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Research Article

Grid-connected photovoltaics prosumers to support smart city development in Rwanda: A case study for Ayabaraya Village

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Abstract: Access to electricity is among the important targets in Rwanda as in other regions. The grid-connected photovoltaic (PV) prosumers market segment can contribute to the rate of access to electricity in Rwanda. Grid connected PV prosumers contribute in not only increasing electricity generation capacity but also producing affordable and reliable electrical energy. Therefore, the current research analyzes the possibilities of interconnection of small-scale prosumers with a national grid. In addition, the bidirectional flow of electricity either from prosumer grid and vice versa, aiming at monitoring the continuous power supply of the load is analyzed. The study is conducted in Ayabaraya village in Rwanda and the load profile for residential, commercial and industrial prosumers are analyzed. In this research, meteorological data from Photovoltaic Geographical Information System (PVGIS) up to 2016 is used to give global horizontal irradiation and ambient temperature. The amount of energy imported from and exported to the grid is determined by the connected appliances, the capacity of the PV system, and the amount of available irradiance at the time. The Home Energy Management System (HEMS), inverter control strategies, and prosumer load types are considered. The simulation reveals that available irradiance less than 30W/m2 at a time is below the grid-tie inverter's threshold power thus, the prosumer imports electricity from the grid. At irradiance larger than 30W/m2, the prosumer may optimize self-consumption and injects the surplus into grid.

***Keywords**:* *Electricity, Grid-connected, Load profile, Prosumers, PV, Self-consumption*

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1. INTRODUCTION

The government of Rwanda is targeting to develop smart cities in all corners of the country with an electricity access rate of 100% and incorporate the highest leveraging Information and Communication Technologies (ICT) to sustain economic and social development growth [1]. The smartness in cities is based on the lifestyle and typical living conditions of a large number of people living in proximity. Smartness in energy, Telecommunication infrastructure, transport, governance, environment, living conditions and people are indicators of smart cities [2,3]. This requires affordable electricity, reliable and sufficient to satisfy the demand of the customers. Thus, there is strong cooperation between smart cities and electricity generation systems [4,5]. However, the electricity access in Rwanda is still low, as of August 2021, the cumulative connectivity rate is 65.9% of Rwandan households including 48.1% connected to the national grid and 17.8% accessing through off-grid systems, mainly solar. To overcome this electricity access gap in due time, the current research proposes an approach of self-cleaning carbon-neutral buildings tapping into the grid-connected PV system prosumers and sending power back to the grid in combination with the self-consumption variant in response to demand [6]. The prosumers, namely, users who are both producers and consumers will support the sustainability of energy generation in these cities [7-11]. By involving the customers in energy demand response, by asking them to modify their normal consumption patterns in response to a utility's need will lead to reliable and sustainable energy generation and consumption. That has started and the electricity market has been made open and by now, a limited number of prosumers are running their business in Rwanda [12,13]. So far, the power purchasing agreement (PPA) is being used as a contractual document between prosumers or energy developers and national utility, which stands for an electricity retailer.

The current research analyzes a case of solar-PV as a new class of prosumers [14], which will contribute much in increasing electricity generation capacity in Rwanda. The concept of grid interconnection and smart microgrid is considered [15], aiming at increasing the self-reliance in both cities of Kigali and other secondary cities of Rwanda [16,17]. The solar is chosen for referring to the higher rate of insolation along the year in Rwanda [18,19], ranging between 4.5 and 5 kW/m^2. The Law No: 21/2011 OF 23/06/2011 governing electricity in Rwanda, restricts the individual or company/institution with electricity production capacity less than 50 kW kilowatts to get the license for injecting power to the grid is putting a curb on augmentation of prosumers and shall be amended [20]. However, for network stability and quality of the supply [21-25], the minimum power rating of grid-connected three-phase inverter available at the market, the license shall be given to any prosumer with generation capacity greater or equal to 3.3kW.

2. PROBLEM STATEMENT

The government of Rwanda is targeting 100% access to electricity by 2024. However, by august 2021, the electricity access was at rate is 65.9%. There is a challenge to cover the remaining percentage of access within two years. The current research analyzes feasibility of transforming ordinary electricity consumers to prosumers, aiming at involving the Rwandan population in electricity generation. The priority of prosumers is satisfying their loads with the self-generation and selling surplus electricity to grid, and only use electricity form grid to supply light loads, when generation is not sufficient or possibly for a limited time a day. The regulation and laws governing prosumers and regulation of converting an isolated grid into a grid-connected could impact the decision to become a prosumer. The prosumers would use solar energy to consume self-generated energy and supply the surplus to the grid, assisting the government in meeting its goal of 100% electrification and reducing CO_2 emissions created by using diesel generators to meet greater residential peak demand [26]. Many researchers did similar researches focusing generally on methods for satisfying load demand and increase the PV market. However, all researchers have not considered the incapacity of some electricity consumers to work as prosumers due to their low income generation. Yet, they did not specify the on/off sequence electrical appliances depending on the capacity of self-generation, load demand and purchase price of electricity from the grid. The current research proposes the way to overcome the aforementioned gap, and solve the problem of low electrification rate in Rwanda. The present research explored the feasibility of transforming the consumer to prosumers looking at electricity purchasing capacity of the Rwandese people, potential investing capacity in solar energy, use of rooftop spaces of building to accommodate solar generators, impact of bidirectional load flow with the existing power network infrastructures.

3. PROSUMERS GENERIC ALGORITHMS

The researchers have proposed various algorithm such as novel optimization algorithm [27], genetic algorithm approach for sizing integrated PV-BESS systems for prosumers [28] and algorithm of power estimator for grid connected PV systems done by Manel [29]. Based on working principles, these algorithms are compared in Table 1. The above listed algorithms have the following gaps: The loads are only households, the impact of commercial and industrial loads is not considered. In addition, the households are not grouped in tiers as per their corresponding power demand. By considering only the satisfaction of the household loads, the possibility to sell surplus generated electricity to grid is ignored.

Table 1. Types of generic algorithms.

Type of Algorithm	Novel optimization Algorithm	Generic Algorithm	Power Estimator for Grid Connected PV Systems
Algorithm Description	Integration of PV and Super-capacitors in the household (residential)	Integration of PV and Battery Energy Storage Systems (BESS) for Prosumers in households (residential)	Maximum Power Tracking (MPPT) for PV array
Function	Optimal management and sizing of each component	Sizing the components	Control strategy to meet MPPT
Application	Self-consumption in Residential	Self-sufficiency generation in Residential	PV array injecting power in grid

The novel optimization is fully adaptable and configurable with residential, commercial, industrial, and power systems for all types of renewable energy sources [27]. This novel algorithm shown on Figure 1 is also applied in the research. Figure 1 shows PV systems, battery and super capacitors supply the load as indicated by p_{s+}^{j} ; p_{b+}^{j} and p_{fcr+}^{j} arrows, and inject the surplus electrical energy to grid as indicated by an upward regulation arrows p_{g+}^{j}. Contrary, when self-generation capacity is low, the load withdraws the missing amount of electrical energy from the grid as shown by the downward arrow p_{g-}^{j}.

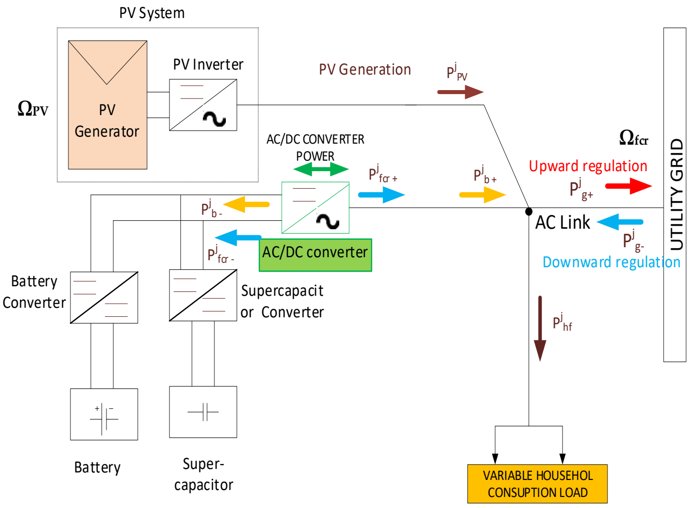


Figure 1. Setup of the PV household-prosumer in the novel power and energy management optimization algorithm [27].

The power imported from the grid has three components as shown on the following equation. The first component p_{hf}^{j} serves to supply the house hold loads, the second and third components p_{b-}^{j} *and* p_{fcr-}^{j} are used to charge battery and super capacitors respectively as presented in Eq. (1).

$$p_{g-}^{j} = p_{hf}^{j} + p_{b-}^{j} + p_{fcr-}^{j} \tag{1}$$

where p_{g-}^{j} is power imported from the grid, p_{hf}^{j} is the power consumed by the load, p_{b-}^{j} is the power used to recharge battery and p_{fcr-}^{j} represents the power to recharge super- capacitors.

All PV systems, battery and super capacitors produce DC voltage, therefore, an inverter converts DC voltage to AC voltage with respect to the grid frequency Ω_{fcr}. The AC/DC converter is reversible and can convert AC voltage to DC voltage and vice versa depending on the input source type. Battery and super-capacitors are connected to DC-DC converters with objective to keep DC voltage level within acceptable limits depending on input voltage rating of inverter or operating voltages of battery and super-capacitor respectively. Figure 2 represents the block diagram considering prosumers with residential, commercial and industrial loads, respectively. The industrial and commercial buildings have much space to accommodate a huge PV array resulting in higher electricity generation capacity, whereas residential buildings have less space. The generated electricity from PV serves to satisfy the local load demand which is drawn as current I_{LD}, sends surplus of electricity to grid. When the PV generation is less than the demand, the grid sends the missing amount of electricity to the loads.

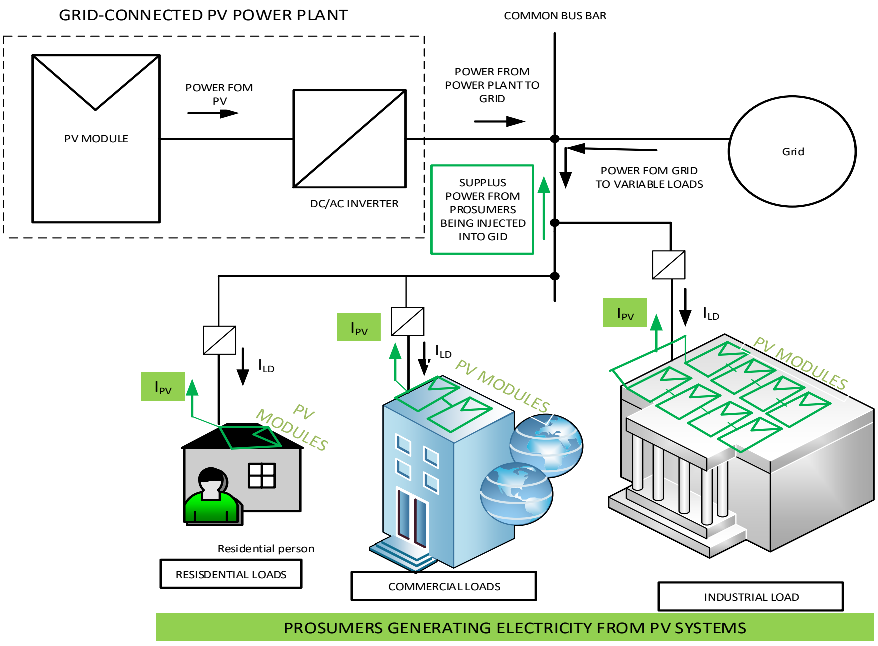


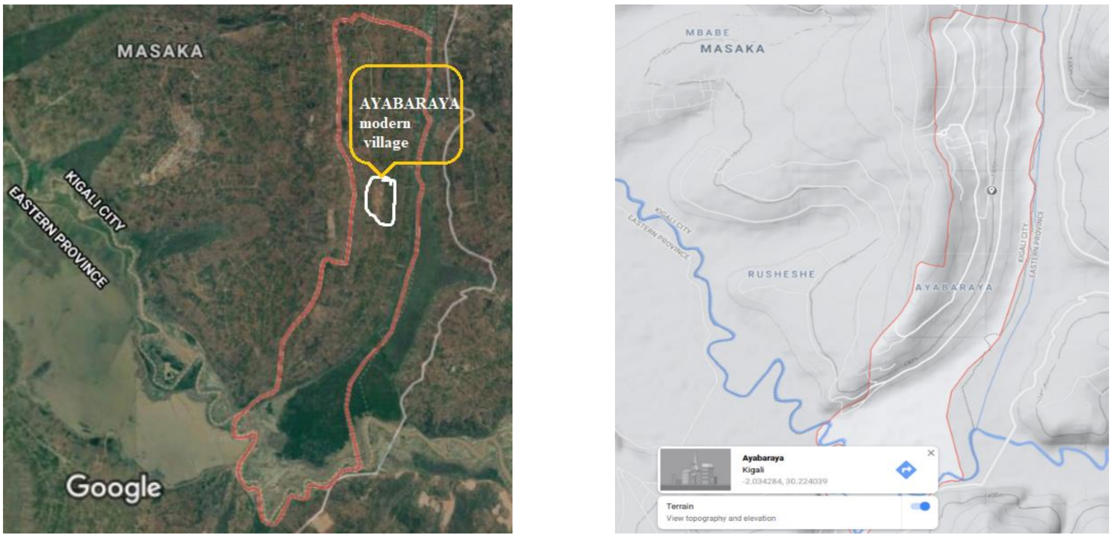
Figure 2. Block diagram of grid connected prosumers in the Ayabaraya Village.

4. AYABARAYA VILLAGE

4.1. Location and Meteorology Data

For the successful implementation of the project, Ayabaraya modern village has been chosen as a case study. The shape of building roofs, the space availability, the solar irradiance and availability of power lines are assessed in this village. The selected site is located in Kicukiro district, Kigali city, Rwanda.

The topography and geographical features of the site are presented in Fig. 3(a,b). Ayabaraya modern village is at 1400 m above sea level. Its additional coordinates are -2.034284 of latitude and 30.224039 of longitude.



(a) (b)

Figure 3. Topography and elevation of Ayabaraya modern village: (a) Topography, (b) location coordinates

4.2. Daily Meteorological Data of Ayabaraya Village

The load curves are assessed aiming at evaluating the required PV system capacity, and installation mode. PVGIS 2016 provided the global horizontal irradiation and ambient temperature as shown in Fig. 4, the blue curved horizontal line presents the day-to-day ambient temperature with average of 20.51 ºC along the year, while the vertical yellow lines represent the available average daily solar insolation in kWh/m^2/day along a year, and it is ranging between 4.5 and 5.5 kWh/m^2/day.

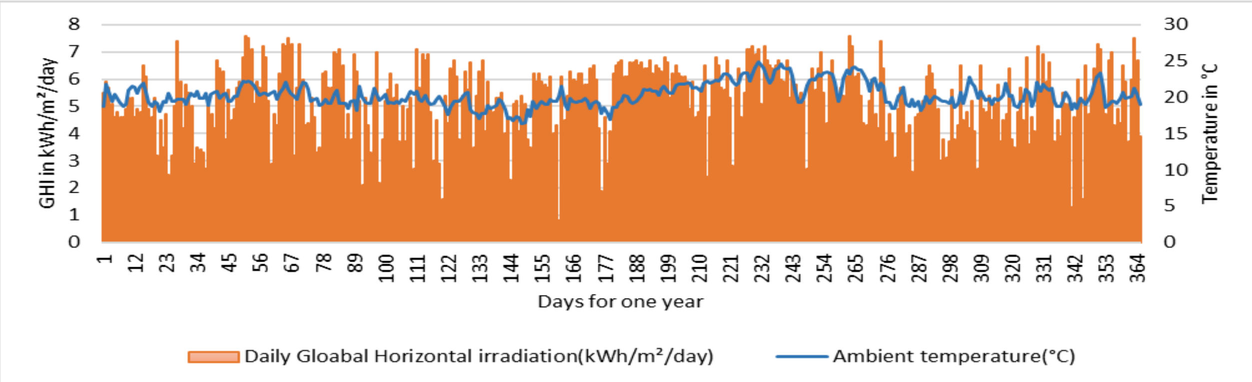


Figure 4. Daily meteorology data for Ayabaraya along a year.

The load profile for domestic house, commercial and industrial buildings at Ayabaraya modem village were collected and classified by Rwanda national electrification plan [30]. The consumers were classified into 5 tiers: The load profile for Tier 1 through Tier 4 are for residential and Tier 5 is for commercial and industrial captive power prosumer set according to their daily energy consumption as well as the type of load [30]. Customers for Tiers 1 and 2 categories have low income henceforth they are not considered as potential prosumers in this current research.

The graphic presentation of load profile for each prosumer and tier category is presented in Figure 5(a-f), where Tier 4 prosumers have high power loads operating during day time, while the loads for the Tier 3 prosumers are mostly turned-on during the night, Tier 5 is classified as commercial prosumer consuming much energy during the day time. In Figure 5(a), a daily load profile of a single prosumer of Tier 4 is shown, whereas Fig. 5(b) present a daily profile of 20 prosumers of Tier 4 either grouped or ungrouped. Fig. 5(c) shows a daily load profile of a single prosumer of Tier 3, whereas Fig. 5(d) shows the daily load profile for 60 prosumers of Tier 3. Either grouped or ungrouped, their load profiles do not change as shown in load profile for Tier 5 (Fig. 5(e,f)), which are commercial and industrial prosumer such as medical health center and grinding-milling machine factory.

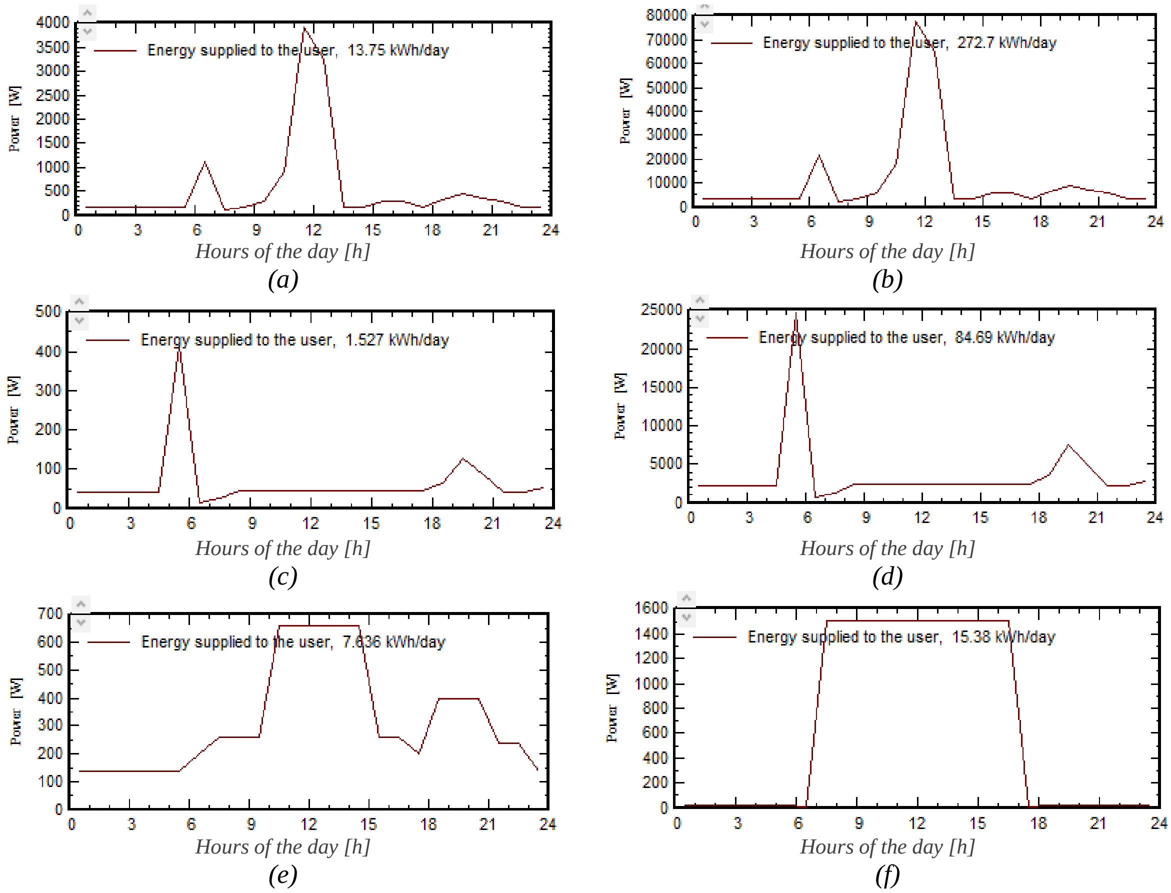


Figure 5. Daily load profile (a) a Single prosumer load profile-tier4 (b Grouped prosumer load profile-tier4 (c) a Single prosumer load profile-tier 3 (d) Grouped prosumer load profile-tier 3, (e) medical health center and (f) grinding-milling machine factory.

5. GRID-CONNECTED PV PROSUMERS SIMULATION AT AYABARAYA VILLAGE

5.1. Simulation Algorithm

The simulation was conducted aiming at controlling the load and electricity surplus injection into grid by use of HEMS. The irradiance varying from 0 to 1600W/m^2 was monitored by a pyranometer as shown on Figure 6. For the simulation work, a Siemens PLC software called Logo comfort was used to simulate the value from the pyranometer sensor and actuate the switches, whereas a PVsyst was used to design, simulate and analyze the whole system with technical and economic effect. The function was proposed to be the output power of PV array and is represented in Eq. (2) as follows:

$$y = xPV_{area}\,\eta_m \qquad (2)$$

With x standing for the irradiance values from the pyranometer; PV_{area} representing the PV array area and η_m the module efficiency which is kept constant. To develop a function that controls the inverter operation, we set the operating conditions of the inverter including power threshold. During the simulation using PVsyst, it was set to 1% of PV array power. Note that the minimum threshold power is 0.5% of PV array power. If the measured irradiance value is less than 30 W/m^2, the grid-inverter cannot operate. The grid acts like a backup and the prosumer consumes electricity from the grid. In contrary, if the irradiance is greater than 30 W/m^2, the grid-inverter starts to operate.

Eq. (3) controls the inverter to start/stop only while Eq. (4) controls on/off for connected prosumers' loads and enables electricity exportation.

$$f(y) = f(x_n, PV_{area}, \eta_m) = \begin{cases} 0 \ , if\ x_1 < Py_0 \\ f(x_1, PV_{area}, \eta_m) \quad , if\ x_1 > Py_0 \end{cases} \tag{3}$$

$$f(y) = f(x_n, PV_{area}, \eta_m) = \begin{cases} 0 \ , if\ x_1 < 30W/m^2 \\ f(x_2, PV_{area}, \eta_m), if\ x_2 < 200W/m^2 \\ f(x_3, PV_{area}, \eta_m)\ , if\ x_3 < 400W/m^2 \\ f(x_4, PV_{area}, \eta_m), if\ x_4 > 400W/m^2 \\ n = 1,2,3,4 \end{cases} \tag{4}$$

Figure 6 is the algorithm incorporating the HEMS, inverter control strategies, and the prosumer load types. The pyranometer sensor plays a great role in HEMS. Figure 7 represents the wiring diagram and PLC configuration of HEMS described in Figure 6. The decision of importing from or exporting electricity to grid depends on the actual irradiance values measured by the pyranometer. The followings are scenarios happening in operation:

If the pyranometer measures irradiance p_y, which is less than 30 W/m^2, then there is no possibility to generate electricity with PV system for inverter safety with respect to load demand at that time. The utility grid acts like a backup for the prosumer, where the electricity is imported from the grid.

If p_y ranges between 30 W/m^2 and 200 W/m^2, PV system generates limited electricity, which satisfies only light load such as lamps, phone charger. Consumers of electricity relies on both PV system and grid to satisfy their maximum electricity demands.

If the irradiance is between 200 W/m^2 and 400 W/m^2, electricity generation from PV increases, henceforth, both lamps and small power outlets are electrified. Depending on actual power demand, less electrical energy is imported from or exported to the grid.

If the pyranometer indicates an irradiance greater than 400 W, the generation is expected to exceed self-consumption capacity of the customer, and thus, more electricity will be exported to grid. In additional to this, the prosumer whose high rated power loads such as air conditioning, electric water heater and cloves washing machines is urged to maximize the self-consumption of their self-generated electricity from PV system.

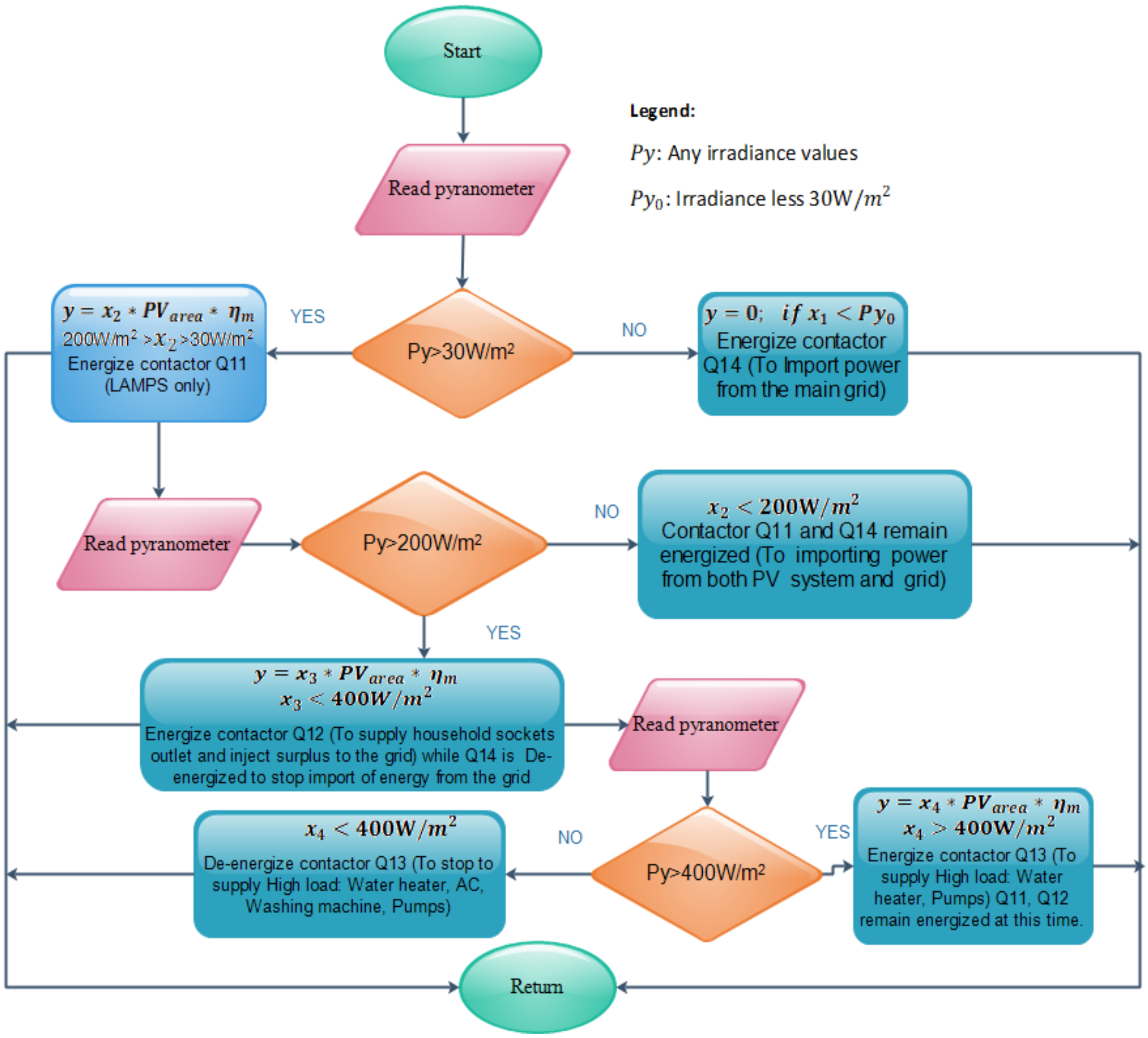


Figure 6. The prosumer algorithm based on the available irradiance.

This algorithm was simulated using PLC Siemens software to integrate HEMS, Figure 7 presents the wiring diagram and PLC configuration. The electricity production, consumption studies were simulated in PVsyst software. The on-grid inverter is turned off, when the irradiance is in range of x_1 and it is turned on when the available irradiance exceeds x_1; at this time the grid acts as backup. If the irradiance reaches the range of x_2, the inverter turns on and energy is drawn from both grid and PV system to supply the light loads such as lamp, phone chargers, radio and TV. During this time, both switches Q11 and Q14 remain energized. Energy is exported to the grid when the irradiance is in range of x_3, the switch Q14 de-energizes to allow a prosumer maximize the self-consumption, and this means no grid power is imported. The high-power loads such as electric water heater, air conditioners, pumps, cloves washing machine and etc., are switched on, when irradiance is in range of x_4 and the switch Q13 energizes via PLC output command. F1, F2, F3, F4, F5, and F6 shown in Figure 7 stand for Protective devices preventing any feeder to be damaged by abnormal current and voltage.

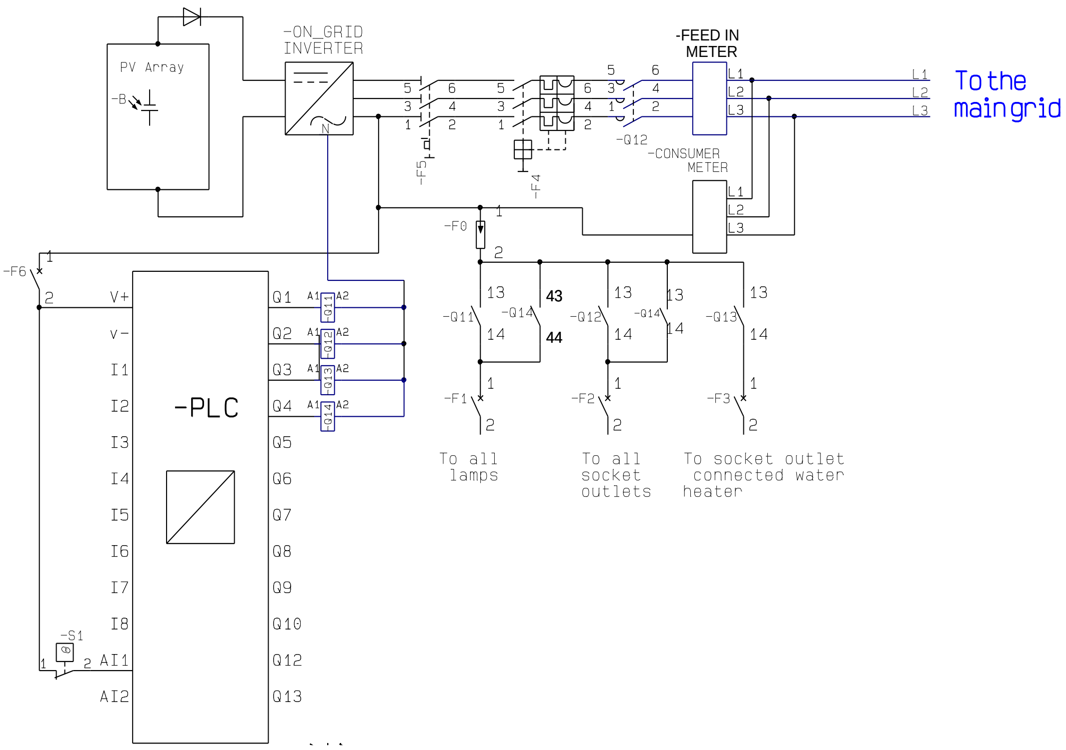


Figure 7. Wiring diagram and PLC configuration.

5.2 Parameters of Used Inverters per Tier Category

The inverters have been selected based on the tier category and the potential power output. Table 2 illustrates the parameters of the inverters including brand, MPPT input, ratings and efficiency of the inverters. All inverters are 3 phase types, henceforth the line-to-line output voltage of each inverter is 400V. The output power ratings vary with category of prosumers. However, the minimum power ratings cannot be less than 3.3kW. Power electronic technology used in an inverter are transformer less with an objective to reduce the size and the cost of the inverter. IGBT and FET semiconductors were preferably used because they have advantages of producing less harmonics and switching power losses.

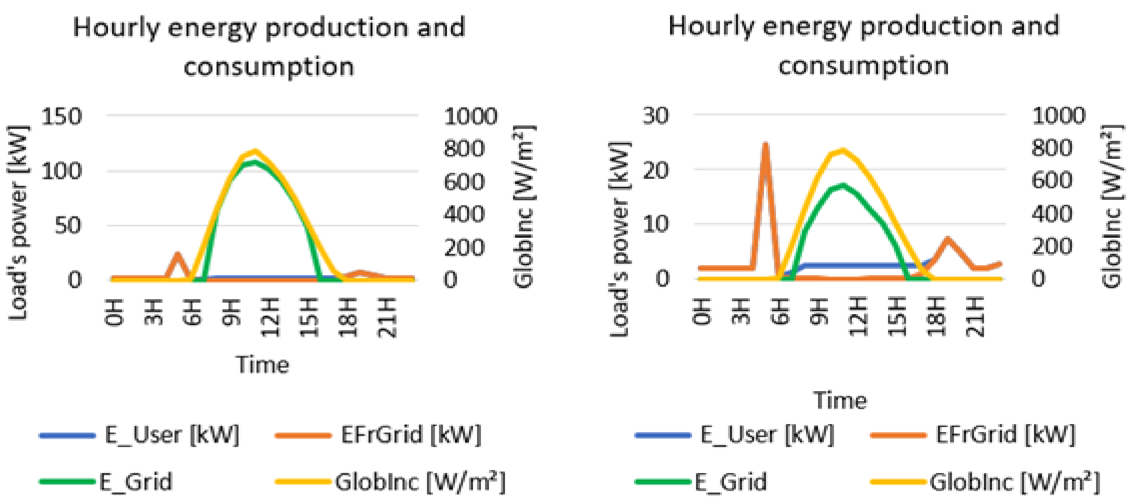
Table 2. Inverter property for each prosumer category

Tiers	Tier 4- SINGLE	Tier 4- GROPED	Tier 4- UNGROPED	Tier 3- SINGLE	Tier 3- GROPED	Tier 3- UNGROPED	Medical Center
	Prosumer Shed Roof House						(Commercial Building)
Brand- Model	INVT Solar tech. BG4KTR (4KW, 3 PHASE with 2 MPPT)	Prime Volt-PV-75000T-U	SofarSolar SOFAR 4.4KTL-X	SofarSolar SOFAR 3.3KTL-X	Huavei Tech. SUN2000-25KTL-US	SofarSolar SOFAR 3.3KTL-X	SofarSolar SOFAR 30000TL-G2
Number of Inverter	1.00	1.00	20.00	1.00	1.00	60.00	1.00
Number of MPPT	2.00	4.00	1.00	2.00	4.00	1.00	2.00
Input Rated power of Grid-tie three-phase inverter (kWac)	4.00	75.00	4.00	3.30	25.00	3.30	30.00
Minimum MPP Voltage	200.00	200.00	160.00	160.00	250.00	160.00	230.00
Maximum MPP Voltage	800.00	1000.00	960.00	960.00	950.00	960.00	960.00
Output (Grid) Voltage	400.00	400.00	400.00	400.00	400.00	400.00	400.00
Nominal AC Power (kVA)	200-800	75.00	4.00	3.00	25.00	3.00	30.00
Maximum Efficiency	98.1%	98.6%	98.0%	98.0%	98.4%	98.0%	98.0%
Power Electronic Technology	Transformerless made with FET	Transformerless made with IGBT					

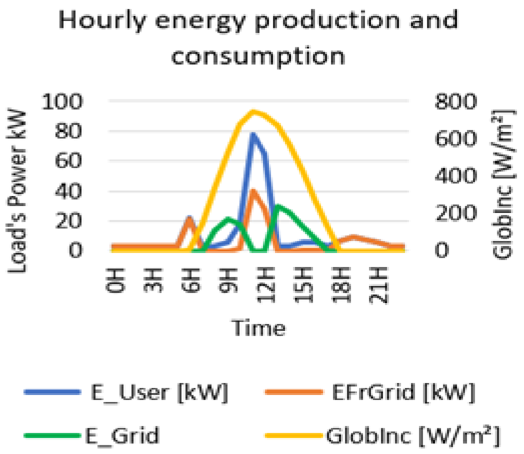
The used inverters are intelligent and have ability to prioritize the self-power consumption of solar energy by prosumers to reduce the dependence to the electrical grid. The inverters can measure the power of PV generation, compare it with maximum power demand from the load, then gives an overview of all relevant energy flows in the loads and grid. In case, the electricity from the solar PV system is not enough to satisfy the maximum power demand, the inverters control should have the capacity to allow electricity from the grid to contribute to the remaining part. Contrary, if the generation capacity is greater than demand, the surplus of electricity is sent to the grid.

6. RESULTS AND DISCUSSION

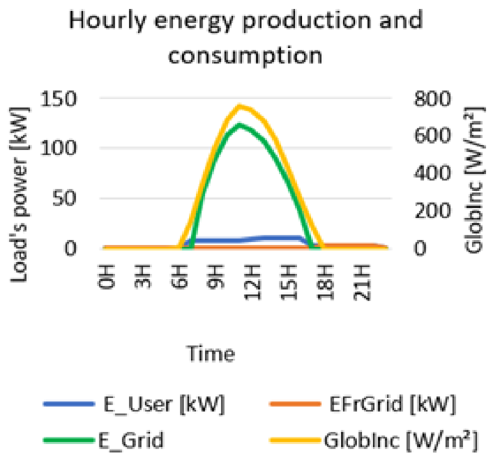
The energy use, imported from and exported to grid depends on the actual appliances supplied, the PV system capacity and the available irradiance at time. Figure 8 shows the energy source type and quantity of energy consumed by user, imported from or injected into grid along a day for different tiers. The amount of energy imported from and sent to the grid varies with irradiance and time. The self-consumption of the prosumer is at high rate at a minimum of 400 W/m^2 of irradiance, specifically from 09:00 up to 15:00. This results into low operation cost of prosumers electrical appliances due to low cost of self-consumption in comparison to the grid electricity tariff. However, it is mandatory to have irradiance 400 W/m^2 for PV prosumers to run heavy loads including water heater, air conditioner, washing machines in order to maximize the self-consumption which is at very low cost. The peak demand caused by high power load cause draws much current exceeding the grid-tie inverter capacity, therefore, both grid and PV system run simultaneously to satisfy the demand. For Tiers 3 and 4, both grouped and ungrouped types, during the low insolation period, prosumers behave like ordinary customers buying electricity from grid. When insolation is at maximum level, prosumers concentrate on satisfying their loads with PV system. For Tier 5, the load is small compared to the generation capacity of prosumers, therefore, they inject more electricity into grid.



(a) *(b)*



(c)



(d)

Figure 8. Daily energy production and consumption analysis with PV prosumer algorithm: (a) tier 3 ungrouped prosumers, (b) tier 3 grouped prosumers, (c) tier 4 prosumers; (d) tier 5 stands for commercial house prosumer.

The legend description for Figure 8 is given as follows: *GlobInc* is the global incident in coll. Plane (the result of the transposition of the irradiance from horizontal to the plane of the array); *E_User* means energy supplied to the user (prosumer); *E_Grid* is Energy injected into grid while *EFrGrid* is energy imported from the grid.

7. CONCLUSIONS

The discussion focuses on the way of transforming electrical consumers living in a common village into prosumers. A bidirectional energy meter is linking the prosumers electricity plant and the grid. The minimum capacity of power of prosumer is 3.3 kW, and can be generated either by a single customer or group of many customers. The scope of amending the law governing electricity in Rwanda is not covered in the current research and will be discussed by other researchers. We suggest that the reverse power flow in the distribution system, voltage stability, power quality, harmonics, and protection that prosumers confront for their on-grid PV installations can be covered in another research. Changing ordinary customer of electricity to prosumers is one way to increase the electricity generation capacity. In smart villages, grouping customers together as a single prosumer leads to low investment for individual person. Ungrouped prosumers produce more annual electricity than grouped prosumers, however, it has high implication cost associated with the required grid-tie inverter and PV modules per individual prosumer. The commercial and industrial buildings are also potential prosumers that use the free available rooftop space to generate more electricity. Looking on the electricity market stability, continuous power supply and power quality factors, it is realized that the prosumers with grid-connected systems are more advantageous compared to off-grid system. The existence of the law accepting energy producer with at least 3.3 kW to inject electricity into grid will increase the number of prosumers leading to augmentation of electivity generation capacity.

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