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Investigating the Impacts of Energy Access Scenarios in the Nigerian Household Sector by 2030

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Abstract: Lack of access to modern forms of energy continues to hamper socio-economic development in Nigeria, and about 94% and 39% of the Nigerian population do not have access to clean cooking equipment and electricity, respectively. The United Nations Sustainable Energy for All initiative and Sustainable Development Goal number seven seek to provide universal modern energy for all by 2030. However, the implications of these global goals on Nigeria's energy system have not been well researched in the literature. In this study, we applied the Long-Range Energy Alternatives Planning Systems model to analyse the impacts of different energy access scenarios by 2030 on household energy consumption, CO_2 emissions and local air pollutant emissions. We also analysed different scenarios for biomass renewability in order to understand its impact on household net CO_2 emissions. We found that achieving a 100% modern energy access by 2030 would reduce final energy demand by around 845 PJ, which is equivalent to a 52.4% reduction when compared to the baseline scenario. A 100% modern access would also significantly reduce local air pollutants, but increase CO_2 emissions significantly by 16.7 $MtCO_2$ compared to the baseline scenario. Our analysis shows that the benefits of modern energy access have been limited in Nigeria due to poor financing and low income levels of households. Therefore, we argue that for a 100% modern energy access in Nigeria by 2030, there is a need to explore local and foreign funding sources, and a serious need to couple energy access programs in the country with income-generating activities.

Keywords: energy access; energy policy; household; LEAP; Nigeria; SDG 7

1. Introduction

Energy is an essential element for the socio-economic development and wellbeing of a society. The provision of affordable, reliable and sustainable energy services is pivotal in addressing many of today's global problems, including climate change, poverty and food security [1]. Despite the growing concern about the importance of providing modern energy for all, the number of households globally depending on traditional solid fuels for cooking is increasing [2]. Globally, around 1.06 billion people do not have access to electricity, while around 2.5 billion people do not have access to clean cooking facilities [2]. Nigeria is the most populous country (around 200 million persons) and the largest economy in Africa. However, in Nigeria, around 94% and 39% of the population do not have access to clean cooking facilities and electricity, respectively [2]. The concern assumes even greater significance in the era of climate change, owing to the low adaptation capacity of Nigeria. Moreover, the health consequences attributed to a lack of access to modern energy services are dire, and it also contributes to the depletion of forests which are meant to be carbon sinks.

Historical and current efforts to eliminate energy poverty in Nigeria are not delivering the much-expected results in terms of pace and scale. If the current trend continues, more households are likely to continue depending on traditional solid fuels for cooking in the future. The situation extends beyond Nigeria to other sub-Saharan African countries and countries in Southeast Asia. To that end, the United Nations (UN) in 2010 put forward the Sustainable Energy for All (SE4ALL) initiative, which seeks to provide access to modern energy for all by 2030. This was followed by the declaration of 2012 as the international year of sustainable energy for all (See https://www.timeanddate.com/year/2012/energy.html). Owing to the central role of energy in driving development, the UN agenda for sustainable development goals (SDGs) listed energy as goal number seven—a missing link in the millennium development goals (MDGs) [3].

Recently, energy has been shown to have more positive interlinkages with the other SDGs [4]. Many countries (including Nigeria) have aligned their developmental goals with the SDGs. Realising the goal of providing modern energy access for all in Nigeria by 2030 is very ambitious, and there have been doubts as to whether this goal will become a reality in Nigeria [5]. Different energy stakeholders and opinion leaders in Nigeria have put forward their views on the realisation of this goal, but the impacts of different energy access scenarios by 2030 in the Nigerian household sector remain relatively unknown in the literature. Identifying the impacts of the energy access scenarios can be addressed through the application of energy system models.

Energy system models are tools which can be used to investigate the energy system and environmental emission impacts of different energy/climate policies. In terms of classification, there is no strict grouping of energy system models. However, from a broader perspective, they can be classified into two, namely: bottom-up and top-down models [6]. Bottom-up models represent technologies in detail, but do not capture macroeconomic decision making and system feedback. The bottom-up models are further grouped into simulation, accounting framework, optimisation and multi-agent models. Simulation models attempt to use exogenously determined drivers as well as technical data to quantitatively illustrate energy demand and conversion, which is not based on a cost minimizing pattern. The accounting framework models are usually considered to be a simple form of the simulation models, as they tend to account for the flows of the energy system in terms of physical and economic variables. The optimization models are used to define the set of technology choices that are cost-optimal under a given set of constraints [6].

On the other hand, top-down models represent macroeconomic feedbacks in detail, but provide less information on technologies. The top-down models are further grouped as input–output, general equilibrium, system dynamics, and econometric models [6]. The input–output models are used to describe the general flow of goods and services in an economy, classified into various sectors, as well as users from the perspective of value added and the specific input/output coefficients. The computable general equilibrium models are a class of top-down models that employ actual economic data to evaluate how an economy may react to changes in energy/climate policies or other external factors. The system dynamics models attempt to describe the behaviour of a social system that is interacting over time, using a set of differential equations. The econometric models combine economic theory with statistical and mathematical methods to explain economic relationships using empirical results [6]. For a detailed description of energy system models, see the work of Dioha [7].

Several studies have examined the household energy system using a series of models [8–19]. However, most of the studies have been based in developed and transition economies. In Nigeria, some authors have tried to model different energy scenarios for the Nigerian household sector, including the millennium development goals scenario [20], and the National Renewable and Energy Efficiency Policy (NREEEP) scenario [21]. The Nigerian household sector has also been modelled for different economic and technological scenarios as a part of integrated assessment models [22,23]. However, there are fewer studies examining the energy system impacts of achieving universal modern energy access for Nigerian households. Addressing this knowledge gap will help in improving understanding of the implications of different energy access levels in 2030. Hence, it provides the basis for informed decision-making today, aimed at providing modern energy services in the country.

In this study, we applied a quantitative approach to explore the implications of achieving universal modern energy access in the Nigerian household sector, from the perspective of energy consumption, CO_2 emissions and local air pollutant emissions. The Long-Range Energy Alternatives Planning Systems (LEAP) model was applied to project future energy demand and associated environmental emissions of the household sector for a time horizon of 2010–2030 under a business-as-usual scenario. Alternative scenarios include a pessimistic scenario and an optimistic scenario where universal modern energy access will not be achieved in 2030. Finally, we explored the impacts of 100% modern energy access under the full access scenario. In terms of contribution, the present study introduces one of the earliest case studies in Nigeria that quantitatively analyses the impacts of the UN SE4ALL initiative. This study also departs from conventional methods of considering biomass as renewable energy by looking at the CO_2 emissions impact of unsustainable harvesting of biomass. In a bid to proffer solutions to the energy access problem in Nigeria, we provide policy recommendations that can accelerate universal modern energy access in the country. While the case study presented here is for Nigeria, we believe that the insights emerging from this study can be useful to other developing countries where universal modern energy access is yet to be achieved.

The rest of this paper is arranged as follows: Section 2 presents the methodology used in this study, which includes the LEAP modelling framework and characterisation of energy access scenarios as well as the co-benefits. Section 3 reports the numerical results of the model as well as analysis of final energy demand, per capita energy demand, CO_2 and local air pollutant emissions, and the impacts of non-renewability of biomass. Section 4 discusses the outcome of the results and the key challenges of energy access in Nigeria, and the conclusions are stated in Section 5.

2. Methodology

2.1. Overview of the LEAP Modelling Framework

LEAP is a bottom-up, scenario-based model used for long term energy system analysis and planning. It was developed by the Stockholm Environment Institute, Boston with financial support from the UN Environment Programme and the World Bank. The model has been applied for energy system analysis and climate mitigation studies in many developing countries [24]. As an integrated model, LEAP covers the processes of energy extraction, conversion and consumption in all sectors of the economy. The model can also be used to conduct a cost–benefit analysis for different scenarios. The model is data-intensive and requires the user to input data in a hierarchical form, which includes data in the key assumptions module for socio-economic indices, demand module, statistical differences, transformation, stock change, resources and non-energy sector modules [25].

Economic variables such as gross domestic product, population, number of households, industrial value addition etc. are entered into the key assumption module of LEAP. The total final energy demand by sector is projected using certain parameters such as the activity levels of the demand sectors and the conversion sector's energy production volume, as well as the primary energy supply rate with consideration of losses in the conversion sector. LEAP also accounts for environmental emissions from the production and utilisation of energy. The model is equipped with a technology emission database, which consists of the IPCC Tier 1 GHG emission factors and standard air pollutant emission factors.

With respect to the demand module, LEAP endogenously calculates the final energy demand by multiplying the activity level of an end-use with its energy intensity [25]. Generally, LEAP can estimate energy demand using four different approaches: final energy demand, useful energy demand, stock and transport analysis. The particular method used depends on the modeller, the research question and the level of data available. Final energy demand can be obtained in LEAP using Equations (1)–(5) [25].

$$Final\ Energy\ Analysis,\ E = \sum_{i=1}^{n} Q_I \times I_i. \quad (1)$$

where E = energy demand; Q_I = activity level and I_I = energy intensity.

$$Useful\ Energy\ Analysis,\ E = Q \times \left(\frac{u}{n}\right) \quad (2)$$

where u = useful energy intensity and n = efficiency.

$$Stock\ Analysis,\ E = S \times D \quad (3)$$

where S = stock and D = device intensity.

$$Transport\ Analysis,\ E = S \times \frac{M}{FE} \quad (4)$$

where M = vehicle miles and FE = fuel economy.

GHG emissions are computed in LEAP as per Equation (5).

$$G = \sum E \times Ef. \quad (5)$$

where G represents the total GHG emissions, E the energy demand by a given fuel and Ef the emission factor of the fuel.

2.2. The Nigerian-Household-LEAP (NHL) Model

We used the NHL model to project future energy system impacts of different energy access scenarios for the Nigerian residential sector by 2030. The NHL model is a bottom-up model of the Nigerian residential sector that was developed based on the LEAP modelling framework. The model spans 40 years (2010–2050) with time intervals of 5 years, and accounts for spatial heterogeneity between Nigerian households by splitting them into rural and urban classes—a major characteristic of sub-Saharan African countries like Nigeria [26]. For each category of household, six different end-uses were considered, namely: cooking, lighting, refrigeration, air conditioning, water heating, and miscellaneous electrical appliances, as shown in Figure 1.

Technologies modelled for cooking energy service included traditional three-stone stove systems, induction, liquefied petroleum gas (LPG) and kerosene stoves. For lighting, while there are numerous sources of lighting, only kerosene lanterns and electric bulbs were modelled in the NHL model in order to simplify the analysis. Refrigeration and air conditioning consisted of existing and efficient technologies, while the miscellaneous appliances consisted of fans, DVD player, computer etc. and were modelled as aggregate technology. The main drivers of the model are population, urbanisation, household number and household size. Data on activity levels and energy intensities of end-uses were taken from secondary literature [20,27], while data of the model drivers were mainly obtained from the UN database [28] and the National Bureau for Statistics [29–31]. A detailed development and description of the model is given in Dioha [21].

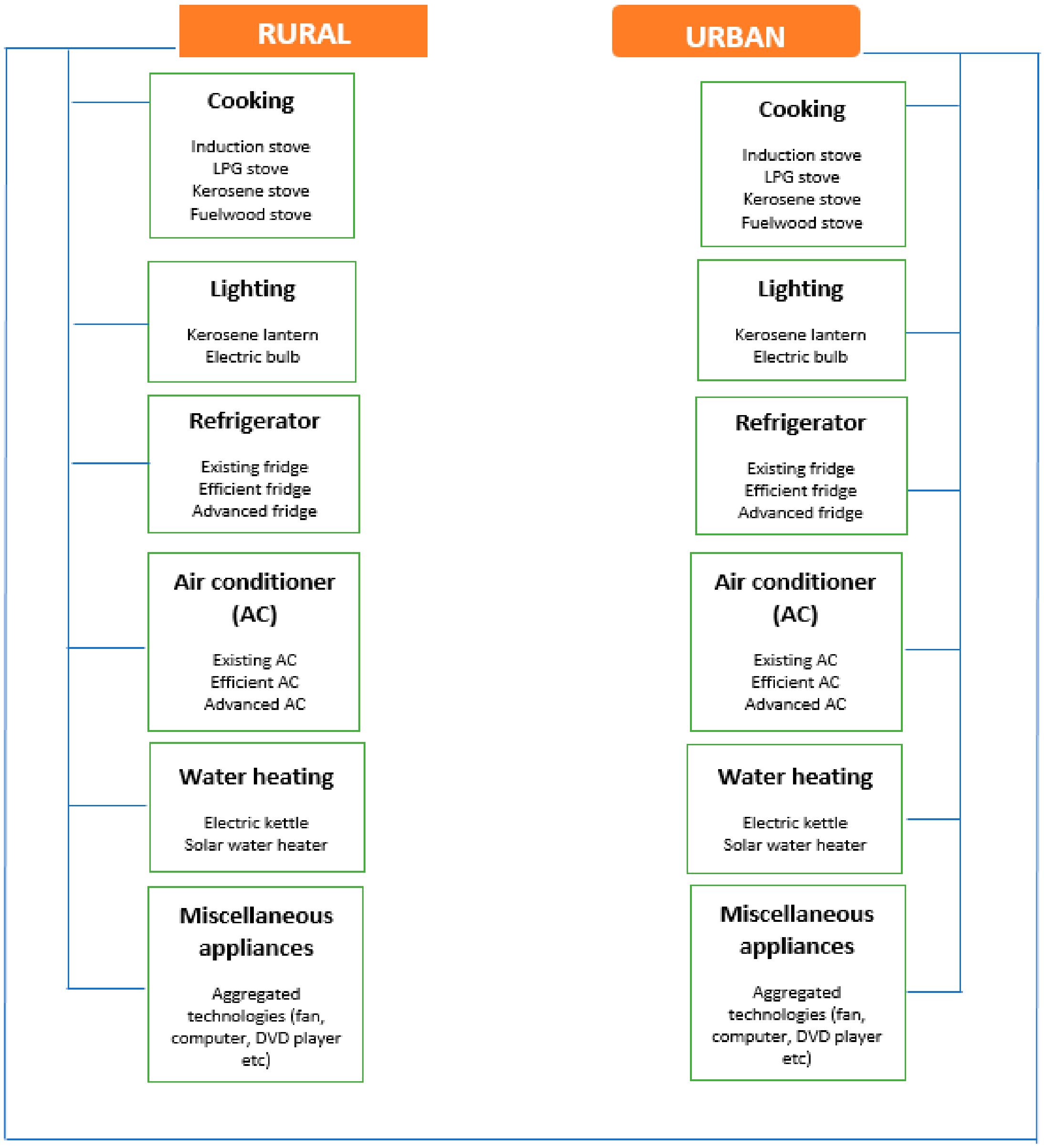

Figure 1. Tree structure of Nigerian household Long-Range Energy Alternatives Planning Systems (LEAP) model.

2.3. Scenarios Description for Energy Access

Scenarios refer to hypothetical outcomes. They illustrate dynamic changes that characterise a series of events within a time horizon. They attempt to explain the causal relationship between events, states, driving forces, consequences and actions, which usually begins from an initial point (i.e., present) to a given picture of an anticipated final state over the time horizon [32]. In this paper, our scenarios refer to consistent sets of assumptions or storylines depicting how energy access levels might evolve in Nigerian households by 2030. The role of scenario analysis in energy policy and planning cannot be ignored, as it goes a long way in managing uncertainties and in aiding decision-making. However, it is worth mentioning that energy scenarios do not attempt to predict the future, but to give insights into the plausible changes in an energy system pathway based on the scenario modelled.

To achieve universal access to clean, affordable, reliable and sustainable energy for all in Nigeria by 2030 is a daunting task, characterised by many uncertainties. To that end, we explored different futures of energy access levels in Nigeria by 2030 to see what benefits they could deliver to the energy system, as well as to provide policy recommendations. With the NHL model, we developed a business-as-usual

(BAU) scenario and other alternative energy access scenarios as follows: pessimistic scenario (PES), optimistic scenario (OPS) and full access scenario (FAS). The aforementioned scenarios are based on different assumptions about how the household energy system might unfold by 2030, based on historical trends and future plans.

While constructing our scenarios, we noted that there is no specific or standard definition for energy access. However, the International Energy Agency (IEA) defines energy access thus: *"a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average."* [2]. From the above definition, a bundle of energy services refers to a minimum of a few lightbulbs, and access to clean cooking facilities refers to at least an improved biomass cooking stove or LPG stove [2]. In this paper, we considered energy access to be the ability of a Nigerian household to use electricity for lighting and LPG for cooking. LPG is been considered as the only modern cooking fuel here because of the abundance of oil in Nigeria, and the convenience of cooking with LPG when compared to improved biomass stoves. Moreover, the NREEEP proposed to move all households in Nigeria to LPG for cooking by 2030 [33].

BAU: The baseline scenario is developed using the storyline that the reference energy system in 2010 will be maintained until 2050 without any penetration of new technologies/appliances into the Nigerian household sector. The scenario assumes that efficiency improvements are frozen and no new attempts are made to improve the income levels of households in order to climb the energy ladder. This scenario also serves as a baseline in comparing the relative energy and environmental impacts of different energy access policy pathways by 2030.

PES: With the current trend of rural energy development in Nigeria, it is unlikely that half of all rural households will switch to LPG for cooking, and very unlikely that all households will be electrified by 2030. With this in mind, this scenario assumes a pessimistic storyline in which few efforts will be put towards providing modern energy for all in Nigeria by 2030. In this scenario, we assume that the national budget for rural electrification is very limited and the private sector is not engaged in the 'game,' which in turn slows down the adoption of clean energy appliances. The scenario also assumes that Nigeria does not receive international funding from donor agencies like the World Bank and African Development Bank for rural electrification and clean cooking equipment, and the entire burden of providing universal energy remains on the limited budgetary allocation of the federal government (FGN).

OPS: Here, we assume an optimistic future of universal energy access in Nigeria. Much of rural Nigeria is expected to be electrified by decentralised renewable energy, and thus, it is assumed that off-grid solutions and mini-grid projects will be expanded in the country, and this will go a long way to provide electricity for the currently unelectrified households. The scenario assumes that national budgetary allocation of the Rural Electrification Agency (REA) will be increased, and this money will be fully directed to enhancing electricity access in rural areas through the coordination of all actors in the rural electrification space of Nigeria. We also assume that greater funds will be generated from international donors for energy access projects, while the Nigerian Alliance for Clean Cookstoves (NACCS) will promote the dissemination of LPG cooking equipment in the country. While these measures will enhance energy access in the country significantly, this scenario does not provide 100% energy access for Nigerian households, but to a level relatively greater than the BAU and PES levels.

FAS: This is the SE4ALL or SDG 7 scenario. We assume that all sources of funds are fully mobilised in the country (national budgetary allocation and international donor agencies). Energy access is considered as a national priority in the nation's development plan, and different actors in the 'game' are providing unique solutions for providing modern energy access. It is also assumed that there is regional cooperation, especially within the Economic Community of West African States sub-region in order to draw experiences from other countries that have robust energy access programmes. Consequently, the comprehensive efforts put forth in this scenario are assumed to provide 100% access to electricity and clean cooking fuel (LPG) for all households in the rural and urban areas of Nigeria by 2030. The specific energy access levels characterising our scenarios are presented in Table 1.

Table 1. Detailed assumptions characterising the energy access scenarios in 2030.

Household Category	Technology	2010 Levels	BAU	PES	OPS	FAS
		Penetration rates of technologies in Nigerian households (%)				
			2030	2030	2030	2030
Rural	Electrification	35.5	35.5	50.0	75.0	100.0
	Kerosene stove	7.9	7.9	5.0	2.0	0.0
	LPG stove	0.4	0.4	20.0	45.0	100.0
	Induction stove	0.2	0.2	0.1	0.0	0.0
	Fuelwood stove	91.5	91.5	74.9	53.0	0.0
Urban	Electrification	87.1	87.1	95.0	100.0	100.0
	Kerosene stove	51.7	51.7	33.0	30.0	0.0
	LPG stove	2.0	2.0	39.0	60.0	100.0
	Induction stove	0.8	0.8	0.5	0.0	0.0
	Fuelwood stove	45.5	45.5	27.5	20.0	0.0

2.4. Scenario Descriptions for Biomass Renewability

As of 2017, around 94% of Nigerian households still depend on inefficient, traditional solid fuels for their cooking energy requirements [2]. The situation is even more pronounced in the rural areas, with around 71% of households depending solely on fuelwood for cooking [34]. If innovative solutions are not provided quickly, the number of households depending on fuelwood for cooking will escalate rapidly in the future. Fuelwood contains bioenergy, and biomass is considered a renewable source of energy. However, this theory only holds when biomass is sustainably harvested. Thus, if fuelwood is sustainably harvested for cooking (i.e., renewable), the net CO_2 emissions from fuelwood combustion will be zero, as it is assumed to be re-absorbed during the next planting season. In contrast, the literature suggests that not all fuelwood is sustainably harvested, and, in fact, the fraction that is unsustainably harvested can vary from 0–90% globally [35]. Hence, a higher fraction of unsustainably harvested fuelwood will have a corresponding impact on net CO_2 emissions, which makes switching to LPG more environmentally friendly.

The LEAP model considers biomass to be renewable, and thus produces net zero CO_2 emissions. However, the model also provides results of biogenic CO_2 emissions coming from fuelwood combustion. In this paper, we considered different scenarios for biomass renewability: a sustainable scenario, which is reported by LEAP under the assumption that fuelwood is a net zero CO_2 emitter, and then more realistic scenarios where we assume that 95%, 90%, 85%, 80%, 75% and 70% of biomass is sustainably harvested. Data on the sustainability of biomass consumption are rare for Nigeria, thus our biomass renewability scenarios were informed by earlier studies which made assumptions of unsustainable biomass consumption in the range of 20% [36] and 30% [37] in developing regions of the world.

2.5. Co-Benefits of Modern Energy Access

An under-researched, yet highly important aspect of household energy transitions is the co-benefit. Going beyond finances, another reason why household energy transition is at a slow pace in Nigeria is the lack of information by policymakers on the multiple benefits modern energy access can potentially deliver. For any effective policy change, these co-benefits need to be quantified and communicated appropriately. While providing universal energy access in Nigeria may incur more investments, if the co-benefits are considered, the true cost may be lower than the initial investment estimated. Thus, it is important that researchers and policymakers understand this dimension in energy transition analysis.

In this study, we paid particular attention to household air pollutants. The use of kerosene lanterns for lighting and traditional fuelwood stoves for cooking releases indoor air pollutants such as carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx) and sulphur dioxide (SO_2), which cause respiratory diseases.

In fact, the World Health Organisation has estimated that, in Nigeria, around 79,000 deaths annually could be attributed to indoor local air pollutants due to the use of inefficient traditional fuelwood stoves [38]. Thus, in this paper, we analysed the mitigation of CO, NMVOC, NOx and SO_2 due to the alternative energy access scenarios in 2030. The co-benefits of modern energy access can facilitate other development goals. For example, access to modern cooking equipment can help reduce the time spent (mostly by women and children) in gathering fuelwood every day and the burden of carrying the fuelwood for long distances on foot from the forest. The time saved can be put into other productive activities such as education and trade, which in turn puts more wages into their pockets, thereby reducing poverty and inequality among their male counterparts.

3. Model Numerical Results

In this section, we report on the few key implications of each energy access scenarios from the perspective of household final energy demand, per capita energy demand, energy mix, CO_2 emissions and local air pollutant emissions.

3.1. Final Energy Demand

In the BAU or frozen scenario, only the current technologies are available in Nigerian households. As can be observed from Figure 2, the final residential energy demand in the BAU is expected to increase at a compound annual growth rate (CAGR) of 3.32% from 839 petajoules (PJ) in the base year to around 1613 PJ in 2030. This represents around a 92.3% increase in comparison with the base year value. This future increase in final energy demand is due to the projected increase in the number of households and urbanisation. In the PES, there is a gradual adoption of efficient cooking and lighting equipment. Our analysis of the results of the PES indicates that final energy demand is expected to decrease by around 224 PJ in 2030 in this scenario; this value represents about a 13.9% reduction when compared to the BAU.

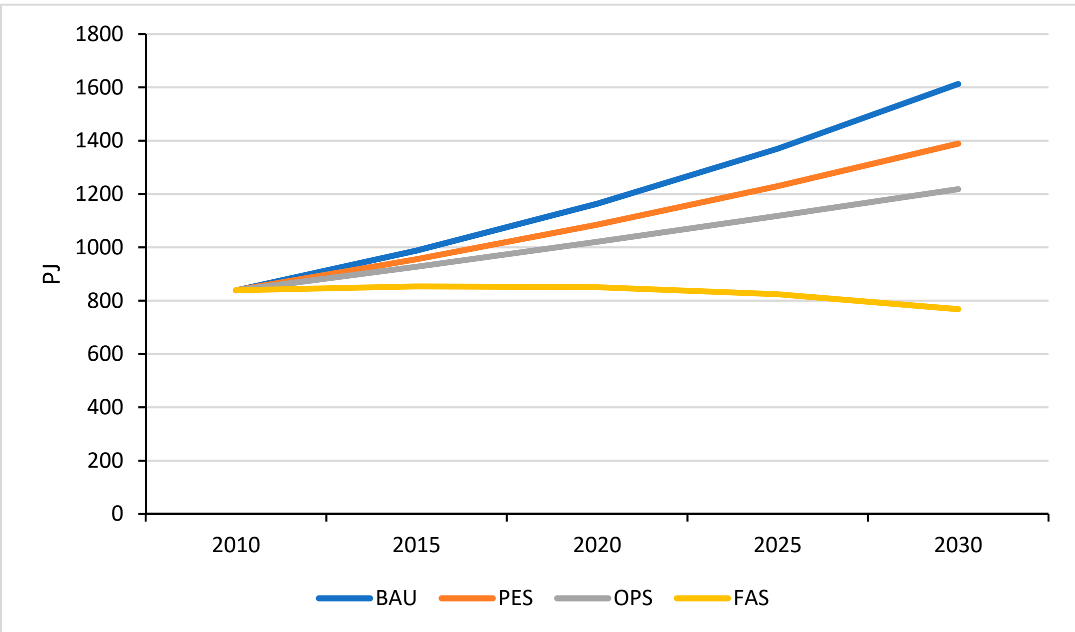

Figure 2. Final energy demand projections for all scenarios.

Driven by greater penetration of efficient cooking and lighting equipment, analysis of the OPS indicates that final energy demand in this scenario will drop by around 395 PJ in 2030; this value represents around a 24.5% reduction in comparison with the BAU case. In the FAS, it was assumed that the SE4ALL agenda or SDG 7 goal will be fully realised by 2030. Our analysis of this scenario suggests that the final energy demand will drop by about 845 PJ. This value indicates around a 52.4% reduction in final energy consumption when compared to the baseline scenario. All in all, the foregoing results suggest that the alternative energy access scenarios will deliver lower energy demands at different rates relative to the BAU.

3.2. Per Capita Energy Demand

Figure 3 illustrates the outcome of the per capita energy demand analysis. Owing to the importance of energy in the socio-economic development of a society, per capita energy demand is sometimes used as a measure to analyse the development level and wellbeing of a society [39]. In the BAU, per capita energy demand grows at a CAGR of 0.78% from 5.26 GJ/person in 2010 to around 6.14 GJ/person in 2030. In the PES, it was observed that per capita energy demand increases at a CAGR of 0.03% to 5.29 GJ/person in 2030. Our analysis indicates that in the OPS, per capita energy demand will drop at a CAGR of 0.63% to 4.64 GJ/person in 2030.

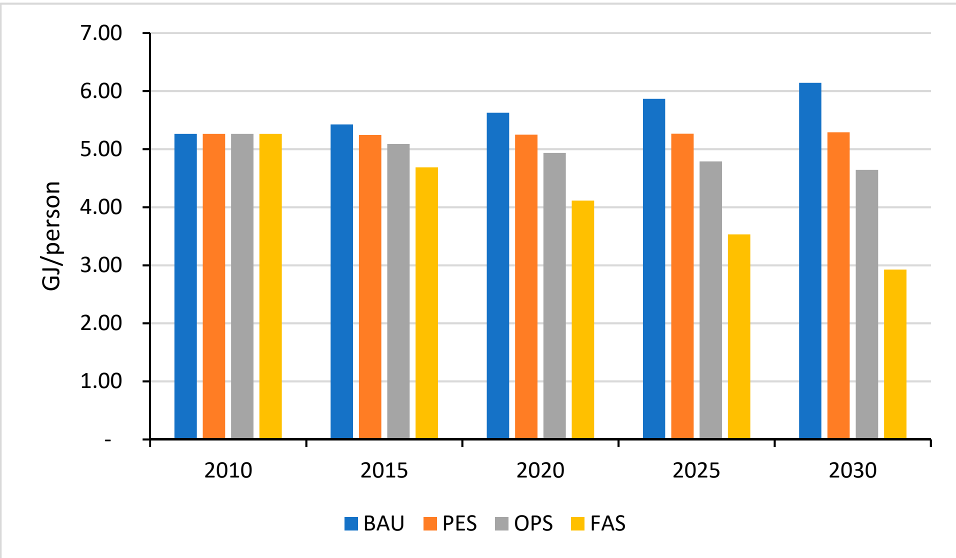

Figure 3. Per capita energy demand projections for all scenarios.

Finally, analysis of the FAS suggests that per capita energy demand will fall at a CAGR of 2.90% to 2.92 GJ/person in 2030. The current results show that per capita energy demand is expected to be reduced across the alternative scenarios due to the intervention of energy efficient appliances in the Nigerian household sector. One might ask, "Does this mean that the wellbeing of Nigerians is undermined in the alternative energy access scenarios?" Certainly not. However, the current results suggest that per capita energy demand as an indicator for energy development or wellbeing of a society needs to be refined, as it does not account for energy efficiency or sustainability issues.

3.3. Energy Mix

Results of the fuel mix in the energy access scenarios are reported in Figure 4. The results show that in the BAU, fuelwood is the most consumed fuel in Nigerian households, accounting for around 77.2% of the total energy consumption in 2030. Fuelwood is used for cooking and heating in Nigerian households. Thus, the present result concurs to the assertion that cooking is the most energy-intensive activity in Nigerian households [40]. Kerosene, LPG and, to some extent, electricity also supply a very small part of the Nigerian household cooking energy requirements. Our additional analysis of the BAU indicates that kerosene, electricity and LPG account for, respectively, about 12.6%, 9.7% and 0.5% of the final energy consumption in 2030. However, in the PES, with small improvements in energy efficiency, we observed some changes in the energy mix. The results show that the percentage of fuelwood in the final energy consumption will drop to 65.79%, while the consumption of electricity and LPG increases to 12.19% and 12.65%, respectively.

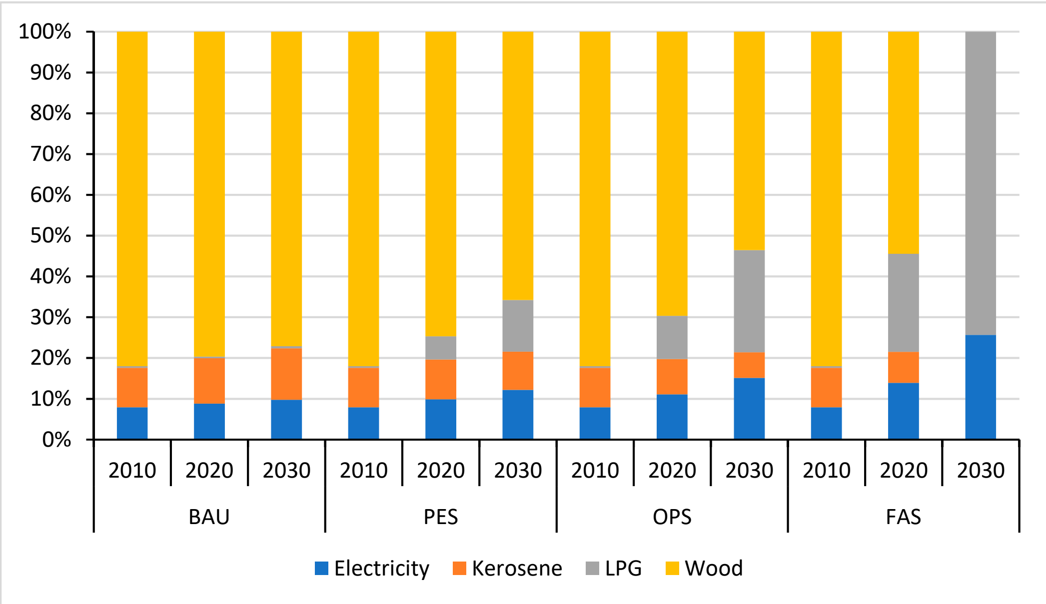

Figure 4. Fuel mix projections for all scenarios.

However, kerosene consumption drops to 9.37%, indicating the gradual penetration of LPG into the Nigerian household cooking sub-sector in comparison to the BAU case. In the OPS, analysis indicates that greater efforts in LPG penetration will decrease fuelwood and kerosene consumption significantly relative to the BAU and PES. Our analysis indicates that fuelwood and kerosene will account for 53.55% and 6.24%, respectively, of final household energy demand in 2030 in the OPS. We also observed a higher percentage of electricity and LPG consumption, accounting for 15.13% and 25.08% of final household energy demands, respectively. In the FAS, fuelwood and kerosene are completely phased out from the Nigerian household sector, and our results indicate that LPG will be the most consumed fuel in the sector with a share of 74.35%, while electricity is expected to account for the remaining 25.65%.

3.4. CO_2 Emissions

Among all GHGs, CO_2 has been identified as the most prominent GHG from the energy sector, and it is responsible for around 60% of the rise in climate forcing since the pre-industrial era [41]. Figure 5 illustrates the results of CO_2 emissions from the household sector for all energy access scenarios. The CO_2 emissions reported here are direct CO_2 emissions from the residential sector, and do not include embedded emissions from the electricity sector and biogenic emissions from biomass combustion. Results indicate that in the BAU, CO_2 emissions are expected to grow at a CAGR of 4.67% from 6.1 million tonnes of CO_2 ($MtCO_2$) in the base year to around 15.2 $MtCO_2$ in 2030. This value also corresponds to about a 150% in comparison with the base year. However, in the PES, results indicate that CO_2 emissions will increase by 4 $MtCO_2$ in 2030; this value represents a 26.3% increase when compared to the BAU case.

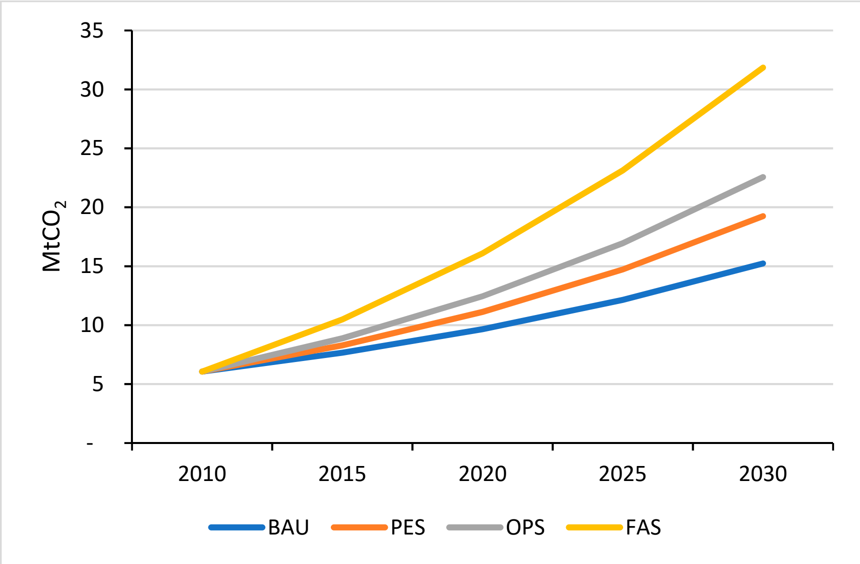

Figure 5. CO_2 emissions projections for all scenarios.

Our analysis of the OPS suggests further increase in CO_2 emissions. The results indicate that CO_2 emissions will rise by 7.4 $MtCO_2$ in 2030 in this scenario; this value corresponds to a 48.7% increase relative to the BAU. In the FAS, all households are assumed to migrate to LPG cooking equipment and electric lighting. Analysis of the FAS indicates that CO_2 emissions will grow significantly by 16.7 Mt CO_2 in 2030; this value represents an over 100% increase in comparison with the BAU. While LPG is considered to be a clean cooking fuel from the perspective of local environmental air pollutant emissions, it is worthwhile to note that LPG is still a fossil fuel, which releases CO_2 emissions during combustion, such as in the cooking process. Hence, the significant increase in CO_2 emissions in the alternative energy access scenarios can be attributed to the aforementioned characteristics of LPG.

3.5. Scenario Analysis Results for Biomass Renewability

In analysing the results of CO_2 emissions in the alternative energy access scenarios, we found that the FAS produced the largest amount of CO_2 emissions (32 $MtCO_2$) (Figure 5). In Figure 6, we analysed the net CO_2 emissions of the household sector in 2030, under the assumptions that 95%, 90%, 85%, 80%, 75% and 70% of biomass is renewable in the FAS. The assumptions regarding the renewability of biomass made a significant impact on net CO_2 emissions. Under 95%, 90%, 85% and 80% biomass renewability scenarios, our analysis shows that net CO_2 emissions will be around 25.0, 18.2, 11.4 and 4.6 $MtCO_2$, respectively. This implies that a complete shift to LPG will reduce CO_2 emissions from the Nigerian household sector if we assume that biomass is not sustainably harvested in the country.

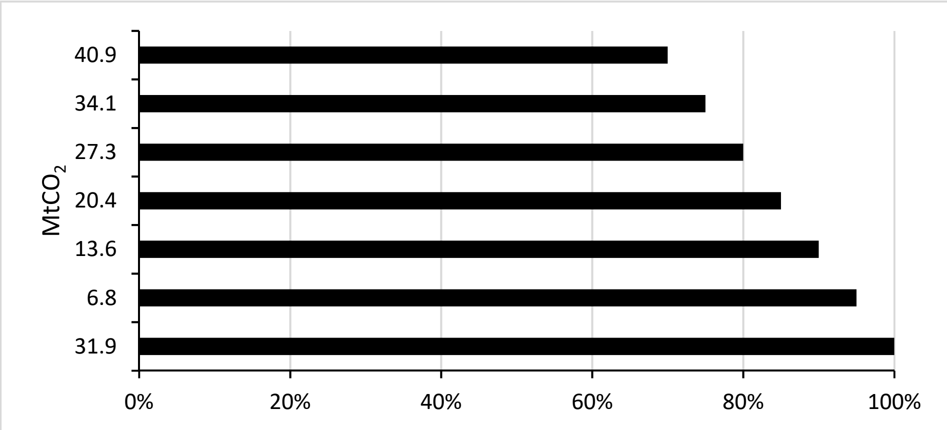

Figure 6. Household sector CO_2 emissions under different biomass renewability scenarios.

In the 75%, and 70% biomass renewability scenarios, we observed negative net CO_2 emissions of −2.2 and −9.0 $MtCO_2$. These results also suggest that if we assume that 25–30% of biomass is unsustainably harvested, then a total shift to LPG for cooking could even produce a deep decarbonisation of the Nigerian household sector. This is because the CO_2 emissions produced from LPG usage are overshadowed by the CO_2 emissions emitted from burning non-renewable biomass. However, it is worth mentioning that the current estimations should be considered with a marginal view, as there are no data yet and no well recognised approach for calculating the sustainability of biomass consumption in Nigeria.

3.6. Local Air Pollutant Emissions

The impacts of energy access on local air pollutants are presented in Figure 7. The air pollutants analysed here encompass CO, NMVOC, NOx and SO_2. In the BAU, CO, NMVOC, NOx and SO_2 are expected to increase by 80.8%, 80.8%, 88.3% and 157.2%, respectively, in 2030 in comparison with the base year levels, due to the massive use of inefficient cooking equipment such as the traditional fuelwood stoves. However, in the alternative scenarios, analysis of CO emissions indicates that it will reduce in 2030 by 26.4%, 47.3% and 99.5% in the PES, OPS and FAS, respectively. For NMVOC, analysis suggests that its emissions in PES, OPS, and FAS are expected to decline by around 26.4%, 47.4%, and 99.6% respectively in 2030. With respect to NOx emissions, our results indicate that by 2030, its emissions are expected to reduce by about 22.0%, 39.3%, and 80.3% in PES, OPS, and FAS respectively.

The analysis of SO_2 emissions suggests that they will fall by 2030 by around 36.1%, 61.1% and 100% in the PES, OPS and FAS, respectively. Overall, the results presented here indicate that local air pollutant emissions will reduce in the alternative energy access scenarios, which further implies better air quality, and in turn, better health conditions for Nigerians. Taking a broader view of the results, the co-benefits of energy access policies can facilitate the achievement of other SDGs such as those related to good health and gender equality. While the results presented here are in the form of numbers, the insights drawn from the results should be considered when making decisions/initiatives regarding energy access in Nigeria.

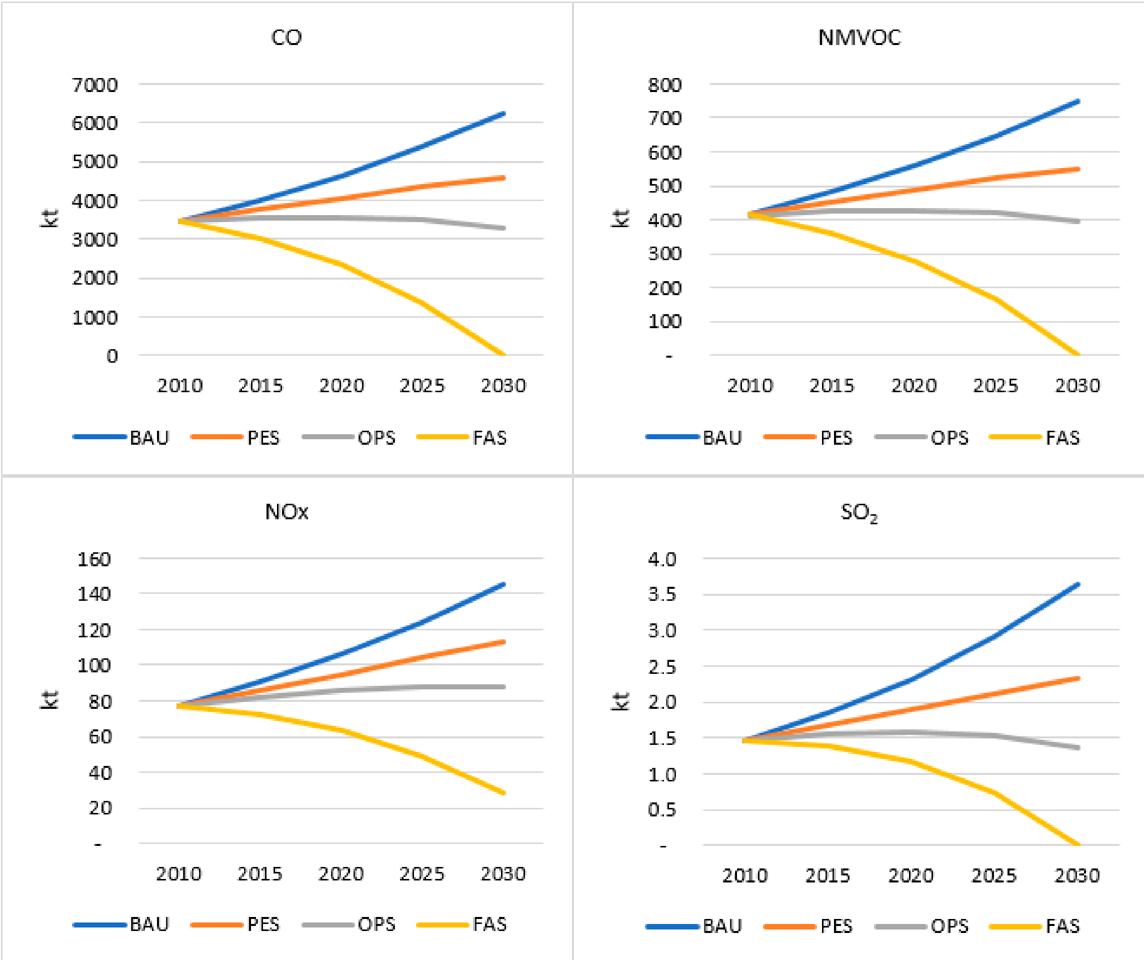

Figure 7. Air pollutant emissions projections for all scenarios.

4. Discussion

Recently, there has been a growing concern globally around the need to provide universal energy for all, due to its potential benefits. In Nigeria, efforts are underway to provide electricity for all unelectrified households by 2030 and to promote the transition to cleaner cooking equipment. For example, the World Bank is supporting the REA with around US$350 million to improve access to electricity services for rural households, small and micro enterprises, and public educational institutions (http://projects.worldbank.org/P161885?lang=en). Additionally, the NACCS is working towards delivering about 10 million improved/clean cook stoves to Nigerian households and institutions by 2020 (http://iceednigeria.org/ic/partnerships/nigerian-alliance-for-clean-cookstoves-nacc/). These proposed projects could accelerate the 2030 energy for all agenda in Nigeria, but it remains to be seen when these ambitious projects will become a reality.

Several studies on household energy transitions exist in Nigeria, but quantitative analysis of the energy system impacts of different energy access scenarios in 2030 remains uncertain. The modelling assessments presented here show that achieving 100% universal modern energy access in Nigeria will drastically reduce energy consumption by over 50% in comparison to the BAU case. The modelling results also suggest that providing modern energy for all Nigerian households will significantly improve residential air quality as well reduce net CO_2 emissions from the sector, if we assume that around 25% of fuelwood is unsustainably harvested. Accordingly, the benefits of energy access policies are numerous, and one might ask why access to modern forms of energy continues to elude many households in Nigeria despite the numerous co-benefits it can potentially deliver. The answers are not far-fetched, and they are largely well known. The main obstacles to energy access in Nigeria include inadequate financing, low household incomes, inadequate planning and poor governance, as well as weak human/institutional capabilities [1].

The international community has long been informed of the close relationship between household income levels and modern energy access. It is not surprising that developing countries such as Nigeria, with a large percentage of the population living on incomes less than $2 per day, usually have low electrification rates, and a large percentage of the population cooking with inefficient, traditional biomass stoves. Despite the importance of this issue, millions of Nigerians continue to live without access to basic modern energy services. This situation is expected to change only a little by 2030 unless more vigorous efforts and actions are taken (https://www.iea.org/energyaccess/modernenergyforall/).

In terms of improving access to electricity in Nigeria, inadequate financing of the power sector remains a major challenge. Ohiare [42] estimated the total investment requirements to electrify all households in Nigeria by 2030 at around US$34.5 billion (an average of US$2 billion annually), and also suggested that the grid solution is economically viable for around 98% of households. The investment requirement is very high, and way beyond the average annual budgetary allocation of the REA [43]. This situation, therefore, calls for new financing models. If Nigeria wants to achieve the targets of universal electricity for all by 2030, then there is a need to mobilise funds from all sources. Experience has shown that achieving universal electrification in Africa cannot be realised without meaningful mobilisation of local funds [44].

Thus, Nigeria should not only rely on international support, but focus more on local financing, then the country may seek foreign support to augment the shortfall in local finances. Internally, it is important for Nigeria to increase the national budgetary allocation for rural electrification, as well as encourage the participation of relevant stakeholders. Meaningful achievements can be achieved when private sector finances are also mobilised. For example, commercial financial institutions can provide soft loans, micro-finance and equity for electricity project developers in the country. Secondly, after all the local sources of financing have been exploited, Nigeria can seek support from international donor agencies in the form of debt relief and concessional loans.

On electricity access, recent developments in the Nigerian electricity sector have shown that many households will be electrified via off-grid and mini-grid solar PV technology. However, recent projects have not delivered the required results. Sustainability of renewable energy projects remains an issue in Nigeria, and many of the installed projects cease to exist after 2 years of installation. This can partly be attributed to the poor participation of the local community in renewable energy projects. For effective development of renewable energy solutions in Nigeria, project developers need to engage local communities, whether by in-kind contribution such as labour and time or in decision-making. Hence, the projects won't be a 'give away' project, but will promote ownership and care of the projects, as the local community also become stakeholders in the project. Additionally, for successful off-grid renewable energy solutions, project developers need to train local technicians and households on how to operate the technologies. Finally, project developers should provide after-sale services to ensure that communities actually maintain installed technologies. This can be achieved through product guarantees, assurances and free maintenance workshops [45].

In terms of access to modern cooking equipment, many studies have argued that low household income is the major factor limiting the transition to clean cooking facilities in Nigeria [46,47]. However, other latent factors such as geographical region, household size, place of residence and educational level also play a role [48]. Thus, the focus on improving clean cooking equipment in Nigerian households should be on enhancing rural incomes. While there are many ways to achieve this, one of the most innovative ways is to couple energy services with employment. It is therefore only pertinent that energy access initiatives include programs that spur productive use of energy, which in turn drives income generation, thereby reducing poverty and increasing the ability to climb the energy ladder. Moreover, an earlier study has opined that efforts which succeed in combining productive uses with income generation activities into energy access programs may well turn out to be the key solution towards achieving universal modern energy access in sub-Saharan Africa by 2030 [49].

Additionally, there is a need for new business models in order to enhance the adoption of clean cook stoves in Nigeria. In this context, subsidies will play a key role, as they will go a long way to reduce the cost of stoves for poor rural households. The subsidies are usually recovered from carbon finance by the business owners. There have been good examples of successful improved cook stove models which Nigeria can learn from. Typical examples include the Atmosfair in Rwanda. In this model, the revenue derived from carbon finance is used to reduce the cost of the Save80 stoves for poor households. In Ghana, carbon finance has been used to help local businesses promote the Gyapa stoves through marketing, capital investment, working capital support, as well as technical training. Nigeria can also learn from the SURYA program of India, where LPG stoves are provided for households through a technology-enabled model in which payment is made with embedded mobile control technology. Beyond the business models, there are also dedicated funding sources for clean cook stoves which Nigeria can explore, such as the Global Alliance for Clean Cookstoves Spark Fund, Deutsche Bank Clean Cooking Working Capital Fund, the Base of the Pyramid Exchange Fund (BIX Fund) and the USAID Loan Guarantee Facility [50].

5. Conclusions

Access to modern energy services remains a huge challenge for many households in Nigeria, and the current study has shown the impacts which different energy access scenarios could have on household energy consumption and environmental emissions by 2030. We have outlined different energy access scenarios which are possible by 2030 in Nigeria, based on the scale of efforts put towards providing universal energy for all in the country. The realisation of energy for all in Nigeria by 2030 is a major challenge. As outlined earlier in the paper, the success of this goal would bring a number of economic and health benefits to those currently without modern energy access. The achievement of this goal would also go a long way to positively impact wide-ranging aspects of other SDGs.

The study showed that achieving 100% energy access will deliver the largest benefits for Nigerian households, when compared with other scenarios in which universal energy access wasn't achieved in 2030. We also showed that, contrary to earlier assumptions that LPG could increase the carbon footprint of Nigerian households, LPG could actually decarbonise the household sector if we assume that a certain percentage of fuelwood is unsustainably harvested. The paper further showed that beyond energy demand and climate concerns, there are also co-benefits of achieving universal modern energy access. The present study analysed the co-benefits from the perspective of indoor air pollutant mitigation. However, we recognise that there are multiple other benefits that full energy access could deliver, and, thus, there is still room for further and more detailed analysis on this subject. The study also recognised that despite the numerous potential advantages accruing from modern energy access, funding will be a huge obstacle, and, as such, innovative financing strategies will be needed if Nigeria wants to achieve anything near the target of universal energy for all by 2030.

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