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Research article

Rural electrification in Nigeria: A review of impacts and effects of frugal energy generation based on some of e-waste components

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ABSTRACT

Nigeria is the seventh most populous country in world being the highest in Africa. The country is blessed with vast natural resources and is one of the highest producers of oil in the world. However, the inadequate supply of electrical energy is a major setback in the nation's economic development. Thus, there is need for an urgent and immediate solution to address the electricity access situation in Nigeria. It is in view of this that we first present an overview of the electrical energy situation of Nigeria (especially in the rural areas). The benefits of rural electrification and it impacts are discussed to buttress the need for electrifying rural areas and an overview of the abundant renewable energy resources in Nigeria is presented. As a proposed solution to improve the electricity situation, the concept of a reuse solar photovoltaic system based on e-waste components and old materials is presented. The system comprises repurposed Power Supply Unit (PSU) from old desktop computers, old thermal car Lead-acid batteries, old solar panels and Uninterruptible Power Supply (UPS) units. The possibility of adopting this solution in Nigeria depends on the amount of e-wastes generated annually thus necessitating the need for an analysis to see the annual impact of this system on electricity access based on the amount of available e-waste. Using the huge amount of e-waste generated/received annually in Nigeria, the feasibility of our solution is assessed by estimating the possible number of households that could be electrified by the second life renewable energy systems we propose. Due to the lack of official data in this field, certain constraints and assumptions were defined for the purpose of this analysis which resulted in obtaining a range of results that showed the possible impacts of adopting the reuse system. The analysis showed the minimum and maximum impacts the reuse solution could have on electricity access in Nigeria, based on best and worst case scenario respectively. The results further showed that an average of 287,000 households can be electrified annually if this solution is adopted, causing 2.2 % increment in population with electricity access in a year (between 620 thousand and 4.1 million individuals). Thus, the result is an indication that it is possible to achieve immediate growth in electricity access based on renewable energy integration, frugal innovation and reuse/repurposing of e-waste materials. In addition, this extension of their lifespan reduces their ecological footprint. It is expected that the energy demands of the continuously growing population can be met by strict adherence to set targets including adoption of smart-grids, generation diversification and focusing on rural electrification.

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1. Introduction

Nigeria is located on the west central African axis lying between Latitude 4° and 14°N and Longitude 2° and 15°E. According to the UN and World bank [1], Nigeria is classified as a lower middle-income country which is bordered by four different countries and the Atlantic Ocean. Having a land area of about 924,000 km^2 and an estimated population of 220 million as at 2023, it is the most populous country in Africa. Poor development in the electricity sector can be attributed to the fact that 80 % of Nigerians live below poverty line [2,3]. Generally, majority of the population are under-electrified while the gross of un-electrified population are mostly found in the rural areas because they are not connected to the national grid [4]. Adequate, sufficient, stable and reliable electricity supply is one important aspect that is required to improve the quality of life of a common man for smooth growth and economic development [5]. The lack of electricity would automatically translate to the lack of availability of technological applications, deterioration of health and safety, unsafe conditions and many more which would in turn have a negative effect on the economic aspect of both individuals and communities [6,7].

Access to electricity is one major condition for economic growth [5]. In most developing countries like Nigeria, rural areas have zero or insufficient access to electricity thus making their economic output low [8]. Recent studies have proven that access to electricity can increase productivity time and have an overall effect on economic output [9,10]. A positive effect on the overall human life, an immediate effect on health, labour and education as well as increase in income are all gains of electrification [6,10,11]. The dependence on electrical energy operated devices such as phones, computers, radios, television, heaters amongst other have made electrical energy access an important aspect of human life. For example, a simple gas cooker or kerosene stove can now be replaced with an electric hot plate; a kerosene lantern can be replaced with rechargeable bulbs and solar lamps and so many more. Thus, the exposure to poisonous gases is reduced within the household leading to an improvement in overall health. Nigeria has abundance of natural resources where more than 25 different resources are officially mined including large oil and gas reserves [12,13]. Being amongst the top ten nations with gas reserves, Nigeria has a huge energy resource such as tar sand, coal and lignite amongst others. Although there is also abundance of fossil fuel, the high rate of deforestation (55.7 %) which puts Nigeria at the highest in the world just ahead of Vietnam (54.5 %) is projected to completely deplete by 2050 if actions are not taken [12,14]. On the contrary, the presence of renewable energy resources is also abundantly significant in Nigeria most especially solar, hydro, wind and biomass. Solar is the most predominant with a daily potential of around 4000–6500 Wh/m^2 while the hydro potential is about 15,000 MW capacity. A wind speed of 2.0–7.0 m/s depending on the location, and an estimate 140 million tons of biomass per year depicts a huge potential of renewable energy resources [15].

It is agreeable that provision of electricity is an expensive investment when compared to the immediate, direct profit accrued after electrification. This is the reason why a lot of developing nations have been unable to provide adequate electricity to most part of their populations. Most of them still depend on conventional ways of energy generation which have seemingly been overstretched and require grid expansion as well as additional generation stations. Several authors such as [16–20] have analysed the situation of electricity in Nigeria, citing the causes and proposing solutions [21]. proposed the solution to focus on adoption of renewable energy for generation expansion while suggesting the importance of low cost electrification options [19]. estimated the potentials of biomass, hydro, wind as solar energy as a solution to the Nigerian energy crisis while indicating that exploration of these alternative generations will benefit more than the dependence of gas powered generation [18]. highlighted issues such as incomplete privatisation, underdeveloped gas supply infrastructure, and ineffective or weak regulations as the root causes of the electricity crises in Nigeria. More like previous publications, solutions proposed were to concentrate on decentralised solar PV generation and strengthened regulation while adopting a long term financial support to enhance the electricity generation system [22]. identified corruption and inefficiencies as one of the major reasons for stagnation of electricity growth in Nigeria. Off-grid generation, context specific policies and introduction off-grid renewable energy generation for Small and Medium Enterprises (SMEs) was proposed as a viable solution to improve the electricity situation in Nigeria. Most of these authors have accepted that the lack of technological manufacturing industries has made countries like Nigeria to depend on importation of technology, as such they solely depend on imported electrical and electronic equipment and components to catch up with current technological trends. In addition, the cost of electricity is also one of the hindering factors causing the poor status of electrical energy access in these countries. This serves as a justification to seek new ideas for generating and providing electricity to rural areas without supply or with insufficient access to electricity. It is in this vein that we proposed the review of the current status of electrical energy in Nigeria to understand the challenges and explore possible solutions that can mitigate the causing factors. Most solutions previously provided have focused on two key perspectives; integration of off-grid renewable energy solution and low cost electricity generation. They however did not further propose how the cost of electricity infrastructure can be significantly reduced without dependence on government or NGO financing. In this paper, we have proposed and investigated the feasibility of adopting an original and very cheap reuse solution to provide off-grid electricity to rural areas based on renewable energy and second life materials from e-waste.

1.1. *Problem statement*

The increasing menace of global warming and the need to propose cheaper alternatives for electricity generation has been the motivation for a lot of novel initiatives in the energy industry. The absence of reliable electricity infrastructure in rural areas hinders economic development and limits access to essential services. Thus there is a need to explore the possibility of providing cheap and clean electricity to the most vulnerable, in a different and original way. A possible solution is by integrating renewable energy solutions with e-waste recycling initiatives to concurrently address environmental sustainability challenges and reduce the impact of e-waste accumulation.

1.2. Objectives and methodology

The main objective of this study is to investigate the feasibility and the impacts of adopting a reuse solar generation system on electricity access in Nigeria. To achieve this, the current status of electrical energy situation needs to be illustrated to depict the current need for an emergency solution and to show that the situation has not improved in recent years. Since the reuse solution depends on renewable energy sources and e-waste materials such as old batteries and power supply units from desktop computers, the availability of renewable energy and status of generated e-waste is studied to ensure the proposed solution is implementable. Thus the step by step procedure involved surveying the status of electrical energy in Nigeria, exposing the benefits of rural electrification, reviewing the renewable energy potential and available e-waste, and finally, analysing the impact of adopting the reuse solution on energy access.

The paper is structured as follows; the first part discusses electrical energy status in Nigeria while the second part talks about rural electrification and its impact. The third part is on renewable energy status and microgrids while the fourth part presents the idea of re-use of electronic waste for energy generation. Finally, the impact of adopting reuse of electronic waste for energy generation on energy access in Nigeria was analysed and results were shown.

2. Electrical energy status in Nigeria

The electrical energy consumer sector in Nigeria is the fastest growing form of energy which was estimated to have consumed about 23,000 GWh of electrical energy in 2019 [23]. Thus, several means of generation will continuously be explored to meet the increasing demand for quality supply of electricity. Conventional power generation stations such as coal-fired, gas and nuclear-powered plants as well as hydroelectric power stations are the most common means of generating electricity in the country. However, as the world is considering more economical and environmentally friendly alternatives, the global energy mix is becoming more complex [24]. Several factors such as greenhouse gas emission, electrical losses, lack of resources in developing countries and increasing demand has forced suppliers of electrical energy to seek for alternative and clean means of generating electricity [25]. This has led to the introduction and proposal of several ideas and alternatives such as; Renewables, Distributed Generation, Microgrids etc. to tackle the above-mentioned factors and ensure consumer demands are met.

The world electrification status is approximated at 90 % with 790 million people still living without electricity. This is obviously a threat to achieving the United Nations 2030 Sustainable Development Goal number 7 (SDG7) of ensuring availability of clean reliable and cheap energy to all individuals. The more alarming aspect is the fact that projections have indicated that 650 million people will still be without electricity by 2030, 85 % of which would be from Sub-Saharan Africa [26]. In Nigeria, the lack of adequate electricity supply is not a new scenario to majority of consumers because millions of Nigerians do not have access to grid electricity. According to World bank SDG report in 2020, Nigeria is not amongst the top ten countries with electricity access in Africa, with Egypt, Algeria, Seychelles and Morocco having 100 % access to electricity. Nigeria on the other hand has 62 % of its population with access to electricity even though majority of these individuals have more than 10 h of blackout period daily [27]. The situation in rural areas in Nigeria is particularly severe with only 41.1 % grid access rate, majority of which are 'under-electrified' meaning they have less than 12 h of grid electricity per day [28]. Currently, about 77 million individuals out of a population of more than 200 million people do not have access to electricity [29].

The power sector development in Nigeria can be traced back to 1896 when electricity was first generated in Lagos (South-western Nigeria) to deliver energy to a consumers at a peak capacity of 60 kW [30,31]. Over the years, several agencies have been created, revised and repositioned to oversee the affairs of electricity supply in Nigeria. The Nigeria Electricity Supply Company (NESCO), the Electricity Corporation of Nigeria (ECN), National Electric Power Authority (NEPA) and Power Holdings Company of Nigeria (PHCN have all managed affairs of electricity in Nigeria over time [31,32]. NEPA managed all the affairs of electricity in Nigeria between 1972 and 2005. As at 1988, Nigeria's generation capacity was 4574 MW with an estimated population of 90 million [13,33]. NEPA was

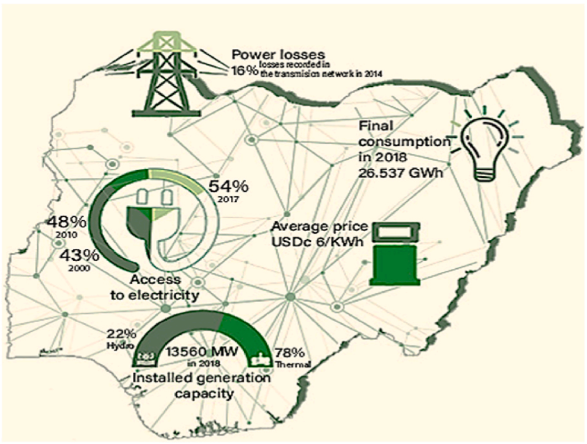

Fig. 1. A pictorial summary of the Nigerian energy situation as at 2018 [36].

unbundled in 2005 to create the Power Holding Company of Nigeria (PHCN) which was charged with the task of restructuring and privatising the power sector. As a consequence, the government-maintained ownership of the Transmission Company of Nigeria (TCN) and privatised the Generation companies (GENCOs) and Distribution Companies (DISCOs). In 2013, assets were handed over to 6 GENCOs and 11 DISCOs to oversee their affairs independently. Afterwards, a regulatory Nigeria Electricity Regulatory Commission (NERC) was created to oversee the affairs of mutual interests like tariffing, quality of service delivery, and other regulations [34]. The energy situation of Nigeria as at 2018 is shown in Fig. 1. These values are yet to improve and currently, Nigeria has a total of 28 grid-connected generation stations which are mostly gas-fired powered and some hydropower stations [19,23,35].

Data obtained from the National Network Control Centre (NCC) has shown that for the past five years, average annual generation output ranged from 3,257 MW to 3,867 MW per day. This indicates gross underperformance of the generating stations due to factors such as ageing, faults and poor maintenance, insufficient gas supply, inadequate infrastructure, breakdown of some units and many other factors [19]. This is the reason why there is no growth in the annual consumption of electricity from the national grid between 2014 and 2019, as shown in Fig. 2.

On August 1, 2020, Nigeria had a record peak generation of 5377 MW surpassing the previous record of 5375 MW in 2019. This amount of energy was successfully transmitted and distributed at 21h30 and now stands as the highest ever peak generation. The National Electricity Regulatory Commission (NERC) stated that the entire transmission network of the country can safely handle only a meagre 6,000 MW even though the country currently has an installed capacity of 16,021 MW and a generation capacity of 7652 MW [37]. Thus, even if there is sufficient increase in generation, there is also a corresponding need to improve the transmission capacity. Fig. 3 shows a summary of the annual total energy generation data between 2015 and 2020, which was directly obtained from the Network Control Centre (NCC) of the Transmission Company of Nigeria (TCN).

3. Rural electrification in Nigeria

Nigeria, being a developing country cannot ignore the positive impact of rural electrification. World Bank data showed that 48 % of Nigerians are rural dwellers; an indication that Nigeria needs to focus more on rural electrification to steer economic development [28]. Rural electrification will reduce the burden of overpopulation in urban areas, improve condition of living of rural dwellers, reduce mass migration to cities, improve economy of rural areas and overall GDP [38]. Another additional benefit of rural electrification is reduction in poisonous gas emission due to decrease in the use of fossil fuels. This is why most countries and governments have been encouraged to concentrate on electrifying rural areas.

In1981, rural electrification was proposed in Nigeria so as to electrify 301 local government headquarters by connecting them to the national grid and bringing electricity closer to the people in rural areas [39]. The target was to reduce economic disparities and empower local government secretariats to enable them discharge their constitutional duties diligently. The aim was to accommodate and ensure all tiers of government independently carry out their functionalities. By 1999, the number of local government headquarters had grown to 774. Thus, an implementation committee on Rural Electrification was inaugurated and as at 2003, about 600 local government headquarters were connected out of 774. Significant success was not achieved because local government headquarters don't depict rural areas as a whole and population growth rate was much higher than electrification rate as evidently shown in [40].

A national policy tagged "*National Energy Policy*" was reformed and adopted in 2005 with several objectives which included rural electrification, grid expansion, renewable energy generation and grid decentralisation amongst others were outlined. In summary, these strategies focused on funding, grid expansion/extension, increasing generation, adoption of renewable energy and other incentives to reduce rural-urban migration. The draft was to serve as a blueprint for future economic and sustainable development, supply and utilization of energy resources. The overall policy had five broad objectives [39]:

1. To enhance energy security in the nation through diversifying the energy supply mix,
2. To increase energy access especially in the rural and semi-urban areas,
3. To facilitate employment creation and empowerment,
4. To protect the environment and mitigate climatic change,
5. To build local capacity.

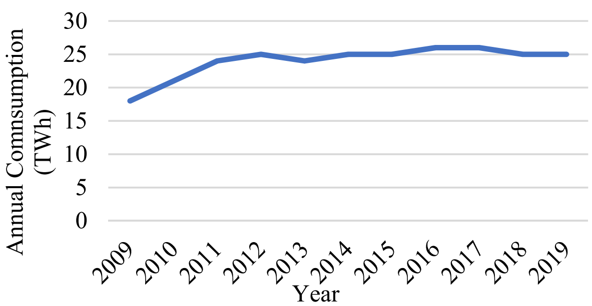

Fig. 2. Annual consumption of electricity in Nigeria [23].

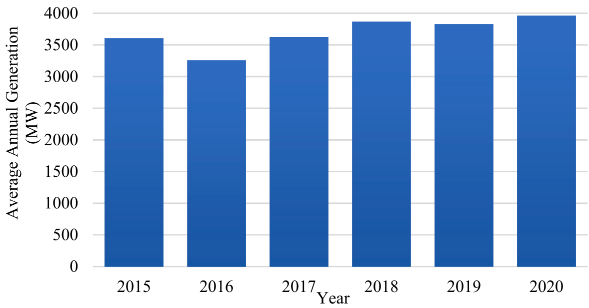

Fig. 3. Annual mean generation output 2015 and 2020.

However, up till date, the status of rural electrification in Nigeria still has a long way to go. Most rural households are still under-electrified despite these policies and proposals. In order to justify, the effect of rural electrification in any nation, the positive effects or impacts of rural electrification will be discussed briefly.

3.1. Impact of rural electrification on lighting

Lighting at night is one important aspects of human life. Poor lighting methods such as candles, fuel-based lanterns, open fires and many others as shown in Fig. 4 were used to illuminate night-time in the absence of electricity. Asides the poor illumination from these alternative sources of lighting, it poses a health and emission hazard to the users and the ecosystem respectively. Electrification in areas where these techniques are still used for lighting at night will positively improve the quality of the night life, reduce risk to inhalation of hazardous gases, better eyesight and reduce greenhouse emission [41] and help the children in their homework. Furthermore, the need for continuous purchase of fuels and dry-cell batteries will also be eliminated. In Nigeria, the World Bank Lighting Africa-Nigeria project has so far affected about 1.8 million rural dwellers between 2014 and 2018 with an approximate reduction of 162 thousand tons of greenhouse emission. The impact of electrification has encouraged users to discard most of these fuel-based lighting sources for more efficient and cost-effective alternatives such as Light Emitting Diode (LED) bulbs.

The adoption of electric sources of lighting already has a positive impact of electrification for nightlife, thus improving work hours and productivity during the night time [42]. This impact has also favoured the LED technology which has gone as high as 90 % penetration in countries like Senegal because houses that have electricity supply prefer to buy these rechargeable lamps to use during outages [9]. Data from countries like Burkina Faso and Rwanda have shown that rural electrification will impact the choice of lighting as there was significant reduction in the use of fuel-based sources of lighting over a period of two years [41].

3.2. Rural electrification impact on education

Education and learning are key factors in any country. The number of available lighting hours can have an impact on studying and learning thereby improving awareness, motivation and overall output of individuals. It has been shown that the effect of electrifying rural areas in Peru increased studying time [45]. However, there is a relative distraction as provision of electricity also means access to leisure devices such as televisions and radios and many more, but this effect may vary from household to household. Studies have shown that 90 % of parents have agreed that the provision of electricity would increase the study time of children while 55 % also

Fig. 4. Lantern, wax candle and traditional wick lamp as against LED lamps used as sources of lighting [42–44].

agreed that leisure time would also increase if electricity is available [46]. In 2009, a study in Senegal was able to prove that availability of electricity resulted in an increase in study time after nightfall from 21mins to 30mins [9]. This indication may not be consistent in every other part of rural Africa but is a sign that with the right resources and discipline, electrification would hopefully have positive impacts on education and in turn, improve performance of school children in their academic activities.

3.3. *Impact of rural electrification on greenhouse emissions*

As at 2013, indoor air pollution is the third most significant risk factor for global diseases ranking, after high blood pressure. This is basically caused by use of fuel sources in various activities in the house such as kerosene stove for cooking, candle and local lamps for lighting and many other [47]. Several elements such as Carbon dioxide, Ammonia, Nitrogen IV oxide and many more contribute to the release of greenhouse gases as shown in Fig. 5.

Another significant source of greenhouse emission is the use of back-up generators by houses and companies. Most small unit generators are powered by either petrol or diesel which comprises an Internal Combustion or Compression Engines that release a lot of toxic gases during operation. The total amount of electrical energy generated from back-up generators from 2018 to 2023 for Africa amounted to about 40 TWh annually, in which Nigeria alone has contributed about 40 % [40,41]. Similarly, in Nigeria, more than 2, 600 MW of decentralised diesel and gas generators are installed [49]. Emissions are majorly from the power generation, transport and industry, fuel-based cooking and lighting. Several households in Nigeria for example, still depend on firewood and kerosene as sources of cooking [50]. On the contrary, access to electricity will mitigate these damages and help in achieving target emission reduction goals [41]. The world is presently moving towards higher global temperature which would mean increased land ambient temperature, melting of arctic regions and rise in nominal sea levels, in which burning of fuel is also a contributor. This justifies the need to provide clean and reliable electricity for rural areas so as to slow down the rate at which rural dwellers contribute to emission of greenhouse gases. Nigeria is a signatory to the Paris agreement of 2015 which aims at effectively reducing the emission of CO_2 and holding it beyond 2° in 2040 by encouraging energy generation via clean sources [51,52]. This seems unrealistic as there is no significant increase in grid-tied electricity generation since 2015 and the adoption of RE is mainly by standalone mini/microgrids comprising solar photovoltaic generations mostly adopted for private and personal use. Furthermore, the reduction of greenhouse emission and provision of energy for all, has been captured in the Sustainable Development Goals of the United Nations [53]. Thus, increasing rural electrification would not only help Nigeria in reducing the emission of poisonous greenhouse gases but also help the world in achieving the target emission reduction by 2040.

3.4. *Rural electrification impact on economy*

Labour, employment, agricultural outputs, productivity and overall development are major indicators which directly affect economy. An improvement in electrification has been proven to affect these factors and further improve the economic situation of any nation. In addition, there is a direct relationship between rural electrification and income, especially for newly connected homes because of the possibility of increased business opportunities from home such as commercial operation of milling or electric grinding machines for profit; a peculiar situation in rural areas. The increase in working hours is another index for improved profit because there is more productive time as a result of electrification [9]. As an example [54], has shown that rural electrification has a positive effect on the Gross Domestic Product (GDP) or per capita income in sub-Saharan Africa. Fig. 6 shows a relationship between rural population growth, rural electrification, rural/urban electrification and GDP per capita.

Evidences have also shown that electrification of rural areas can be directly related to some sustainability metrics which have certain factors such as technological, economic and financial, social or societal, environmental factors, regulatory factors health, safety, gender and security. Nigeria in particular has recorded an increase in income of specific artisans due to electrification in southern Nigeria [55]. studied, evaluated and investigated the impact of rural electrification in Niger-Delta area of Nigeria via grid extension. The study demonstrated some benefits of rural electrification on the average income of different enterprises where a 16 % overall increase in profit was recorded due to electrification. A summary is shown in Table 1. Most developed nations have been able to

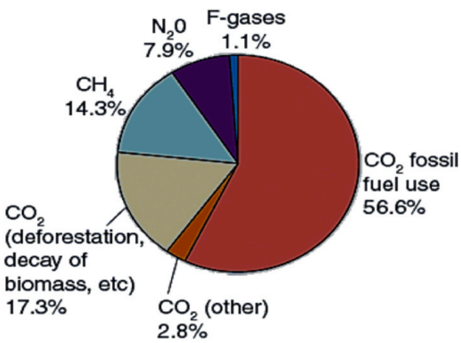

Fig. 5. Sources of greenhouse gas contribution [48].

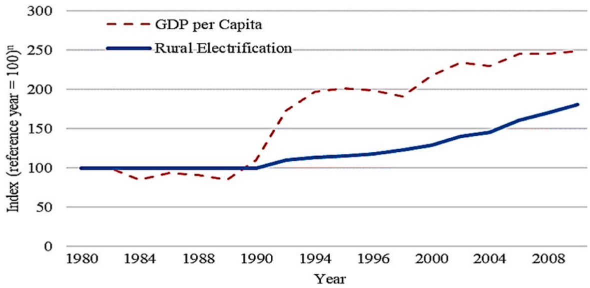

Fig. 6. Relationship between rural electrification and GDP per capita [47].

generate and supply electrical energy to rural areas in order to boost their GDP per capita and continue to move a stable economy [56].

4. Solutions to improve rural electrification

The first attempt to improving rural electrification is to consider all possible solutions and create policies to strictly guide the implementation of these solutions. The introduction of renewable energy generation should also be included in the solution approach as this is the cleanest means of energy generation available. Recent innovative ideas such as smart microgrids should be considered as an alternative to grid expansion while frugal innovation and use of local renewable energy scheme and ideas should be introduced. An example is the introduction of tax exemptions for solar and renewable energy related projects which was introduced in 2015 [57]. This was deduced to have contributed to the increase in solar installed capacity from 10 MW to 73 MW between 2015 and 2022 [58]. An overview of the renewable energy status in Nigeria will shed more light on the potentials yet to be explored for energy production.

4.1. Adoption of renewable energy as a solution in Nigeria

It is undoubtedly clear that Nigeria has abundance of sustainable and renewable power source assets like sunlight, biomass, hydropower and wind. Hydropower sources which are the most significantly used sustainable power sources have potentials which add up to 10,000 MW for large hydropower and 734 MW for small hydropower [15]. Wind energy has a capability of 150,000 TJ for every year, created by a normal breeze speed of 2.0–7.0 m/s. Solar radiation is evaluated at 4.0–6.5 kWh/m^2 daily, and 144 million tons of biomass is available annually [59]. Fig. 7 shows the wind speed and solar radiation maps of Nigeria of Nigeria with the variations all around the country. Sadly, these resources are however underexplored as there is currently no single renewable source of generation connected to the national grid except the conventional hydro dams which have been built many decades ago.

Furthermore, several initiatives have been introduced to have meaningful intervention in the renewable energy sector of Nigeria over the years. These include the Vision 20:2020 renewable energy plan, Renewable Energy Master Plan (REMP), the ECN/UNDP intervention, Sustainable development goals 2030, Renewable Energy and Energy Efficiency Project (REEEP) and many others [39,60]. In summary, the key objectives of these initiatives in line with the Vision 20:2020 renewable energy plan [60,61]:

a) To increase generation, transmission and distribution capacity for adequate and sustainable power supply. Generation of 16,000 MW by 2013 was envisaged,
b) To have an optimal energy mix of gas fired plants (12,730 MW), coal (900 MW), hydro (2250 MW) with other renewable i.e. wind, solar and biomass that could give a total of 16,000 MW by 2013 using appropriate technologies,
c) To have introduced 1 GW of biomass power generation plant with 1 % input form Solar and Wind energy into the national electricity mix by 2020,
d) To reduce wastage of electricity by promoting efficient practices through introducing demand side management, publicity, encourage use of energy saving equipment,
e) To promote effective utilization of coal to complement the nation's power needs and ensure the much-needed power generation mix,
f) To harness a significant contribution of hydropower potential for electricity generation with the mini and micro hydropower schemes developed for electricity extension to rural and remote areas,

Table 1
Improved profit of electrified enterprises [55].

S/N	Enterprise	% Increase in Profit due to Electrification
1	Agriculture and Agro-related	123.8 %
2	Health	99.3 %
3	Artisans (e.g. Barbers, Welders)	157.8 %
4	Relaxation Spots	83.5 %
5	Mini-grocery Retailers	95.1 %

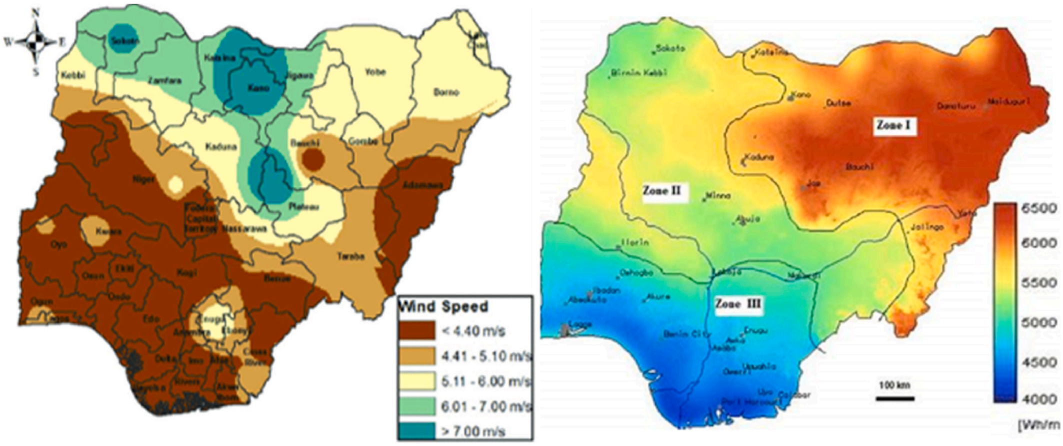

Fig. 7. Wind (left) and Solar (right) maps of Nigeria [15].

g) To ensure a significant contribution of the wind energy to the electricity generation mix in the areas feasible.
h) To make effective use of the solar energy resources for electricity generation, particularly in the rural and remote areas.
i) To encourage local production transport fuels which will include 10 % biofuels

Though, the timeline was between 2000 and 2013, only a few of the projects have been developed in this regard and until now, hydroelectric power is still the only main source of renewable energy. Asides gas-fired plants, there is very little or no input from other sources.

Thus, the introduction of other ideas was adopted in 2015 because the projection for 2008 was yet to be met, an indication that the projections listed in Table 2 were not feasible. As at 2022, there was a total installed capacity of 2380 MW of hydropower generation, 2200 kW of wind generation, about 70 MW of solar (mostly stand-alone, and a lot of undocumented small solar generating units) and none currently from biomass [41,58]. Unfortunately, the annual amount of renewable energy generation has not received any significant increase for the past 10 years as shown in Fig. 8. In fact, the share of renewable energy generation is reducing due to failure of some hydro power stations. This is in contrary to the fact that Nigeria signed the 2015 agreement in Paris Conference of Parties (COP 15) to the United Nations Framework Convention on Climate Change (COP–UNFCC) where the Intended Nationally Determined Contribution (INDC) framework of Nigeria was presented and tagged as "Reduction form Business as Usual" [62]. The key measures of the Nigeria INDC are which are to be achieved by 2030 are [62]:

1. Ending of gas flaring and introduction of efficient gas generators
2. Inclusion of 13 GW off-grid solar PV
3. 30 % energy generation efficiency (2 % annually)
4. Smart agriculture and reforestation
5. Shifting from cars to buses for mass transportation

The INDC goals were also reiterated in the COP26 commitment to achieve net-zero carbon emission by 2060. With the renewable potential of Nigeria in mind, it is possible to integrate 13 GW off-grid solar energy systems in to its energy generation network while also improving the electricity grid [63]. Unfortunately, when considering the integration of renewable energy into the grid, Nigeria is still progressing slowing when compared to Africa and the entire world as evidently shown in Fig. 9.

4.2. Adoption of microgrids/minigrids

Since it is obvious that there is abundance of renewable energy resources in Nigeria, the introduction and development of renewable energy based generation systems such as smart minigrids, microgrids and even nanogrids should be massively adopted

Table 2
Renewable Energy Generation Projections for Nigeria set in 2005 [15].

Resources	2008 Projection (MW)	2015 Projection (MW)	2030 Projection (MW)
Hydro (Small, Medium and Large)	14,759	23,360	59,900
Solar PV	5	120	500
Biomass	–	100	800
Wind	1	30	40
Total	14,765	23,610	61,240

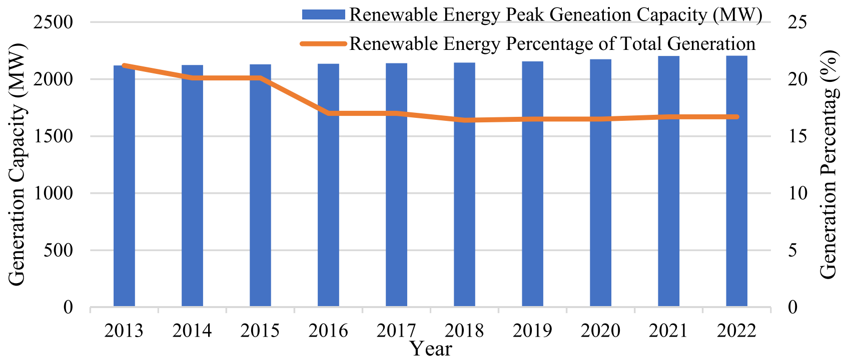

Fig. 8. Annual renewable energy capacity of Nigeria, from 2013 to 2022.

across different parts of Nigeria [64]. has highlighted the several benefits and advantages of smart microgrids such as small-scale hydro stations and mini wind stations (mostly between 50 kW and 1 MW capacity). Improved reliability, economy, efficiency, security and safety, peak shaving strategy in battery energy saving systems and many more are advantages of smart microgrids [65]. The use of biogas and its beneficial potential should also be considered to develop small clusters of smart microgrids. This will definitely reduce the need for grid expansion which is currently being considered, giving room for grid decentralisation and enduring optimum use of all the different kinds of renewable energy available in all regions of the country.

The National Electricity Regulatory Commission (NERC) in its bid to promote the adoption of microgrids and smaller units of distributed generation, introduced the minigrids regulation of 2016. The regulation amongst other aspects gave room for the introduction of a tariffing system named as "Multi Year Tariff Order (MYTO)" in which small manufactures of electrical energy from renewable sources only between 100 kW and 1 MW can now sell their excess to the grid [49]. It was however noticed that most investors are sceptical in utilising this opportunity due to the long-term return on investment period. Despite challenges such as decaying grid network, poor network security, energy theft and so many more [35,66], a few minigrids projects have been successfully commissioned in Nigeria. More recently is the 89.9 MW project tagged "Energizing Education Program (EEP)" launched in 2019 by the Rural Electrification Agency to energize Thirty-Seven (37) federal universities and seven (7) teaching hospitals via off-grid solar energy [67]. As at December 2020, two universities have been completed and commissioned. Another notable microgrid system is the 100 kW capacity solar PV microgrid in Tunga-Jika, Niger state. There are more than fifteen active stand-alone microgrids which are functioning in Nigeria as at 2020 [68]. While there is significant progress in the introduction of minigrids in Nigeria, Rural Electrification Agency (REA) in Nigeria constantly updates its websites with the number of minigrids connected which had exceeded 99,450 connections as at December 2023. However most of these installations are grid-connected and are owned by individuals or a few group of people who can afford the luxury of installing these systems for personal use.

4.3. Adoption of reuse of electrical and electronic materials

The concept of re-use, reduce and recycle is a multi-beneficial approach to solving many current challenges in the world. A lot of materials being used by humans are discarded once the primary function is exhausted without exploring second-life usages or possibilities of recycling.

Nigeria is the second largest producer of e-waste after China. This is largely because most of the electronic gadgets used in Nigeria are imported from other countries outside Africa. The importation data collected in 2010 showed that already used gadgets amount to 50 % of imported electronic gadgets in Nigeria. This in an indication that the annual quantity of imported devices is invariably equal with new devices that are imported into Nigeria. Reports in 2010 further showed that about 600,000 tons of used electrical and electronic equipment are imported to Nigeria annually with more than 50 % of these items coming from Europe and Northern America.

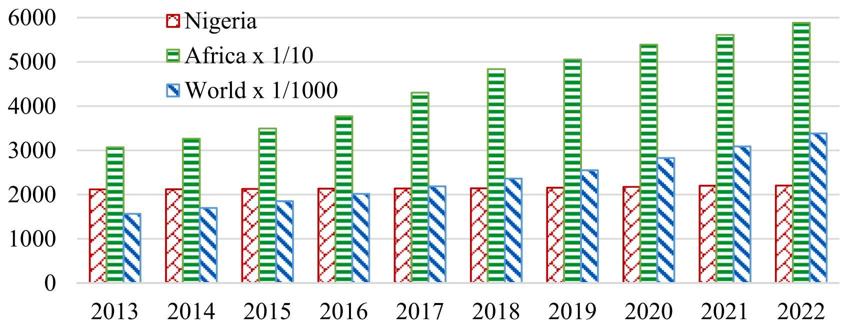

Fig. 9. Annual renewable energy capacity of Nigeria, Africa and the World from 2013 to 2022 [58].

Furthermore, unconfirmed sources have indicated that about 1.1 million tons of e-waste were generated in Nigeria in 2019 only. This is unsurprising as more than 30 % of the used products that are imported into Nigeria are non-functional and immediately become e-waste [69]. In as much as e-waste is obviously a threat to global health and there is a lot of used electronic gadgets readily available in Nigeria (the obvious reason being that it is cheaper than new ones), it will be rewarding to make use of the e-waste devices for re-use and recycling purposes. This is the motivation of this study; which is to investigate and analyse the possibilities of adopting re-used e-waste components for energy generation in Nigeria.

The reutilization of used electrical and electronic devices can be done in different ways. No matter how old a device was used, it is obvious that some components will still be viable if subjected to recycling and can be repurposed or redesigned to serve a new function entirely. The concept of reusing e-waste component specifically for energy generation purposes was articulated in Ref. [70], where Power Supply Units (PSUs) from desktop computers were repurposed to serve as DC-DC converters for battery charging or driving induction machines [71].

This recycling is done for the sole purpose of generating electricity through renewable energy sources as shown in Fig. 10 and will in-turn have the following effects;

1. Availability of cheaper stand-alone generating units
2. Improve electricity access to remote and rural areas
3. Reduce carbon emission from dumped e-waste
4. Economic growth due to increase in access to electricity

The benefits of reusing electrical/electronic components can be indirectly related to increase in energy access if the right policies are put in place. In a country like Nigeria where there is sole dependence on importation (of both new and used electronic equipment), it will be very easy to implement and adopt this technique to remote and rural areas that are mostly dominated by low-income earners without grid connection. To buttress the positive effect of reuse of electrical and electronic waste, a direct relationship can be proposed to show a positive effect of reusing electronic components for the purpose of energy generation on energy access. In as much as this proposed solution is mainly targeted at rural areas with small load demand, a simple load assumption for basic equipment in a typical rural household is presented in Table 3. Six basic appliances are considered as essential loads for the purpose of cost reduction and simplicity as shown by the load duration curve in Fig. 11. This load duration curve was developed using the analytical technique based on intuition to mimic the general behaviour (up to 70 % accuracy) of a typical consumer (under most stringent scenario). For this analysis, only Solar generation would be considered for Fig. 10 and AC loads because this is the most readily obtainable scenario in Nigeria. In order to continue this analysis, a generalized solar system components sizing technique was used to obtain the battery capacity and determine the total number of used batteries that will be required to sustain basic household loads (with more concentration on rural areas).

For this aspect of the analysis, one day of autonomy is selected and a Maximum Depth of Discharge (MDOD) of 80 % for the 12 V re-use batteries. These batteries are expected to be thermal car engine batteries which can be locally bought from a corner chop. The battery daily amount of energy (E_d) based on Fig. 11 was obtained using equation (1) [72];

$$E_d = \int_{0h}^{24h} \left(P_{(load),t} * \frac{1}{\eta_{inv}} \right) dt = 4167\,Wh \tag{1}$$

where η_{inv} is the efficiency of the inverter which was selected to be 0.9.

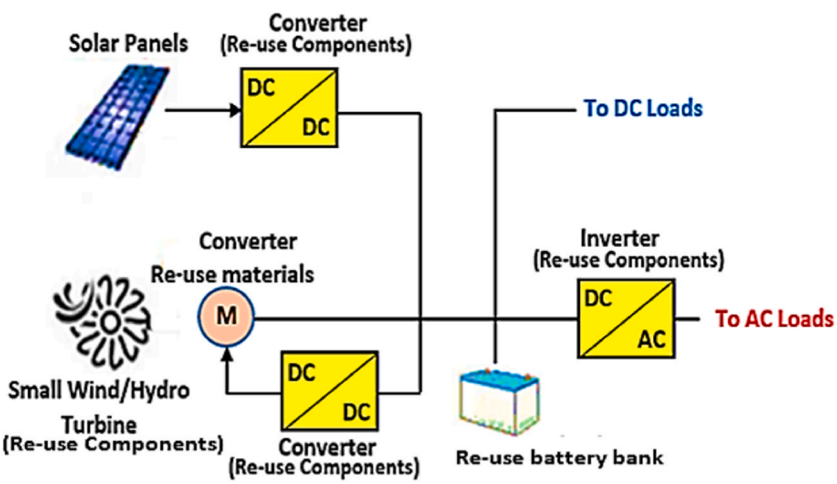

Fig. 10. Hybrid generation of electricity based on reuse [71].

Table 3
Essential load data for a rural home.

S/N	Appliance	Ratings (W)	Daily hrs of usage	Energy (kWh)
1	Television	65	5	325
2	Radio	5	7	35
3	CFL Lightings (×5)	26 × 2	15	780
		26 × 3	6	468
4	Rechargeable (Mobiles, lamps) (×3)	5 × 3	4	60
5	Fan1	40	14	560
6	Fan2	120	7	840
	Total	**375**		**3068**

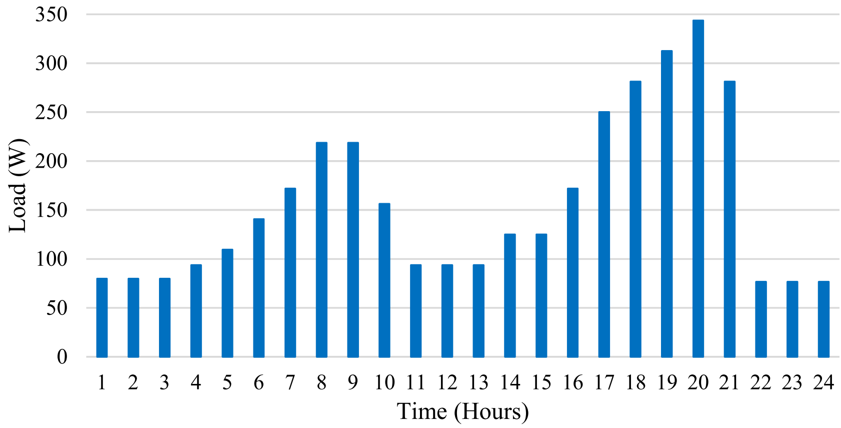

Fig. 11. Load duration curve of a typical rural household.

And the battery total capacity (C_{bat}) can be obtained using equation (2);

$$C_{bat} = Days\ of\ autonomy * \frac{1}{MDOD} * \frac{E_d}{12} = 434Ah \tag{2}$$

The main aim of the sizing calculation is to determine the number of components required by each household based on the essential load duration curve in Fig. 11. This will guide in performing further analyses on the number of possible households that can be served by the reuse solution. The summary of components required is shown in Table 4.

The Power Supply Unit and used batteries are the major determining factors which are proposed to be the independent variables that would determine the possibility of deploying the reuse solution for energy generation. This is due to the fact that solar panels are always readily available and because the second-hand market for solar panels is not yet fully developed. The solar panel market in Nigeria is a readily available market which is ever growing due to the large population of the country and the inconsistency in grid supply. The solar panel market is oversaturated and readily available with a total worth of about 2.9 billion dollars [27]. This makes it quite easy to conclude that availability of solar panels will not be a constraint in adopting the reuse solution as the panels can be easily purchased in most parts of the country. Some assumptions which were made based on information obtained in market surveys in Nigeria. These assumptions which were to ensure that we depict as much as possible a realistic scenario, are as follows:

1. Asides the battery and PSU from desktop computers all other components are abundantly available.
2. For every discarded desktop computer, one PSU is available for reuse purpose.
3. Only 3 types of 12V batteries were considered for the reuse solution based on popularity in Nigeria. These are the 44Ah, 52Ah and 75Ah.
4. The average weight of one battery was measured to be 14 kg.

Table 4
Number of components per household.

Component	Units
No. of PSU (330W each)	2
No. of 12V Batteries (44Ah)	10 units
No. of 12V Batteries (52Ah)	9 units
No. of 12V Batteries (75Ah)	7 units

5. The weight of a desktop computer is approximately 29 kg. This is based on the old desktop computers that are widely found as scraps in Nigeria.
6. All PSUs can be repaired and repurposed for the use of this solution.
7. Only 20–50 % of the old batteries are adopted for this solution.

Some important parameters used in the calculations and analysis are defined as follows;

U_{avail} Weight of used lead acid battery discarded annually
U_{LAB} Weight of used lead acid battery that can be recycled or reused
U_{rep} Weight of used lead acid battery dedicated for reuse energy solution
nU_{rep} Number of used lead acid battery that can be recycled or reused
$nBAT_{hh}$ Number of households that can be served with used lead acid battery
EW_g Total weight of e-waste/UEEE generated annually in nigeria1psu
EW_{im} Total weight of imported e-waste/UEEE in Nigeria
EW_{lo} total weight of locally generated e-waste/UEEE in Nigeria
WPC_{avail} Weight of desktop computers readily available
$nPSU$ Total number of PSUs available
$nPSU_{hh}$ Total number of PSUs available per household
nEA_{hh} Total number of households that can be equipped by both power supply units and batteries simultaneously

4.3.1. Analysis of re-use battery availability

According to Ref. [73], the total amount of U_{LAB} annually generated in Nigeria hovers around 106 thousand tons, out of which 90 % are resold or illegally recycled [73,74]. This is an indication that there is a huge availability of U_{LAB} within the Nigerian market and thus the possibility of easily obtaining these batteries for energy storage is further analysed. Using equation (3), the total amount of used lead acid battery that is available annually can be obtained

$$U_{LAB} = 0.9U_{avail} \tag{3}$$

However, it is assumed that not all these batteries will be reused for sole purpose of energy generation, thus using equation (4), a range of 20–50 % of the available batteries will be used in this analysis at an interval of 5 % each, for the purpose of energy generation.

$$U_{rep} = y * U_{LAB} \quad for\ y = 0.2 : 0.05 : 0.5 \tag{4}$$

For any typical battery, it was observed that the weight is not specific to Ah rating but varies from different manufacturers and technology. The weight of a car battery mostly ranges between 12 kg and 22 kg depending on the manufacturer. Based on popularity, an average weight of a 14 kg was used for one battery whereby the total weight of battery (U_{rep}) is used to obtain the total number of batteries available annually as shown in equation (5)

$$nU_{rep} = U_{rep}/14 \tag{5}$$

Finally, the total number of batteries was used to obtain the number of households that can be served based on three scenarios as shown in equation (6). The three cases are based on three different batteries as shown in Table 4 corresponding to 7 units, 9 units and 10 units of batteries in relation to their respective capacities.

$$nBAT_{household} = nU_{rep}/nb \tag{6}$$

where; nb is the number of units of battery (i.e. 7, 9, or 10 respectively). The number of households that can be served using the available batteries for each value of y is shown in Fig. 12. Depending on the capacity of battery adopted, the blue, green and red bars

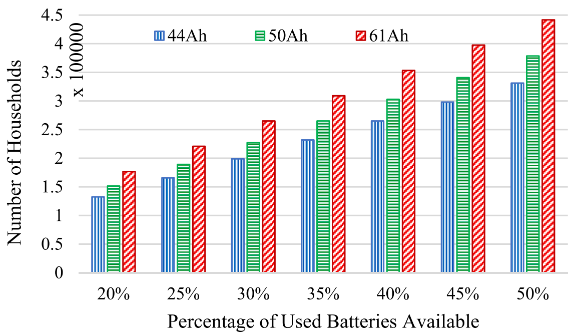

Fig. 12. Number of households that can be served by used batteries only.

represent the 44Ah, 50Ah and 61Ah batteries respectively.

4.3.2. Analysis of re-use PSU availability

The number of PSUs available can be analysed using annual weight of PSUs obtained from UEEE obtained in Nigeria. There are two sources of UEEE or e-waste in Nigeria which are actually e-waste generated within Nigeria and e-waste imported into Nigeria from other countries. Nigeria generates between 260,000 and 500,000 tons of e-waste annually [75]. The data obtained from Ref. [76] showed that desktop computers comprise 7 % of the 15,600 tons of the UEEE imported into Nigeria annually, 30 % of which is immediately discarded due to various faults. This information which is represented in equation (7) was used to obtain the possible number of PSUs that can be obtained annually in Nigeria based on the amount of desktops discarded annually.

$$\begin{aligned} 260,000\,tons \leq EW_g \leq 500,000\,tons \\ EW_g = EW_{im} + EW_{lo} \end{aligned} \tag{7}$$

Note that then weight of desktop computers readily available for use can be easily ascertained from the amount of imported e-waste which is immediately discarded due to faults (30 %). Equation (8) outputs the total weight of desktop computers readily available.

$$WPC_{avail} = 7\%\ of\ 0.3EW_{im} + x\%\ of\ EW_{lo} \tag{8}$$

It is assumed that the value of x ranges from 2 % to 7 % because there is no data stating the amount of desktop discarded locally. This is a safe assumption because desktop computers comprise 7 % of the annual importation data. Using equation (9), the number of available PSU can be obtained from the weight of discarded desktop computers since one PSU is contained in one desktop computer which weighs a maximum of approximately 30 kg.

$$nPSU = WPC_{avail}/30 \tag{9}$$

Finally, to obtain the total number of households that can be served, equation (10) was used to obtain the total number of PSUs available, since each household only requires 2PSUs.

$$nPSU_{hh} = 0.5 * nPSU \tag{10}$$

For each value of x [from equation (8)], the results of the number of household that can be served/supplied annually based on number of PSUs is shown in Fig. 13. As expected, Fig. 13 shows progressive increase in the possible number of households that can be served based on three different situations of minimum, average and maximum value of EW_g. The blue, green and red bars represent minimum value of EW_g, average value of EW_g and maximum values of EW_g respectively.

It is important to note that the two analyses (battery and PSU) cannot be used to finally conclude on the total number of households that can be given electricity access using the re-use idea. In order to finally conclude the analysis, the total number of households that can be served annually can be based on three different scenarios which are described using equations (11)–(13). The minimum value between the total number of Power Supply Units and number of batteries available is used to conclude on the total number of households that can be supplied. Similarly, the average and maximum values are also selected based on these conditions so as to conclude the possible number of households and corresponding population respectively.

$$\text{Scenario 1}: nEA_{hh} = \min[nPSU_{hh}; nBAT_{hh}] \tag{11}$$

$$\text{Scenario 2}: nEA_{hh} = av.[nPSU_{hh}; nBAT_{hh}] \tag{12}$$

$$\text{Scenario 3}: nEA_{hh} = \max[nPSU_{hh}; nBAT_{hh}] \tag{13}$$

The results shown in Table 5 is an indication that if this solution is aggressively adopted, it will have a significant impact on the percentage of individuals with access to energy in Nigeria and automatically improve the quality of life of rural dwellers. This means that the amount of population with access to electricity will increase significantly, especially if there is more dedication to the reuse of e-waste materials. The possibility of electrifying up to 5 % of the population annually can serve as an immediate solution while implementation of long term solutions such as transmission line upgrade and expansion and integration of new grid-connected generators are proposed in the COP 25 INDC agreements.

5. Conclusion

The status of electrification in Nigeria has shown that several inputs are required to meet an optimum supply of electrical energy for the large population of the country. Despite the fact that almost half of the population in Nigeria have access to electricity, they are underserved based on global benchmark for electrical consumption. The causes of these energy sector issues in Nigeria have been reviewed and a possible immediate solution has been proposed to mitigate and improve access to electricity by concentrating on rural and remote areas. The plans have not been always strategically followed which is why there is continuous decline and deterioration in the state of electrical energy availability to the population (especially rural dwellers) of Nigeria. Reviewing and renewing these plans and targets will not improve the percentage of rural dwellers with energy access except if the targets are modified within the set time range. This is because population is continuously growing and a lag in expansion of electricity infrastructure would linearly translate to continuous decline in the percentage of individuals having access to electricity. It is expected that the energy demands of the continuously growing population can be met by strictly following the set targets which were highlighted in the INDC including

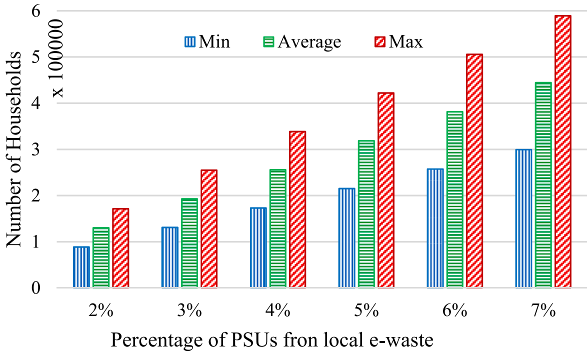

Fig. 13. Number of Households that can be served by PSUs.

Table 5
Results of households that can be equipped with re-use solution annually.

	Minimum	Average	Maximum
Households	88,794	242,286	589,139
Population	621,558	1,696,002	4,123,973
Percentage of Total Population	0.3 %	0.8 %	2 %
Percentage of Population without Energy Access	0.8 %	2.2 %	5.3 %

introduction of smart-grids, massive renewable energies integration and focusing on continuous electrification of rural areas. Emergency solutions such as microgrid integrations, reusing and recycling old components for energy generation, massive investments in renewable energy integration as well as strict focus and compliance on set targets and policies will be necessary.

In a more practical perspective, based on the renewable energy potential of Nigeria, e-waste generated and available local materials (PSUs and old car batteries), this study has shown that between 88,000 and 589,000 households can approximately be electrified annually. The adoption of the reuse solution for energy generation can have an instant effect since the materials are sourced locally and, there is no need for long term grid expansion. This solution can directly affect between 620 thousand and 4.1 million individuals (or an average of 2.6 % of the population without access to electricity) annually depending on the scenario. Thus, an increase in population with electricity access can be achieved annually. However, some challenges in implementing this solution include the availability of reuse batteries since in Nigeria generally, old batteries are exported for recycling purposes thus there will be a market competition for availability of old batteries. In addition, from a technical perspective, the reuse solution does not guarantee the same efficiency as a new solar system which could lead to more frequent replacement of components thereby limiting the availability of these components. Irrespective of these hindrances, the overall benefits of reusing electronic wastes are not limited to energy access but will also reduce carbon emission in the long run. Further analyses can be done to see the effect of adopting this solution on carbon emission reduction and economic improvement as well as reduction in rural-urban migration.

Data availability

Data included in this article are adequately referenced and publicly available.

CRediT authorship contribution statement

Abdulrahman Olaniyan: Writing – original draft, Visualization, Investigation, Formal analysis. **Stéphane Caux:** Writing – review & editing, Formal analysis. **Pascal Maussion:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Abdulrahman Olanyian reports financial support was provided by Petroleum Technology Development Fund.

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