them to afford one. Since each family will be able to pick between DC and AC power depending on their family capacity, this will aid in increasing the rate of energy access. This model, on the other hand, assumes that each family will have access to direct current (DC) electricity because there are already available and affordable DC products given by Solar home energy supplier firms in Rwanda such as (Mobisol, BBOXX, NOTS SOLAR LAMP Ltd & Barefoot Power Ltd, etc) [34].

Due to the fact that many villages would be connected to one another, this study took into consideration a village that appears to have an average demand in comparison to other villages. Additionally, a 30-kW system was evaluated for each of the 10 villages. As the quality of life in the village improves, the people who live there will have the financial conditions that allow them to have the power grid brought closer to them. As a result, the microgrid that was suggested would be integrated with the grid electricity, as was discussed in section three. As a result, the demand growth is not taken into account in this study. This is due to the fact that the additional demand that is anticipated for the future will be satisfied by the power supplied by the grid, given that individuals will have the possibility to group together to contribute to the transmission of electricity from the national grid.

Fig. 2 depicts a simulation of the suggested model in MATLAB Simulink.

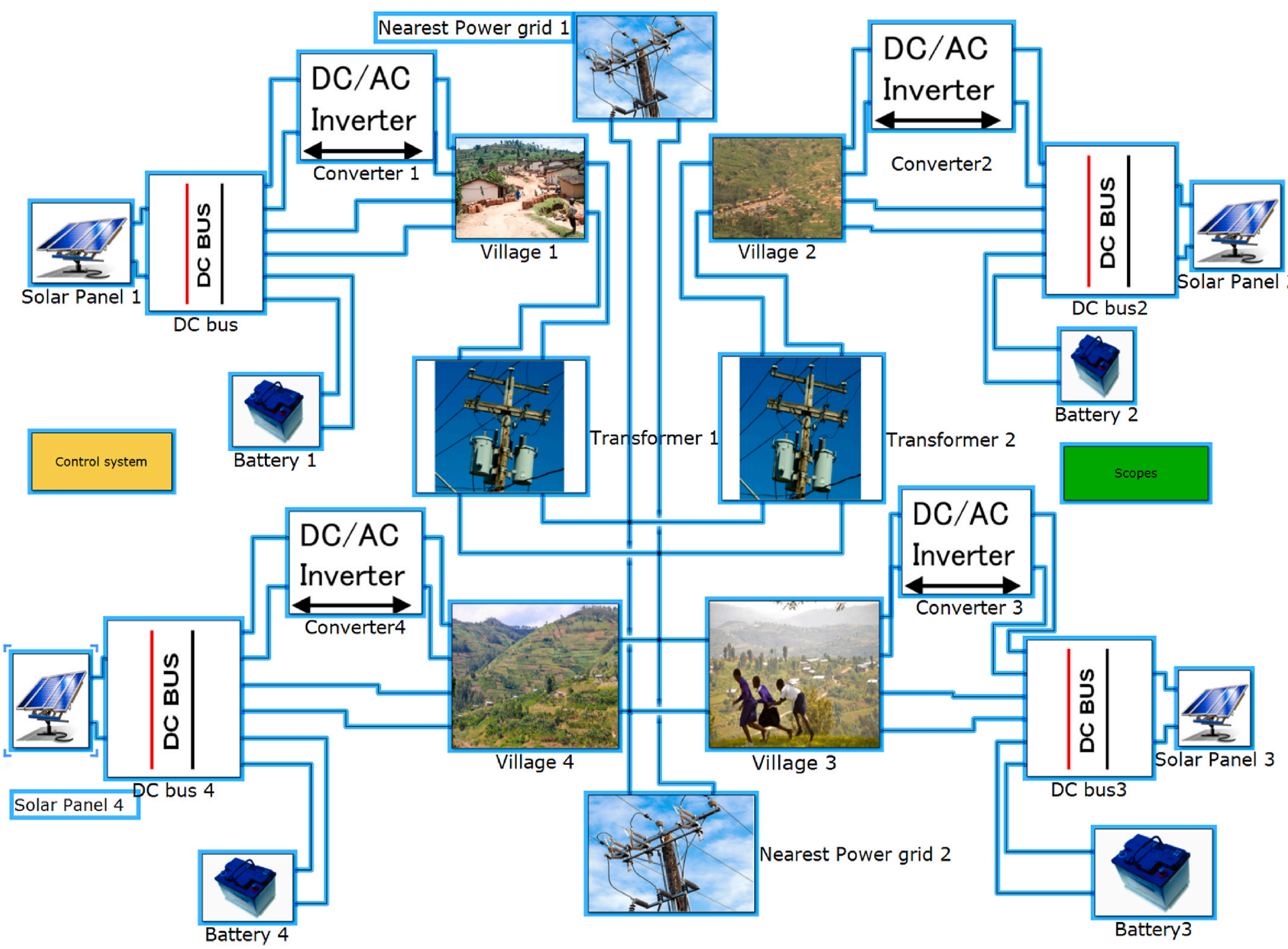

Fig. 2. Model for rural area energy management.

The inverter, battery, and PV management is achieved by developing an intelligent control-based future grid integration of hybrid PV-Batter storage mobile microgrid (the control system is shown in yellow and is developed in Figs. 3–5). With such a system, the problem is how to determine when the battery should be charged to provide the best energy efficiency. The proposed intelligent control which uses the Fuzzy Logic control is to optimize energy distribution and provide an extended future prediction for grid integration. The inverter is used to convert DC into AC whereas DC-DC converter is used in Solar PV to convert variable DC into constant DC. The AC Bus is connected to batteries through charge controller. Here battery will ensure reliability of the power system for all climatic conditions. Batteries will charge when the power generation from solar PV system is in excess and it will discharge when the power generation from solar PV is not enough to meet the load demand.

The configuration of the system consists of three basic components, which are seen in Fig. 3 through 6, and these are the inverter controller, the PV controller, and the battery controller. In this case, photovoltaic panels are a component of the power generator. Within the framework of the system, the output electrical power is delivered to the loads that have been assigned the highest level of importance. When the amount of power produced by the generator is greater than the amount of electricity required by the loads, the surplus power is used to charge the battery. The surplus power is subsequently supplied to the local distribution network, if such a network exists, provided that the loads are not capable of using up the entire output power and that the battery has been fully charged. Fig. 3 depicts the fuzzy-based inverter controller, which works by comparing the actual output voltage (V-Dc) to the reference voltage (V_{ref}). This comparison results in the production of an error signal, which is then utilized to establish the switch duty cycle.

Fig. 4 depicts the fuzzy-based inverter controller, which works by comparing the actual output voltage (V-pv) to the reference voltage (V_{ref}). This comparison results in the production of an error signal, which is then utilized to establish the switch duty cycle to obtain the desired power output.

The fuzzy control theory was developed specifically for hybrid systems with the goal of improving overall system performance through optimization. The design criterion stipulates that in order to keep the maximum operational point, both the solar device and the battery have to be fed by a maximum power point tracker simultaneously. When a Li-ion battery is being charged or discharged, the disparity that exists between the actual load and the total power generated must be taken into consideration. The MPPT controller is depicted in Fig. 5, which also provides further information regarding the fuzzy logic-based MPPT Controller. In this circumstance, the MPPT controller is connected to the fuzzy logic controller in order to achieve maximum power point tracking. This was done so that the maximum power point could be tracked. The gate pulse for the DC-to-DC converter is derived from the output of the fuzzy logic MPPT controller. In this particular instance, the same PV module is utilized with the same degree of uncertainty. The voltage and the current signal that are output from the PV Module are then provided to the Fuzzy Logic Based MPPT controller.

3.1. Mathematical model of system components

Distribution losses in the system will be computed using DC power flow analysis with the assistance of the modified Newton-Raphson Method provided in Ref. [35] in order to assess the distribution efficiency of the system. It is expected that the power loss, represented as $W_{loss(t)}$, will be determined by the following factors: a) power sharing configuration in a certain group of households, i.e. village, b) required voltage value in the village, and c) peak load values in each house. It is proposed in this model that a town with n-houses be represented as a complex matrix of a placed conductor (x,y) resistance. The conductance 1/R of a conductor is represented by the expression (1).

$$\frac{1}{R} = \begin{bmatrix} \frac{1}{R_{11}} & \cdots & \frac{1}{R_{1n}} \\ \vdots & \ddots & \vdots \\ \frac{1}{R_{n1}} & \cdots & \frac{1}{R_{nn}} \end{bmatrix} \tag{1}$$

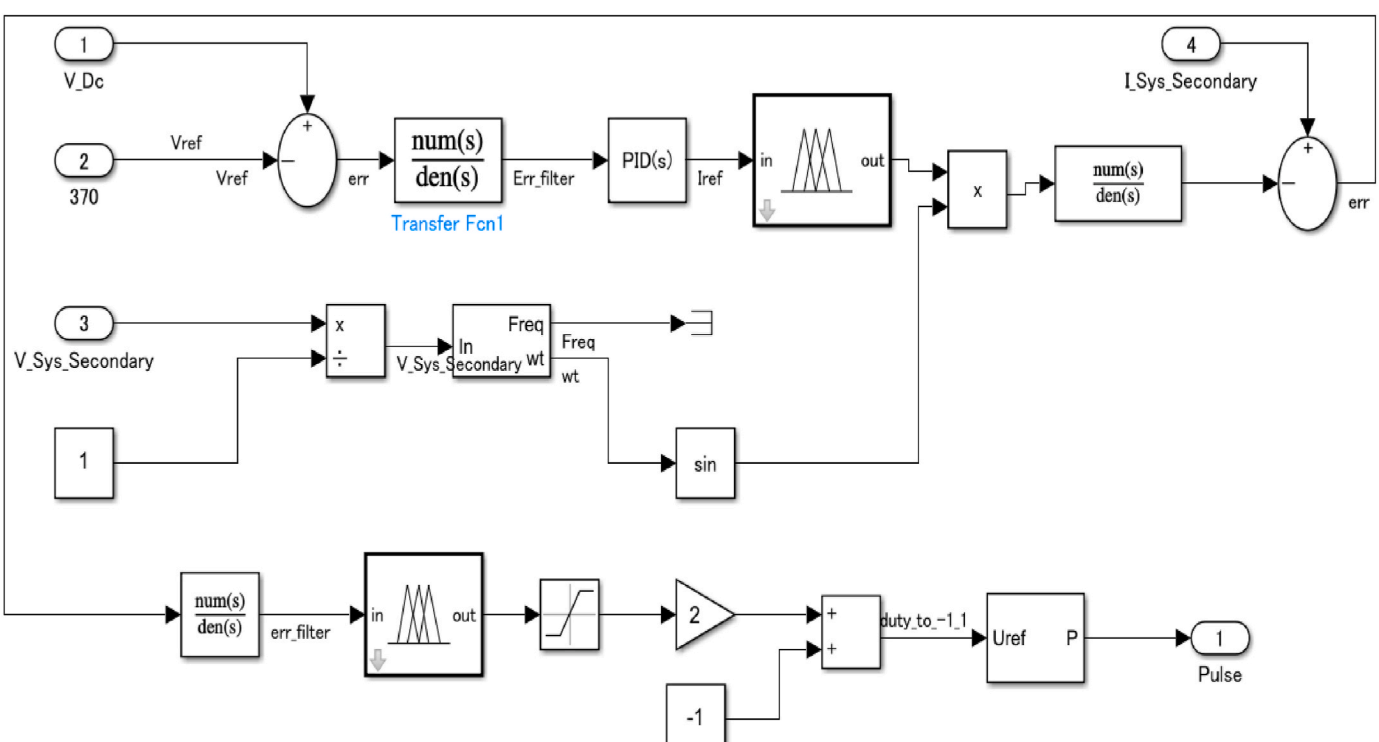

Fig. 3. Proposed inverter fuzzy logic-based controller.

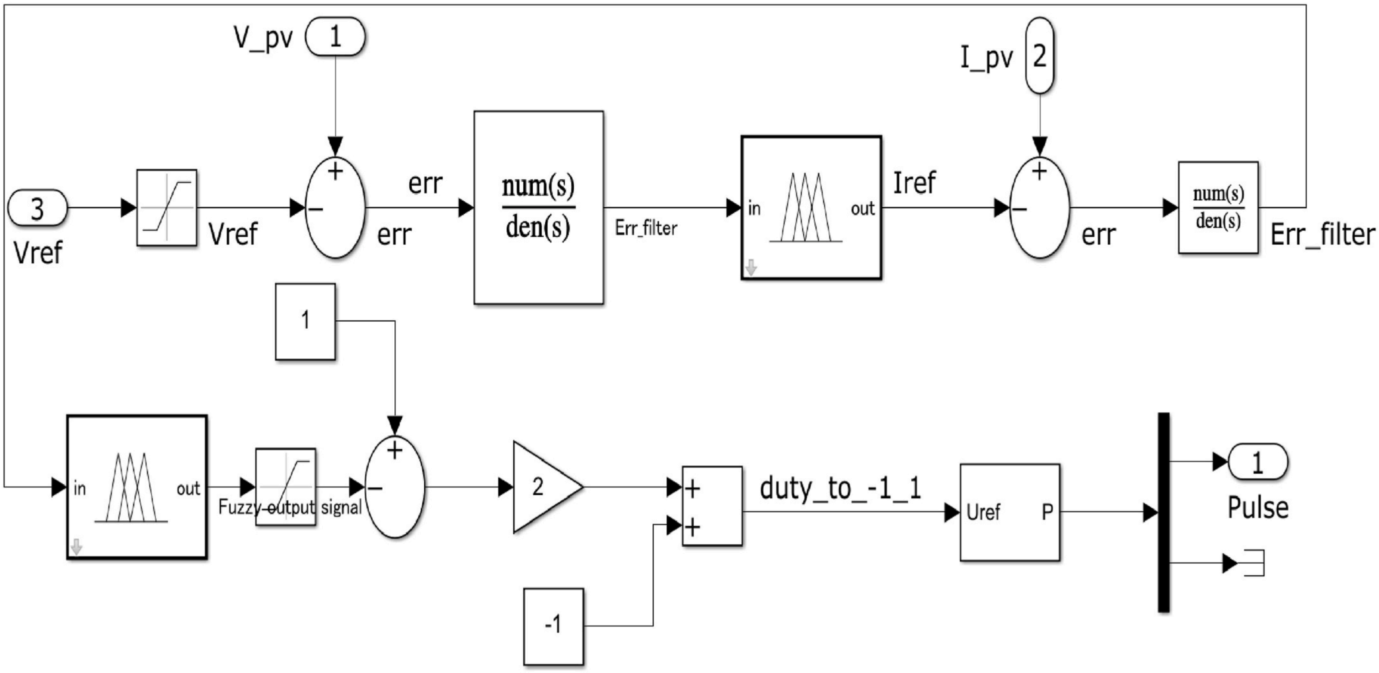

Fig. 4. Proposed PV fuzzy logic-based controller to obtain optimum and stable power.

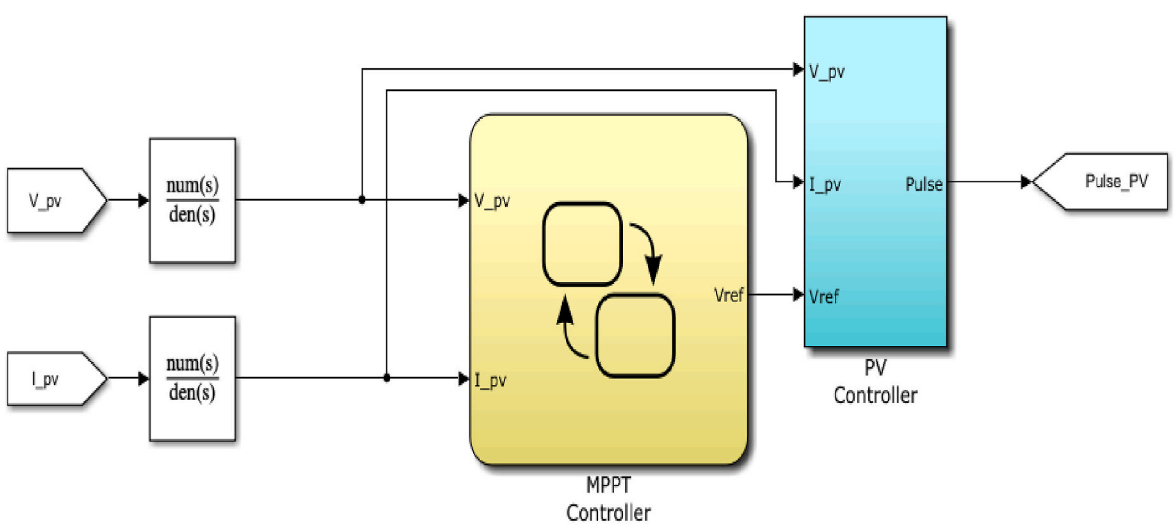

Fig. 5. Maximum power point tracking controller.

And therefore, using (2) the power loss is determined.

$$W_{loss} = \frac{1}{2}\sum_{x=1}^{n}\sum_{y=1}^{n}\frac{1}{R_{xy}}\left[V_x\left(V_x - V_y\right) + V_y\left(V_y - V_x\right)\right] \tag{2}$$

With V, the potential difference at a given point of a conductor.

Individual solar PV panel power output (sending end power) at any time (t) can be calculated from incoming solar radiation by applying the following formula to the panel's output [36–39].

$$P_s(t) = P_{rat} * d_{PV}\left(\frac{I_m(t)}{I_c}\right) \tag{3}$$

In which P_{rat} representing the power rating of the Pv module or the output power during standard operating conditions, expressed in kilowatts, d_{PV} is the PV downgrade factor (percentage), I_m is the intensity of solar energy that strikes the Pv module (kW/m^2), and I_S is the incoming radiation measured using normal test procedures (1 kW/m^2). The total amount of power generated by solar PVs can be calculated using the following formula in equation (4)

$$P_{send}(t) = \sum_{i}^{N} P_{Si}(t) \tag{4}$$

The generated power includes DC and AC power as some households chose DC power or AC according to their financial status. Thus, send end power is recalculated as in (5)

$$\begin{bmatrix} P^{dc}_{send} \\ P^{ac}_{send} \end{bmatrix} = \begin{bmatrix} P^{dc}_{receive} \\ P^{ac}_{receive} \end{bmatrix} + \begin{bmatrix} W^{dc}_{loss} \\ W^{ac}_{loass} \end{bmatrix} \tag{5}$$

The charge status of the battery bank (SOC) can be calculated as follows:

The process for releasing the charge is as follows:

$$E_{sbat}(t) = E_{sbat}(t-1) * (1-\gamma) - \left[\frac{E_{load}}{\rho_{inv}} - E_P\right] \tag{6}$$

Charging process:

$$E_{sbat}(t) = E_{sbat}(t-1) * (1-\gamma) + \left[-\frac{E_{load}}{\rho_{inv}} + E_P\right] * \rho_{batt} \tag{7}$$

Where $E_{sbat}(t)$, $E_{sbat}(t-1)$ are battery stored energy at a time (t) and $(t-1)$; γ is the stored energy utilisation rate; E_{load} the required energy for the load at a time (t); E_P is the generated energy by PV system; ρ_{inv} is inverter working efficiency and ρ_{batt} is battery storage charging efficiency. Based on the availability of solar PV generation, and Maximum Demand Limit (MDL). When it comes to batteries, the controllers regard them as another generation when the power is being discharged and as another load when the power is being charged. The equality in (8) gives the controller signal for the battery operating mode.

$$C^b = \begin{Bmatrix} 1, \text{during chaging period} \\ 0, \text{during floating period} \\ -1, \text{during discharging period} \end{Bmatrix} \tag{8}$$

When the solar power generation is high, the consumer should operate the loads. This, in turn, explains why solar panels and battery banks should be sized in such a way as to minimize their overall cost while also optimally utilizing resources. Next section determines the economic and optimal model of the system.

3.1.1. Economic modelling and system optimization

For a lower total cost of investment, investment in power, and reliance on the grid, battery banks and solar panels should be sized at their most efficient level. Reducing the Cost of Energy (COE) costs money, which is why the COE objective function takes the form of equation (9).

$$\min COE = \left(\frac{K_c + K_R + K_O}{E_s}\right) \tag{9}$$

K_C = Capital cost,
K_R = Replacement cost
K_O = Operatingcost
E_S = Annual solar PV energy

For this system, the capital cost is the sum of the PV total capital cost K_{PV} and battery bank capital cost K_B with an added capital recovery cost $\lambda(Disc, P_L)$ as in (10).

$$K_C = (K_{PV} + K_B)\lambda(Disc, P_L) \tag{10}$$

$Disc$ = The discount rate, P_L = Project durability

$$\lambda(Disc, P_L) = \left[\frac{Disc(1+Disc)^{P_L}}{(1+Disc)^{P_L} - 1}\right] \tag{11}$$

It is the same for the replacement cost where it is given in (12)

$$K_R = (K_{RPV} + K_{RB})\lambda(Disc, P_L) \tag{12}$$

The operation cost is also the total of individual operation cost for PV (K_{OPV}) and battery (K_{OB}) as given in (13)

$$K_O = (K_{OPV} + K_{OB}) \tag{13}$$

The annual solar PV energy is calculated as in (14)

$$E_S = \sum_{y=1}^{Y} P_S * \left(\frac{Disc_{PV}}{60}\right) \tag{14}$$

where, Y = Days of the year

The constraints for the objective function are defined below:

The installation cost of PV and battery system requires to be within the allowable limits of investment cost that is flexible for the remote areas consumers. This will then affect the energy tariff that is to be affordable for poor people. Thus, it should be less that maximum initial cost as presented in equation (15).

$$C_{iPV,Bat} \le C_{i\ \max} \tag{15}$$

Another constraint that can be discussed is the size of the system components that should not be above the upper limit (maximum limit). This maximum size is decided by the consumer, due to their affordability. The system size constraint is given as in equation (16).

$$0 \le S_{PV}, S_B \le S_{\max} \tag{16}$$

Where, S_{PV}, S_B, and $S_{\max}$: are the size of PV components, size of battery bank, and the maximum size of PV and battery bank components respectively.

The consumer power injected to the grid during the year is controlled to stabilize the grid. In this regard, the power provided by consumers over a given period, should be less that the predefined limit. The power injection constraint is given as in (17).

$$\frac{\sum_{y=1}^{Y} \Delta P_S \frac{Disc_{PV}}{60}}{\sum_{y=1}^{Y} P_S * \left(\frac{Disc_{PV}}{60}\right)} \le ED_{\max} \tag{17}$$

Where ED is the power export factor$_{max}$ and ΔP_S the exported power to the grid as in (18)

$$\Delta P_S = P_S - P_{Lim} \text{ if } \frac{P_S}{P_{Lim}} \ge 1, \text{or } 0 \text{ otherwise} \tag{18}$$

To solve this optimization problem, the binary particle swarm optimization [40] is used.

3.2. Solar PV design for the case study

There's Renewable-based energy sources that have enormous promise in Africa. Renewable energy capacity in Africa could reach 310 GW by 2030 [41–43] with the abundance of resources on the continent. Hybrid power systems such as renewables-based mini-grids, such as those found in Africa, could help the continent construct a climate-resilient, low-carbon economy in a post-pandemic world [43–45]. Rwanda is especially well-positioned for renewable energy development. Its abundant natural resources and sunny location would make it prime for clean energy infrastructure [46]. However, it experiences a relatively high occurrence of technical and non-technical issues throughout the power supply value chain. The paper suggests that renewables-based hybrid mini-grids could help bridge supply and demand while offering the country's 12 million inhabitants energy access. The proposed micro-grid is a DC and AC-coupled system. The study found that a total panel size of 30 kW made up of 80 units of 380 W monocrystalline solar modules can be used to supply one village. The studied area is divided into 10 villages and the system that can be deployed to each village has a 20 kWh Lithium-ion battery accompanied by a 48 V, 32 kV A inverter, and managed by a custom-made micro-grid management software.

3.2.1. Case study area load estimation

The loads generated by the various businesses in the area are classified as domestic, agricultural, community, and rural industries. However, due to the fact that the majority of agricultural activities are located far away from inhabited areas, the agriculture load is not taken into consideration in this design because they are assumed to have their own separate power supply design. The community load comprises elementary and middle schools, churches, households, as well as village administrative offices. In addition, small business solutions (village cinema, barber shop, grain milling) are considered in this study. The data presented in Table 2 show the characteristics and the estimated load profile for the area under study in order to estimate the possible

Table 2
Case study area load characteristics.

Consumer	End user device	power [W]	Qty	Total (W)	Time of use (h)	Energy (Wh/day)
Schools						
1	Lighting	20	210	4200	8	33600
2	Computer	60	18	1080	6	6480
	Sub total			**5280**		**40080**
Churches						
1	Lighting	20	40	800	5	4000
2	Megaphone	15	3	45	3	135
3	Office lighting	30	10	300	4	1200
4	Miscellaneous	500	1	500	7	3500
	Sub total			**1645**		**8835**
Households						
1	TV (21′ inch)	100	15	1500	4	6000
2	Radio	10	100	1000	4	4000
3	Lighting	20	250	5000	10	50000
4	Miscellaneous	500	1	500	6	3000
5	**Sub total**		**6200**		**63000**	
Health centre						
1	Vaccine Refrigerator	250	4	1000	24	24000
2	Microscope	50	3	150	12	1800
3	Lighting	20	80	1600	12	19200
4	Water Heater	1000	2	2000	8	16000
5	Computers	60	30	1800	20	36000
	Subtotal			**5550**	**97000**	
Small Businesses						
1	Shops	500	2	1000	**12**	12000
2	Posho mill	9500	1	9500	**6**	45000
				10500		**57000**
Total	**Subtotal**			**29.2 kW**		**265.9 kWh/day**

electricity generation technology mix to supply the undergone activities.

3.2.2. PV modules sizing

The solar resource information used for selected village at a location at $2^0 8'$ S latitude and $30^o 5'$ E longitude was derived by PVGIS for Africa. (http://re.jrc.ec.europa.eu, February 14, 2017). Data on the monthly averages of the daily radiation sum on a horizontal surface were used, as well as the tabulated monthly averaged daily insolation incident, including the calculated clearness index values for each month. The clearness [10–12] is defined as a measure of the fraction of the solar radiation that is transmitted through the atmosphere to the earth's surface.

The technical design components of the solar system for the case study distant area are described in this part. It identifies the plant, offers project information, material characteristics (photovoltaic modules, batteries, inverters), system solution criteria, and technical specification for important components. The photovoltaic system is designed to be located in GAKENKE district and it is estimated to be linked to the utility grid's 400 V three-phase low voltage distribution network (in future) and it is supposed to be under the responsibility of the grid operator. The selected site dimatic data are presented in Table 3 [47].

After taking into consideration the predicted total load for the village, as shown in Table 2, and the amount of solar energy that has been collected for this village, it is necessary to determine the maximum capacity of PV panels that will be deployed. After solving for the maximum solar panel capacity using equations (3) and (4), the results show that a total power of 30 kW is required from the PV system. The PV Syst software is used to model the PV system. To realize the strings, the photovoltaic generator is made up of PV modules that are connected in series, as well as electric cables that connect modules to electrical panels and to one other. Table 4 shows the simulation results for the properties of a solar generator as well as the components that make up the generator, mainly strings and modules.

The series-parallel design is used in the photovoltaic generator with a nominal power of 30 kW. The circuit is made up of 40 strings each with 2module sections connected in series. When it comes to the photovoltaic system, the best conversion group consists of two three-phase inverters with a combined output of approximately 32 kW. The optimal photovoltaic system is equipped with 2 battery banks for a total of 8 batteries.

3.2.3. System productivilty

Using data derived from the NASA-SSE source of climate data, it was determined that the system's productivity was proportional to the average monthly global sun radiation incident on the installation site's horizontal surface. Among the factors taken into consideration are the nominal power (30 kW as obtained by considering the total predicted load for the village), the angle of tilt and azimuth (After investigating with several adjustments over different seasons, it was observed that 30 and 0° provided the best solar output.) of the solar-electric generator, the losses on the solar-electric generator (resistive losses, losses due to temperature differences between the modules, reflection losses and mismatching between strings), the effectiveness of the converter, and the rate of refraction (reflectivity losses and unbalance within strings) are all taken into consideration.

In the design of this work, the load consumption can be covered either, by the direct PV generation, by battery bank, or by utility grid when the designed microgrid is connected to it. The daily maximum consumption coverage characteristics for each month is presented in Fig. 6 (when the system is not connected to the grid) and in Fig. 7 (when the microgrid is extended to be connected to the grid).

Results show that the load coverage is almost provided by the battery and the maximum consumption is recored in October, September, Jannuary, March, May and July. As presented in Table 1, the projected total maximum energy demand per day for the community is roughly 265 Wh. However, the findings in Fig. 8 show that the maximum energy output occurred on one day in July, with a total of approximately 305.56 kWh produced. As a result, it is demonstrated that the system is capable of meeting the demand with an approximate energy loss of approximately 10%, which is within the allowable losses percentage. The maximum PV generator contribution is also recorded in July, where it provides 61.5 kWh whereas the minimum contribution is recorded in October with a contribution of 22.5 kWh. It can be observed that most of the energy produced by the solar panels is stored in the battery and then discharged to the load. This demonstrates that the most energy consuming village activities take place in the afternoon and are mostly focused on the household, hospital, and school, with lighting being the most energy-intensive activity. As illustrated in Fig. 6, the maximum amount of energy stored in the battery and then discharged to the load was around 282 kWh per day in October. As the model design proposes

Table 3
Data for the case study area.

Installation site	
Location	GAKENKE
Address	RWANDA
Longitude	29.77°
Maximum temperature	25.44 °C
Minimum temperature	16.05 °C
Irradiation on a horizontal plane	1777.55 kWh/m^2

Table 4
Electrical characteristics of the photovoltaic generator.

Nominal power PV modules number	30 kWp 80
Intercepting surface	154.4 m^2
Strings number	40
Maximum power voltage	48 V
Maximum power current	16.52 A

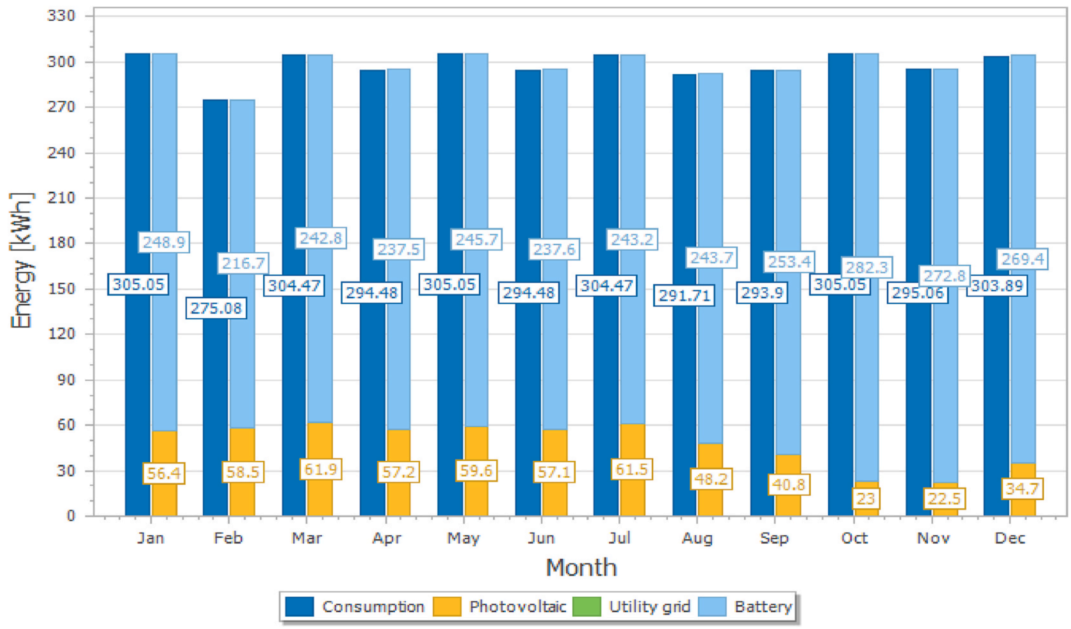

Fig. 6. Daily maximum Consumption coverage in each month when the system is off grid.

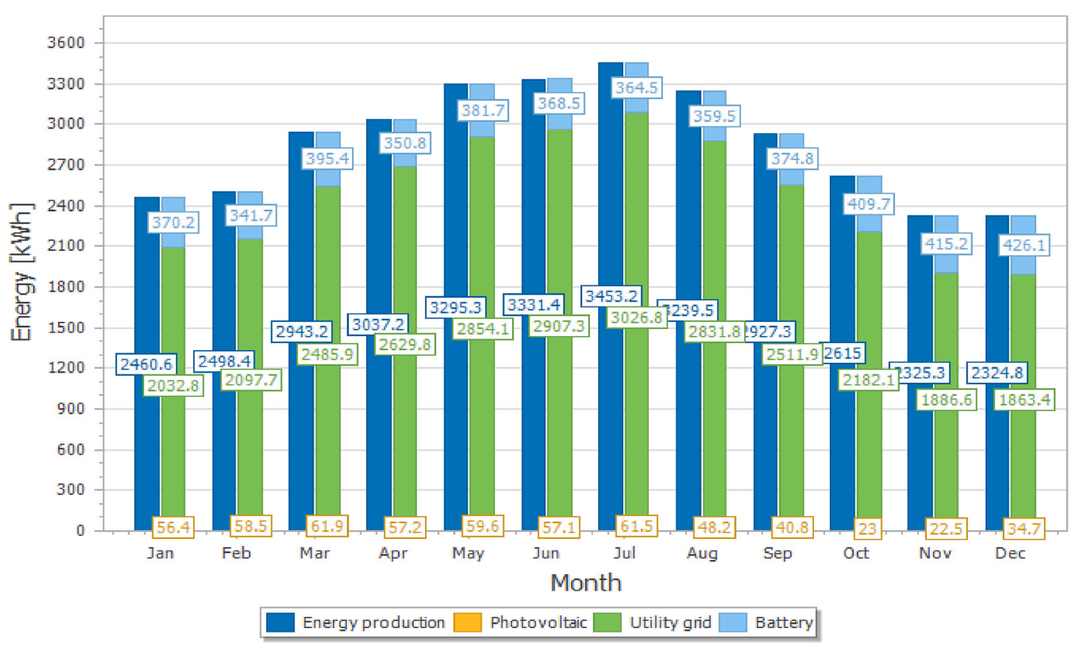

Fig. 7. Energy production when the system is connected to the utility grid.

the future utility grid connection, results show that when the system is connected to the grid, the grid energy is recorded to be the most used. It is proposed in the control framework to use the electricity stored in the battery during peak hours, when people in metropolitan areas consume a large amount of electrical energy. Similarly, to what was mentioned in section 4.1, it is intended that the load will be turned off when consumption is low, allowing the PV and grid generation to be connected to the battery, which will then deliver electricity during peak demand. Comparing the maximum stored energy to the system without grid intervention, where the stored energy was around 282 kWh, when the grid connection is taken into consideration, the maximum stored energy increases to 426 kWh (see Fig. 7).

Increasing the village's electricity rate, as described in the introduction section, would be a great opportunity to improve people's quality of life while also boosting economic growth and improving healthcare and education facilities. As a result of the installation of off-grid energy, the ownership of electricity appliances rises, and as the village lifestyle improves, the deployed mini grids are eventually connected to the national grid. The predicted trend in monthly energy output over the course of the calendar year shows a maximum amount of energy produced per day of 3453.2 kWh in July, and a minimum amount of energy produced per day of 2324.8 kWh in November, based on observations for the current possession of electrical appliances in the village and how they would likely change over the time. The grid would contribute a total of approximately 3004 kWh when compared to the estimated generation presented in Fig. 6. This explains how the village's lifestyle would improve due to the introduction of mini grid systems first, and then gradually connecting to the national grid.

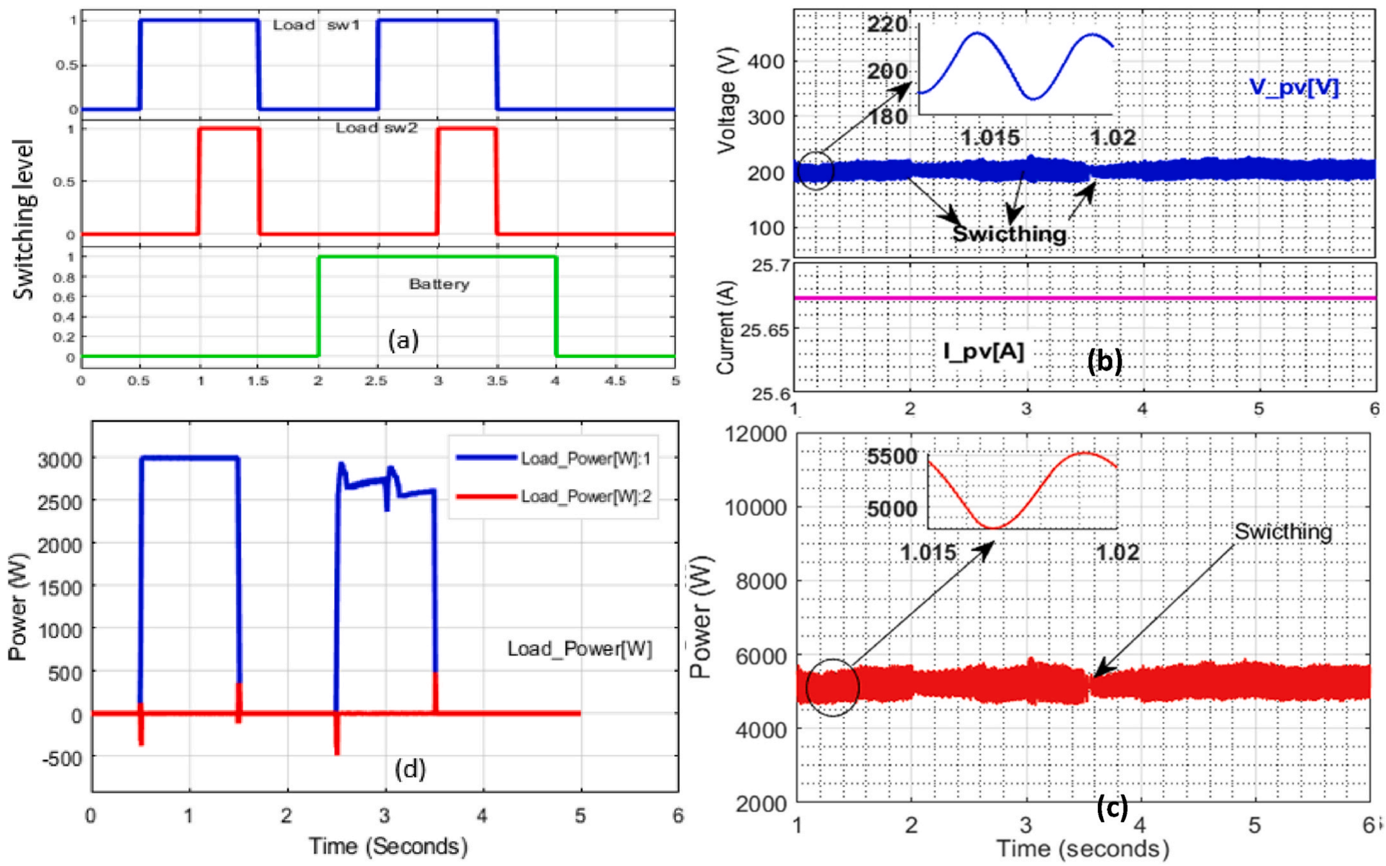

Fig. 8. Simulation results (a: Control signals, b: Solar PV output voltage, c: Generated solar PV power, d: AC and DC power usage characteristics).

4. Simulation and discussions

4.1. System technical analysis

The control system showing the load and battery switching is shown in Fig. 8a. In the simulation, the load is expected to be switched off when consumption is low which connect the PV and grid generator to the battery. As the battery state of charge reaches to a preset value, the battery is then switched off connecting the PV generator to the consumers. The analyzed results are the Voltage, current, and power characteristics as shown in Fig. 8. Be reminded that the results are for an area with four villages whose characteristics are discussed in section 2. In this study, we compare the maximum power injected into or drawn from a microgrid at various points in time, and we make some interesting observations that lead to important conclusions about the relative choice of either of the systems in terms of their respective maximum power performances and costs under similar applications and conditions, as well as their relative cost. The results are improved by adding a zoomed part of the waveform (see Fig. 8b and c). In Fig. 8d, the results are not stable as there are some peaks. The peaks cannot explain that the results are not stable, because it is only the magnitude that is changing. This is normal as the users are random and the value of the consumed power will change following the number of connected users.

The solar PV voltage shown in Fig. 8b represents the single-phase root mean square voltage and current measured at the terminal of PV generator. Results show that the root mean square voltage is around 230 V. However, due to the DC to AC converter, there are some variations in voltage magnitude as it can be seen a zoomed part of the waveform. It is seen that at the starting of load and battery switching, there is a reduction in voltage, but this disturbance stabilizes itself automatically. In contrary however, the current drawn by load from the solar PV microgrid stays constant during battery and load switching. As a result, this makes the power generated take the shape of the generation voltage. The generated power from solar PV is shown in Fig. 8c. There is no interruption of power from PV generator. This explains well how the maximum production from solar is used where it is transferred to the battery for storage and the remaining is used by load. It is in this regard that the system proposed is an energy management without adding high-cost equipment that could make difficult the rural area habitants to connect to the electricity.

In Fig. 8d, results show the energy consumed directly from the PV plant and that consumed from battery are presented. This include DC users and AC users as it was proposed in the system design. In blue, it is shown the power consumption by AC users which is high compared to DC. As it is shown in led, DC power users are few, but the remaining power is stored by battery bank. Considering that the lifestyle of people living in the case study area villages improves, the villages are supposed to change in small towns and the infrastructures are built. As a result, the utility grid transmission lines are expected to reach in these areas, and the proposed off grid PV solar system is connected to the national grid. In simulation, the 10 kV distribution line is used as medium voltage and stepped down for microgrids to be connected to it at the secondary side of low voltage distribution system. Results show a three-phase voltage with a maximum value of 9.9 kV (see Fig. 9a). As it can be seen from the voltage waveform, the solar PV generation has no remarquable effect on grid voltage profile and this makes the system to be reliable.

Because the secondary winding of transformer is connected to the load (when PV and battery are disconnected) the transformer primary current decrease as shown on the current waveform. The current reduces from the starting to the first second and to the fourth second. This is due to the switching of battery and load as shown in Fig. 8a. Results show that when the battery is switched on, the grid primary current decreases whereas the current increases as the battery is switched off and when the load is connected to the grid as shown in Fig. 9b. In addition, results

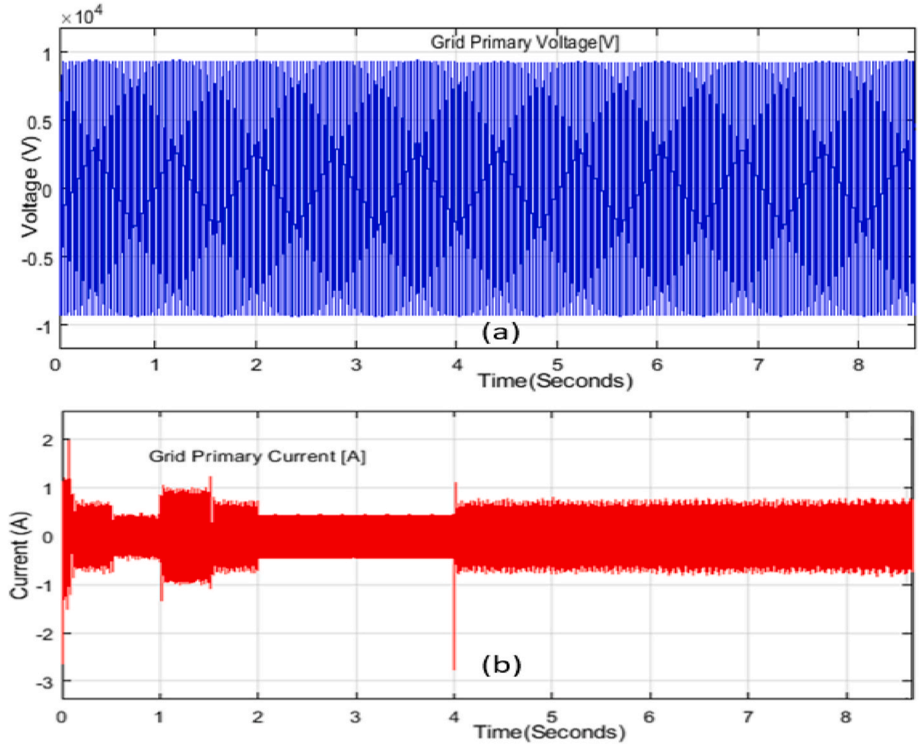

Fig. 9. Grid primary side parameters (a: voltage, b: primary current waveform).

show a three-phase distribution low voltage of around 300 V when the loads are connected to the grid. However, when the loads are supplied from the battery, i.e., PV solar supplied load, the voltage at the secondary of the distribution transformer increases to around 400 V with some small dips due to load switching off. Contrary, the grid secondary current returns to zero while it increases to around 47 A when loads are connected to the grid (see Fig. 9b). It is expected that the integration of renewable energy with grid will have some effects on voltage profile, but there are not highly remarkable as results show. The waveform of the voltage across the secondary of distribution transformer is shown in

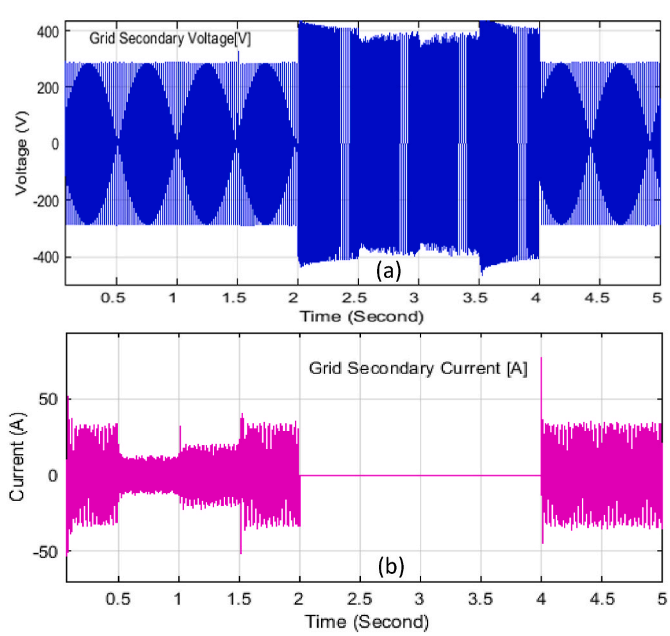

Fig. 10. Grid secondary parameter (a. Voltage waveform, b. current waveform).

Fig. 10a.

4.2. System economics analysis

Table 5 depicts a summary of component costs that considers the existing market system as well as the reduction in system component costs that occurs from time to time. The data supplied are used in the simulation study, and as indicated in Table 5, costs include: capital costs, replacement costs (10 years considered), operation and maintenance (O&M) costs, and other costs. The expenses of the components that have been described include the charges of shipment and installation.

A more accurate evaluation of the benefits and costs of various load management and energy conservation measures is carried out in the context of enhancing the quality of people' power usage in rural areas. An electrical scheduling approach for the village energy management systems (VEMS) that is both cost-effective and comfort-aware, and that can be expressed as a mixed integer nonlinear (MINL) problem, was developed to do this. The following is the formulation of the electricity scheduling for VEMS system: Given that the primary goal of VEMS is to reduce consumer costs while still meeting their daily energy needs, it is possible to characterize this goal in terms of the objective function as shown in (14) to (18). The savings on energy bills, net profit, cumulative cash flow, and net present value are all considered in the economic analysis. The findings reveal that energy cost savings rise over time, although only by a tiny amount over a twenty-year time frame. However, as illustrated in the graph given in Fig. 11, both the cumulative cash flow and the net present value increase at a pace that is almost

Table 5
System components cost.

Components	Capital cost (Euro/kW)	O&M cost (Euro/kW/yr)
PV panels [48]	900	30
Storage system [49]	630	2
Power converter [50]	650	6
Miscellaneous [48]	230	2

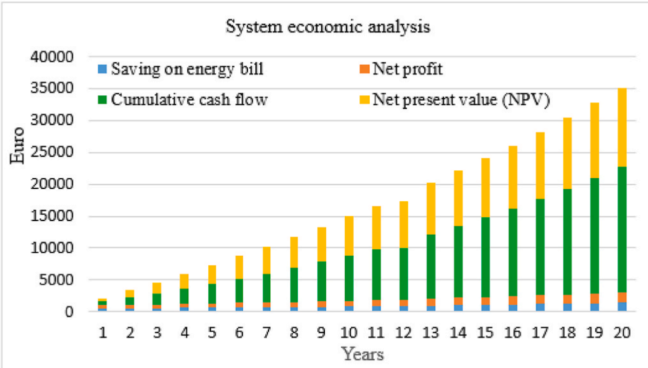

Fig. 11. System metrics, comprising energy bill savings, net profit, and cumulative cash flow.

exponential.

Consumers that consume up to 200 kWh per month pay EURO 0.12 per kWh at the retail level, according to the Rwanda Energy Group (REG) [10]. The energy cost of a PV small grid system is estimated to be EURO 0.108/kWh based on similar studies [51]. Following the comparison of the costs, it becomes evident that the predicted cost of energy for a grid-connected house is more expensive than the residential consumer tariff for a house connected to the village's small grid (which is lower). The planned small grid system, as opposed to the national grid, provides a greater economic benefit, allowing for easier access to power, which in turn contributes to the achievement of expedited rural electrification goals.

5. Conclusion

According to the findings of this study, each of the country's 30 districts has a section that is dominated by remote areas, where people live in isolated locations and their homes are located far apart from one another. It was discovered that, because of this demographic arrangement, there is still a barrier in connecting families. This is always owing to the high costs associated with providing grid electricity in sparsely populated areas with mountains, when demand is also extremely low, as previously stated. On the other hand, it has been noticed that residences are located far apart from one another, causing them to remain disconnected because it is impossible to provide electricity in such a remote place.

To mitigate this challenge, the study offers a micro-grid configuration model, which will make it easier to provide energy to the population living in some isolated places, according to the findings. As the population's lifestyle is not yet improved, results show that the load coverage is almost provided by the battery and the maximum consumption is recorded in October, September, January, March, May, and July. The maximum PV generator contribution is recorded in July, where it provides 61.5 kWh whereas the minimum contribution is recorded in October with a contribution of 22.5 kWh. As the model design proposes the future utility grid connection, results show that when the system is connected to the grid, the grid energy is recorded to be the most utilized. The savings on energy bills, net profit, cumulative cash flow, and net present value are all considered in the economic analysis. The findings reveal that energy cost savings rise over time, although only by a tiny amount over a twenty-year time frame. However, both the cumulative cash flow and the net present value increase at a pace that is almost exponential.

In terms of the technical study of the system, the findings of the simulation suggest that the root mean square voltage is approximately 230 V. Nonetheless, because of the DC to AC converter, changes in voltage magnitude are noted at the beginning of the load and at the battery connection; however, this disturbance stabilizes itself automatically after a few seconds. The current drawn by the load from the solar PV microgrid, on the other hand, remains constant during the battery and load changeover process. It follows as a result that the power generated has the shape determined by the generation voltage. The results also reveal that there is no interruption of power from the PV generator, which explains how the maximum production from solar is used, where the majority of it is sent to the battery for storage and the remainder is used by the load to power the system. In this regard, the method offered is an energy management system that does not require the installation of expensive equipment that would disturb the residents in rural areas.

Author statement

Thank you for giving us the opportunity to submit a revised version of our manuscript. We appreciate the time and effort that you and the reviewers have dedicated to providing your valuable feedback on our manuscript. We have been able to incorporate changes to reflect most of the suggestions provided by the reviewers. We have highlighted the changes in red color within the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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