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Yield Assessment of Off-grid PV Systems in Nigeria

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***Abstract*— Off-grid PV systems are providing critical access to energy services for millions of people throughout the globe. However, optimum sizing of these PV systems still poses a challenge, as inadequate system sizing could result in low system reliability and/or high cost of electricity generated. This paper presents a hybrid method of sizing off-grid PV systems for undefined electricity consumption. It then compares this sizing with off-grid PV systems installed in Nigeria – ranked the most populous electricity-deficit country in the world. The yields of the installed off-grid PV systems are also simulated for four major cities in Nigeria. Results show that for the over 1.5MWp of off-grid PV systems installed in the country, there is a potential 1.11 – 3.04 MWh of unutilised surplus electricity, which can supply 2hours of green electricity to at least 2,000 Tier-2 households during peak demand in the dry hot season. Thus, our hybrid model provides design and operational insight to off-grid PV system optimization.**

***Index Terms*—Photovoltaic systems, Off-grid PV, standalone PV, solar home systems, PV yield**

I. Introduction

Off-grid Solar PV systems are fast paving the way for electricity access in Sub-Saharan Africa (SSA) where approximately 592 million people lack access to electricity. This represents approximately 75 percent of the global population without access to electricity and this figure is likely to increase due to the (electrification) setbacks incurred by the Covid-19 pandemic [1, 2]. In most of these countries, the main technical obstacles to electricity access include aging grid infrastructure requiring extensive reinforcement investment and the limited network coverage of the existing infrastructure [3-5]. Thus, off-grid solar photovoltaic (PV) systems comprising mainly of mini-grids and off-grid solar home systems (SHS) have become increasingly important when considering expediting access within cost constraints for these communities [2]. As of 2018, more than 35 million people gained Tier 1+ electricity service access through standalone home systems or renewable-based mini-grids [1]. Declining costs of small-scale solar PV installations means they are increasingly seen as a practical and cost-effective solution for bridging the electricity-access gap, especially in rural areas which make up approximately 80 percent of the population without access to electricity [2]. However, the optimum sizing of the system components has been one of the major technical challenges regarding the design of off-grid PV systems, especially in rural and developing regions.

In the literature, different methods have been proposed for the sizing of off-grid PV systems but the most commonly used methods are the intuitive and numerical methods [6]. The intuitive method is a simplified calculation of the system components usually based on the worst-case scenario such as the worst month or the average monthly insolation [7]. It is best used for initial system approximation or estimation as it easily results in surplus or deficit solar production. It is also the main method used by many off-grid PV system installers [8]. Numerical methods, also known as simulation-based methods, are further categorised into stochastic and deterministic methods. They give detailed and more accurate sizing by simulating the uncertainties associated with the solar resource and load demand variations. In the stochastic approach, these uncertainties are simulated as hourly demand(s) and insolation data [4, 5] while the deterministic approach makes use of daily averages for both demand and insolation data [9]. The drawback of the numerical method is the large amount of input data required and the long computational time needed to simulate the performance of the system over a wide range of configurations. Hence, heuristics methods have also been proposed in the sizing of off-grid PV systems [10]. These methods are constrained in providing short term solutions that typically oversize the PV system components, to risk mitigate the loss and cost of system reliability and availability.

In the Sub-Saharan country of Nigeria which ranks 1st as the largest electricity-deficit nation in the world with an annual per capita electricity consumption of 157 kWh/capita [11] and over 85 million people lacking access to electricity [1], off-grid solar PV systems are rapidly being deployed with at least 1.5MWp off-grid SHS installed nationwide. Given the country's daily PV power potential of 3.2 – 4.8 kWh/kWp [12], this is an average daily electricity production of 4.8 – 7.2 MWh. However, experimentally measuring and evaluating solar PV yields often involve huge costs and take many years [13], especially in the case of dispersed SHS. It is therefore important to ensure that these off-grid PV systems are properly designed to provide the required energy and minimize losses, especially unutilized, surplus PV generation. This paper presents a hybrid method of sizing off-grid solar PV systems for undefined electricity consumption and compares this sizing with that obtainable in the country. Using the Global Solar Atlas online tool [14], it simulates the expected yields of the installed off-grid PV systems and analyses the surplus (or deficit) PV generation for four major cities in Nigeria. The remaining part of this paper is structured as follows: section II describes/present the sizing of off-grid PV systems and the estimation of household demand when

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demand is undefined; section III presents the yield assessment simulations for off-grid PV systems installed in Nigeria. It also describes the method of surplus yield estimation used, and section IV concludes with the discussions of results and state the further work to be done.

II. OFF-GRID PV SYSTEM SIZING

Off-grid PV system components are usually designed to meet the average daily demand specified by the user. Thus, for any N number of loads to be powered from a stand-alone or off-grid PV system, the daily energy requirement E_{load} is given as:

$$E_{load}\,(\text{kWh}) = \sum_{i=1}^{N}(l_i \times t_i) \tag{1}$$

where l_i is the power rating of each load measured in Watts (W) and t_i – the duration of use in hours. The battery-bank capacity, which defines the minimum battery bank size requirement based on estimated usage, is then given as:

$$E_{Batt}\,(kWh) = (E_{load} \times \text{DA})/(\eta_{inv} \times \text{DoD}) \tag{2}$$

With battery-bank capacity E_{Batt} given in (kWh), E_{load} is the estimated daily demand, and η_{inv} is the inverter efficiency, often given as 90% for most inverters. DA denotes ***days of autonomy*** where the batteries meet the daily demand without being recharged, while battery ***depth of discharge*** (DoD) expressed as a percentage of the rated battery capacity, indicates the maximum amount of charge that can be discharged from a battery. The available site insolation, field temperature, and panel nameplate capacity are all key to the proper sizing of a PV array. This is because the yield of the PV array must supply the required demand and recharge the batteries to a full state of charge. So, the capacity of the PV array measured in kW_p is given as:

$$P_{array} = E_{load}/(\eta_{sys} \times PSH) \tag{3a}$$

$$N_{PV} = P_{array}/P \tag{3b}$$

where P_{array} is the PV array capacity, E_{load} the daily demand to be met, PSH measures the available site insolation per day, and η_{sys} is the PV system efficiency which includes panel conversion losses, shading losses, module mismatch, wiring ohmic losses, temperature losses, inverter losses as well as battery-charging losses. Equation (3b) defines the actual number of PV panels in the array (N_{PV}) which is a function of the panel nominal power – P measured in W_p. Off-grid PV inverters convert the electricity generated and stored in the battery into the (alternating) form used by most household appliances. These off-grid PV inverters are rated by a maximum output ac power (P_{ac}) that is at least 120% of the peak load to be powered, and a maximum input dc power (P_{dc}) that is at least 110% of the installed PV array. Hence, the power ratings (P_{ac}, P_{dc}) of the inverter to be used must be such that:

$$\{(P_{ac}, P_{dc}) | P_{ac} \geq (1.2 \times \sum_{i=1}^{N} l_i) \wedge P_{dc} > (P_{array}/1.1)\} \tag{4}$$

These are the major balance of system (BOS) components sized in line with the required load demand. Other system components include the solar charge controller which regulates the charging of the batteries by the PV array and prevents overcharging. Proper sizing of cables with regards to cable ampacity and voltage drop is also very important. Undersized cables not only clip the electricity yield of the array, but also pose a fire hazard from overheating and insulation breakdown. Therefore, cables should always be sized such that the cable ampacity is sufficiently matched to the maximum output current of the PV array, batteries, and inverter, respectively. Equipment grounding must also be in place to protect from dangerous voltages either from faulty equipment or from lightning strikes.

A. Estimating household demand

The validity of off-grid system sizing depends on the accuracy and completeness of the defined load/demand. When the exact duration of electricity usage is not known as is often the case with first-time electricity users in rural and developing areas, the minimum evening hours stipulated in the World Bank Multi-Tier Framework (MTF) [15] can be used as the minimum demand period. This is because many household appliances are often used in the evenings. Also, the MTF gives the minimum requirements for measuring households' access to electricity across six tiers of access using a combination of energy attributes. Thus, for each tier of household appliances typically used by Nigerian households as shown in Table 1, the daily demand is estimated as the sum of all loads, with peak load assumed to be in continuous use during the evening hours. Consequently, for the four Nigerian cities of Abuja, Kano, Lagos, and Port Harcourt with daily PSH of 5.0, 5.5, 4.2, and 4.0 respectively, the minimum off-grid PV system sizing for the different tiers of households is shown in Table II. This sizing is also based on the available system components in the country.

TABLE I. LOADS PER HOUSEHOLD-TIERS IN NIGERIA [16]

Appliances & wattage	Tier 2	Tier 3	Tier 3	Tier 4	Tier 4	Tier 5	Tier 5
15W LED Lights	4	6	8	10	10	10	12
50W Fan	1	2	3	3	3	2	4
120W TV	1	1	1	2	1	1	2
Gadgets (20W lot)	1	1	1	1	1	1	2
Sound System (60)	-	1	1	2	1	1	2
200W Small Fridge	-	1	-	-	-	1	1
300W Large Fridge	-	-	1	1	1	1	1
800W Microwave	-	-		1*	1	1	1
400W Deep freezer		-	-	-	-	1	1
1.5kW Washing machine	-	-	-	1*	1*	1*	1*
750W Water pump	-	-	-	1*	1*	1*	1*
1kW Air-conditioning Unit	-	-	-	-	-	-	1*
Peak load (W)	**250**	**590**	**770**	**980**	**1,600**	**2,150**	**2,480**

* used during daylight sunny hours only

B. Comparison with actual installations

Table III shows the sizing of the off-grid PV systems installed for the same tiers of households in Nigeria. A comparative analysis with the sizing in Table II shows an actual similarity in battery sizing, except for the largest Tier-5 household sized with ten 200Ah/12V batteries (24 kWh battery-bank). However, there is a sharp contrast in PV array sizing where the PV array sizes are observed to be constant for the different tiers of households, irrespective of location. The array capacities are also observed to be twice the peak load served and range from 0.5 – 5 kWp for the smallest to largest households, respectively. This intuitive method of PV array sizing is based on the premise that the array's instantaneous yield should power the instantaneous peak load after derating for field conditions, irrespective of location. This can easily result in a surplus or deficit yield production.

TABLE II. OFF-GRID SHS SIZING FOR HOUSEHOLDS IN NIGERIA

Load and system sizing		Tier 2	Tier 3	Tier 3	Tier 4	Tier 4	Tier 5	Tier 5
Load/ Energy Audit	Peak load (W)	250	590	770	980	1,600	2,150	2,480
	Time of use (hrs)	2	3	3	4	4	4	4
	Daily Energy (Wh)	**500**	**1,770**	**2,310**	**3,920**	**6,400**	**8,600**	**9,920**
Battery sizing	Battery-Bank (Wh)	1111.11	3933.3	5133.33	8711.1	14222.2	19111.1	22044.44
	(200Ah/12V)	**1**	**2**	**2**	**4**	**6**	**8**	**9**
Abuja (5.0PSH)	PV Array (Wp)	153.8462	544.6154	710.7692	1206.154	1969.231	2646.154	3052.308
	# of Panels (250W)	**1**	**2**	**3**	**5**	**8**	**11**	**12**
Kano (5.5PSH)	PV Array (Wp)	139.86	495	646.154	1097	1790.21	2406	2774.82
	# of Panels (250W)	**1**	**2**	**3**	**4**	**7**	**10**	**11**
Lagos (4.2PSH)	PV Array (Wp)	183.15	648.35	846.15	1435.897	2344.32	3150.18	3633.7
	# of Panels (250W)	**1**	**3**	**3**	**6**	**9**	**13**	**15**
Port Harcourt (4 PSH)	PV Array (Wp)	192.31	680.77	888.46	1507.69	2461.54	3307.69	3815.39
	# of Panels (250W)	**1**	**3**	**4**	**6**	**10**	**13**	**15**

TABLE III. SIZES OF INSTALLED OFF-GRID SHS IN NIGERIA [16]

Household Tiers	***Tier 2***	***Tier 3***	***Tier 3***	***Tier 4***	***Tier 4***	***Tier 5***	***Tier 5***
Peak load (W)	250	590	770	980	1,600	2,150	2,480
Battery-Bank (Wh)	2,400	4,800	4,800	9,600	14,400	19,200	24,000
(200Ah/12V)	**1**	**2**	**2**	**4**	**6**	**8**	**10**
PV Array (Wp)	500	1,000	1,500	2,000	3,000	4,000	5,000
# of Panels (250W)	**2**	**4**	**6**	**8**	**12**	**16**	**20**

III. OFF-GRID PV YIELD ASSESSMENT

The installed off-grid PV systems are therefore analysed for their electricity yield and to determine any unutilised (surplus) yield. The electricity yield of each installed PV system can be numerically estimated/determined using Equation (5):

$$PV\ Yield\ (kWh) = P_{array} \times \eta_{sys} \times PSH \qquad (5)$$

where P_{array} denotes the PV array size in kW_p, η_{sys} denotes the off-grid system efficiency often estimated as 65% [8] and the available site insolation is indicated by PSH. PV simulation tools like the publicly available Global Solar Atlas can also be utilised to simulate the yields of the installed off-grid PV systems. This is an online tool that provides an overview of the solar energy potential for a site or region. It also provides reliable introductory-level data including month by hour (12x24) PV electricity yield estimates [12]. Fig. 2 shows the simulated electricity yield per kWp of PV systems installed in Abuja, Kano, Lagos, and Port Harcourt. Kano city has the highest yield with daily electricity production of 3.91 – 4.91 kWh/kWp in the rainiest and sunniest month, respectively. This is followed by Abuja with daily yields of 3.07 – 4.79 kWh/kWp, Lagos with daily yields of 3.16 – 4.23 kWh/kWp, and Port Harcourt with daily yields of 2.856 – 3.622 kWh/kWp. These results also show a conversion efficiency of approximately 81% compared to the 65% used in Equation (5). This is because the online tool does not include the battery-system losses observed in off-grid PV systems with batteries.

A. Assessment of surplus PV yield potential

The surplus PV generation is also estimated by subtracting the daily demand of the households from the yield of their respective PV systems. In this study, two maximum daily demand profiles based on the battery depth of discharge (DoD) are defined. The 50% DOD demand profile represents the maximum quantity of electricity that can be consumed from the batteries daily. The 80% DOD maximum demand profile indicates the maximum (permissible) amount of electricity that can be consumed from the installed battery-banks without damage to the batteries.

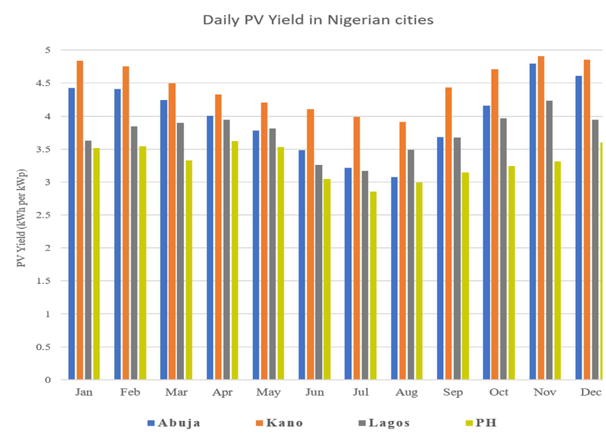

Figure 1. PV yield per kWp of SHS installed in Nigeria

1) At maximum demand of 50% Battery DOD

Fig. 3 shows the surplus PV generation for the off-grid PV systems, after the maximum demand consumption of 50% battery DOD. The simulation results show that in the dry sunniest month of November, excess yields of 1.912 kWh/kWp, 2.026 kWh/kWp, 1.353 kWh/kWp, and 0.742 kWh/kWp can be achieved in Abuja, Kano, Lagos, and Port Harcourt, respectively. These unutilised excess yields – if traded on a local P2P electricity market/exchange – have the potential of powering at least three additional Tier-2 households; except for Port Harcourt city where the excess yield per kWp can only power/supply one additional tier-2 household. This means that for the over 1.5MWp off-grid PV systems installed in the country, there is a potential 1,110 – 3,040 kWh of unutilised electricity capable of supplying two hours of electricity to at least 2,000 additional Tier-2 households in the evenings/night-times. In the rainy months of June to September where the demand and insolation are at the lowest in the country, the 1.5kWp PV system is the only installation in Port Harcourt with an excess yield. This is because the array of the 1.5kWp PV systems are slightly oversized for their households' demand, thus the excess yield of 1.404 kWh. However, excess yields of 0.192 kWh/kWp, 1.029 kWh/kWp, and 0.284 kWh/kWp can still be generated (this season) in Abuja, Kano, and Lagos, respectively. These can also supply an additional 1 – 2 Tier-2 households in the respective cities.

2) At maximum demand of 80% Battery DOD

Fig. 4 shows the surplus yield generation when daily consumptions are at a maximum 80% battery DOD. Results show that the daily PV yields are mostly incapable of supplying this demand; hence the deficit yield productions shown as negative yields. As seen in the figure, regions with a low solar resource like Lagos and Port Harcourt are most affected, as the installed PV arrays in these cities are incapable of generating the required electricity. However, the 1.5kWp off-grid PV systems being slightly oversized for their demand can generate an average surplus of 1kWh and 0.5 kWh for Lagos and Port Harcourt, respectively. The same size of PV arrays/systems installed in regions of high solar resource availability (like Kano) perform better as they generate an average surplus yield of 0.21 kWh/kWp during the dry sunny season, while the 1.5kWp PV systems generate an average yield of 2.08 kWh all through the year. Similarly, a surplus yield of 0.18 kWh/kWp was observed in the peak sunny month of November in Abuja, except for the 1.5kWp off-grid PV system which generates an average excess yield of 1.7 kWh during the dry season. If traded on a local P2P electricity market, these excess PV yields (especially from the 1.5kWp PV systems) can supply an additional one to two Tier-2 households in Port Harcourt and Lagos, while powering three to four additional Tier-2 households in Abuja and Kano, respectively.

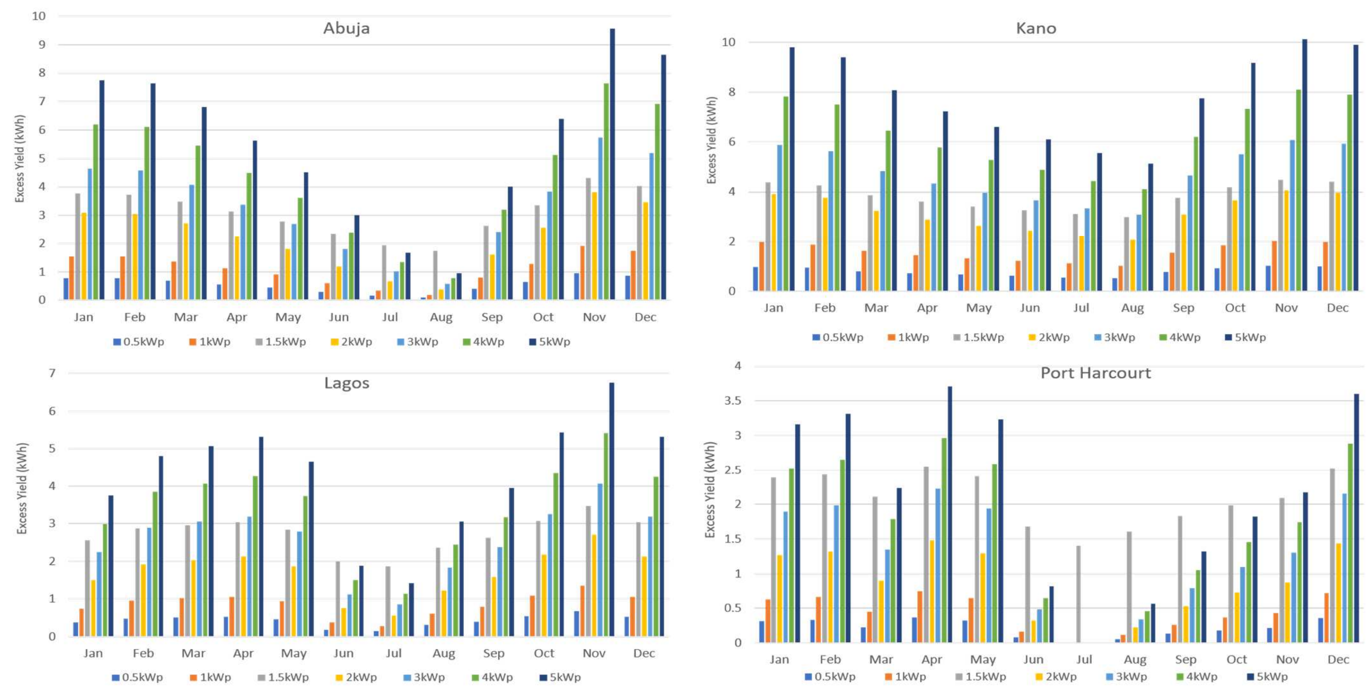

Figure 2. Surplus PV Yields from SHS installed in Nigeria, after maximum demand of 50% Battery DoD

IV. Conclusions

This paper developed a methodology for sizing off-grid PV systems and assessing the average yield production when the daily electricity consumption is undefined. It also presented a method of evaluating the surplus yield potential for off-grid PV systems by specifying two maximum daily demand profiles, based on battery depth of discharge (DOD). The sizing of off-grid PV systems for different tiers of households commonly found in electricity-deficit countries like Nigeria was also presented and results compared with actual systems installed in Nigeria. An assessment of the surplus yield production showed that at a maximum consumption of 50% battery DoD, the surplus daily yield generated is approximately 1.912, 2.026, 1.353, and 0.742 kWh/kWp for Abuja, Kano, Lagos, and Port Harcourt cities, respectively. On the contrary, a shortfall in yield production was observed when the daily maximum demand was at 80% battery DOD, except for the 1.5kWP off-grid PV systems. These systems being slightly oversized, generated a surplus yield of 1.7, 2.08, 1.0, and 0.5 kWh/kWp for Abuja, Kano, Lagos, and Port Harcourt cities, respectively. This goes to show that an inaccurately sized off-grid PV system generates losses in the form of surplus unutilised electricity or system reliability. Furthermore, the surplus yields per kWp generated have the potential of powering at least three additional Tier-2 households, especially during the dry season when both the solar resource and demand are high. Thus, for the over 1.5MWp off-grid PV systems installed, there is a potential 1.11 – 3.04 MWh of unutilised electricity, which can supply two hours of green electricity to at least 2,000 additional Tier-2 households in the evenings/night-times of the dry hot season when demand is high. Further work to be done includes the modelling of a peer-to-peer (P2P) local electricity exchange where these surplus yields can be negotiated amongst peers in the community/network.

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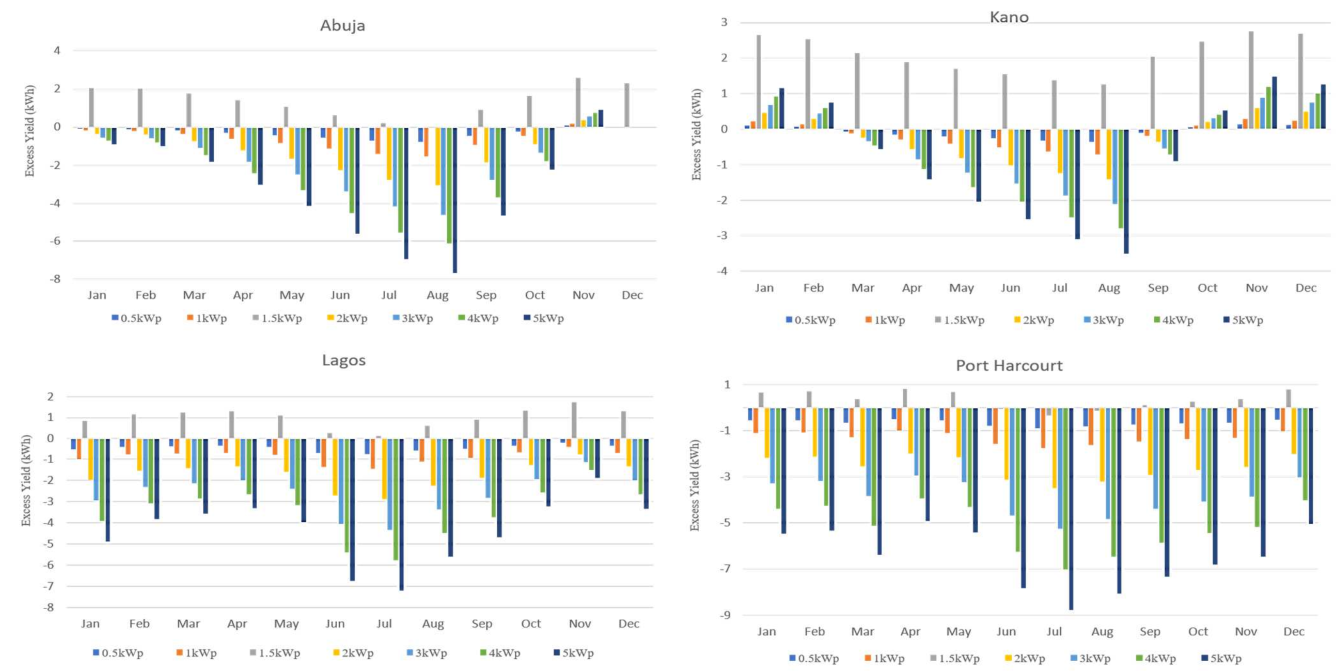

Figure 3. Surplus PV Yields from SHS installed in Nigeria after maximum demand of 80% Battery DoD

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