Ugwoke, B.; Sulemanu, S.; Corgnati, S. P.; Leone, P.; Pearce, J. M.

Demonstration of the integrated rural energy planning framework for sustainable energy development in low-income countries: Case studies of rural communities in Nigeria

Published in:
Renewable and Sustainable Energy Reviews

DOI:
10.1016/j.rser.2021.110983

Published: 01/07/2021

Document Version
Peer reviewed version

Published under the following license:
CC BY-NC-ND

Please cite the original version:
The Integrated Rural Renewable and Sustainable Energy Planning Framework for Low-Income Countries

B. Ugwoke, S. Sulemanu, S. P. Corgnati, P. Leone, J. M. Pearce

1: Energy Center Lab, Department of Energy Politecnico di Torino Italy
Via Paolo Borsellino 38, 1, 10138, Torino, Italy.
2: IHS Towers, VI, Lagos, Nigeria.
3: Department of Materials Science & Engineering and Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI, 49931, USA
4: Department of Electronics and Nanoengineering, School of Electrical Engineering, Aalto University, Espoo, Finland

e-mail: blessing.ugwoke@polito.it, web: http://www.energycenter.polito.it/

Abstract

A consensus is forming that shows that decentralized renewable energy may be the most appropriate method for electrification of rural communities as it enables countries to leapfrog the development of conventional electric grids. This type of energy-based economic development holds great promise and yet there are still unanswered questions of how best to move rural areas to adequate renewable energy. Therefore, this study provides integrated rural energy planning for improving localized renewable energy access in low-income countries. Using rural Nigeria as a case study, this paper presents a new methodology for locating and planning integrable off-grid renewable energy systems. The aim of the method is to illustrate a unified road map for energy planning and system design with renewable energy integration geared towards improving energy access in rural areas. Utilizing GIS-based tools, rural communities are identified, and their viable renewable energy resources are estimated. Adopting the reference building approach, seasonal disaggregated energy demand profiles are obtained at community scale with an hourly time-step. These are obtained markedly in the absence of smart-metering equipment and measured datasets on energy use. This method has wide applicability across areas with similar energy access and rural development issues especially in sub-Saharan Africa and developing Asia.

Keywords: Integrated Energy Planning; Integrated Rural Planning; Demand Profile; GIS; Nigeria
1.0 Introduction

Although the use of the term developing country (or less economically developed country (LEDCC)) is debated, it is generally agreed to refer to a country with a less developed industrial base and a low Human Development Index (HDI) relative to other countries [1]. In 2010, the HDI was reformulated to include a life expectancy, education and income indices to better gauge the development of a given country [2]. The countries in sub-Saharan Africa were ranked the least developed [2] and although there is a general trend of increased urbanization, the majority of people continue to live in rural areas in sub-Saharan Africa [3]. It is well-established that the availability and adequate supply of energy is needed to drive development [4], yet roughly 20% of the world’s population do not have access to electricity [5]. Today, electricity is viewed as the type of energy most valued and needed for development [6]. Thus Sustainable Development Goal 7 (SDG7) calls for universal access to sustainable energy by 2030 [7]. It appears that decentralized renewable energy may be the most appropriate for rural communities [8], [9], [10], [11] as it may enable countries to leapfrog the development of conventional electric grids [12], [13]. This type of energy-based economic development holds great promise [14] and yet there are still unanswered questions on how best to move rural areas to adequate renewable energy [15], [16], [17].

To better answer this challenge, this study provides integrated rural energy planning for improving energy access in rural communities of the developing world while also tackling the already identified challenge of lack of systematic planning regarding rural electrification [18], [19]. The aim here is to introduce a method to provide a unified road map for energy planning, system design, and operation with renewable energy integration geared towards improving localized energy access in rural areas. This paper presents a proposed systematic methodology for locating and planning integrable off-grid energy systems for rural applications. It is focused on two aspects of energy planning. Firstly, the method uses identification of rural areas that present themselves as “low hanging fruit” and the estimation of available renewable resources in those areas. Secondly, the method estimates the rural energy demand in the absence of smart instrumentation and obtains an overall disaggregated energy demand profile with an hourly time-step at a rural community scale. Demand side management can be based on both demand response and energy efficiency [20], [21], [22]. Therefore, six composite energy demand reductions strategies are adapted for demand side management based on energy efficiency and indoor environment quality (IEQ) principles. The steps are demonstrated in a case study of Nigeria. The results are discussed in the context of using an integrated rural renewable and sustainable energy planning framework for all low-income countries.

2. Case Study: Nigeria

Nigeria was selected as a case study because is prototypical for developing countries in sub-Saharan Africa that needs rural electrification. Nigeria is the largest economy in Africa [23] and also doubles as the “the poverty capital of the world” [24]. It was reported that as of June 2018,
approximately 87 million Nigerians were living in extreme and abject poverty [25], [24]. As a result, Nigeria earned a sustainable development goal 1 (SDG1) status of “Poverty Rising” [25]. Nigeria is the most populous African country and ranks seventh most populous country in the world [26]. At an annual population growth rate of 2.6% [27], Nigeria would become the third most populated country on the globe with a population of 480 million people by 2050, having reached 200 million people in 2019 [28]. Half of the Nigerian population also resides in rural areas (51%) [29]. Of the entire rural population, only 41% have electricity access, which is well below the 86% electricity access for the urban population in Nigeria [30].

Nigeria’s rural areas chiefly depend on agriculture for sustenance, which still drive the Nigerian economy with farming and fishing making up nearly half (47%) of Nigeria’s gross domestic product (GDP) [31]. As in other developing countries throughout the world [32], there is a chasm between urban and rural development in Nigeria despite the Nigerian government’s programs, initiatives, and policies beginning in the 1980’s to foster the development of rural areas [33] including prominent strategized initiatives [34].

In Nigeria a rural area is defined as those with a population density less than 200 persons per km², situated more than 10 km from city borders and at least 20 km from the nearest 11KV transmission line [35]. Although rural areas of Nigeria have been referred to as economic goldmines with features for tourists’ attractions, these areas lack basic infrastructure including pipe-borne water supply, primary health care service, literacy of the workforce, motorable roads and electricity access [34]. There is a host of issues limiting further rural electrification, including a lack of inclusive, definite planning and concise action steps [36]. Indeed, there have been cases of decommissioning and abandonment of already implemented off-grid energy systems primarily due to the gross underutilization of system capacity [37].

Fortunately, many rural communities in Nigeria are situated near indigenous renewable energy (RE) resources such as hydro, solar, wind and biomass and these resources can be harnessed to spur the deployment of appropriate small-scale RE-based energy systems [38]. These systems are viable alternatives for rural electrification [15] given the geographic isolation of rural settlements situated in hilly terrain and mountainous landscapes that prevent economic national grid extensions to the area [39].

2.0 Integrated Rural Renewable and Sustainable Energy Planning Framework

Appropriate energy planning considers the entire lifespan of the distributed energy system and entails going from conceptualisation, through implementation and operation down to monitoring stages to inform sustainable developmental pathways [40]. This can then serve as a blueprint for co-ordinated joint efforts geared towards driving rural energy access [41]. There is a need for an integrated rural energy planning approach that would streamline and standardize the rural energy planning process [42]. This will enhance the understanding of the different rural customer segments to capture the inherent market potential for rural electrification [43], [44], [45]. Moreover, there is the need to take into consideration the local contexts together with the apparent social and cultural intricacies involved [46]. A suitable rural planning strategy includes viable availability of territorial resources at a local scale and performs robust and targeted and disaggregated energy demand estimates [47]. This demand would factor into energy supply
estimation to optimize the energy production (Ugwoke et al. 2020). All of these factors are paramount to enhance sustainable investments, drive down operating costs, and consequently raise the affordability of the procured energy service for the rural consumers [48]. Additionally, there is a need to encourage an all-inclusive participation and consider the developmental efforts already in play in these rural areas [46]. Addressing these complexities as a whole provides an “integrated rural planning approach” [49].

In order to move a rural developing region towards a sustainable state there are three approaches that will be integrated here into the Integrated Rural Renewable and Sustainable Energy Planning Framework: 1) Integrated Rural Planning Approach, 2) The Integrated Energy Planning (IEP) Concept, and 3) Integrated Rural Energy Planning.

2.1 Integrated Rural Planning (IRP) Approach

Okafor [49] carried out a pioneering study to investigate the idea of infusing an integrated planning framework for rural development in Nigeria. He investigated the spatial planning ideology, especially at a territorial or localised scale. On the discourse of IRP, one key element almost entirely absent in many rural development schemes is spatial planning especially in terms of functional disposition and geographic scope [50], [49]. This is vital to discern the linkages and interfaces between the built environment and their neighbouring surroundings that house viable resources needed for their development [51]. Accordingly, the United Nations [52] has called for an amalgamation of approaches. This is inadvertently the consensus among many proponents of this concept [53], [54]. The concept of IRP embodies the coalition of co-ordinated joint multifaceted approaches that are widely applicable across multiple sectors with the underlying aim of addressing rural developmental issues [53]. IRP is an intricate concept encompassing the different dimensions of technological, economic, societal, environmental and cultural dispensations and necessitates the uptake of a concise integrated approach incorporated with a spatial planning methodology [49]. IRP is predisposed to location dependency which considers viable native resources that can facilitate rejuvenation of the local economy[54].

2.2 The Integrated Energy Planning (IEP) Concept

The IRP approach is applicable to multiple sectors, but there is a consensus that rural energy access is of the greatest importance [55], [56], [9], [57], [6] as it reinforces the backbones of sustainable development: the environment, the economy and social wellbeing [58], [59], [40]. The energy sector also has ripple effects on other sectors (i.e. agriculture and non-agricultural) alike and can thus leverage the interdependency of these sectors [49]. IEP has been deemed a multi-pronged, dynamic and long-term paradigmatic energy planning process [60] with a contextual and process-based perspective from a territorial disposition [61]. IEP embodies a holistic and systematised investigation of energy issues within a unified policy framework to obtain a set of optimal energy solutions. It entails multi-disciplinary stakeholders’ involvement and one critical result of the entire process is the realization of an energy master plan [62]. Procedurally, IEP is comprised of the geography aspects, socio-economic dispensations, energy demand & supply estimates, energy balance resolution, policy and environmental impact assessments [40], [63], [46]. IEP as a requisite for sustainable development ensures that current
and future energy demand may be addressed in the most cost optimal, efficient, socially-
beneficial and environmentally-friendly manner [62]. It purposes to inform energy infrastructure
investments and policy formulation strategies to shape the future energy landscape for a given geographic extent [62].

IEP shares similar attributes with IRP and they are both prescribed as long-term undertakings
[49], [40]. They both require all-inclusive engagement of multi-disciplinary stakeholders [53],
[60] and they are ultimately tasked with driving sustainable development in their respective
domains [51], [62].

2.3 Integrated Rural Energy Planning (IREP)

Integrated rural energy planning entails energy planning in a rural context which is a complex
and dynamic undertaking [46]. Accordingly, IREP aims to incorporate appropriate energy
solutions to deliver modern energy access to rural dwellers [64]. Herington et. al [46] concluded
that rural energy planning ought to be more participatory involving all the key stakeholders in
plenary sessions. In addition to being place oriented, IREP is also a process oriented [64]. IREP
places emphasis on techno-economic, socio-cultural and political issues with people centred
criteria to proffer sustainable technical interventions for localised energy access [46]. Therefore,
IREP calls for a coherent approach espousing integrated long-term, energy planning, and energy
system modelling to analyse the complex dimensions and interrelations of rural energy solutions
[46]. Moreover, it buttresses features of IEP and IRP including integrated resource assessment
and planning, life-cycle assessment, multifaceted character, etc [61].

Considering the vast potential of RE resources in many rural areas [65], it becomes essential to
provide strong support for IREP to facilitate their efficient use (Ugwoke et al. 2020). Moreover,
given the localized dispersion associated with these energy resources, the inclusion of a spatial
planning element into IREP becomes indispensable [66]. In addition, with the levels of
disaggregation and complexities envisaged, it would deem it appropriate to inculcate a bottom-
up method that is location dependent in the framework [67]. Regarding IREP, Rojas-Zerpa and
Yusta [68] reviewed some salient aspects to be considered. The first being the application zone
especially since distributed generation is advocated for rural areas [9], [11], [69]. The second
aspect is the planning horizon of which long term comes highly recommended, thus prescribing
long-term energy planning tools. The third aspect is decidedly the objective, which could be
multifaceted to consider environmental, economic, social, cultural and/or institutional
dimensions. The last aspect is the technological systems for the energy planning exercise. This
study is performed based on all these different aspects of IREP.

Indeed, to actualize integrable off-grid rural energy solutions, it is essential to carryout robust
energy demand estimations and forecasting [70], [71]. Kazas, Fabrizio and Perino [72] buttressed
the need to estimate detailed energy demand profiles with well-defined time resolutions. They
considered the geographic context, built environment characteristics and the lifestyles of the
inhabitants. These attributes inform design, sizing and optimization of decentralized energy
systems at local scales. On a global scale, some attention has been given to energy planning for
developing countries [73], in addition to electrification planning [68]. From a Nigerian
perspective and at localized scales, more work is needed to determine what strategies would inform the IREP framework geared towards sustainable rural development [65]. This provides research opportunities including local RE potential mapping, exploring avenues for energy saving and embracing energy efficiency at local levels (Ugwoke et al. 2020). The IREP framework is presented in a brief and concise scheme using three methodical action steps as depicted in Figure 1, which informs the methods in this study.

IREP provides a decentralized planning approach that buttresses the development of indigenous renewable energy resources to spur sustainable development at localized scales [74]. Regarding rural energy modeling and planning, there are several tools being adopted in the scientific literature such as the open source spatial electrification (OnSSET) tool [75], the off-grid market opportunity tool [76], the Reference Electrification Model (REM) [77], the Network Planner tool [78] and a host of other applications for electrification pathways [79]. These tools are mostly open source and adopted for rural electrification planning at national and regional scales. Additionally, these tools can be integrated into the IREP framework especially for the site identification and selection step.
3.0 Method & Materials

The comprehensive methodology aims at demonstrating the integrated rural energy planning framework geared towards locating, planning and operating integrable off-grid energy systems for rural applications. As shown in Figure 1, this paper has three focus areas: 1) identifying rural communities that present themselves as low hanging fruit opportunities to deploy RE, 2) evaluating the viable RE resource potential utilizing geographic information system (GIS) based approaches, and 3) robust and targeted energy demand estimation using the reference building (RB) approach.

3.1 Site Identification and Selection

Site identification and selection entailed detailed map analysis utilizing GIS-based tools. Suitable communities were identified for the implementation of integrable off-grid energy system. These selections were based on well-defined macro criteria related to four dimensions: the built environment, economy, society and energy [80] Subsequently, the viable RE resource potential in these communities were evaluated to select the most suitable mix of resources to electrify these communities.

3.1.1 Rural Community Selection

Suitable locations were identified and selected based on the integrated low-hanging fruit approach proposed by Szabo et al.[10], where they advocated for “brownfield investments”, which are the utilization of existing infrastructure for business [81]. Excerpts from the Nigerian Rural Electrification Agency (REA) and Mentis et al. [69] also informed this process. In this study, the low-hanging fruits encompass rural settlements clearly suitable for implementing decentralized renewable energy generation systems. This would require harnessing local RE resource potential and applying appropriate technological transformation options [82], [83], [84], [85]. Such as exploring the small hydropower (SHP) potential [86] of some non-powered dams constructed for irrigation purposes or flood control. The solar potential would be harnessed by incorporating solar photovoltaic (PV) systems in appropriate locations [17]. Agricultural waste biomass can also be explored as they do not compete for land, water and fertilizers with food crops [87], [88]. The Nigerian Energy Database (NED) [89] provided GIS data sets, which included ground level geospatial data, map databases, the current existing and planned transmission network, population data, demographic data sets, administrative areas, and power plants locations. The availability of official geo-referenced databases for non-electrified communities and electricity infrastructures, provided by the REA, the off grid market opportunity tool [76] and the Economic Community of West African States (ECOWAS) web-based open source Electrification Pathways tool, ECOWAS Regional Centre for Renewable Energy and Energy Efficiency (ECREEE) [90] facilitated this study. Firstly, the available spatial data were collated, systematized (with respect to the EPSG: 4326 – WGS 84 coordinate reference systems (CRS) [91]) and verified by viewing the locations remotely on Google map. After the spatial processing of the data, different GIS layers were obtained using the free and open source QGIS 3.4.15 package [92]. They were overlaid on each other and further analyses were performed to yield digital maps showing suitable locations for utilizing various RE
technologies. These locations were subsequently analysed to access the RE resource potential and expected electricity output on a location by location basis with more details in the next section.

### 3.1.2 Renewable Energy (RE) Resource Assessment

The RE resource potentials were mainly calculated from renewable energy resource maps [93], [94], [95], available meteorological data [96] and other geographic information including landcover and land use maps [97]. The approach put forward by the International Renewable Energy Agency (IRENA) [98] and correlations contained in other existing scientific literature ([69], [99], [10], [100]) were adopted. This involved going from the theoretical potential to the technical potential. Overall, this encompassed data collection and collation from RE resource maps, and landcover maps. Data processing and synchronization (formatting and harmonizing) followed. This led to the extraction of location-based data for RE resource potential calculations. The obtained results were compiled into integrated digital maps to aid visualization and comparison of the local RE conditions. This was more insightful than an aggregated overview on the entire country.

The technical energy available from solar PV ($E_{\text{PV}}$) in GWh/yr was evaluated using:

$$E_{\text{PV}} = \frac{\text{SRA} \times \eta \times A}{GCR}$$  \(1\)

where SRA, the solar resource availability is the irradiation for the target location in kWh/m$^2$/yr from the Photovoltaic Geographical Information System (PVGIS) database [95]. In order to be conservative, $\eta$ the PV module efficiency, was set at 17% as it represented the average efficiency of commercial PV modules [101], [102]. The efficiency of PV devices continues to increase [103], [104], [105] and near term (e.g. lab demonstrated) technologies already predict an increase in efficiency and decrease in cost [106], [107], [108], [109]. GCR, the ground cover ratio for estimating the ground areas compared to the area of the PV panel on the order of 5 was adopted [98]. A, the available area in km$^2$, was set to the extremes of 5% and 100% of the inhabited area calculated in the GIS analysis to depict cases of land availability in the elicited localities. It is assumed that a traditional solar ground mounted system with tilt angles, azimuth angle and no shading to provide optimal yearly production.

The potential hydropower generation (energy yield), $E_{\text{hydro}}$ in each non-powered dam was estimated using:

$$E_{\text{hydro}} = \eta \times \rho \times g \times H \times Q$$  \(2\)

where $\eta$ is the generating efficiency with a value of 85% [100]. $\rho$ is water density of 1000 kg/m$^3$ and $g$ is gravitational acceleration of 9.8 m/s$^2$. $H$ is hydraulic head in m and $Q$ is design water flow in m$^3$/s. The last two parameters being location dependent were sourced from diverse sources: $H$ was based on ([110], [111], [112], [113]) and $Q$ based on the African Flood and Drought Monitor Tool (AWCM) [96].
Agriculture crop residues were the only biomass category (waste biomass) considered being readily accessible feedstock for biomass-fired power plants. The approach entailed estimating the net primary production of the plant matter. Then applying the residue to crop ratio and availability factor of the residue for energy production to deduce the amount of energy obtainable from the agricultural crop residues. Only harvested crop production areas in use are considered. Forest areas, protected areas, and other unfarmed arable agriculture land were excluded zones from the bioenergy potential assessment. These analyses were facilitated the Global Atlas for Renewable Energy [93] and Global Agro-Ecological Zones (GAEZ) model developed by the Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA) [94]. The analysis resulted from a two-fold estimation approach namely; estimating the residue generated within a typical temporal cycle of 1 year for a given geographic area and then estimating the energy content of the residue material. The energy potential ($E_{bio}$) in GWh/yr for a rural community, was estimated as follows:

$$E_{bio} = \frac{\sum R_i \times r_i \times Q_i \times d_i \times a_i \times \eta}{3600}$$

where $R_i$ is the annual production of crop, i in t/yr. This was obtained as a product of the harvested land in 1000 ha [94] and the average productivity per yield in t/ha/yr [93]. $r_i$ is the residue-to-product ratio of crop i [114]. Q is the lower heating value of the given crop residue in GJ/t [115]. $d_i$, the dry matter fraction obtained based on moisture content of the crop [116]. $a_i$, the residue availability fraction was 95% for rice, 90% for millet, 30% for maize (corn), 35% for soybean, and 100% for cassava [117], while other crop residues adopted 60% [99]. $\eta$ is the efficiency of the energy conversion process. This research considers the biomass integrated gasifier technology. The conversion efficiency of 30% is used for the estimation of the technical potential based on recommendations for efficient technologies considering life cycle environmental impacts and annual costs [118].

3.2 Energy Demand Estimation

For optimal design of integrable off-grid RE system, robust estimation of the hourly energy demand of the given locality is required [119], [120]. At disaggregated energy use levels, this can also inform demand side management strategies. Demand estimation approaches have been broadly categorised into 1) the top-down approach and 2) the bottom-up approach [121]. Top-down approaches are mostly data intensive and reliant on large quantities of historical data, which are scarce for rural areas. A bottom-up approach, specifically the reference building (RB) approach has been adopted for the energy demand estimation in this study as it provides disaggregated energy demand profiles showcasing the detailed energy end-use at a local scale.

3.2.1 The Reference Building Approach: The Onye-Okpon (OO) and Giere (GI) Case Studies

The RB approach allows for the projection of the energy demand profiles taking cognisance of local conditions including the geomorphological setting of the built environment, usage, operation, habitation and climatic disposition of the locality [122]. The approach was applied to
Onyen-Okpon and Giere, which were selected rural settlements to capture the divergent climatic situations in the country. Onyen-Okpon (Figure 2) is in Obubra Local Government Area (LGA) of Cross-river state, South-East Nigeria. Giere (Figure 3) is in Dange Shuni LGA of Sokoto state, North-West Nigeria. Onye-Okpon represents a medium off-grid site, while Giere represents a small off-grid site. They are both agrarian communities as agriculture accounts for its chief source of income including farming food crops and agro-processing industries including grinding mills. There is the prevalence of artisans whose business activities include provision of personal services (e.g. tailors, salons, retail trade, etc.) and community establishment (e.g. health centre and public schools) [123], [124]. The RB distributions depicting the local built environment are shown in Figures 4 and 5 for the two communities.

Figure 2. Aerial Image of Onye-Okpon [125]
Figure 3. Aerial Image of Giere [126]

Figure 4. Reference Building distribution (Legend: 2BDB-two bedrooms bungalow, 3BDB- three bedrooms bungalow, FMFY-central corridor “face me I face you” building, RHC-rural health centre, PSCH-public (primary) school and SSS-small-scale shops.) [123]
A complete definition of the main features and consumptions of the RBs are reported in [122]. The overall demand ($E_{\text{demand}}$) in kWh was estimated using the equation below based on the total amount of buildings in the communities.

$$E_{\text{demand}} = \sum E_{RB} * A_{RB} * N_B$$

where $E_{RB}$ is the energy use in kWh/m$^2$ per RB, $A_{RB}$ is total floor area in m$^2$ and $N_B$ is the number of buildings. Hourly energy demand profiles at a community scale were obtained from the aggregated community demand. The typical monthly day (TMD) approach proposed in [72] was applied to obtain the seasonal demand profiles. These yielded days for the characteristic seasons namely the dry season (“Winter”) and the rainy season (“Summer”). Energy saving potential and the associated economic benefits were estimated based on six composite scenarios comprising indoor environment quality (IEQ) and energy retrofit & energy efficiency (Ugwoke et al. 2019). The investigated scenarios include Standard retrofit-IEQ I, Standard retrofit-IEQ II, Standard retrofit-IEQ III, Advanced retrofit-IEQ I, Advanced retrofit-IEQ II and Advanced retrofit-IEQ III. The investment costs for the retrofit measures were estimated based on the costs of building materials presented in Table A1 in the appendix. The discounted payback period was estimated considering the discount rate of 4.25% [127] and a calculation period of 20 years for both residential and non-residential buildings categories. The shadow rate [128] concept was applied to estimate the job creation attributable to the implementation of the retrofit measures. This considered the income tax rate of 24%, the average construction gross annual salary of US$2,349.49, the unemployment rate of 32% and the employment multiplier (number of new jobs) for the construction sector in Nigeria to compute the new jobs from new investments ([129], [130], [131]).

4.0 Results & Discussion

4.1 Low Hanging Fruit Sites
Fourteen “low hanging fruit” RE sites of all kinds were extracted and populated on a digital map in addition to three mini-hydro sites. These are shown in Figure 6. One of the fourteen sites was in a protected area (naturally conserved zone) and as a result was excluded for bioenergy consideration. The use of GIS based tools afforded a standardised and transparent procedure for selecting promising prospective sites [132]. Given the geopolitical disposition of Nigeria, this would help eliminate the bias and nepotism that oftentimes shroud the site selection process [133]. The mini-hydro sites are located in states where surveys had been carried out [134]. Some sites are near the country’s border and neighbouring countries (e.g. Niger). This could present opportunities for exploring cross-country or transboundary co-operation on power generation projects. This would, in turn, address the issue of gross under-utilization of the small hydro potential in the region through combining mutual RE resources.

![Figure 6: Identified locations (Low hanging fruits and mini-hydro sites).](image)

4.2 Renewable Energy Resource Potential

The comparative proportions of the available viable RE resources are depicted in Figure 7. Fourteen locations presented solar energy potential in the range of 0.1 to 11.6 GWh/yr for a minimal available land area (5% of inhabited area) and 1.7 to 232.7 GWh/yr for a maximum available land area (100% coverage). The bioenergy potential for thirteen locations encompassed the range of 0.03 to 3.45 GWh/yr. Two of the hydropower sites have the potential to generate...
>1MW (small-scale). One site has the potential for <1MW (mini-scale) based on the classification schemes for the sub-Saharan African region [10] and Nigeria [134]. Overall, the cumulative potential capacity for solar energy and bioenergy reached 37.1 to 741.6 GWh/yr for the entire fourteen sites., 17.6GWh/yr for thirteen sites and 10.41MW for three sites respectively. Hydropower energy production was not estimated in this study due to complexities of water availability and future work is needed to quantify this potential energy production. The northern locations had the highest solar-irradiation figures. However, they do not maintain this position in terms of viable resource availability due to land availability. The southern locations had more desirable low hanging fruit options. The dispersion of the RE resources was quite random. Some sites favoured solar energy others favoured bioenergy in terms of the magnitude of the RE potential, although it should be noted that for any give surface area far more energy can be provided from PV than any form of bioenergy or even bio-sequestration [135], [136]. This land availability value was based off of the current land use, which in this case is heavily dominated by farming. One potential method to allow for both bioenergy and solar PV production, which looks particularly promising is the concept of agrivoltaics [137], [138], [139], [140]. Most of the proposed biomass crops were well spread across all the locations. They were mostly staple food crops popularly grown in the country as seen in Figure 8. The exceptions were oil palm and coffee which are predominantly grown in Southern Nigeria [141]. Future work is needed to take into account the potential of these crops for agrivoltaics in Nigeria. The biomass crops also represent energy crops that could provide for different generations of biomass feedstocks [142]. As such, they can be regarded as easily leverageable bioenergy fuel options which are indeed promising.¹ The RE resource potential map is a critical source of information that provides a visual representation of the apparent RE situation. This can be useful to spark an open dialogue on IRP [143], [144]. This can also drive the IREP process and strategies for exploiting the sustainable development of these RE options [145].

¹ It should be noted that the GAEZ model considers the phenomenon of soil fertility by inculcating historical and baseline climatic resources data. These are reflected in the land resources database used for the simulation.
a) At 5% available of community land area for solar PV.

b) At 100% available community land area for solar PV.

Figure 7: RE potential of identified locations (low hanging fruits and mini-hydro sites).
4.3 Community Energy Demand Profile: Rural electrical energy usage

The monthly energy demand over a year is as shown in Figure 9. The hourly energy demand profile is disaggregated into lighting (L), electrical appliances (EE) and space cooling (SC). These profiles were obtained for days in the seasonal periods (the dry season ("Winter") and the rainy season ("Summer")) as shown in Figure 10. The TMD approach resulted in a typical dry season day in April and February for Onye-Okpon and Giere respectively. A typical raining season day in July was obtained for both locations. The hourly load demand profiles were obtained for these days.
Figure 9: Community monthly energy demand for Onye-okpon and Giere.

a) Dry Season- Onye-okpon

b) Rainy Season- Onye-okpon
There are some variations in the monthly energy demand within the seasonal periods. The dry season (precisely the month of May) constituted the highest demand due to the hot and dry weather experienced in both locations. The lowest demand occurred during the rainy season (August for Onye-Okpon and January for Giere) due to the incessant Harmattan weather in this location. This mirrored the situation prevalent in the country even with the geographic location disparity reported previously [146] [147]. Throughout the year, the space cooling (SC) accounted for the highest projected energy end use. However, the cooling demand is expected to continuously rise given the effects of climate change in the region [148]. These effects are almost uniformly spread across the globe irrespective of the minimal contributions from these rural settlements [149]. As such it becomes imperative to peruse demand reduction strategies in these locations [150], [151]. There is a slight variation in the lighting and electrical appliances monthly demand and the average daily load for these electrical components (L and EE) arrived at 140 kW and 36kW for Onye-Okpon and Giere, respectively. These correlated with the estimations made by the REA [124].

The seasonal hourly load demand is shown in Figure 10. The load peak interval consisted of two prominent peaks (5AM to 8AM in the morning 7PM to 9PM in the evening), which can be attributed to people rising in the morning and returning home in the evening. The off-peak periods consisted of minimum load demand in periods from 12AM to 5AM in the morning and 8AM to 6PM when the residential building demand drastically drops as people are sleeping or outside their residences, respectively. During the day the demand is attributed to a few non-

---

2 The Harmattan is a season in West Africa, between the end of November and the middle of March, which is characterized by dry and dusty northeasterly trade wind blowing from the Sahara Desert.
residential buildings. Overall, the shape of the community load profile mimics that attributable to the typical domestic energy usage [152]. Electricity use is almost entirely relegated to the morning and evening periods and hinges on the inhabitants’ occupancy. The demand profiles buttress the insufficiency of productive end use loads, which is typical of many rural settlements. The overall demand is dominated by the presence of many residential buildings (see Figure 2). This is synonymous with the shape of the load profile reported in [152] where physical measurements were taken in some rural African settlements. Considering a household size of six persons in rural areas and the number of households in the communities, the per capita demand may be estimated as 1,641 and 635 kWh/person/year for Onye-okpon and Giere, respectively. Of this the electric (L and EE) component of the demand of 392 and 135 kWh/person/year for Onye-okpon and Giere, respectively. Based on the UN Secretary General’s Advisory Group on Energy and Climate Change (AGECC) and their indicator for Incremental Levels of Access to Energy Services [153], the energy usage falls under Level 2. This prescribes productive levels of energy usage within the range of 100 to 2,000 kWh/person/year. However, this per capita estimation would be shrouded in gross uncertainties given minimal information on the actual population at such localized scales. This study, however, was within the range. Other studies, like the World Bank multi-tier approach [154] can be more easily broken down as it provides a tiered indicator for individual households, while this study focuses on community scale. However, the individual building energy demand for the residential buildings come under the Tiers 4 and 5 based on the obtained results.

---

3 It should be noted that these communities are largely unelectrified and from the time-of-use surveys the energy consumption during the day was from the non-residential buildings. It is anticipated some daytime energy consumption from residential buildings in the future as the communities are electrified. In addition, as these are agrarian communities, the demand from agro-processing endeavors are tied to the SSS where there is the grinding and milling sector.
Figure 11: Community potential energy savings and demand reduction percentage (Legend: IEQ = Indoor environmental quality).

Figure 12: Investment costs and discounted payback for the two communities.
The potential for energy saving is shown in Figure 11 and this examines opportunities for demand side management based on energy efficiency and IEQ principles. The impacts of the suggested measures on the community’s energy demand proffer overall reduction at varying levels. For Onye-Okpon demand reductions up to 49%, while Giere’s demand reductions reaches up to 52%. The Advanced retrofit-IEQ II, and Advanced retrofit-IEQ III Emerged as the most optimistic scenarios and yielded the highest economic benefits accrued from energy savings. These results buttress the assertion by Alstone et al. [8] that demand-side energy efficiency in collaboration with the innovative off-grid energy solution could alter the market dynamics of energy access. This could also make available increasingly affordable and reliable energy services in rural areas especially since many residents have resorted to self-generation at $0.49/kWh (₦150/kWh) for petrol generators or $0.59/kWh (₦180/kWh) for diesel generators [124]. At a diesel cost of $0.83/L (₦250/L) locally [123], these options are exorbitant and not sustainable, thus severely raising the energy expenditure of these unelectrified households. More so, the ensuing benefits from energy savings are shown in Figure 11. The investment costs and payback periods are reported in Figure 12, while the additional benefits of green jobs for the communities are shown in Figure 13. The time value of money is considered when using discounted payback unlike the regular payback period. Therefore, the discounted payback period will be longer than the regular payback period, but care must be taken when using it to ensure it is being compared to other discounted investments so a return on investment is accurate [155], [156], [157], [158].
5.0 Conclusions

Integrated rural energy planning provides a strategic scheme for drafting local energy master plans. These can facilitate local renewable energy mapping and support the building of a strategic energy vision at a local level. In this study, an integrated rural energy planning scheme has been successfully outlined. Overall, the findings here can be regarded as a proverbial “springboard” to facilitate the discovery of other low-hanging fruit for RE deployment in rural areas of the developing world. The obtained results serve as inputs for the next comprehensive energy modelling step in the IREP framework. This framework finds applicability across areas with similar energy access and rural development issues especially sub-Saharan Africa and developing Asia. The obtained results have shown integrated digital maps of economically viable solar energy, hydropower, and bioenergy potential that exist in these locations. These offer a concise visual representation of the local RE potentials to inform plausible developmental alternatives as well as to guide action plans towards achieving sustainable development. Finally, the results also provide robust information on the load consumption curves, which are crucial for the optimal planning, sizing, design and configuration of integrable off-grid RE-based energy systems. Opportunities for demand reduction are identified, which can inform demand side management and other energy conservation strategies.

DECLARATION OF INTERESTS

The author declares that are no competing interests.

ACKNOWLEDGEMENTS

This work has been facilitated by the financial support from Eni S.p.A Italy by virtue of the Eni Award 2017 prize and the Witte Endowment.

APPENDIX 1

Table A1: Cost of building materials and equipment for the retrofit measures.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Costs (Naira)</th>
<th>Costs (US $)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows shades ($/m²)</td>
<td>12,000.00</td>
<td>39.16</td>
<td>[159]</td>
</tr>
<tr>
<td>Roof Insulation ($/m²)</td>
<td>6,200.00</td>
<td>20.23</td>
<td>[160]</td>
</tr>
<tr>
<td>Wall Insulations ($/m²)</td>
<td>7,920.00</td>
<td>25.84</td>
<td>[160]</td>
</tr>
<tr>
<td>Floors covering ($/m²)</td>
<td>8000.00</td>
<td>26.11</td>
<td>[161], [159]</td>
</tr>
<tr>
<td>Double glazed windows ($/m²)</td>
<td>14,000.00</td>
<td>45.68</td>
<td>[160]</td>
</tr>
<tr>
<td>Stone coated roofing sheet ($/m²)</td>
<td>2,450.00</td>
<td>7.99</td>
<td>[159]</td>
</tr>
<tr>
<td>LEDs lighting ($/unit)</td>
<td>1,050.00</td>
<td>3.43</td>
<td>[160]</td>
</tr>
</tbody>
</table>
Window air-conditioner ($/unit) 90,000.00 293.69 [162]
Single-duct VAV system, no reheat HVAC systems ($/unit) 1,189,069.00 3880.14 [160], [162]

References


(accessed May 22, 2019).

(accessed April 29, 2019).


https://doi.org/10.1093/jae/12.4.564.

[33] Ibenegbu G. Rural development in Nigeria since independence. LegitNg 2018.
https://www.legit.ng/1098547-rural-development-nigeria-independence.html
(accessed May 24, 2019).

https://doi.org/10.23918/ijses.v4i2sp1.


https://doi.org/10.1016/j.renene.2013.01.057.


[67] Brandoni C, Polonara F. The role of municipal energy planning in the regional energy-


[135] Groesbeck JG, Pearce JM. Coal with Carbon Capture and Sequestration is not as Land


[149] Durodola OS. The Impact of Climate Change Induced Extreme Events on Agriculture and


