The hidden benefits of stand-alone PV module efficiency limits

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Abstract. Energy and cost savings from a PV installation in a dwelling is influenced by a number of variables including occupant behaviour and the feedback mechanism accompanying the PV system. This monitoring device can reveal the energy efficiency opportunities present in real-time. The same way an in-home smart metre shows how much energy is being consumed by a household, a PV metre highlights both the generated power and the amount being used at any point in time. Results from a field survey revealed that post-PV installation, there was increased electricity awareness and energy conservation amongst the households. It was further found that in addition to the presence of a feedback metre, conscious energy management efforts arising from the part of the PV adopters and users led to the energy and cost savings. Most importantly, it was revealed that the energy savings were primarily driven by PV efficiency limits. These findings were used to develop a PV efficiency cycle demonstrating how the energy conservation and use efficiency occurred. The study showed the implications and proposed ways by which PV can be promoted in emerging economies.

1. Introduction
The deployment of green energy technologies and energy efficiency are the two core tenets of the transition to a low-carbon future. The goal is to advance renewables and encourage resource-use efficiency especially in the transport, industry and residential sectors which constitutes the bulk of energy use globally [1]. It is generally accepted that following this path would ensure the security of vital energy systems via the use of more sustainable energy sources. This is because conventional fossil-based sources are environmentally harmful.

The decision to limit atmospheric greenhouse gases (GHGs) and promote cleaner energy systems is linked to the first UN Framework Convention on Climate Change (UNFCCC). Subsequently, the Paris agreement held in December 2015 led to a renewed commitment towards this agenda. Today, over 170 nations including Nigeria have ratified this agreement [2]. Notwithstanding, many economies worldwide still rely on heavily polluting conventional fuels predominantly coal, crude oil and natural gas for their electricity production. The UN estimates that around 80% of global energy and 66% of electricity production comes from fossil fuels and contributes an estimated 60% of greenhouse gas (GHG) emissions responsible for climate change [3].

Since buildings account for up to 40% of energy use as well as 30% of the share of CO\textsubscript{2} worldwide [4], most green energy policies and initiatives focus on improving energy use in buildings especially dwellings. One of the most deployed green power technologies in dwellings is solar photovoltaic (PV)
systems. Evidence from studies reveal that the uptake of decentralised low carbon technologies such as PV, can result in energy savings for the household [5], [6]. Keirstead [7], reported a 6% savings from the use of such modern energy technologies in a UK study. The presence of a feedback monitor led to the savings in Keirstead’s study. Through monitoring of occupants’ energy use in a PV adopted social housing, Bahaj and James [8] reported a correlation between occupant behaviour and energy consumption.

In addition to examining the experiences, challenges and energy-saving potential of installing PV in urban dwellings in Nigeria, this paper goes further by investigating the processes by which PV adopters saved energy and costs, if at all. This paper is structured as follows. The next section discusses the patterns of electricity use and energy consumption in Nigeria including PV generated electricity use. Next, the research methods are discussed. Subsequently, a discussion of the results is detailed. Finally, the conclusions, recommendation and implication of research are presented.

2. Patterns of electricity use and energy consumption in Nigeria

Energy demand in Nigeria is a function of rising population and economic growth. The outcome of rise in population and growth in gross domestic product (GDP) of 6% between 2006 to 2015 is increased demand for electricity [9]. Electricity demand in Nigeria is broadly categorised into industrial, residential and commercial sectors. However, demand from the residential sector has in the past decades taken up the bulk of final electricity consumption [10]. Figure 1 illustrates.

![Figure 1. Total electricity demand in Nigeria by sector 2011-2013 Source: Ugulu, 2016.](image)

Some explanations for the residential sector constituting over 50% of total energy demand stems from the fact that most urban households substitute central electricity with auto-generation and kerosene while rural households rely mainly on kerosene due to the low grid connectivity rate to this group. The unreliable grid infrastructure operating under 6GW [11] in Nigeria for a population of over 185million people [12] has meant that electricity is rationed, load shedding is commonplace and power outages is frequent. Secondly, in order to minimise damage to equipment from grid power outages, the commercial and industrial sectors depend heavily on private power plants and less on central electricity. This situation has made most Nigerian households’ and general end-users “experienced” conventional private power generators.

2.1. Solar PV, monitoring device and feedback

In a typical domestic rooftop PV system, a monitoring device is attached to the inverter as part of the installation. This in-home metre helps to monitor performance in terms of power being generated and used at any particular time and helps users ascertain peak periods for scheduled and other high demand usage. With grid-connected PV systems that support feed-in tariffs (FITs), this monitor or metre aids the export and import arrangement [7]. The device helps to coordinate the feeding-in and the buying back process from the grid (in the case of net metering) hence cutting energy costs for consumers.
2.2. Energy efficiency and conservation
Energy efficiency and conservation from PV use has been previously reported in studies but for different reasons. Hast et al. [6] revealed savings from a consumer response study in China citing the motivation as environmental concerns and energy savings. In the UK, Keirstead [7] found that the presence of monitors or metres resulted to a 6% savings in energy cost for the PV households. Using results obtained from nine social housing residents, Bahaj and James [8] presented proof of a reduction in energy use in PV households but the source of savings was unclear as Stedmon et al. [13] also noted. This study aims to fill this gap from the perspective of microgeneration technology users in developing countries where such studies are lacking.

2.3. End-user behaviour and the rebound effect
While there is a link between domestic PV use and energy savings, in some cases, an improvement in supply using renewables can result in a rebound effect for households. Under a rebound, improvement in technical efficiency and falling prices lead to increased consumption; thus, offsetting the reduction in energy consumption earlier experienced [14]. In the case of a PV installation, a rebound would mean that post-PV adoption, energy consumption increases rather than dropping compared to pre-retrofit work. This is often due to changes in user behaviour as some dwelling occupants tend to add more appliances to the existing ones defeating the purpose of efficiency of use and savings.

3. Research methods
Following similar consumer response studies, a qualitative approach was taken. Interviews were conducted and aside questions relating to socio-demographics, questions generally covered relevant aspects of a PV such as system size, drivers, role of PV monitor feedback, energy use efficiency, payback time and challenges and suggestions for increased uptake. Questions were essentially designed to discern if a feedback mechanism such as PV metre can lead to changes in energy demand by examining the pre and post-purchase behaviour of the adopting households. This is to gain insight into the effects of PV uptake on the adopters’ overall energy consumption. Understanding the behavioural modifications and demand management techniques employed would be the basis for any energy efficiency bid.

3.1. Sampling and sample size
Purposive sampling was used. This is a permissible technique in qualitative studies (Robson, 2002). In this type of sampling, the researcher’s judgment is relied upon based on study interest and rationale. Some PV adopters interviewed were identified from a questionnaire survey for a different but related study. Others were selected via referral. This is a situation whereby an interviewed adopter refers the researcher to other users. A total of 14 adopters were interviewed as experiential data require fewer participants [15]. Bahaj and James did a similar PV study in Southampton UK using 9 households [9]. Respondents were primarily drawn from Lagos State, Nigeria. Due to the small number of PV users here, respondents were taken from other states i.e. cities in Nigeria such as Abuja (Federal Capital City) Delta, and Edo. Open-ended semi-structured interviews were carried out and the interviews recorded using an MP3 recorder. The interview questions largely examined the role of feedback mechanisms such as PV monitor. This was done to understand the relationship between PV use and energy savings as identified in literatures [6]–[8]. In addition, it was designed to ascertain if the variables at play are interconnected and if the reports were consistent when applied to a developing country with unreliable grid electricity supply.

4. Results and analysis
In order to ascertain whether PV could help bring about household energy use efficiency and management, its contribution towards helping to modify household energy consumption behaviour was examined. Through the inclusion of questions bordering around whether the adopter’s installation
had a monitoring metre attached, the location of the device and how frequently the monitor was viewed, this important aspect was analysed. The findings were positive and revealed that PV use can contribute to increased energy use awareness and in consequence reduce overall demand, improve supply and encourage de-consumption.

One reason behind the energy use management uncovered was the presence of a feedback metre on the inverter. This supports Keirstead’s [7] finding. All but one of the adopters stated having a display monitor on their PV inverter. With most of the adopters’ inverter located inside the dwelling, there were more regular checks by the energy conserving and efficient households.

The presence of an inverter monitor can influence the number of checks on a PV system which can in turn lead to more energy use conservation and efficiency of use. There was an almost five-fold increase in energy use monitoring and conservation following the introduction of PV. See Figure 2. Therefore, the use of PV directly impacts on households and consumers energy demand and fosters interaction between the users and the system. This interaction is the direct result of PV output limitations.

![Adopters energy use efficiency](image)

**Figure 2.** Energy use and savings pre and post-PV

### 4.1. The hidden benefits of PV module power limitations

One of the most interesting discoveries of this study was that household PV adoption leads to increased energy use awareness and subsequently energy conservation and efficiency. An almost fivefold increase in energy management was reported by the adopting households’ post-PV. They said the presence and location of the feedback metre helped. Like smart metres, PV metre does not only provide useful information for adopters, it served to place control in the hands of the users in a way centrally-supplied electricity does not. This directly impacted household’s energy demand and fostered interaction between the users and the system. The energy management opportunity was therefore a function of the high costs of a sizable PV, the presence of an in-house metre and most essentially, the output limits of PV. It is this latter feature of PV that makes for its distinctiveness. Figure 3 details the energy-saving processes taken by the PV adopters and users.
Figure 3. The PV efficiency cycle

The continuous processes illustrated in Figure 2 above serve to indicate the crucial steps that PV-adopting households in urban Nigeria take to achieve energy use efficiency. Starting from Step 1 when the PV is installed, the PV electricity generating households start to notice the improvements to their energy demand which PV has enabled. This excitement stems from the fact that it may be the first time the users have had uninterrupted supply for a while, without the need to use alternative sources like fossil-based generators that require constant fuel purchases. This excitement, plus metre/monitor checks, draws the users closer to the workings of a PV unit.

Clockwise from point 1, at Step 2, PV design limitations start to bear on the users as they realise that they cannot use their PV for every appliance but mainly for essentials. Due to its non-dispatch design, the users then realise that they have to conserve power to allow the efficient running of the device. At this stage, energy use management becomes the sole prerogative of the PV adopters as they make sure that unnecessary plugging in of every household appliance is avoided and discouraged. Increased electricity and energy use awareness arises from the restrictive use of PV and prevents overconsumption habit formation by households. This new energy use awareness creates the “conditioning effect” resulting in behavioural changes (Step 3) which is the most important role of a PV module as it pertains to energy cost savings, efficiency and environmental sustainability.

It thus falls on the households to begin to search out other ways they can reduce consumption in order to make the device function more effectively and efficiently. This leads to greater awareness and the consideration and uptake of modern power saving household appliances and building technologies (Step 4). Also, other possible avenues to minimise energy consumption is sought. Here, energy efficiency ideas like purchasing more energy saving appliances and retrofitting the building for passive cooling and heating, to allow for natural airflow and solar gains to the dwelling, become more realistic. This is a form of climate change building adaptation that PV utilisation can stimulate.

Some households would voluntarily make these building changes having had the opportunity to observe first-hand the energy dynamics of a PV unit. For other non-adopting households, the government (Step 5) can assist with support instruments (with particular emphasis on efficiency) to encourage PV adoption e.g. by mandating the building construction industry and private developers
to incorporate low-carbon technologies in dwellings such as the German pioneered Passivhaus standard. It should be noted that not in all cases is the PV cycle sequential as it appears on the diagram. For example, those individuals with high technical knowledge might bypass the energy awareness and conditioning phase (behavioural change) by deliberately installing their PV to be used with certain selected appliances in the home. They could include a PV controller or exclude power guzzling devices like multiple A/Cs from the unit to better manage the system. Nevertheless, their use of PV will still demand that they routinely check their energy consumption as solar radiation and daylight intensity varies daily and hourly. Notwithstanding, the point of the cycle is that most adopters will pass through the 4 initial phases and then decide if there is further need for additional adjustments such as more building retrofit works to accommodate the proper function of the solar panels.

5. Conclusions, recommendations and research implications of findings
This paper is evidence that a simple decision to install solar PV in order to improve power supply to a home can bring about a whole range of unforeseen positive behavioural changes and long-term benefits for the adopting households and society at large. Also, energy and power shortages can lead to adjustment, sometimes unconsciously. This is because, with scarcity, serious reflection begins. It is highly unlikely that a rebound situation would arise as the surveyed households were very conscious of their energy use made possible by the PV feedback metre and decades of energy management. The PV efficiency limits served as a reminder to households that electricity needs to be conserved for regular power to be guaranteed and for the system to function optimally. The metre readings and PV capacity limitations were what compelled the users to make the necessary changes. While it may appear as an inconvenience, it was the reason for the savings and the adopters did not find it inconveniencing. Not yet identified in discourses is this “conditioning effect” of PV. In fact, this aspect of PV is often described using negative connotation. For example, the well-known issue of PV efficiency receives this description. Meanwhile, silicon module and cell efficiencies have exceeded 20% [16], [17], while in a recent study researchers Burlingame et al [17] and others [18] reported an efficiency level of >15% for Organic PV (OPV). However, PV output limits is frequently cited as a hindrance. While one cannot deny the existence of output limitations and capacity factor issues, there seem to be an understated usefulness of solar PV in this regard. Dismal as PV efficiency limits may appear, published research gives credence to its immense prospects.

Since the aim of promoting renewables is to limit emissions and for energy security, PV is one of the best micro-generation technology (MGT) for this purpose because it acts as a “conditioner” for households to adjust. This notable feature can be best visualised in the energy demands of households in developing nations, where citizens experience long hours of power outages. Having experienced load-shedding, power rationing for a long time, adjusting to PV-supplied power becomes much easier. The long periods of national power shortages have prompted energy frugality which PV deployment helps to preserve. Unlike in OECD countries where citizens are used to decades of constant power to their homes, widespread PV use becomes difficult because it is certainly not going to meet their very high energy needs. This is probably the reason why the hidden benefits of PV output limitations are yet to be established in more developed countries. However, it is only such limitations that can help reintroduce de-consumption and reinforce demand reduction and eventually help accomplish energy efficiency goals. If national and global emissions targets are to be met, there is an urgent need to support widespread uptake and diffusion of residential PV in emerging economies using fiscal and non-monetary incentives.

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