A Biased Load Manager Home Energy Management System for Low-cost Residential Building Low-income Occupants

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Abstract
This research paper presents the development of a biased load manager home energy management system for low-cost residential building occupants. As a smart grid framework, the proposed load manager coordinates the operation of the inverter system of a low cost residential apartment consisting of rooftop solar photovoltaic panels, converter and battery, and provides a platform for discriminating residential loads into on-grid and off-grid supply classes while maximizing solar irradiance for optimum battery charging and improving consumer comfort from base levels. Modelled in a Matlab simulation environment, the system incorporates a converter system for maximum power point tracking using a hopping algorithm, with a dedicated mechanism for smart dispatch of specified loads to meet the users' comfort based on the priority ranking of the loads. Results obtained indicate a 34% reduction in electricity cost, 26% reduction in carbon emissions and a 4% increase in comfort level for the photovoltaic/battery/utility option compared to the utility only option. The results further show that cost is a major factor affecting the users' comfort and not necessarily dispatch of appliances to meet energy needs. The research can be useful for encouraging the adoption of the photovoltaic/battery/utility option by low/middle income energy users in developing countries.

Keywords: - low-cost residential buildings, BLM-HEMS, hopping algorithm, consumer comfort, return on investment, carbon footprint

Highlights
- Presents a load manager for low-income residential homes.
- Evaluates the contribution of the load manager in improving household comfort.
- Evaluates associated reduction in carbon emissions and electricity cost.
- Discusses and presents solution to the challenge of adopting the load manager.

1.0 Introduction
Energy (electricity) access is still a major problem for over 800 million people in sub-Sahara Africa (SSA) and South Asia. In Nigeria, over 80 million people are still without

access to grid electricity. Various reasons have been attributed to the inability to extend the grid and increase electricity access; cost of grid expansion, ageing transmission networks, mounting debts and poor generation. In arguing on the need for increase in electricity access, its impact on the socio-economic life of consumers has been highlighted with energy (electricity) poverty linked to actual poverty. Electricity access has also been opined to be a major factor that determines the level of success of the millennium development goals (MDGs) [1]. The sustainable development goals (SDGs) as a successor to the MDGs has goals 7 and 11 aimed at ensuring affordable and clean energy and building sustainable cities and communities. In achieving goals 7, electricity access to affordable and clean energy is being targeted to reduce emissions and make cities safe and sustainable (goal 11) by 2030 [2].

Solar home systems (SHSs) have been a much-researched alternative proposed for off-grid and on-grid homes. In Brazil for example, a study on the economic and technical advantage of domestic solar hot water systems (DSHWS) was conducted in [3] where it was discovered that annual savings on electricity bills was about 38%. Similarly, [4] conducted a survey across Uganda and Kenya where it was discovered that the adoption of solar PV systems has led to reduced usage of kerosene (for lighting) and reduction in phone charging outside of homes. In a review work by [5], the utilization of solar thermal collectors vary across regions with major uses including district heating, process heating, swimming pool heating etc. As a scalable alternative, homes could purchase configurations of photovoltaic (PV) panels, batteries, converters and inverters that meet their specifications (cost, capacity, number of supply days without sunshine etc.). Studies have also been conducted on the integration of SHSs with the conventional grid for offsetting peak loads leading to feed-in-tariffs (FiTs) systems that compensate consumers for electricity sold to the grid [6]. In managing these SHSs, various home energy management systems (HEMs) have also been proposed. While the incorporation of SHSs in developed economies (Europe, North America, Australia, Singapore, Japan) is mainly to improve the penetration of renewable energy and robustness of the electricity grid in the developed economies, it serves a different purpose in Nigeria. Due to the peculiarity of electricity supply in Nigeria (frequent blackouts and grid collapse, low grid coverage network, ageing generation, transmission and distribution network, low number of metered households etc.), SHSs is often deployed as an alternative to grid supply.

Based on the study in [7], about 69% of Nigerians are poor (using the baseline of 55000 Naira, $180.33 yearly income). Table 1 presents the absolute poverty measure for 2003/2004 and 2009/2010 across Nigerian states cutting across the geo-political zones in Nigeria. The baseline yearly earning used in 2003/2004 was about 29000 Naira ($95.08). The breakdown of the average monthly expenditure of households in the different geo-political zones within Nigeria on gas, electricity, petrol and diesel is presented in Table 2 [8] while Table 3 presents a summary on the frequency of electricity blackouts across the geo-political zones in Nigeria [9].

Across the states of interest, expenditure on electricity monthly constitutes 4.42% (Abia), 2.03% (Borno), 4.7% (Edo), 2.78% (Katsina), 2.76% (Kogi) and 5.9% (Lagos) of the total monthly expenditure of households. The percentage values however must not be used in ranking states. This is because, in actual monetary terms, purchasing power and actual expenditure of households vary across the geo-political zones. For example, while households in Lagos spent 13105 Naira ($43) monthly on electricity, it was 9972 Naira ($33) in Abia, 8152 Naira ($27) in Edo, 5401 Naira ($18) in Kogi, 2216 Naira ($7) in Borno and

2667 Naira ($9) in Katsina. In the use of alternative electricity sources, Lagos state (considering our states of interest) has over 26% of its households having generator as an alternative [10] with only 68% of its households using the grid as their only source of electricity. Solar PV penetration for Lagos according to [10] is put at 0.2% of its population. The consequence of the high penetration of petrol and diesel generators within Lagos is high carbon footprint since it has been generally established that the residential and building sector accounts for over 40% of global energy consumption [11].

The advent of SHSs has inadvertently increased discussions and research on HEMs due to the increasing need to match supply with demand. Owing to the variability and stochastic nature of weather elements, HEMs have proven to be a viable platform for ensuring that SHSs are well utilized to guarantee consumer comfort and satisfaction. An energy flow management algorithm was presented in [11] for a grid-connected PV system that incorporated battery storage while [12] designed and tested a HEMs integrating a learning prediction algorithm that was based on neural-network for forecasting power production of a house's solar PV plant and its power consumption across a time span. The effect of sending feedback on previous energy consumption to households was also evaluated by comparing consumption drop/increase across a time frame in [13] where a 3.4% drop in energy (electricity) consumption was observed. Data error impact on HEMs was studied in [14] while [15] presented a conceptual distributed integrated energy management (diEM) system for residential buildings. The aim of [15] is to minimize operational energy cost for households through load shifting to maximize renewable energy power produced. A life cycle assessment was conducted by [16] where the environmental impact of HEMs in terms of their potential benefits and detrimental impacts was evaluated. A negative energy payback time was computed for home automation devices due to the energy consumption of smart plugs. Foresee™ was presented by [17] as a user-centred HEMs for optimizing its operations to achieve efficiency and utility cost savings. Abushnaf et al. in [18] made extensive arguments on the ability of HEMs to optimize residential building energy use especially in tackling the problems of green-house gas emission and energy wastage. Further reading on HEMs can be found in [19].

The objectives of HEMs vary. For example, in [20], a project is presented to increase the monetary value of photovoltaic (PV) solar production for residential application with the aims of reducing the cost of electricity and improving the local utilisation of solar PV. Also, in [21], game theory was used in formulating an energy consumption scheduling game to minimise energy costs and reduce the peak-to-average ratio of the total energy demand. Similarly, in [22], the objective of HEMs was improved well-being/comfort while [23] describes the development of a control system for demand-side management in the residential sector with the incorporation of embedded generation. The utilization of car battery discharging in achieving peak shaving was studied in [24] with up to 64% reduction in peak demand achieved. In [25], the problem of optimally scheduling a set of appliances at the end user premises for a reduction in electricity cost while taking into consideration such factors as comfort and timeliness was solved, while reduced cost and optimized consumption pattern were the objectives of HEMs in [26]. Also, HEMs sought to optimize consumption and improve well-being in [27], while reduced cost, emissions and optimized consumption were the objectives of HEMs in [28]. Furthermore, various scheduling approaches have been reported in literature. For example in [29], simple linear programming was used for an optimisation model in adjusting the hourly load level for a given consumer in response to hourly electricity price. The aim was to maximize the utility derived by the consumer subject to a minimum daily energy consumption level. Also, simple linear programming was also applied in [30] to achieve a trade-off between minimizing the electricity payment and minimizing the waiting time for the operation of each appliance in a household under real time pricing. A modified and mild intrusive genetic algorithm (MMIGA) was applied in [31] for the optimal allocation of load in an off-grid household while MMIGA was applied in [32] for optimally scheduling appliances for a grid connected house considering the user preference. In [33], a constrained multi-objective optimisation problem (CMOP) is formulated and solved using evolutionary algorithms (EAs).

The localization of HEMs in Nigeria has been extensively researched in literature. In [31], the authors designed a load manager for optimizing the dispatch available solar PV power among competing loads for an off-grid house. While the proposed load manager aimed at optimizing available power, issues such as comfort and relevance of dispatched goods to overall user satisfaction were not considered. An improvement was provided in [32] where the authors developed an interface for on-grid homes in managing their electricity consumption with the influence of grid interruption and for varying daily budget. While comfort result was not evaluated in [32], user satisfaction was evaluated in [34] and used in dispatching loads. The concept of scalable SHSs for various households was also considered in [35] with various hybrid configuration of electricity sources evaluated for cost, emissions and energy dumping in [36]. A load manager utilizing mixed integer linear programming for improving the comfort level of households utilizing PV/battery under intermittent solar power was proposed in [37] while a rule based load management scheme for a stand-alone PV/battery system in a residential building was developed in [38].

A critical observation of the literature on HEMs application and management in Nigeria shows that none has been able to present a comprehensive management system for low/middle income homes, especially in addressing the issue of PV/battery sizing based on the financial level of the household and synergizing the PV/battery system operation with the grid to dispatch specific loads at specific times. Furthermore, none of the researched literature on HEMs management in Nigeria has presented a complete report on the potential payback period carbon footprint reduction (when compared with other alternatives) and energy cost/kWh utilizing PV/battery/utility for a low/middle income household.

This work thus models and investigates the PV/battery/utility option for a low-cost residential house that incorporates the BLM-HEMS for smart load dispatch, battery management and intelligent converter control, and compares its associated statistics such as electricity cost reduction, comfort/satisfaction level improvement, carbon footprint reduction and return on investment (RoI) with the Utility only option and Utility/generator option (without BLM-HEMS). In doing this, this work advocates for the adoption of the PV/battery/utility option as a viable alternative to mitigate grid interruption and improve the satisfaction level of low/middle income households with cost constraints.

In this paper, we acknowledge that the adoption and utilization of HEMs faces critical challenges in Nigeria due to the rising cost of electricity and frequent blackouts in the country. However, the high prevalence of poverty and low purchasing power of Nigerian households mean that most PV/battery systems are usually undersized for load and number of days without sunshine. The demerit of such sizing means that conventional HEMs fail to meet user expectations in terms of load management, comfort/satisfaction level, cost reduction, reduction in carbon footprint etc. Also, most HEMs are for off-grid homes or application. The disadvantage of off-grid applications means that the advantage of lower electricity cost from the utility (when available) cannot be leveraged during insufficient PV/battery capacity.

This paper presents BLM-HEMS which offers households with grid supply the opportunity of leveraging the advantage of low electricity cost from the utility in dispatching their loads along with the PV/battery. This configuration – PV/battery/utility being advocated in this paper incorporates BLM-HEMS in MPPT tracking, efficient battery management and smart load dispatch to improve household comfort, reduce electricity cost and carbon footprint and guarantee the repayment of the initial purchase and installation costs within 25 years of operation based on the evaluated yearly savings. The proposed solution aims at tackling the problem of low comfort/satisfaction level often encountered from households with undersized PV/battery systems with utility (grid) availability.

The rest of the paper is organized as follows; Section 2.0 presents the methods including modelling of the PV panels, converter design, battery management and load dispatch while the results and discussions including sensitivity analysis and policy recommendations are presented in Section 3.0. The paper is concluded in Section 4.0.

2.0 Methods

In justifying the proposed methods, we first justify its need by evaluating a comfort expenditure plot (figure 1) for both the use of the utility and the generator (independently) in meeting the needs of a household.

Table 4 presents the daily utilization profile of loads (LP1 – LP6). The computation of the monthly cost of dispatching loads (LP1 – LP6) assuming uninterrupted power supply is shown in equations (1) – (3). As seen from equations (1) – (3), about \$14.43 representing about 33.5% of the average monthly expenditure on electricity is expended in dispatching LP1 – LP6 (if grid is assumed available throughout) monthly.

Compensating for poor power supply and frequent grid interruptions, a fraction of $C_M^{\cos t}$ (moderated monthly electricity cost) is usually expended. Table 5 presents the Needs – Appliances Matrix for a low-cost house under consideration. The loads (appliances) under consideration (LP1 – LP6) are classified based on their ability to dispatch the need class (lighting, cooling, entertainment and others) being considered. For example, LP2 (indoor lighting) and LP3 (outdoor lighting) are the only appliances (loads) that can dispatch the lighting (indoor and/or outdoor) need of the house at any time. The associated costs of unmet hourly load due to power outage and the hourly cost of dispatching loads LP1 – LP6 using the Utility only options are presented in Table 6. Equation (4) provides the computation of the associated utility-based comfort level of the household under consideration. The next best alternative to a middle-class home electrification is the petrol generator. Table 7 presents some basic facts associated with a typical 6.5 kVA petrol generator which is predominant among homes surveyed around the low-cost housing estate.

Assuming full dispatch always for LP5 and LP6, then @ = 1 and & = 1. For hours 1 – 7 and 17 – 24 during weekdays and weekends and $df = 0.85$, total daily consumption (T_{DC}) without df moderation amounts to 8087 Wh.
By incorporating df ,

$T_{DC}^{M} = T_{DC} \times df$ (1)

This implies that $T_{DC}^{M} = 8087 \times 0.85 = 6873.95 Wh/day$

Assuming 30 days/month,

$MC = T_{DC}^{M} \times 30 = 6873.95 \times 30 = 206218.50 Wh$

Converting to kWh results in $MC = 206.22 kWh$

$E_{PC} = \$0.07 / kWh$ (2)

This implies that $C_{M}^{\cos t}$ is evaluated as;

$C_{M}^{\cos t} = MC(kWh) \times E_{PC}$ (3)

$C_{M}^{\cos t} = 206.22 \times 0.07 = \$14.40$

Where, T_{DC}^{M} is the demand factor moderated total daily consumption (Wh or kWh), MC is the monthly electricity consumption (Wh or kWh), E_{PC} is the electricity cost per unit (\$/kWh) and $C_{M}^{\cos t}$ is the monthly cost of T_{DC}^{M} (\$). j is the index of the needs-set J such that $J = \{N-1, N-2, N-3, N-4\}$, $H_{i,j}$ is the hour i demand for need j, $C_{i,j}^{utility}$ is the utility cost of dispatching need j for hour i and $C_{i,j}^{Total-unmet}$ is the baseline comfort cost of need j for hour i. The comfort level for dispatching need j in hour i using the utility is $U_{i,j}^{utility}$. It must be pointed out that the $C_{i,j}^{unmet}$ values for computation shown in Tables 6 and 8 assume full dispatch of all appliances related to the needs (N-1, N-2, N-3 and N-4) and is $C_{i,j}^{Total-unmet}$.

In the results, the actual values for $C_{i,j}^{unmet}$ would be computed based on the appliances selected by the user and eventually dispatched for the hour under consideration. While it is expected that the computation of $C_{i,j}^{unmet}$ would directly sum the associated comfort costs for unmet loads intended to be dispatched, $C_{i,j}^{unmet}$ sums up the comfort cost of dispatched loads. The reason for this is because the baseline comfort of the household is assumed based on all the loads associated with a need being dispatched. Thus, equations (4a) and (4b) aim at penalizing the differential established by $C_{i,j}^{Total-unmet} - C_{i,j}^{unmet}$.

The computation of $U_{i,j}^{utility}$ in the case of full dispatch is as follows:

Given baseline comfort level $U_{baseline}$ to be 5, then

$$U_{i,j}^{utility} = U_{baseline} - \frac{C_{i,j}^{utility} - C_{i,j}^{unmet}}{C_{i,j}^{unmet}} \quad (4a)$$

However, when all the appliances scheduled for dispatch in an hour to meet any need are not all dispatched eventually due to PV/battery for instance being insufficient, then equation (4a) is modified to become equation (4b) as:

$$U_{i,j}^{mtd} = U_{baseline} - \frac{C_{i,j}^{mtd} - C_{i,j}^{unmet}}{C_{i,j}^{Total-unmet}} \quad (4b)$$

Such that $C_{i,j}^{unmet} \leq C_{i,j}^{Total-unmet}$ and for fixed $C_{i,j}^{mtd}$, as $C_{i,j}^{unmet} \rightarrow C_{i,j}^{Total-unmet}$, $U_{i,j}^{mtd}$ increases, where $mtd = \{utility, PV/battery/utility, utility/generator\}$, $C_{i,j}^{unmet}$ is the sum of the comfort cost of the loads dispatched for the hour and that were intended to be dispatched, $C_{i,j}^{mtd}$ is the hourly cost of dispatching electricity for any *mtd* while $C_{i,j}^{Total-unmet}$ is the cumulative/baseline comfort cost for any need ($0.13 for N-1, $0.05 for N-2, $0.02 for N-3 and $0.05 for N-4). Table 9 presents the comfort based cost for each appliance which is used in computing $C_{i,j}^{unmet}$. It is observed from Table 9 that N-1 need has the highest $C_{i,j}^{Total-unmet}$ of $0.13 followed by N-2 ($0.05) and N-4 ($0.05) with N-3 having the lowest at $0.02. The build-up of $C_{i,j}^{Total-unmet}$ for N-1, N-2 and N-4 is based on their sub-units (LP2(1) – LP2(6), LP3(1) – LP3(2), LP4(1) – LP4(3), LP5(1) – LP5(3) and LP6(1) – LP6(2)). We can thus infer based on $C_{i,j}^{Total-unmet}$ for the various needs (N-1, N-2, N-3, N-4) that lighting takes the most priority, followed by cooling, others and entertainment. Expanding on equations (4a) and (4b), 3 scenarios are likely to occur:

- Scenario 1: $U_{i,j}^{mtd} < U_{baseline}$, this is possible if and only if $C_{i,j}^{mtd} > C_{i,j}^{unmet}$. A possible explanation for this scenario is when no loads are dispatched to meet a need.
- Scenario 2: $U_{i,j}^{mtd} = U_{baseline}$, this is possible if and only if $C_{i,j}^{mtd} = C_{i,j}^{unmet}$. This scenario though possible is highly unlikely considering the wide disparity between $C_{i,j}^{mtd}$ and $C_{i,j}^{unmet}$.
- Scenario 3: $U_{i,j}^{mtd} > U_{baseline}$, this is possible if and only if $C_{i,j}^{mtd} < C_{i,j}^{unmet}$. This scenario is very likely especially as loads get dispatched to meet needs. Thus, an increase in $U_{i,j}^{mtd}$ is expected as $C_{i,j}^{unmet} \rightarrow C_{i,j}^{Total-unmet}$.

The computation of the associated cost of running the generator for an hour based on Table 7 is shown subsequently. Hourly fuel cost (assuming 1.6Litres/hour) is $0.76 at $0.48/Litre while emission from the generator for the hour is evaluated to be 3.8272kgCO_2. Using $0.07/kWh, the cost of emissions is computed to be $0.69. The hourly maintenance fee (for 180 operations hours/month) translates to $0.03. A total hourly cost of $1.48 is thus obtained. The computation of $C_{i,j}^{generator}$ and $U_{i,j}^{generator}$ is shown in equations (5) – (6).

$$C_{i,j}^{generator} = \frac{H_{i,j}}{\sum_i \sum_{j=1}^{4} H_{i,j}} \times 450.90 \quad (5)$$

$$U_{i,j}^{generator} = U_{baseline} - \frac{C_{i,j}^{generator} - C_{i,j}^{unmet}}{C_{i,j}^{Total-unmet}} \quad (6)$$

Table 8 presents the evaluated values from equations (5) – (6)

The plot of the various comfort levels for the utility and generator as well as the cost in dispatching needs N-1, N-2, N-3, N-4 is shown in figure 1.

The huge costs involved in using generator as an alternative to the utility in meeting needs thus informs the need for a more affordable alternative system that is both cost effective and environmentally friendly. Furthermore, the proposed system must incorporate smart concepts that would enhance its operation and overall performance.

2.1 The proposed alternative energy system

Figure 2 presents the proposed alternative system for meeting electricity needs of the household under consideration. It is observed from figure 2 that the proposed system consists of an inverter system (1 kVA), converter system (boost), battery (100 Ah, 24V), PV (2 x 80 Wp) panel and a smart manager BLM-HEMS. The units (number) of the battery and PV panels are the maximum that can be afforded by the household.

The loads in the house are divided into two classes (Class 1 and Class 2) as shown in Table 12. BLM-HEMS provides a platform

- ✓ For measuring weather condition (real time) to determine optimum operating condition of the converter. This is achieved through a hopping algorithm that is designed to track the maximum power point (MPPT) of the PV panel in real time by sampling results from either the incremental conductance method, perturb and observe method or normal operation (fixed duty cycle). The sampling duration of the converter is thus influenced based on the method that provides the maximum power.
- ✓ For managing battery state of charge. Battery management is done to ensure that law of energy conservation is obeyed with battery discharge only allowed within the permitted limits.
- ✓ Optimally dispatching Class 1 loads. In dispatching of loads under constrained supply, the optimal dispatch profile that results in better consumer comfort is always followed.

It must however be pointed out that the grid is never used in charging the battery. The methods for implementing the proposed alternative system described in figure 2 involve modelling of the PV system, converter system, battery management system and load dispatch. The detailed description of each method is presented subsequently.

2.2 Photovoltaic modelling

The typical equivalent circuit of a solar cell is shown in [39] where $\boldsymbol{I_{sc}}$ is the current generated due to the photoelectric effect (i.e. solar radiation hitting the PV panel and causing electrons to be emitted and flow in the connected circuit), $\boldsymbol{I_D}$ is the current that flows from the p junction to the n junction due to the diffusion of charge carriers, and is used to represent the net drop in the photo generated short circuit current ($\boldsymbol{I_{SC}}$), $\boldsymbol{R_{sh}}$ is a resistor of high value that is used to represent losses due to defects in the PV panel, $\boldsymbol{R_s}$ is the series resistor of low value used to represent losses due to the metal contacts that convey electrons, $\boldsymbol{R_L}$ is the load resistance connected to the PV panel output, $\boldsymbol{I}$ is the load current i.e. the current that flows through the connected load $\boldsymbol{R_L}$ and $\boldsymbol{V}$ is the terminal or load voltage (i.e. voltage across the load $\boldsymbol{R_L}$). Newton-Raphson is employed in solving equation (7).

Given any $f(x) = y$, where y is a linear homogeneous equation, $if \ \ni \ any \ f(x_o) = 0$ and r is a suggested root where $x_o, r \in R$

Then, if $f(r) \neq 0$,

The distance $x_o - r = h$ can be reduced by updating $r \ \ to \ \ r_{new}$ as follows:

$r_{new} = r - \dfrac{f(r)}{f^{'}(r)}$, $r = r_{new}$ while $h = x_o - r$

The stopping criterion is a problem of accuracy. If f_v is the accuracy point and $h = -\frac{f(r)}{f^{'}(r)}$, the searching will stop when $abs(h) \le f_v$.
Thus if,

$$I = n_p I_{sc} - n_p I_s (e^{q(Vn_s + IR_s/n_p)/AKT_c} - 1) - \frac{Vn_p / n_s + IR_s}{R_p} \quad (7)$$

Then,

$$F(\mathrm{I}) = I - n_p I_{sc} + n_p I_s (e^{q(Vn_s + IR_s/n_p)/AKT_c} - 1) + \frac{Vn_p / n_s + IR_s}{R_p} \quad (8)$$

Where A is the ideality factor, q is the charge, K is the Boltzmann constant and T_c is the PV cell temperature. The I-V and P-V performances under varying temperature and irradiance are shown in [40, 41].

2.3 Converter model

In modelling a suitable dc-dc boost converter for the proposed BLM-HEMS, a voltage source (V_i) is utilized to represent a PV panel and a voltage controlled current source ($I_{pv}(V_i)$) to represent the equivalent PV short circuit current generated through the photoelectric effect as shown in figure 3. Applying Kirchhoff's laws to figure 3 yields the state representation for both "ON" and "OFF" states.

During the "OFF" state, i.e. $S_1 = 0$, $r_L I_L + L\frac{dI_L}{dt} + V_o = V_i + r_i(I_{pv} - I_L)$. Re-arranging yields,

$$\frac{dI_L}{dt} = \frac{1}{L}V_i - \frac{(r_L + r_L)}{L} I_L - \frac{1}{L}V_o - \frac{r_i}{L} I_{pv}(V_i) \quad (9)$$

Similarly, for current at the input side, $I_{pv}(V_i) - C_i \frac{dV_i}{dt} = I_L$. Re-arranging yields,

$$\frac{dV_i}{dt} = -\frac{1}{C_i} I_L + \frac{1}{C_i} I_{pv}(V_i) \quad (10)$$

Also, at the output side, current is computed $I_L = C_o \frac{dV_o}{dt} + \frac{V_o}{R_L}$. Re-arranging yields,

$$\frac{dV_o}{dt} = \frac{1}{C_o} I_L - \frac{1}{C_o R_L} V_o \quad (11)$$

The equivalent state space equation is shown in equation (12) while figure 4 presents the equivalent circuit during the "OFF" state.

$$\begin{bmatrix} \dot{V}_i \\ \dot{I}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{C_i} & 0 \\ \frac{1}{L} & -\frac{(r_i + r_L)}{L} & -\frac{1}{L} \\ 0 & \frac{1}{C_o} & -\frac{1}{C_o R_L} \end{bmatrix} \begin{bmatrix} V_i \\ I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{C_i} \\ \frac{r_i}{L} \\ 0 \end{bmatrix} I_{pv}(V_i) \quad (12)$$

During the 'ON" state, i.e. $S_1 = 1$, $V_i + (I_{pv}(V_i) - I_L)r_i = I_L r_L + L\frac{dI_L}{dt}$. Re-arranging yields,

$$\frac{dI_L}{dt} = \frac{1}{L}V_i - \frac{(r_i + r_L)}{L}I_L + \frac{r_i}{L}I_{pv}(V_i) \tag{13}$$

Similarly, $I_{pv}(V_i) - C_i\frac{dV_i}{dt} = I_L$. Re-arranging yields,

$$\frac{dV_i}{dt} = -\frac{1}{C_i}I_L + \frac{1}{C_i}I_{pv}(V_i) \tag{14}$$

At the output side, the capacitor is discharging and this yields $-C_o\frac{dV_o}{dt} = \frac{V_o}{R_L}$. Re-arranging yields,

$$\frac{dV_o}{dt} = -\frac{1}{C_o R_L}V_o \tag{15}$$

The equivalent state space equation for the "ON" state is shown in equation (16) while figure 5 presents the equivalent circuit during the "ON" state.

$$\begin{bmatrix} \dot{V}_i \\ \dot{I}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{C_i} & 0 \\ \frac{1}{L} & -\frac{(r_i + r_L)}{L} & 0 \\ 0 & 0 & -\frac{1}{C_o R_L} \end{bmatrix} \begin{bmatrix} V_i \\ I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{C_i} \\ \frac{r_i}{L} \\ 0 \end{bmatrix} I_{pv}(V_i) \tag{16}$$

Equation (17) presents the comprehensive equation that represents both the "ON" and "OFF" states based on the value of a with $a = 0$ during the "ON" state and $a = 1$ during the "OFF" state. Figure 6 (a and b) presents the transient and steady state response of the capacitor voltage and inductor current.

$$\begin{bmatrix} \dot{V}_i \\ \dot{I}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{C_i} & 0 \\ \frac{1}{L} & -\frac{(r_i + r_L)}{L} & -\frac{a}{L} \\ 0 & \frac{a}{C_o} & -\frac{1}{C_o R_L} \end{bmatrix} \begin{bmatrix} V_i \\ I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{C_i} \\ \frac{r_i}{L} \\ 0 \end{bmatrix} I_{pv}(V_i) \tag{17}$$

Table 10 presents the associated parameters for the PV panel, converter and battery utilized in modelling where η_{PV} is PV efficiency, r_i is internal resistance of input capacitor of capacitance C_i, r_L is input side series resistance to inductor, R_L is load resistance, F_s is sampling frequency of the converter, k is duty cycle of converter, C_o is capacitance of output capacitor, L is inductance of input inductor, η_{batt} is battery efficiency, DOD is depth of discharge of battery, σ is the monthly self-discharge rate of battery, V_{mp} is the maximum power voltage for the PV panel, I_{mp} is the maximum power current for the PV panel and η_{inv} is inverter efficiency. Other associated costs include generator initial purchase cost ($491.80), installation cost ($81.97) and lifecycle (5000 hours). Table 11 presents the detailed costs (initial purchase, installation etc.) and hourly operations for PV/battery, Utility and Generator. For further reading on converter design and modelling including the different topologies, refer to [42-44].

2.4 Maximum Power Point Tracking

Generally, the output of photovoltaic generation systems (PGS) are influenced directly by varying solar irradiance and ambient temperature. Coupled with the problem of shading, it thus becomes necessary to operate PGS at maximum power [45]. Historically, mechanical systems were first developed to move solar panels in order to get maximum solar radiation while subsequent designs known as electrical MPPT utilized the operating voltage/current profile of solar panels to adjust converter switching frequency for maximum power tracking [46]. PV systems are designed to operate at maximum output power levels for any solar irradiance intensity and temperature with their load impedance determining their output power. To provide for operational control, a DC/DC converter is inserted between the PV panel and the batteries with the PV panel array forming the input to the DC/DC converter and the batteries and load forming its output. With the DC/DC converter acting as an impedance matching circuit, a computing system can modify the duty cycle (and implicitly the input impedance of the DC/DC converter) until the system reaches maximum power point (MPP) [46].

Various MPPT techniques such as fixed duty cycle, beta method, hill climbing/perturb and observe, incremental conductance, constant voltage and current, fuzzy logic controller etc. have been extensively discussed by [47]. A current perturbation algorithm (CPA) with a variable perturbation step and fractional short circuit current algorithm (FSCC) was proposed by [48] to determine an optimum operating current. Furthermore, [49] applied a radial basis function network-sliding mode (RBFNSM) and a general regression neural network (GRNN) for MPPT control. For wind application, there was a 5.7% improvement in performance over the PI control mechanism with power extraction efficiency of 84% and a transient time response of 0.3 second. Similarly, [49] achieved a 15% improvement over the perturb and observe method with a transient response time of 0.09 second for PV applications. Other applications of novel MPPT algorithms include [50] where a hybrid power control system (consisting of the Wilcoxon RBFN and the improved Elman neural network) for grid connected hybrid power generation system was proposed, [51] where a fuzzy-logic-based voltage-regulated solar MPPT system for hybrid power systems was proposed and [52] that developed a high performance neuro-fuzzy indirect wavelength-based adaptive MPPT control for PV systems.

In tracking maximum power point (MPP) for this work, a hopping algorithm is developed. The hopping algorithm evaluates maximum solar power based on a modified incremental conductance method, perturb and observe method and normal operation. The maximum value in real-time is chosen and used in adjusting the duty cycle of the converter. There have been extensive discussions on incremental conductance and perturb and observe methods in literature [53-59]. From figure 7, the monitoring of the behaviour of $\frac{dP}{dV}$ is a trigger for adjusting the converter duty cycle (in incremental conductance) while the successive difference between power $P_t - P_{t-1}$ is used in adjusting voltage in perturb and observe method. The slight modification added to the incremental conductance method is in the converter duty cycle variation. Rather than varying the sampling time for the "ON" state using a fixed step value, i.e. $t_{ON} = t_{ON} \pm \Delta$, "ON" state time is varied using a varying fraction of t_{ON} to produce $t_{ON} = t_{ON} \pm (frac \times t_{ON})$. The hopping algorithm is further described in Algorithm 1.

2.5 Battery management

The internal working structure of BLM-HEMS is shown in figure 8. The state of charge of the battery $SOC(t)$ at any time t is defined as the charge quantity in the battery at the time t and is defined/bounded as:

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \tag{18}$$

The minimum charge quantity $(SOC_{\min})$ is a function of the DOD, i.e. $SOC_{\min} = f(DOD)$ which implies that $SOC_{\min} = (1 - DOD) \times C_{batt}$, with $SOC(t) = SOC_{\max}$ at maximum charge C_{batt}, where C_{batt} is the capacity of the battery (100 Ah). Under operation of the PV panel, 3 possibilities could occur.

- ✓ Case 1: $D_i(t) < E_{PV}(t)$ which would result in battery charging.
- ✓ Case 2: $D_i(t) = E_{PV}(t)$ which would result in $SOC(t) = SOC(t) \times (1 - \sigma)$
- ✓ Case 3: $D_i(t) > E_{PV}(t)$ which could result in either battery charging or discharging.

Where $E_{PV}(t)$ is the PV panel power output at time t and $D_i(t)$ is the time t demand. The battery management function of the BLM-HEMS is to ensure that equation (19) is always maintained for the simulation period (1 day) where $SOC(t_{initial})$ is the battery state of charge at the beginning of simulation time and $SOC(t_{final})$ is the battery state of charge at end of simulation.

$$SOC(t_{initial}) = SOC(t_{final}) \tag{19}$$

2.5.1 Battery charge and discharge models

Battery charging occurs during Case 1 and in Case 3 when the eventual allocation/dispatch of load results in only a fraction of $E_{PV}(t)$ being utilized. During excess power generation from the PV panel as presented by Case 1, the excess power $Sup(t) = E_{PV}(t) - D_i(t)$ gets dumped into the battery as shown in equation (20). Charging in Case 3 as a result of $\alpha E_{PV}(t)$ being dispatched also follows equation (20) where $0 < \alpha < 1$.

$$SOC(t) = SOC(t-1) \times (1 - \sigma) + (Sup(t) \times \eta_{batt}) \tag{20}$$

Given $def(t) = D_i(t) - E_{PV}(t)$ to be the deficit power needed from the battery for hour t due to insufficient PV power, then $\overline{def(t)} = \dfrac{def(t)}{\eta_{inv} \times \eta_{batt}}$ is defined and any of the following discharge types can occur.

- ✓ Type 1: $SOC_{\min} \leq \overline{def(t)} < SOC(t-1) \times (1 - \sigma)$ in which case
$$SOC(t) = SOC(t-1) \times (1 - \sigma) - \overline{def(t)} \tag{21}$$
- ✓ Type 2: $SOC(t-1) \times (1 - \sigma) < \overline{def(t)}$ in which case

$$SOC(t) = SOC_{\min} \tag{22}$$

Further reading on battery systems and management especially for stand-alone PV systems is found in [60].

Algorithm 1: Hopping algorithm description

1. Start
2. Input: $P(t), P(t-1), V(t), V(t-1), k, I(t), I(t-1), \mathrm{t}_{ON}$
3. **Perform Perturb and observe**
4. Perform $P_{diff} = P(t) - P(t-1)$
5. Adjust voltage accordingly - $V(t) = V(t-1) \pm \Delta$
6. Locate $P_{P\&O}^{\max}$ (maximum power for perturb and observe method)
7. **Perform Incremental conductance**
8. Perform $P_{\Delta}(t) = \dfrac{dP(\mathrm{t})}{dV(t)}$ and $G_{\Delta}(t) = -\dfrac{\mathrm{I(t)}}{V(t)}$
9. Adjust t_{ON} accordingly - $t_{ON} = t_{ON} \pm (frac \times t_{ON})$
10. Locate $P_{incr-cond}^{\max}$ (maximum power for incremental conductance method)
11. **Perform normal operation with** k
12. $\dfrac{V_o}{V_i} = \dfrac{I_L}{I_o} = \dfrac{1}{1-k}$
13. $t_{ON} = k \times T_p = \dfrac{k}{F_s}$
14. $P_{normal}^{\max} = I_o \times V_o$
15. **Generate** $\overline{P} = \{P_{P\&O}^{\max}, P_{incr-cond}^{\max}, P_{normal}^{\max}\}$
16. $P(t) = \max(\overline{P})$
17. Output: $P(t)$
18. End

Figure 9 presents the simplified low chart depicting the general BLM-HEMS flow and operation.

3.0 Results and discussion

A typical 2-bedroom residential flat in a low-cost housing estate in Lagos (South-West, Nigeria) is considered. The choice of Lagos is due to the high prevalence of generators within the city [10]. The low-cost flat is assumed to house a family of 4, comprising of the father, mother and children. The combined annual income of the household is 1,200,000 Naira ($6557.38) which translates to a monthly income of 167,000 Naira ($546.45). The monthly income of the family puts them above the poverty line of 55,000 Naira ($180.33) per year [9]. Table 12 presents a typical audit of the major expected electrical appliances in the house with Table 13 providing a further breakdown to the classification of grouped loads in Table 12. From Table 12, assuming a 0.85 demand factor (df) which is closely similar to [31], the peak consumption of the house is estimated to be around 4000 Wh which is usually at weekends from 7pm – 9pm. The location of the low-cost house (Ikeja) means that Ikeja

Electricity Distribution Company (IKEDC) is responsible for billing the case study house. The case study house has a single-phase 240 VAC pre-paid electric meter installed. Based on the prevailing tariff system prescribed by the electricity regulator – NERC (Nigerian Electricity Regulatory Commission) through the multi-year tariff order (MYTO) II, the per unit electricity rate is charged at 21.30 Naira ($0.07) per kilowatt-hour. No additional standing charges are billed the customer.

The tracking of maximum power using perturb and observe, incremental conductance, normal operation and hopping algorithm is shown in figure 10. As seen in figure 10, the hopping algorithm vacillates between the incorporated methods in determining the possible maximum power and adjusting the duty cycle of the converter (shown in fig 12). The overall efficiency in terms of maximum power tracking for a day is 70.90%, 67.59%, 66.36% and 72.20% for normal, perturb and observe, incremental conductance and hopping algorithms respectively. This implies that the hopping algorithm achieves an extra 7% and 9% efficiency in terms of MPPT over perturb and observe and incremental conductance methods respectively. These values compare favourably with the 15% improvement in terms of MPPT by [49].

The transient behaviour for the various MPPT methods is observed in the figure 11 for a 4 seconds window with smaller resolution. Figure 12 shows a snippet of the overall firing sequence of the converter (i.e. the state – ON/OFF of the converter during MPPT) for the various MPPT algorithms. As seen, a similar ON/OFF state sequence is noticed for the perturb and observe and incremental conductance methods which is at variance with the normal operation (No MPPT) of the converter (using fixed duty cycle).

A major impediment to the MPPT tracking by the perturb and observe methods and the incremental conductance method is the rapid change in solar irradiance level which necessitates for rapid adjustment of converter duty cycle and could lead to over or under compensation. However, during stable operations at high power output (>100 W), the perturb and observe and the incremental conductance methods outperform the normal operation with efficiency of up to 95%.

The sizing of the PV/battery system was done for only one day with the battery initial charge set to 10% (being the lowest discharge capacity of the battery). The demerit of this set up thus means that demands from 8pm till 7am will hardly be dispatched by the PV/battery setup. Demands that will be mostly dispatched (depending on the available number of sunshine hours) are demands within the hours from 4pm till 8pm. The analysis of dispatch and comparison of associated costs and comfort will thus centre around dispatch occurring within the hours 4pm till 8pm. Considering the two major seasons in Nigeria (dry and wet seasons), the simulation was run with sunshine data to represent on average, the daily irradiance for both wet season (April to October) and dry season (November to March).

Table 14 presents the demand for the hours (4pm till 8pm) under consideration that are to be dispatched from PV/battery/utility configuration depending on PV/battery capacity and utility (grid) availability. A justification for the selected hours under consideration is found in [61] who opines that the selected hours under consideration form a sub-set of the typical hours of peak demand for low/middle income households. From Table 14, 340 Wh is demanded from4pm – 5pm, 385 Wh is demanded for 5pm – 6pm, 409 Wh is demanded from6pm – 7pm and 396 Wh is demanded from 7pm – 8pm. Total demand for the time spanning 4pm – 8pm is 1530 Wh. The N-1, N-2, N-3 and N-4 needs computation for 4pm till 8pm as well as the appliances selected for dispatch by the user and the eventual wattage of the appliances dispatched are shown in Table 15. It is seen from Table 15 that utility though available for hours 4pm – 7pm, is not utilized in dispatching any selected load from 4pm till 5pm.

However, from 5pm till 7pm when PV/battery capacity becomes insufficient, the utility supplies the shortfall of 4.70 Wh (5pm – 6pm) and 367.63 Wh (6pm – 7pm). Total PV power supplied from 4pm till 8pm is 310.68 Wh while battery supply within the same time span is 453.33 Wh with the utility supplying 372.33 Wh from 4pm till 8pm. Demand unmet within the time from 4pm till 8pm is 396 Wh and occurs particularly within 7pm – 8pm when PV/battery is insufficient and utility is unavailable. Table 16 presents a detailed description of Table 15 in terms of $H_{i,j}, U_{i,j}^{PV/battery}, C_{i,j}^{unmet}$ and savings (nominal) where the nominal savings represent the real savings in actual money terms based on a reduction in utility billing as a result of the dispatch of load from an alternative energy source. All computed values are for a typical day.

The computation of $U_{i,j}^{PV/battery}$ in Table 16 shows the direct relationship that exists between $U_{i,j}^{PV/battery}$ and $C_{i,j}^{unmet}$. For any dispatch of loads (appliances) to meet needs that incurs $C_{i,j}^{unmet}$, then a corresponding drop in $U_{i,j}^{PV/battery}$ is expected. The insufficiency of PV/battery capacity for time spanning 6pm – 8pm leads to a corresponding decrease in $U_{i,j}^{PV/battery}$ with $U_{i,j}^{PV/battery}$ going below $U_{baseline}$ from 6pm.

The battery state of charge during the simulation period is shown in figure 13. It is observed from figure 13 that the battery mainly charges from 8am till 4pm when it starts being discharged. Its maximum charge capacity in terms of power for the day is 780.64 W (65.1% of its maximum capacity) and this occurs at 4pm. $SOC(\text{t}_{initial})$ is 10% and $SOC(\text{t}_{final})$ is 10.8% which satisfies the law of energy conservation. The battery is solely charged from the PV panel with the grid (utility) only coming in (when available) to offset unmet demand. The operational behaviour of the PV/battery/utility system alongside demand and dispatch profile for the day is shown in figure 14. It is observed from figure 14 that total demand within the day (including the specific hours under consideration) is 4420 Wh of which 2161 Wh went unmet (due to utility unavailability and insufficient PV/battery capacity). Utility supply within the day is 1496.60 Wh, PV effective supply (excluding battery charging) is 308.96 Wh while battery supply is 453.44 Wh. Utility supply was unavailable for 11 hours within the day of which 7 were during periods of demand.

In standardizing Tables 15 and 16, there is the need to compare the results obtained for utility with PV/battery and generator as alternatives in terms of associated costs, carbon footprint and return on investment (RoI). Table 17 presents the daily, monthly and yearly cost of dispatch for the effective demand (demand during utility availability) for PV/battery/utility, utility only and Utility/generator. It is seen from Table 17 that for a daily demand of 4420 Wh, the daily effective demand is 2269 Wh (with 7 hours of grid available during the demand hours). While 48.12 Naira ($0.16) is spent daily dispatching 2269 Wh, 31.89 Naira ($0.10) is spent dispatching same demand for PV/battery/utility representing a 33.7% savings. Using the Utility/generator option results in a daily expenditure of 3,198

Naira ($10.49) which translates to 1,167,390 Naira ($3828) in a year.

In terms of RoI, the initial cost of purchase and installation for the PV/battery is repaid within 25 years with 6000 Naira ($19.67) yearly savings of the PV/battery/utility option over Utility only option (for the adopted hourly electricity cost of ₦21.30/kWh). Any outstanding cost however is due to the battery replacement and yearly maintenance within the 25 years. Table 18 presents the equivalent carbon emissions for (PV, battery, utility and the generator) and is used in computing the carbon emissions for PV/battery/utility, Utility only and Utility/generator options (shown in Table 19). In addition to generating the lowest cost for electricity dispatch, the PV/battery/utility option also has the lowest daily carbon emissions (1.179kgCO_2) compared with 1.588kgCO_2 (Utility only) and 28.384kgCO_2 (Utility/generator).

The comparison of evaluated $U_{i,j}^{utility}$, $U_{i,j}^{PV/battery/utility}$ and $U_{i,j}^{utility/generator}$ for the hours 4pm – 5pm, 5pm – 6pm, 6pm – 7pm and 7pm – 8pm is shown in the figures 15 - 18 for N-1, N-2, N-3 and N-4 needs. The superiority of the PV/battery/utility configuration is shown in figures 15, 16 and 18 where it achieves average hourly comfort levels ($U_{avg}^{PV/battery/utility}$) of 5.68 (4pm – 5pm), 5.58 (5pm – 6pm) and 4.97 (7pm – 8pm) compared with 5.32, 5.32 and 4.24 respectively for Utility only option. Another observation is that the PV/battery/utility configuration shows a better integration and seamless operation than the Utility/generator configuration. This observation is better explained in figure 19 which presents the graduation of the hourly cost of dispatching electricity for Utility only, PV/battery/utility and Utility/generator. A common observation from figure 19 is the fact that $U_{i,j}^{utility}$ increases as the hourly electricity dispatch cost difference between Utility only and PV/battery/utility configuration increases. From 4pm – 5pm, the difference in hourly electricity dispatch cost between Utility only (7.24 Naira, $0.02) and PV/battery/utility (0.29 Naira, $0.00) which is 6.95 Naira ($0.02) results in $U_{avg}^{PV/battery/utility} = 5.68$ while for 5pm – 6pm the hourly electricity dispatch cost difference of 7.81 Naira ($0.03) results in $U_{avg}^{PV/battery/utility} = 5.58$. However, for 6pm – 7pm, the hourly electricity dispatch cost of 0.59 Naira ($0.00) results in $U_{avg}^{utility} = 5.59$.

The summary of the associated statistics for Utility only, PV/battery/utility and Utility/generator configurations for 4pm – 8pm is shown in Table 20. In expatiating on figures 15 to 18, Table 20 provides at a glance the $C_{i,j}^{mtd}$, U_{avg}^{mtd}, utility status (available or unavailable), PV/battery capacity (sufficient or insufficient) and demand for each hour between 4pm – 8pm. This is useful in evaluating quickly the performance of each configuration hourly and the best dispatch configuration in terms of selection.

3.1 Sensitivity analysis

From the results obtained, the PV/battery/utility option achieves a yearly savings of about 6 000 Naira using utility electricity charge of ₦21.30/kWh. However, since electricity prices vary across Nigeria based on the distribution company serving a state, we run sensitivity analysis for ₦25.00/kWh, ₦30.00/kWh and ₦50.00/kWh with fixed solar production levels and 0% increment in electricity hourly cost by the utility to determine the effect of hourly electricity cost in influencing RoI. Table 21 presents the yearly electricity cost for Utility only and PV/battery/utility options including their yearly savings and payback period for varying hourly cost of electricity. It is observed from Table 21 that for ₦25.00/kWh, the yearly savings of ₦6 715 ($22.02) translates to a payback time of about 21 years. Similarly, for ₦30.00/kWh, the yearly savings of ₦7 395 ($24.24) results in a payback time of 16 years with ₦50.00/kWh resulting in yearly savings of ₦10 112 and an eventual payback time of about 8.4 years.

The implication of this sensitivity analysis is that across Nigeria, different states with varying hourly costs of electricity have varying potential payback periods. This thus implies that in encouraging the adoption of the PV/battery/utility option, there should be an incentive to the buyer which shows significant potential savings over a reasonable time. Furthermore, while this sensitivity analysis has only examined the effect of hourly electricity cost on payback period computation, advancements in solar PV efficiency imply that there could be further reduction in payback period thus making the adoption of PV/battery/Utility option quite attractive. The attractiveness of the PV/battery/Utility option notwithstanding, solar irradiance plays a crucial role as its stochasticity can increase the payback period invariably making the utility/generator or Utility only options better alternatives.

In benchmarking the results obtained in this work, the savings obtained in [3] show that annual savings on electricity bills was about 38%. For this work, it is seen from Table 21 that annual savings vary from 34% (at ₦21.30/kWh), 52% (at ₦23.00/kWh), 56% (at ₦25.00/kWh) to 64% (ta ₦30.00/kWh) for the considered loads. Furthermore, in terms of peak demand reduction, Table 15 shows that BLM-HEMS achieves an average peak demand reduction of 52% for the time between 4pm – 8pm compared with 42% peak time electricity demand reduction in [3]. The cumulative effect of the peak demand reduction thus implies that the utility can take advantage of BLM-HEMS (as a demand response mechanism) for targeted areas to shave peak demand as also posited in [3] where it was argued that the savings is of more advantage to the utility. The benefits of the significant reduction in peak demand implies that the utility has improved utilization of its supply capacity and can optimally dispatch its generators at reduced operations cost. Furthermore, the utility can balance demand/supply with minimized reserve margins [62].

3.2 Policy discussions for improving the adoption of BLM-HEMS

Energy poverty in Nigeria is both a problem of access (primarily) and mobility (i.e. the ability of households to increase their electricity consumption either by increasing electrical appliances owned or extending the duration of usage of already owned electrical appliances). As noted in [4], there was limited usage of solar PV systems. This is not unusual owing to the huge costs involved in initial purchase and for subsequent upgrades. In order therefore to improve the ownership of more solar PV systems across households, government could implement an additional surcharge for fossil-based electricity generation. This cost which is billed the utility would invariably be transferred to the consumers through higher electricity costs. With higher electricity costs, there is more incentive for households to consider adopting a hybrid system.

However, while the government implements a fossil-based tax on the utility, it must ensure that policy is put in place to reduce the cost of purchase of solar PV systems. According to [1], the government could explore options such as tax exemption for imported solar PV products and financing options for their purchase. Also, considering the need for technical expertise in their set up, government should also encourage the training of skilled manpower necessary for the installation, maintenance and repair of these systems.

4.0 Conclusions

A biased load manager home energy management system (BLM-HEMS) has been proposed and modelled in dispatching specific loads for low income consumers, using low cost buildings in Lagos, South-West Nigeria. The users' electricity appliances have been classified accordingly with the BLM-HEMS which provides an interface for integrating the grid and alternative power system for load dispatch. Based on the maximum amount users are willing to spend, analysis has been conducted to investigate the best configuration (alternative power source) that would lead to an improvement in occupants' comfort level while reducing their electricity bill and carbon footprint.

Results obtained show that the PV/battery/utility configuration offers the best option due to its low yearly maintenance cost, reduced carbon emissions and improvement in consumer comfort compared to the Utility only and Utility/generator configurations. Results have also established that although the Utility/generator configuration is capable of meeting entirely the needs of the user daily, its high operations and maintenance cost coupled with its high carbon footprint decimate drastically any potential savings accrued from its dispatch of occupants' needs. Furthermore, the peculiarity of utility availability in Nigeria (frequent grid interruptions) makes the Utility only option a poor choice owing to the lack of an alternative to offset demand during grid interruptions.

The daily savings of the PV/battery/utility configuration over the Utility only configuration for hourly electricity cost of N21.30/kWh is about 34% with a 26% reduction in carbon emissions by the PV/battery/utility configuration over the Utility only configuration. The yearly savings of the PV/battery/utility configuration of about 6000 Naira ($19.67) translates to about 4% of the cost of initial PV/battery purchase and installation. This implies that the PV/battery/utility configuration can repay the initial purchase and installation costs within 25 years excluding yearly maintenance and battery replacements. In terms of daily usage, the proposed BLM-HEMS is not intended to be complicated as it is envisaged to be interoperable with existing solar PV systems. However, a discrimination of household load points is necessary for easy application of the load allocation component of the BLM-HEMS.

The sensitivity analysis carried out has shown that the adopted BLM-HEMS reacts favourably to higher hourly electricity cost from the utility with potential annual electricity savings of up to 64% and a payback period of 8.4 years. This value exceeds the reported savings in [3] which shows the viability of the proposed BLM-HEMS. Furthermore, the 4% improvement in comfort level for the house also implies that the systems multi-objectives are fully meant. The BLM-HEMS is thus capable of mitigating poverty in households since it guarantees savings for households which can be utilized for other activities or for extending the utilization time of already owned electrical appliances. The BLM-HEMS thus improves the application of solar PV systems beyond basic household needs as presented in [4], by ensuring that yearly savings from the PV/battery/utility option can be utilized in upgrading households SHS for increased solar PV participation in household electricity generation. This implies that such households can engage in other economic activities beyond basic household needs due to improvement in electricity access. This study can be useful for better understanding of on-grid/off-grid home energy systems which are instrumental for future energy planning and incentive analysis in developing countries, including Nigeria.

Future research would be to investigate the effect of load ownership and duration of use on the comfort level and productivity of households. This is necessary to help provide low/middle income households an improved guide to owning electrical appliances that will lead to improvement in their quality of life and overall productivity.

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Table 1: Absolute poverty measure for selected Nigeria states [7]

State	Geo-political zone	Poverty measure (%)	
		2003/2004	2009/2010
Lagos	South-west	69.4	40.3
Abia	South-east	40.9	50.2
Katsina	North-west	72.9	77.6
Edo	South-south	53.6	64.1
Kogi	North-central	91.8	67.4
Borno	North-east	59.8	60.6

Table 2: Average monthly household expenditure (Naira) on gas, electricity, petrol and diesel by geo-political zone [8, 9]

	North-central	North-east	North-west	South-east	South-south	South-west
Gas	300	103	179	807	2890	617
Electricity	5401	2216	2667	9972	8152	13105
Petrol	14233	4688	10393	10895	18019	18516
Diesel	597	351	436	787	538	2659

Table 3: Frequency of blackouts across the geo-political zones [9]

Region	Never	Everyday	Several times a week
North-central	3.3	63.5	26.6
North-ease	1.5	71.3	23.6
North-west	5.0	71.5	17.6
South-east	1.4	60.2	29.1
South-south	3.1	49.5	26.0
South-west	4.4	49.0	41.2

Table 4: Daily dispatch profile for considered loads

Load point	Unit (W)	Weekday time dispatch of load																
		1	2	3	4	5	6	7	13	14	17	18	19	20	21	22	23	24
LP1	200	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0
LP2	96	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
LP3	32	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1
LP4	225	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1
LP5	55	@	@	@	@	@	@	@	@	@	@	@	@	@	@	@	@	@
LP6	75	&	&	&	&	&	&	&	&	&	&	&	&	&	&	&	&	&
Total (W)		257+@+&	257+@+&	257+@+&	257+@+&	257+@+&	128+@+&	296+@+&	@+&	@+&	425+@+&	425+@+&	553+@+&	553+@+&	553+@+&	553+@+&	353+@+&	353+@+&

1 – Valid period for load point dispatch
0 – Not a valid period for load point dispatch
@ - Fraction of others 1 dispatched
& - Fraction of others 2 dispatched

Table 5: Needs – Appliances Matrix

		Needs			
		N-1	N-2	N-3	N-4
Appliances (Loads)	LP1	X	X	V	X
	LP2	V	X	X	X
	LP3	V	X	X	X
	LP4	X	V	X	X
	LP5	X	X	V	V
	LP6	X	X	V	V

X – Need cannot be met by appliance
V – Need can be met by appliance
N-1 is Lighting need; N-2 is Cooling need;
N-3 is Entertainment need; N-4 is others

Table 6: Utility based associated statistics for LP1 – LP6

	Needs			
	N-1	N-2	N-3	N-4
$H_{i,j}$	128 Wh	225 Wh	200 Wh	130 Wh
$C_{i,j}^{utility}$	2.73 Naira ($0.01)	4.79 naira ($0.02)	4.26 Naira ($0.01)	2.77 Naira ($0.01)
$C_{i,j}^{Total-unmet}$	40 Naira ($0.13)	15 Naira ($0.05)	5 Naira ($0.02)	15 Naira ($0.05)
$U_{i,j}^{utility}$	5.93	5.68	5.15	5.82

Table 7: Petrol generator associated characteristics

Generator Characteristics	
Burn rate	1.6Litre/hour
CO_2 emissions per Litre	2.392 kgCO_2/Litre
Hours of utilization per day	6
Monthly maintenance cost	$4.92
Petrol cost/Litre	$0.48

Table 8: Generator based associated statistics for LP1 – LP6

	Needs			
	N-1	N-2	N-3	N-4
$H_{i,j}$	128 Wh	225 Wh	200 Wh	130 Wh
$C_{i,j}^{generator}$	$0.28	$0.49	$0.43	$0.28
$C_{i,j}^{unmet}$	$0.13	$0.05	$0.02	$0.05
$U_{i,j}^{generator}$	3.89	-3.90	-20.41	0.28

Table 9: Comfort cost breakdown for each sub load point and Need

Needs	N-1								N-2			N-3	N-4				
Load points	LP2(1)	LP2(2)	LP2(3)	LP2(4)	LP2(5)	LP2(6)	LP3(1)	LP3(2)	LP4(1)	LP4(2)	LP4(3)	LP1	LP5(1)	LP5(2)	LP5(3)	LP6(1)	LP6(2)
Comfort cost ($)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
$C_{i,j}^{Total-unmet}$	0.13								0.05			0.02	0.05				

Table 10: Associated parameters for PV panel, converter, battery and inverter

PV panel		Converter		Battery		Inverter	
Number	2	r_i	$5m\Omega$	Voltage	24 V	η_{inv}	0.9
Power	80 Wp	r_L	0.2Ω	Rating	100 Ah	Rating	1 kVA
η_{PV}	16%	R_L	15Ω	η_{batt}	0.9		
Cost	$188.12	F_s	$5000Hz$	DOD	90%		
Life cycle	25 years	k	0.5	σ	<3%/month		
V_{mp}	18 V	C_i	$200\mu F$	Life cycle	3 years		
I_{mp}	4.44 A	C_o	$333.33\mu F$	Cost	$200		
Weight	7.4 kg	L	$18.75mH$				

Table 11: Initial purchase, installation and daily operations cost for considered generation sources

		Generation sources		
		PV/battery	Utility	Generator
Costs	Initial purchase	$486.49*	$163.93++	$574*
	Maintenance	$8.20/year	No maintenance fee	$4.92/month
	Hourly operations	$0#	$\$0.07 \times D_{hour}^{k}(kWh)$	$0.09#

*- Inclusive of installation cost

++ - Households were initially charged for pre-paid meters with a payment plan spread across 12 months.

- Charge is flat for the hour as long as demand can be met by available generation capacity.

$D_i(kWh)$ is the hourly demand to be dispatched by the PV/battery.

Table 12: Load audit of use case low-cost house

Device	Code	Number	Unit rating (W)	Total power (W)
Television*	LP1	1	200	200
Indoor light*	LP2	6	16	96
Outdoor light*	LP3	2	16	32
Standing/ceiling fan*	LP4	3	75	225
Others 1*	LP5	-	55	55
Others 2*	LP6	-	75	75
Electric cooker+,**	-	1	1500	1500
Fridge/Freezer+,**	-	1	400	400
Electric kettle+,**	-	1	1000	1000
Pressing iron+,**	-	1	1000	1000
Total				4583

*- Class one load points

**- Class two load points

+- Not considered for alternative power supply

Table 13: Power rating of others 1 and others 2 sub-load points

Class definition	Class constituent	Number	Description	Unit rating (W)	Total power (W)
Others 1	Satellite decoder	1	LP5(1)	10	10
	Phone charger	2	LP5(2)	10	20
	DVD player	1	LP5(3)	25	25
Others 2	Laptop	1	LP6(1)	65	65
	Bedside light	1	LP6(2)	10	10

Table 14: Demand schedule for hours under consideration

	LP1	LP2						LP3		LP4			LP5			LP6	
		LP2(1)	LP2(2)	LP2(3)	LP2(4)	LP2(5)	LP2(6)	LP3(1)	LP3(2)	LP4(1)	LP4(2)	LP4(3)	LP5(1)	LP5(2)	LP5(3)	LP6(1)	LP6(2)
Rating (W)	200	16	16	16	16	16	16	16	16	75	75	75	10	20	25	65	10
4pm – 5pm	V										V		V	V	V		V
5pm – 6pm	V									V		V	V		V		
6pm – 7pm						V	V	V	V	V	V	V	V	V	V	V	
7pm – 8pm	V	V	V	V	V												

V – Load demanded for hour under consideration (does not connote dispatch)

Table 15: Daily needs computation and dispatch schedule

Needs	Time span under consideration			
	4pm – 5pm	5pm – 6pm	6pm – 7pm	7pm – 8pm
N-1	0/0 Wh	0/0 Wh	64/41.37 Wh	96/0 Wh
N-2	75/75 Wh	150/150 Wh	225/0 Wh	75/0 Wh
N-3	200/200 Wh	200/200 Wh	0/0 Wh	200/0 Wh
N-4	65/65 Wh	35/30.30 Wh	120/0 Wh	25/0 Wh
Notes	PV+battery only Utility available	PV+battery+utility Utility available	PV+battery+utility Utility available	No PV+battery Utility unavailable

64/41.37 Wh represents 64 Wh demanded and 41.37 Wh supplied by PV/battery. The deficit is met by the utility (grid) if available.

Table 16: Daily computation of $U_{i,j}^{PV/battery}$, $C_{i,j}^{unmet}$ and savings (nominal)

	Needs for 4pm – 5pm				**Needs for 6pm – 7pm**			
	N-1	**N-2**	**N-3**	**N-4**	**N-1**	**N-2**	**N-3**	**N-4**
$H_{i,j}$	0 Wh	75 Wh	200 Wh	65 Wh	64 Wh	225 Wh	0 Wh	120 Wh
$U_{i,j}^{PV/battery}$	–	5.31	5.94	5.78	5.24	4.98	–	4.98
$C_{i,j}^{unmet}$ (Naira)	–	0.00 ($0.00)	0.00 ($0.00)	0.00 ($0.00)	10.00 ($0.03)	15.00 ($0.05)	–	12.00 ($0.04)
Savings (Naira)	0.00 ($0.00)	1.6 ($0.01)	4.26 ($0.01)	1.38 ($0.00)	0.88 ($0.00)	0.00 ($0.00)	–	0.00 ($0.00)
	Needs for 5pm – 6pm				**Needs for 7pm – 8pm**			
	N-1	**N-2**	**N-3**	**N-4**	**N-1**	**N-2**	**N-3**	**N-4**
$H_{i,j}$	0 Wh	150 Wh	200 Wh	35 Wh	96 Wh	75 Wh	200 Wh	25 Wh
$U_{i,j}^{PV/battery}$	–	5.65	5.94	5.14	4.99	4.98	4.94	4.98
$C_{i,j}^{unmet}$ (Naira)	–	0.00 ($0.00)	0.00 ($0.00)	3.00 ($0.01)	30	5	5	3
Savings (Naira)	0.00 ($0.00)	3.20 ($0.01)	4.26 ($0.01)	0.65 ($0.00)	0.00 ($0.00)	0.00 ($0.01)	0.00 ($0.00)	0.00 ($0.00)

Table 17: Daily, monthly and yearly effective demand cost for the different options

	Daily	Monthly	Yearly
Effective demand (kWh)	2.27	69.02	828.19
Utility only cost (Naira)	48.12 ($0.16)	1470 ($4.82)	17640 ($57.84)
PV/battery/utility cost (Naira)	31.89 ($0.10)	976 ($3.20)	11716 ($38.41)
Utility/generator cost (Naira)	Utility (48.12 Naira, $0.16) Generator (3150 Naira, $10.33)	1470 ($4.82) 95813 ($314)	17640 ($57.84) 1149750 ($3770)
	3198.12 ($10.49)	97283 ($319)	1167390 ($3828)

Table 18: Carbon emissions for PV, battery, utility and generator

Component	**Emission rate**
PV	$72gCO_2e/kWh^{+,@}$
Battery	$50gCO_2/kWh^{++}$
Utility	$0.703kgCO_2/kWh^{*}$
Generator	$3.827kgCO_2/hour^{\#}$

+ - see [63]; ++ - see [64];
* - see [65]; # - Computed in this paper
@ - has been taken to be CO_2/kWh

Table 19: Daily carbon emissions from the various sources

Electricity source	Daily emission
Grid only	1.588 $kgCO_2$*
PV/battery/utility	PV – 0.104$kgCO_2$ Battery – 0.023$kgCO_2$ Utility - 1.052$kgCO_2$**
	1.179$kgCO_2$
Utility/generator	Utility – 1.588$kgCO_2$* Generator – 26.789$kgCO_2$
	28.384$kgCO_2$

*- Utility supply is 2259 Wh

**- Utility supply is 1496.60 Wh

Table 20: Summary of associated statistics for Utility, PV/battery/utility and Utility/generator configurations

Time	Demand	Utility only		PV/battery/utility		Utility/generator	
4pm – 5pm	340 Wh	$C_{i,j}^{utility}$	7.24 Naira	$C_{i,j}^{PV/battery/utility}$	0.29 Naira	$C_{i,j}^{utility/generator}$	7.24 Naira
		$U_{avg}^{utility}$	5.32	$U_{avg}^{PV/battery/utility}$	5.68	$U_{avg}^{utility/generator}$	5.32
		Status	Available	PV/battery	Sufficient	Utility	V
				Grid	Available	Generator	VX
5pm – 6pm	385 Wh	$C_{i,j}^{utility}$	8.20 Naira	$C_{i,j}^{PV/battery/utility}$	0.39 Naira	$C_{i,j}^{utility/generator}$	8.20 Naira
		$U_{avg}^{utility}$	5.32	$U_{avg}^{PV/battery/utility}$	5.58	$U_{avg}^{utility/generator}$	5.32
		Status	Available	PV/battery	Insufficient	Utility	V
				Grid	Available	Generator	VX
6pm – 7pm	409 Wh	$C_{i,j}^{utility}$	8.71 Naira	$C_{i,j}^{PV/battery/utility}$	8.12 Naira	$C_{i,j}^{utility/generator}$	8.71 Naira
		$U_{avg}^{utility}$	5.59	$U_{avg}^{PV/battery/utility}$	5.07	$U_{avg}^{utility/generator}$	5.59
		Status	Available	PV/battery	Insufficient	Utility	V
				Grid	Available	Generator	VX
7pm – 8pm	396 Wh	$C_{i,j}^{utility}$	8.43 Naira	$C_{i,j}^{PV/battery/utility}$	0.29 Naira***	$C_{i,j}^{utility/generator}$	450 Naira
		$U_{avg}^{utility}$	4.24	$U_{avg}^{PV/battery/utility}$	4.97	$U_{avg}^{utility/generator}$	-8.48
		Status	Not available	PV/battery	Insufficient	Utility	X
				Grid	Unavailable	Generator	VV

V – utilized in dispatching hourly needs; X – Source not available for dispatching needs

VX – Source available but not utilized in dispatching needs

VV – Source available and utilized in dispatching needs

*** - PV/battery normal hourly cost of electricity is assumed

Table 21: Sensitivity analysis results for varying $E_{PC}(Naira/kWh)$

E_{PC} $(Naira/kWh)$	Annual electricity cost (Naira)		Yearly savings (Naira)	Payback period (Years)	Annual electricity cost savings (%)
	Utility only	PV/battery/utility			
21.30	17 640 (\$57.84)	11 716 (\$38.41)	5 924 (\$19.42)	25	34
25.00	13 957 (\$45.76)	6 715 (\$22.02)	7 242 (\$23.75)	21	52
30.00	16 749 (\$54.91)	7 395 (\$24.24)	9 354 (\$30.67)	16	56
50.00	27 915 (\$91.52)	10 112 (\$33.16)	17 802 (\$58.37)	8.4	64

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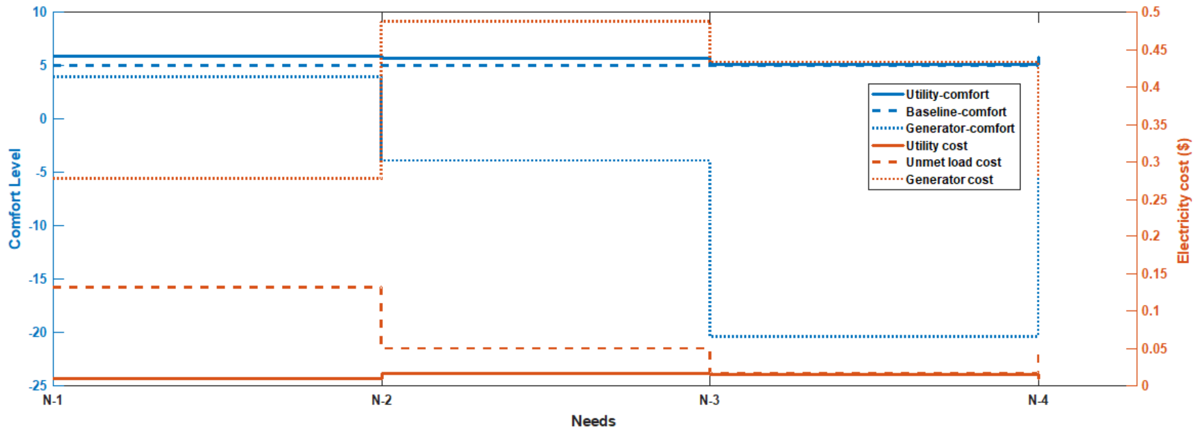

Figure 1: The combined comfort and expenditure plot for utility and generator

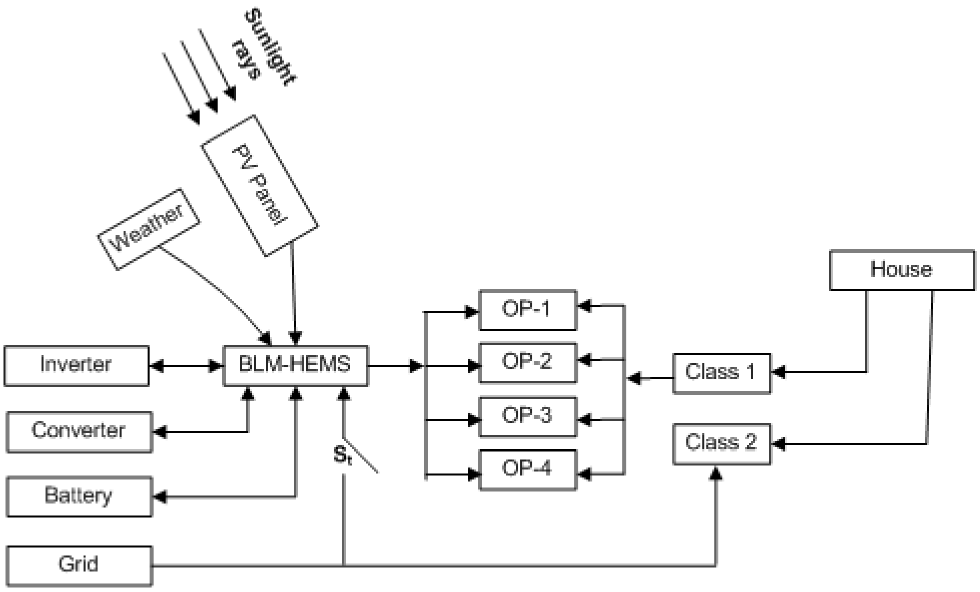

Figure 2: Proposed alternative system

“OP” in figure 2 means option, which represents a sub-collection of electrical appliances.

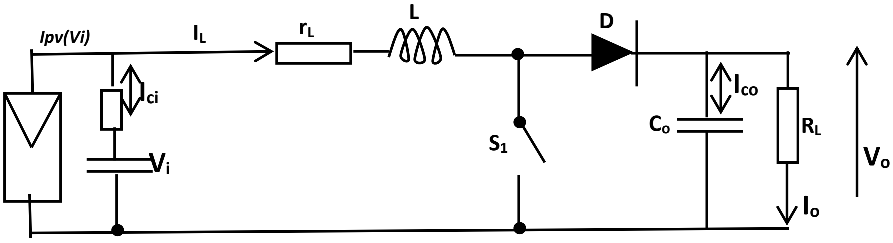

Figure 3: PV/DC-DC Boost-Converter Model

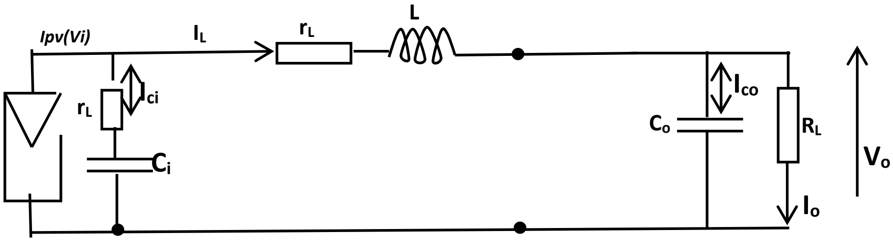

Figure 4: PV/DC-DC Boost-Converter Model for “OFF” state operation

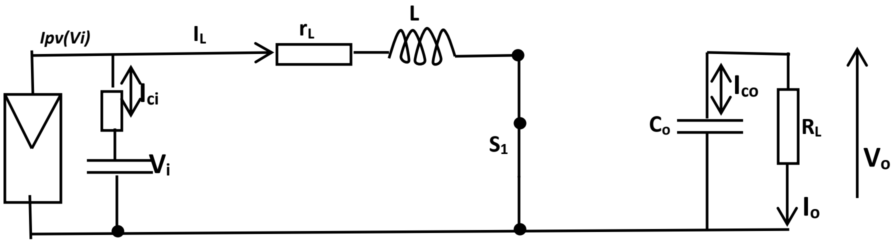

Figure 5: The PV/DC-DC Boost-Converter Model during the “ON” state

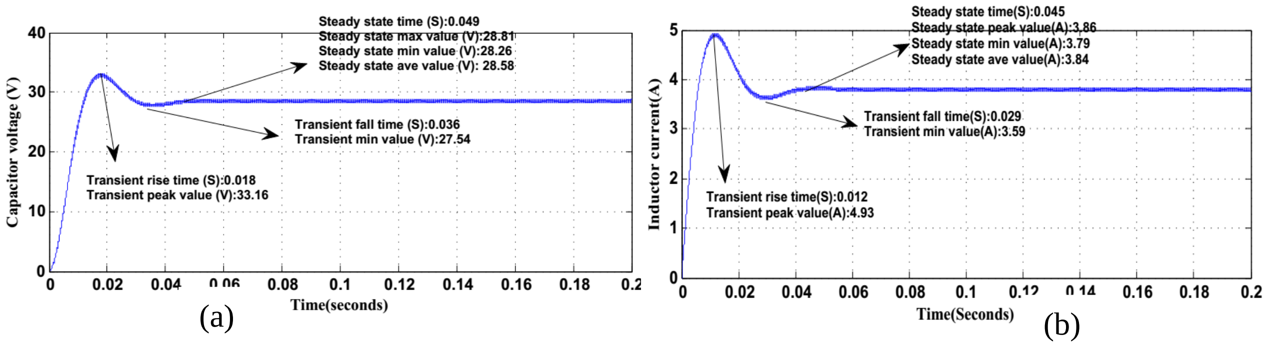

Figure 6: Transient and steady state response for (a) Capacitor voltage and (b) Inductor current

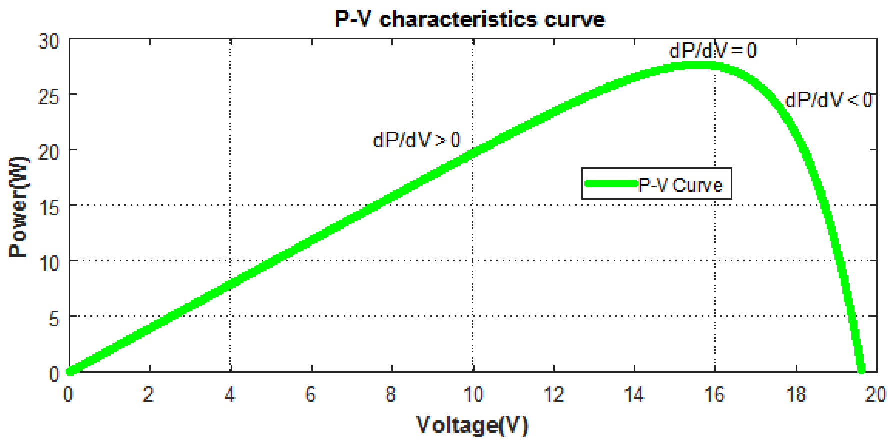

Figure 7: $\frac{dP}{dV}$ monitoring across the P-V profile

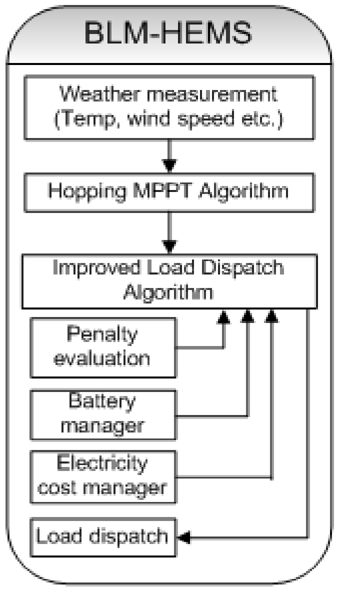

Figure 8: BLM-HEMS internal working architecture

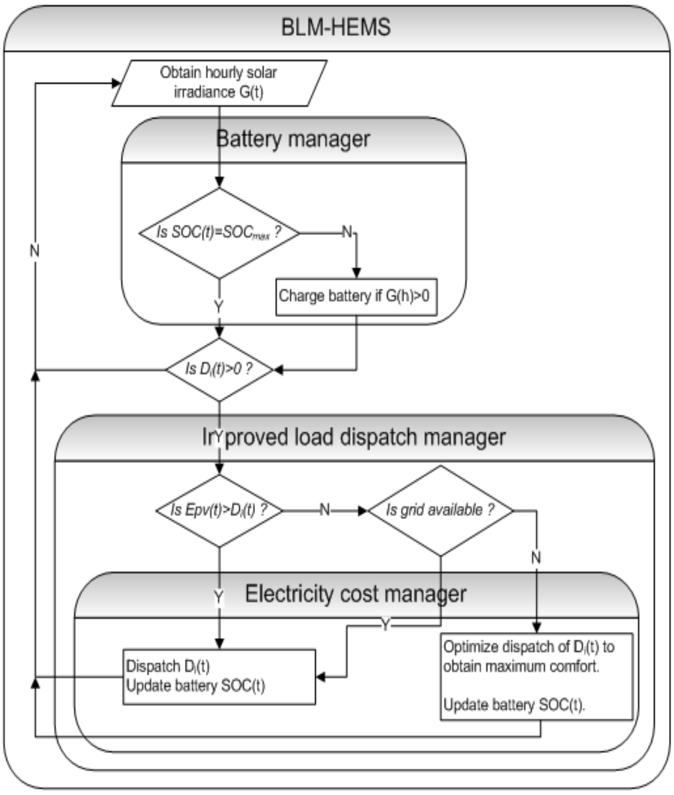

Figure 9: The BLM-HEMS flow chart

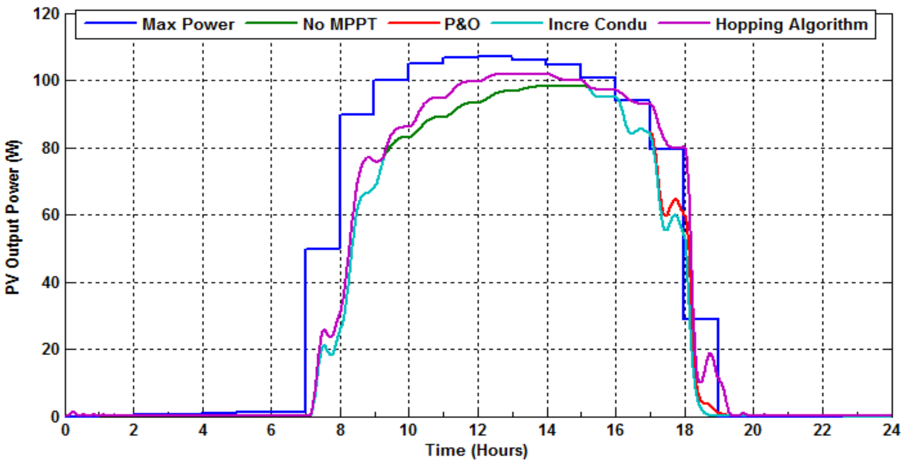

Figure 10: The daily MPPT tracking of the various methods employed

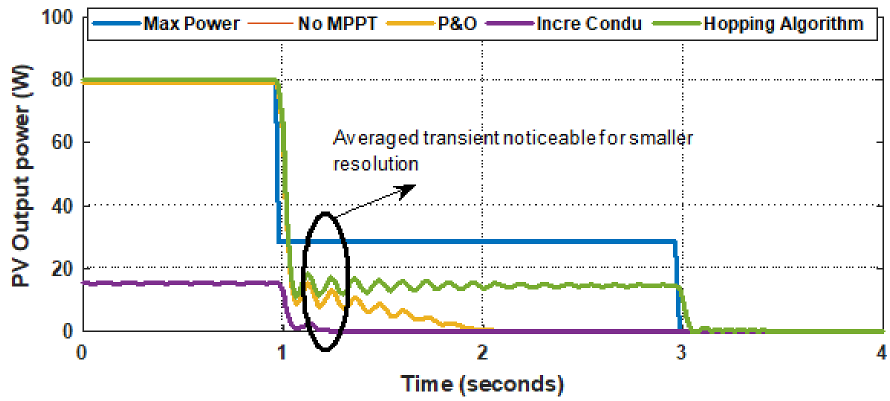

Figure 11: Transient behaviour of the various methods for smaller resolution

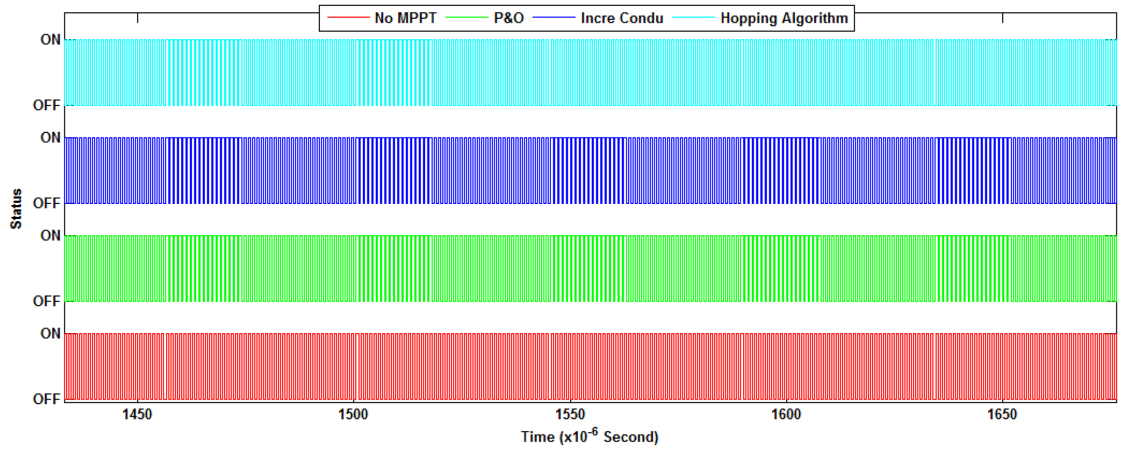

Figure 12: Snippet of the firing sequence of the converter for the various MPPT algorithms

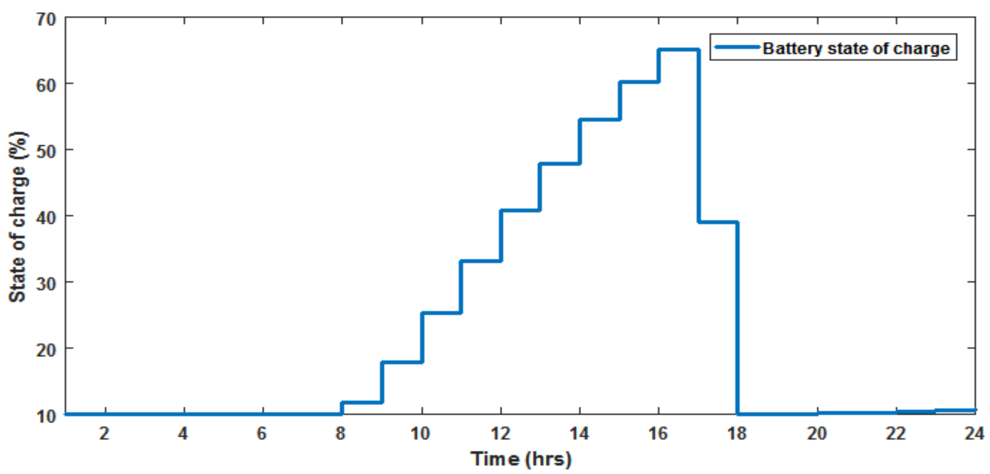

Figure 13: Battery daily state of charge during dry season

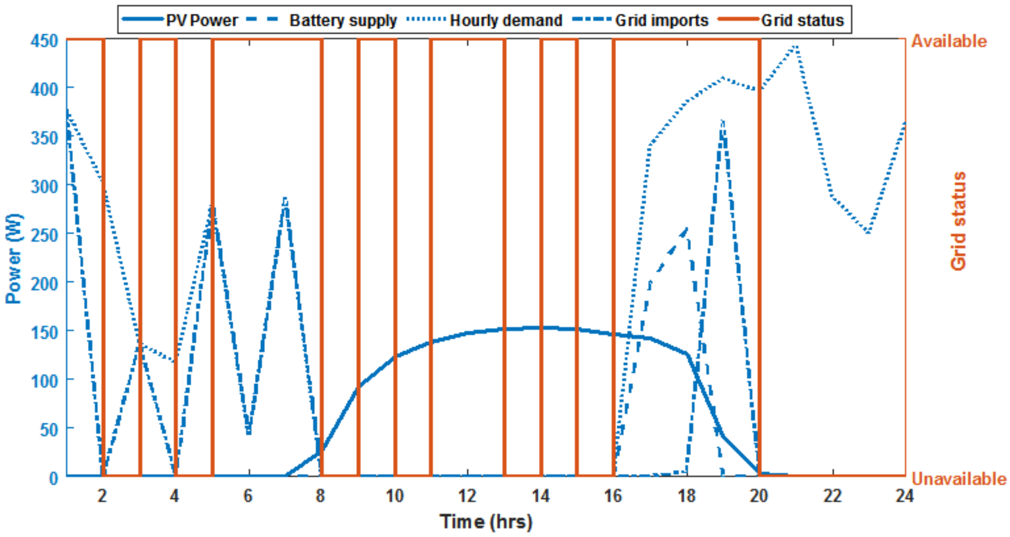

Figure 14: Hourly demand/dispatch profile, utility status and PV/battery capacity

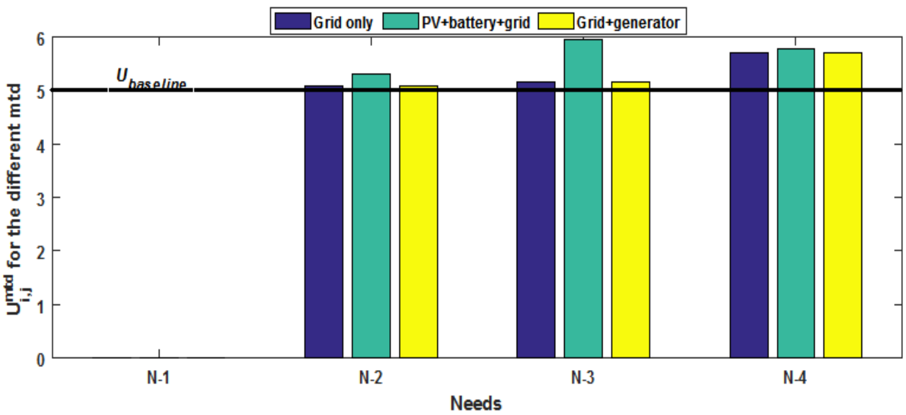

Figure 15: $U_{i,j}^{mtd}$ chart for 4pm – 5pm

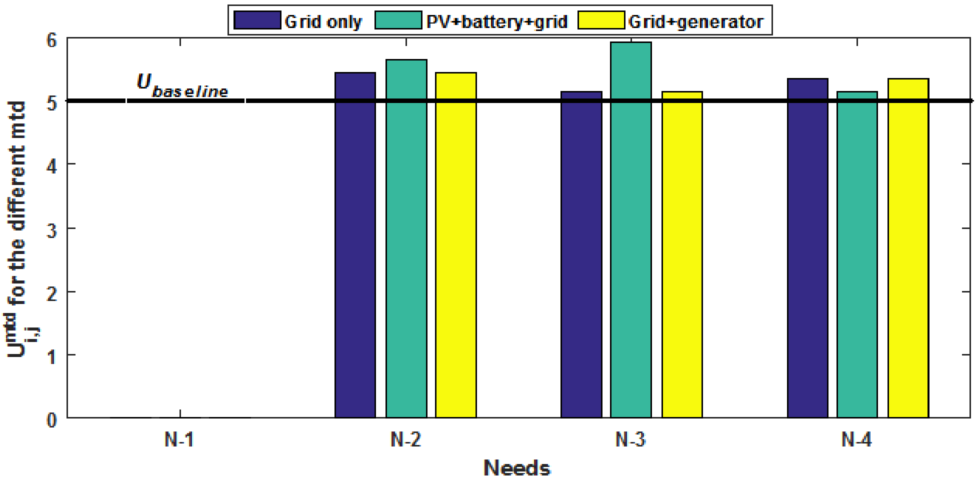

Figure 16: $U_{i,j}^{mtd}$ **chart for 5pm – 6pm**

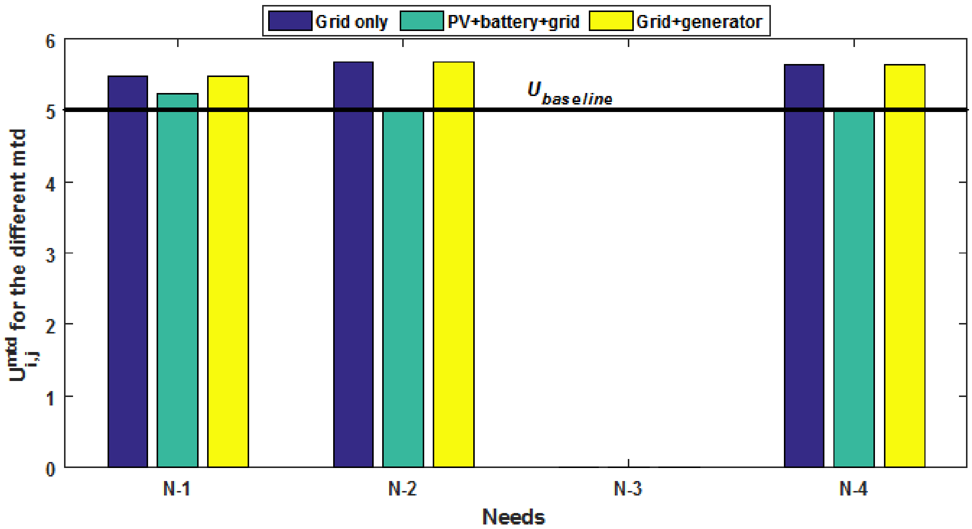

Figure 17: $U_{i,j}^{mtd}$ **chart for 6pm – 7pm**

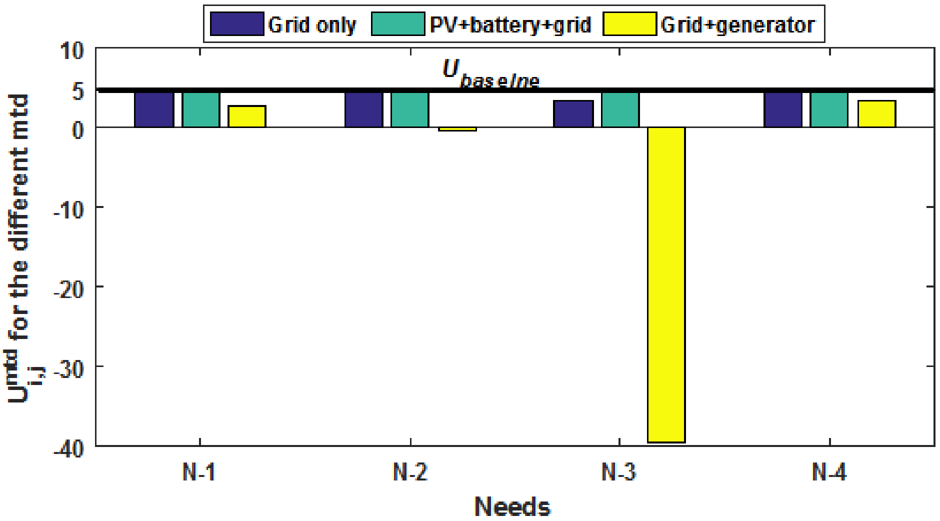

Figure 18: $U_{i,j}^{mtd}$ **chart for 7pm – 8pm**

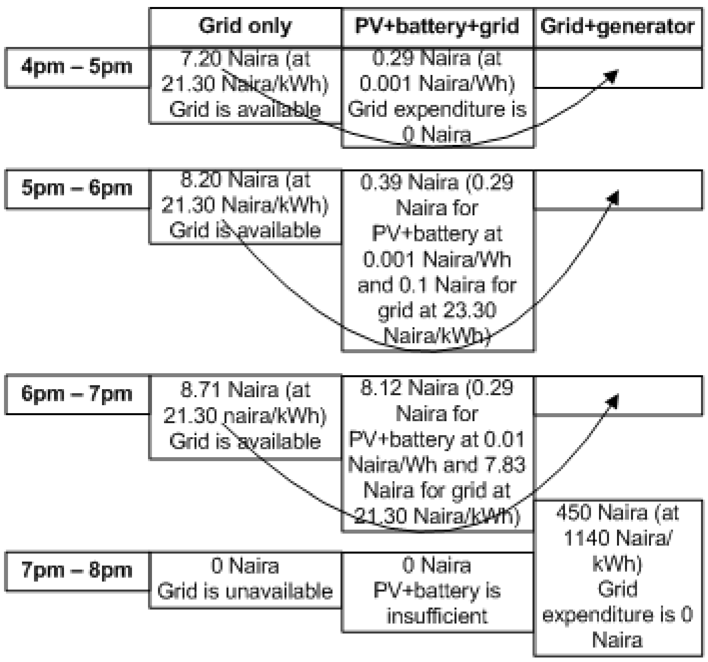

Figure 19: Price fluctuation across the various *mtd*