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ScienceDirect

Journal of Policy Modeling xxx (xxxx) xxx–xxx

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Clean cooking energy transition in Nigeria: Policy implications for Developing countries

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Received 24 December 2021; Accepted 16 February 2022
Available online xxxx

Abstract

Lack of access to clean cooking energy systems negatively affects the health and welfare of millions of people in developing countries. Different factors such as household income, household size, fuel price, and information spread have been identified as barriers to the widespread uptake of clean cooking systems. However, analyses exploring the dynamic influences of these factors towards accelerating clean cooking from the long-term perspective are limited. Here, we employ a system dynamics modelling framework to simulate how various strategies could affect the adoption of clean cooking systems in Nigeria over time. Our results reveal that clean cooking adoption is a fluctuating process, and the trends present a non-linear behaviour. We found that the adoption of clean cooking energy systems would occur faster early in the

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https://doi.org/10.1016/j.jpolmod.2022.03.004
0161-8938/

simulating year among urban households than in rural households. The results indicate that, at low prices of liquefied petroleum gas, many rural households will switch to clean cookstoves with higher adoption rates than consumers in urban households. Additionally, results from baseline scenario analysis revealed that, without significant policy interventions, not all households would switch to clean cooking. Our analysis further indicates that households with fewer members tend to transition quicker to clean cooking options than larger households. The impact of clean cooking due to communication among households would be more significant among rural households than among urban households. While the model results are perceptive, we emphasise that potent policies are needed to accelerate the diffusion and adoption of clean cooking energy systems in Nigeria and other African countries.

Keywords: Bass diffusion model; Clean cooking; Energy policy; Energy transition; Nigeria; System dynamics

1. Introduction

Within the last two decades, various international development agencies, national and local governments, and private sector entities have been working together to improve the diffusion of clean cookstoves and modern fuels among households (Hewitt, Ray, Jewitt, & Clifford, 2018). These efforts are yet to deliver the much-needed results in terms of pace and scale, as both the adoption and the continuous use of modern cooking facilities remain low among households (IEA, 2020). Furthermore, the current Coronavirus disease (COVID-19) has severely limited investment in modern energy systems, thereby pushing countries further away from achieving universal access to clean cooking. If the current trend is not improved, by 2030, clean cooking will still elude about 2.3 billion people, especially in Sub-Saharan Africa (SSA) (IEA, 2017). This scenario shows that the challenge of clean cooking is not equally distributed worldwide. Specifically, rural areas in South America, developing Asia, and SSA are the mostly affected (Bonan, Pareglio, & Tavoni, 2017).

Complexities exist as nations transition to clean cooking energy systems (Kumar, Chalise, & Yadama, 2016) because the systems exhibit unpredictable behaviours as they evolve. Complexities are predominant in the energy sector of emerging economies, primarily due to the dearth of data, lack of infrastructure, weak policy and institutional frameworks, inconsistent implementation of policies and legislation and socio-cultural practices (Jagger et al., 2017). These challenges have affected planning towards evolving energy systems and transition pathways relating to the techno-socio-economic dynamics of emerging nations. Ensuring access to clean cooking in all households in developing countries in the near future will require robust policy reforms (Dioha & Kumar, 2020a). Aside from financing issues, one of the critical obstacles limiting the massive transition to a clean cooking energy system in developing countries is the lack of proper knowledge on the complexities surrounding its diffusion.

This study has taken a closer look at Nigeria – a developing country and the most populous and largest economy in Africa (Dioha & Kumar, 2020b; Dioha, 2020). Despite the plethora of energy resources in the country, about 90% of Nigerian households still depend on traditional inefficient cookstoves for their domestic thermal energy needs (Dioha & Emodi, 2019). The Nigerian government aims to provide its citizens with clean cooking equipment (FGN, 2016). However, such an ambitious goal needs to be informed by a thorough understanding of the complexities surrounding the transition to clean cooking energy systems. Despite decades of existence and experience, the Nigerian energy sector still grapples with ensuring adequate clean cooking systems in urban and especially in the rural areas, thus, suggesting the need for better adoption of clean cooking by the larger population.

Various scholars have inquired into the factors that influence the transition to clean cooking energy systems (Ateba, Prinsloo, & Fourie, 2018; Bisu, Kuhe, & Iortyer, 2016; Danlami, Applanaidu, & Islam, 2018; Debbi, Elisa, Nigel, Dan, & Eva, 2014; Makonese, Ifegbesan, & Rampedi, 2018; Mensah & Adu, 2015; Nyankone, 2018; Paudel, Jeuland, & Lohani, 2020; Rahut, Ali, Mottaleb, & Aryal, 2019; Sana, Kafando, Dramaix, Meda, & Bouland, 2020; Soltani et al., 2019). A large percentage of these studies recognised household-level factors such as household size, level of education, household income, geographical location, fuel availability, the gender of household head, and change of seasons (Bisu et al., 2016; Dagnachew, Hof, Lucas, & Van Vuuren, 2019; Danlami et al., 2018; Debbi et al., 2014; Ozoh, 2018; Soltani et al., 2019; Vigolo, Sallaku, & Testa, 2018). However, a critical assessment of the literature shows that studies employing system dynamics approach towards assessing the nature of clean cooking energy transition are scanty. Also, majority of the studies employ econometric models and survey results to assess the factors affecting clean cooking transition without considering the implications and feedbacks from the long-term perspective.

Here, we aim to advance the frontiers of clean cooking energy transition research by exploring how various factors could influence the transition to a clean cooking energy system using Nigeria as a case study. In this context, we develop and simulate the adoption of clean cookstoves, liquefied petroleum gas (LPG), as a modern fuel using the system dynamics Bass diffusion model. LPG is considered a proxy for cooking fuel in the study because of its low emission factors with insignificant impact on health and its significant penetration in the Nigerian household sector. At this juncture, it is worthwhile to state that we do not intend to predict or forecast the evolution of clean cooking adoption in Nigeria. A different and more pertinent purpose of this study is to generate a high-level understanding of how clean cooking energy transition could occur from the long-term perspective in Nigeria.

We introduce one of the earliest case studies on clean cooking energy transition based on a system dynamics model. In the is study, we have embraced a system dynamics modelling approach that allows the exploration of clean cooking energy transitions from the long-term perspective instead of the conventional economic modelling frameworks. Owing to the dichotomy of energy use in the household sector of developing countries like Nigeria, our study accounts for spatial heterogeneity by splitting the households into rural and urban classes. We took a step further by also providing policy implications of our analysis. We believe that our analysis and findings will inform existing knowledge on clean cooking fuels transition in Nigeria and other developing countries.

Section 2 of this paper presents the study's theoretical framework and methodology. In section 3, we present the results of the study. Section 4 discusses the results, while section 5 wraps up the study with some concluding remarks and policy implications.

2. Theoretical framework and methodology

2.1. *The socio-techno-economic system of clean cooking transitions*

Transition trends range from several perspectives and learning processes which cut across the social, cultural, economic, and technical aspects of the shift. According to Cheap (Cherp, Vinichenko, Jewell, Brutschin, & Sovacool, 2018), three major factors shape energy transition:

economic development, technological innovation, and policy change. Thus, transition processes are multi-faceted (Geels, Berkhout, & Van Vuuren, 2016) and require a systemic approach (Morecroft, 2018). In this study, we explored the shift to clean cooking, considered from an innovative system and co-evolution perspectives. These perspectives assume that changes occur across households and influence the transition to clean cooking (Yu, Hu, Qiao, & Wang, 2019).

According to the World Bank (WB) assessment on clean cookstoves, about 179 million Nigerians lack access to clean cookstoves/technology (ESMAP, 2015). The WB study further suggested that a wide range of factors influence each household's cooking energy choices. These closely interrelated factors include socio-economic circumstances, fuel availability, cultural phenomena, environmental considerations, cookstove characteristics and government policy (Johan Schot & Kanger, 2020). Some other scholars (Li, Trutnevyte, & Strachan, 2015) have emphasised the interconnected relationship between these factors as the socio-economic and technical dimensions to transition pathways. These factors are further simplified according to their underlying variables, as shown in Fig 1.

Fig 1 shows a pseudo-connector of clean cooking parameters. It suggests ways these parameters could be interconnected to form a system driven by policy. The framework describes a clean cooking transition management scheme that illustrates the sustainability concept of transition to clean cooking. Such sustainability theory elements —social, economic, technological — form immediate feedback among infrastructure, clean cooking domestic demand, supply-demand and urbanisation. The connecting arrows suggest that transitioning to clean cooking would follow a systemic pattern, implying that one part of the system parameter affects

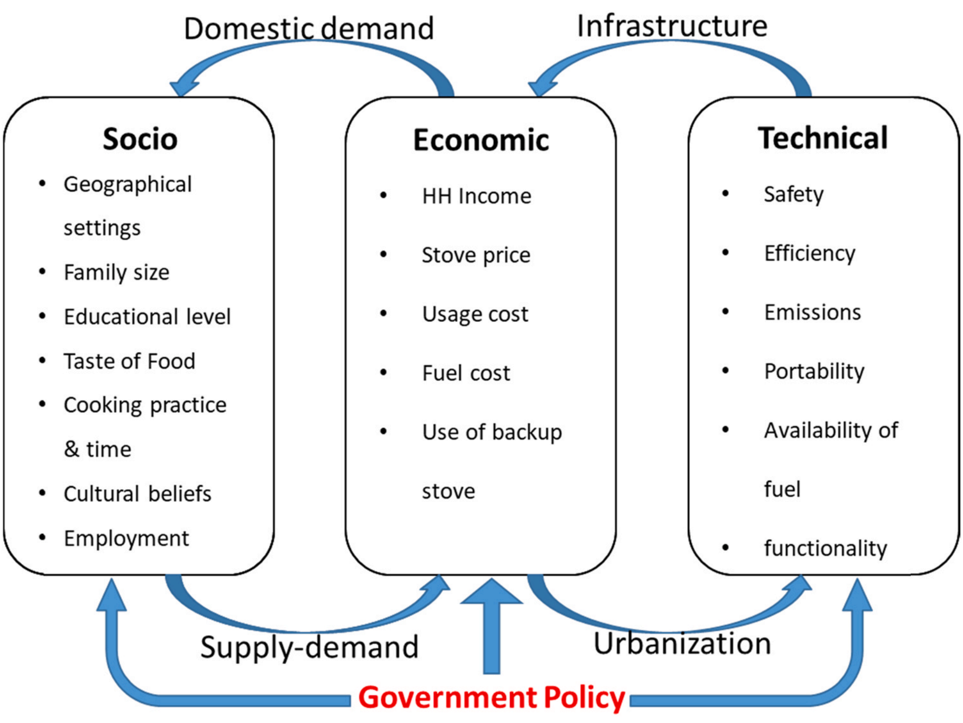

Fig. 1. Overview of clean cooking transition management model.
(Source: Authors) HH= household.

the other parts' outcomes in a continuous loop. Modelled outcomes from the interactions would also influence government policy in the transitions domain. Therefore, these connections are necessary for decision-making to support holistic legislation for clean cooking transitions.

To this end, we employ a Bass innovation and diffusion model, conventionally deployed to study system dynamics. The integrated Bass-System dynamics considers the following model approach:

i) A qualitative system thinking approach — to study interconnections and some feedback between variables to explain innovation theory, such as interconnectedness between market and technology in business and other techno-economic fields (Forum, 2021). This enhances system motivation, learning process, strategies, and quantitative elements, such as fuel price, energy demand, and technology efficiency without compromising other impacting factors.
ii) A quantitative system approach — to explore system behaviour as it changes with time and, thus, shows significant trends by quantitatively assessing policy/control points (leverage points) for legislation and decision making.

2.2. *Study framework and assumptions*

The theoretical framework of this study is rooted in the Bass diffusion model and system dynamics. According to Bass (Bass, 1969), the Bass diffusion model aims to ascertain the number of customers/consumers who will eventually adopt a new product or service. This study considers a composite model, an integrated Bass model and system dynamics. The twin-like model is used to depict the structural analysis of rural and urban household consumers of clean cookstoves as consumer behaviour changes over time.

The Bass diffusion model assumes the following:

a) that diffusion process is dualistic, i.e., consumers either adopt or do not adopt a product;
b) that there exists a constant maximum potential number of consumers at a particular time;
c) that all potential consumers will eventually adopt the product over time;
d) that there is no repeat purchase or replacement of the product;
e) that the impact of the word-of-mouth is independent of adoption time; and
f) that there is no substitute product.

However, there exist some limitations in the use of the Bass model. First, there is the tendency of exaggerating the system behaviour under study. This means that, in reality, not all potential consumers would finally adopt a product, as unforeseen events could make potential adopters reject a product initially intended to be adopted. Second, the bass model cannot handle fluctuations/variabilities such as uncertainties in the adoption processes.

2.3. *Methodological framework of the study*

2.3.1. *Conceptual framework of the model*

The system dynamics (SD) model is relevant for analysing complex systems because it helps to understand mental models through the use of the Causal Loop Diagram (CLD) (Azar, 2012). The CLD uses system thinking practices and mental models to explain causality among interacting variables (Maani & Maharaj, 2004). Thus, it enables a clearer picture and understanding of systemic feedback for complex decision making and policy analysis. The primary purpose of SD methodology is to understand the causes of undesirable dynamics and design new policies to ameliorate them. Undesirable outcomes are produced from the dynamic behavioural patterns of the system variables. This means that the structure creates the behaviour that influences the system boundary (Shari, Moumouni, & Momodu, 2020).

2.3.2. The Bass model and its mathematical formulation

The Bass model, named after Frank M. Bass (Bass, 1969), posits that diffusion processes are uneven and evolve as innovations are communicated through certain systems over time (Maier, 1998). Several researchers have used diverse models to explore the concept of diffusion of innovations in literature, applicable to different sectors such as health and agriculture (Horvat, Fogliano, & Luning, 2020; Naji & Hussien, 2016). Many of these models are based on Frank M. Bass' model of innovation diffusion (Bass, 1969; Milling & Maier, 2017). According to the Bass model, product purchase emanates from two human buying behaviours: 1) innovative purchase behaviour; and 2) imitative purchase behaviour. They can respectively be calculated using two important decision factors: i) coefficient of innovations (p) – coefficient of external influence; ii) coefficient of imitation (q) – coefficient of internal influence (Haggstrom, 2019). The general classical Bass equation model is therefore given, according to Eq 1 as:

$$N = P \times (N - X_{t-1}) + q \times (X_{t-1}) \times (N - X_{t-1}) \tag{1}$$

Where N = Number of consumers who will purchase the product at a time (t).

$N - X_{t-1}$ = Remaining market potential.

X_{t-1} = Adopters of product S_t until period $t-1$ represented by $\sum_{t=0}^{t-1} S_t$.

p = coefficient of innovations.

q = coefficient of imitation.

Eq 1 implies that consumers will adopt a new product or products that are yet to gain general acceptance in the market through i) marketing strategies such as adverts; and ii) those who imitate existing product or initiative users as imitators.

Eq 2 shows the mathematical calculation that models the innovators' buying behaviour.

$$S_t^{inno} = p \times \left(N - \sum_{t=0}^{t-1} S_t\right) \tag{2}$$

The coefficient of innovation (q) is a constant that represents the fraction of innovators of the remaining market potential at any point in time (t). On the one hand, innovative purchasers are not influenced by the number of purchases in the past but make their purchasing decision depending on the spread of the product in the marketplace, i.e., through adverts. They are often referred to as potential adopters of a product or innovation. On the other hand, imitative purchasers are those influenced by the number of purchases in the past. This means that the more customers have adopted the product in the past, the higher the social pressure to purchase it. Imitative purchase over a period of time (t) can be calculated according to Eq 3.

$$S_t^{imit} = q \times \frac{\sum_{t=0}^{t-1} S_t}{N} \times \left(N - \sum_{t=0}^{t-1} S_t\right) \tag{3}$$

The total product adopted in a time (t) can be expressed as the sum of innovative and imitative purchases given in Eq 4. Expression from Eq 4 shows the product life cycle behaviour of the spread of a product in the marketplace.

$$S_t^{tot} = S_t^{inno} + S_t^{imit} = p \times \left(N - \sum_{t=0}^{t-1} S_t\right) + q \times \frac{\sum_{t=0}^{t-1} S_t}{N} \times \left(N - \sum_{t=0}^{t-1} S_t\right) \quad (4)$$

Eq 4 describes the time pattern a product follows through subsequent stages of introduction, growth, maturity and decline according to an S-shape growth.

However, it is essential to note that, in reality, coefficients p and q are independent of any changes in the adoption of innovation over time (t). Also, in the classical Bass model, the coefficients p and q are constants independent of other decision variables such as price, income, and educational level (Milling & Maier, 2017). This independence of variables is a severe shortcoming of the classical Bass model since, in reality, diffusion and transition pathways are strongly influenced by feedback. Therefore, this non-interconnection among influencing variables poses a limitation to using the classical Bass model because it has no room to include feedback mechanisms between the diffusion process and other variables that could be useful for decision-making and policy development. We applied the extended Bass model in a systematic approach using the SD simulation paradigm to ameliorate this shortcoming. The SD quantitative and qualitative model would then be used to model and simulate the Bass innovation and diffusion model by extending the classical Bass model earlier explained in Eqs 1, 2, 3 and 4.

2.3.3. System dynamics formulation of the Bass model

Application of SD to the Bass model is relevant to explaining reasons for the non-linearities experienced in adopters' preferences to transit to other products or services. In this study, the LPG stove represents the product to be adopted. The central questions surrounding its adoption include what time its adoption would be maximum, start losing market value/share, i.e., when would its adoption mature in the future? Models developed in this fashion can serve as simulators to analyse the consequences of strategies and provide an understanding of what policy design would improve the adoption of clean cooking amongst Nigerian households/consumers.

Fig 2 shows a simulated SFD of the classical Bass model, depicting the fundamental simulated structure of the Bass model built upon as per Eq 4. Market potential and accumulation of adoption are represented by the stock component of the simulated classical Bass model.

According to Fig 2, the stocks represented by potential adopters and cumulated adopters are mathematically expressed as $N - X_{t-1}$ and X_{t-1} respectively. The sum of adoption in Eq 4 is represented by the adoption rate, while the innovative and imitative purchases are represented as innovative adoption and imitative adopters, respectively. Therefore, an integrated SD and Bass

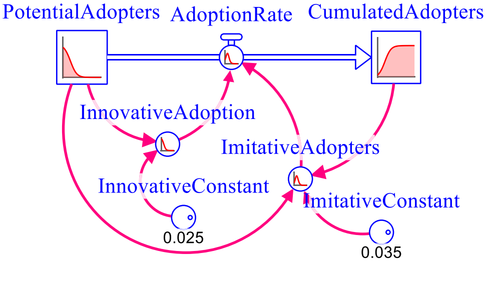

Fig. 2. The simulated stock and flow diagram of the classical Bass model.

model is relevant to providing important insights for energy policy towards local energy transition (Selvakkumaran & Ahlgren, 2020; Zhao & Zhang, 2018), including transitioning to clean cooking (Chalise, Kumar, Priyadarshini, & Yadama, 2018; Kumar et al., 2016).

2.3.4. Building the model

In this study, building the SD model is divided into two stages: i) a qualitative, mental model to guide the development of a stock and flow simulation model; and ii) a quantitative model, to formulate model equations and to perform model simulation in a stock and flow diagram (Maria, 1997). The simplistic SD mental model was developed in collaboration with experts in the Nigerian energy sector as per the underlying structure of the clean cooking adoption. The model was built using STELLA professional software, Version 1.3.1.

Theoretical structure confirmation test verified if the stock and flow structure is consistent with the knowledge about the system (Horvat et al., 2020). A structured review of literature on clean cooking transition, using LPG as an energy carrier, was carried out for model building. To assess the model's performance, variables obtained from the literature review and the structure of the SFD were evaluated for consistency. After the model was formulated, dimension and unit's consistency was ensured and done (Barlas, 1996). Furthermore, to ensure consistency and observe significant trends, sensitivity analysis was performed (presented in the result section) (Hearne, 1987). Also, a structural behaviour test was performed. To ensure the accuracy of the structural behaviour analysis, the simulated model needed to show an S-shaped structural behaviour while reaching the value of the maximum cumulated adopters or reduction in the potential adopters, that is, the stocks. These tests were to ensure behavioural familiarity and consistency (Benjamin & Turner, 2014) with the Bass model and ensure equation consistency in the SFD. Finally, calibration of the model was performed.

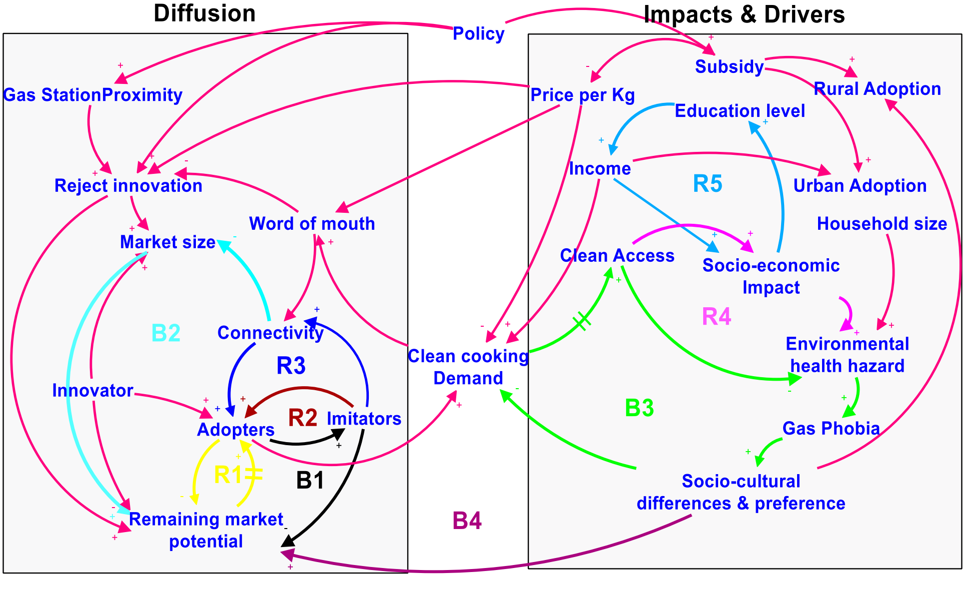

Fig. 3. Causal loop diagram for the adoption of LPG clean-cook stove (Source: Authors).

2.3.5. Developing the causal loop diagram

Fig 3 displays the main feedback loops of a generic simulation model developed to create insight into the dynamics that can occur. The two rectangular boxes represent the sector loops, i.e., diffusion, impact, and sector loops' drivers. Simultaneously, the 'R' and 'B' displayed in different colours are the reinforcing and balancing loops, respectively. The linked diffusion sector feedback loops are controlling loops. This suggests that if diffusion and innovation of clean cooking using LPG commences, it is intrinsically limited or enhanced by the reinforcing and balancing loops. Similar reactions are expected in the impact and drivers of the sector loops.

This intrinsic characteristic means that there is no constant growth in the system's structural behaviour, i.e., our actions and inactions determine the system's dynamics. To buttress this, the continuous growth encountered due to reinforcing loops R1, R2, R3, R4 and R5 would counteract such persistent growth by the balancing loops B1, B2, B3 and B4. Reinforcing and balancing loop structures are illustrated considering loops R5 and B3, so that clean cookstove is adopted due to increased income (R5). In contrast, fear of using gas as a cooking fuel (gas phobia) expressed in B3 would balance the expected continuous growth due to increased income.

2.3.6. Developing the stock and flow diagram (SFD)

The SFD represented in Fig 4 illustrates a diffusion and composite model comprising rural and urban areas, showing the spread or diffusion of clean cookstoves.

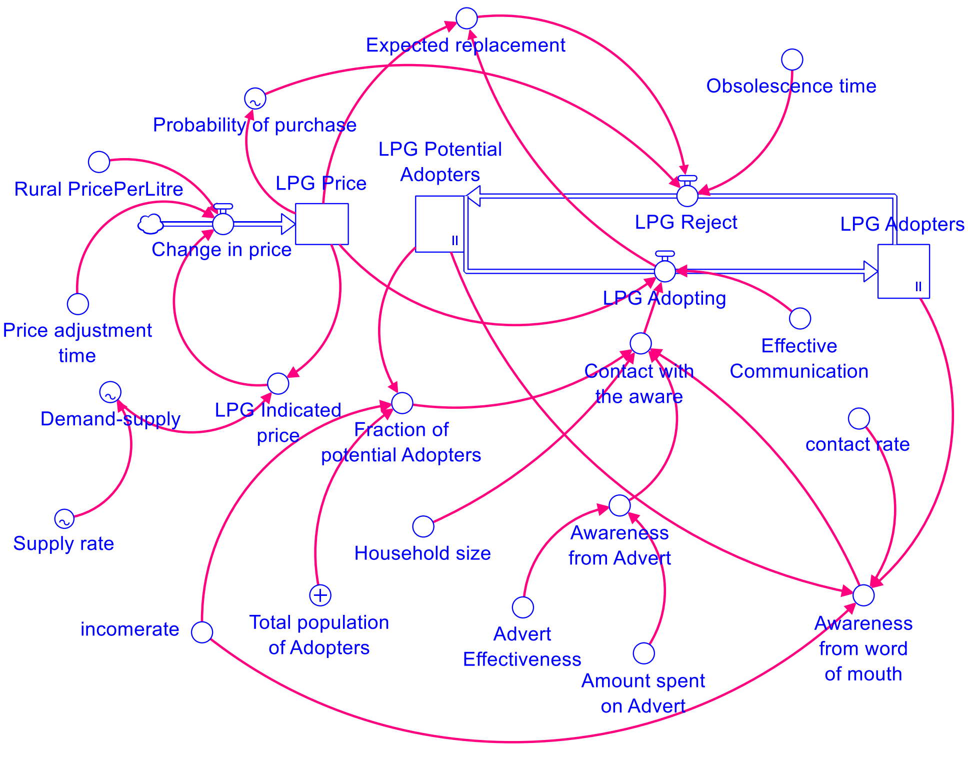

Fig. 4. Stock and flow diagram of an innovation and diffusion model for clean cooking transition.

From potential adopters to adopters: Fig. 4 shows the composite SFD model of clean cooking adoption in Nigeria. It is composite because it indicates the modelled dynamics of clean cooking in the urban and rural households sector of a developing country such as Nigeria. The composite model has considered some assumptions: 1) that rural and urban household areas have the same model equations and structural behaviour; and 2) that they are differentiated with variances in the calibration process due to differences in data input.

The development of the composite model starts with the influence of homogenous variables, which determine imitators and innovators' adoption rate. Such homogenous variables include adverts, promotional activities, and information through word-of-mouth. The model variables are represented in the SFD (Fig 4) as advert effectiveness, awareness with word of mouth and contact with 'the aware',[1] respectively. The innovators start the system with the potential adopters through promotional activities, then imitators who will later spread the information about the innovation by word-of-mouth. However, not all households that had contact with potential adopters transforms into adopters. The converter, effective communication', models the practical impact of word-of-mouth on the potential adopters. For word-of-mouth to be impactful, potential adopters need to know of the product or innovation in the market space as innovators. This would enable potential adopters to become imitators of the product to adopt such innovation.

Furthermore, to create confidence in the model, the study follows a systematic approach that linked sensitivity analysis, calibration, and uncertainty analysis (Tian, Lich, Osgood, Eom, & Matchar, 2016). Sensitivity analysis is employed for the process of scenario analysis. The model's uncertainty analysis was also done using the Monte Carlo simulation process and engaging the Monte Carlo model tab in STELLA software. Simultaneously, the model's structural calibration was done to estimate parameter values in the model. Data obtained from the Nigerian Liquefied Petroleum Gas (NLPG) report (LPG Summit, 2019) is used to calibrate the base run model because LPG consumption and its proliferation among households indicate a steady growth trend. The growth trend compares favourably with the study's base run simulation.

3. Results

3.1. Base run model simulation

Base run simulation is shown in Fig 5. It presents the behaviour and transition of the potential adopters and adopters of clean cooking from 2010 to 2050 in the simulated SD models. The developed SD model was calibrated for the urban household as follows: 7 million total urban households, average household size at 6, household income rate at 8.5%, contact rate at 5% and 1.5% effective communication among urban households (Ateba et al., 2018; Quinn, 2018). For the rural households: 9.94 million households, 8 persons per household, income rate at 7.5%, contact rate at 8.3% and 0.85% effective communication among rural households (Apata, 2016). The composite model has considered US$1.31 per kg LPG price (Nwachukwu, 2011). It is worthwhile to state that these data are for experimental purposes only as their precise future evolution is uncertain. The model has considered a run spec of 40 years, with a

[1] 'The aware' as used in the model refers to those households who are informed about liquefied petroleum gas as a clean cooking fuel but have not necessary adopted the technology.

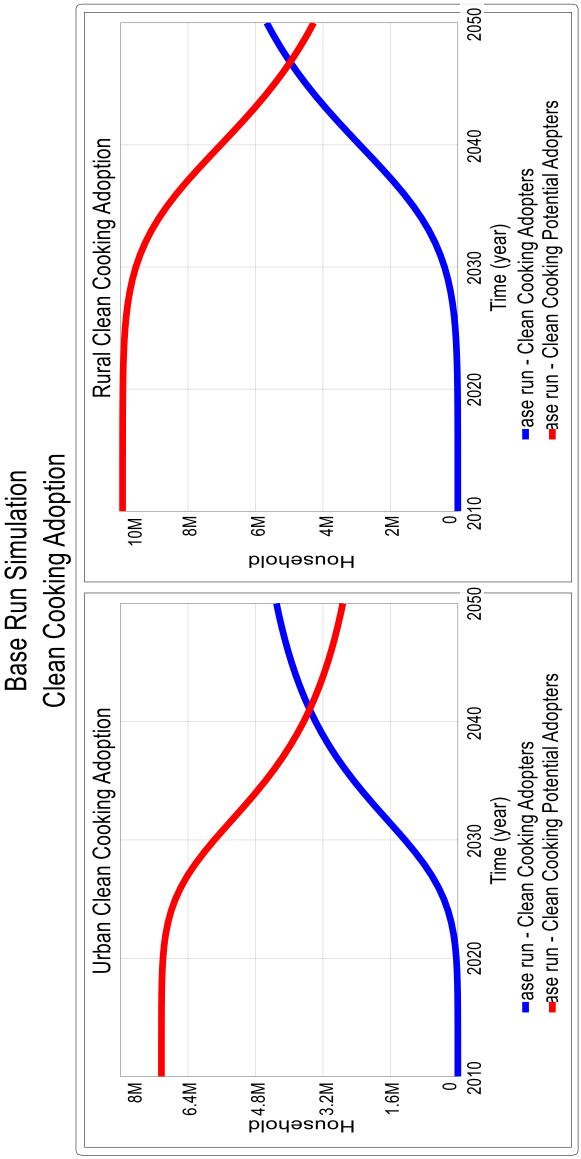

Fig. 5. Base run model behaviour showing changes in the main stocks on the adoption of clean cooking in Nigeria.

start time in 2010 and an end time in 2050. This model does not include Nigeria's population change in the simulation period. This hypothesis was made to simplify the quantitative interpretation of SD model results, where the exact value of stocks at the end of the model run is not as significant as the shape of the curves, suggesting the clean cooking transitions system behaviour. The base run has also assumed that all conditions and parameters are constant without any alteration or adjustment.

The simulated base run represented in Fig 5 shows that the diffusion process of clean cooking is slow in the beginning but peaks in the middle of the simulation period. At the same time, the stock of potential adopters depletes slowly. However, similar simulation trends were observed in both rural and urban households. A decline or a reduction in the number of potential adopters transcends into growth or addition to clean cooking adopters. This decline in the potential adopters suggests that about 1.35 million urban householders would adopt clean cookstoves by 2030 while leaving about 5.68 million households without access to clean cooking facilities. This implies that around 23.7% of the total urban households would have adopted clean cookstove by 2030. Besides, a sharp decline in the potential adopters was observed in 2034 in the base run, which means that more households will naturally transit to clean cookstove without legislative efforts. Still, such a transition may unnecessarily take a longer time to achieve the needed clean cooking energy access.

On the other hand, rural households may consider the reasonable adoption of clean cooking later than urban households. Here, a sharp adoption of clean cooking is observed in 2032 as against 2026 among urban households. This suggests that the slow adoption rate among rural households could slow down the transition to clean cooking in Nigeria. The base run simulation (Fig 5) is also referred to as a business-as-usual scenario. It depicts how the shift to clean cooking in Nigeria would evolve without controlling some influencing parameters. The urban and rural households would experience equilibrium in 2040 and 2047 among potential adopters and adopters, respectively. This three-year difference in potential adopters and adopters making a tie shows the discrepancy among adopters according to their spatial settlements. At the end of the simulation period, the result shows an intriguing narrative – about 37% and 45% of households in the urban and rural areas, respectively, would not transcend into becoming adopters by 2050. This, therefore, suggests reasons for non-linearities in the modelling outcome, thereby presenting the case that not all households (both in the urban and rural areas) would have transited to clean cooking by 2050 in the base run simulation. Fig 6 shows a comparative analysis of the adoption of clean cooking in rural and urban households.

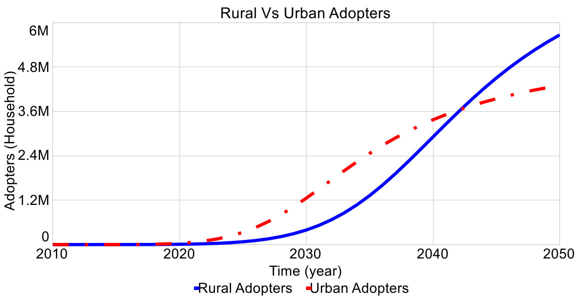

Fig. 6. Comparative analysis of rural and urban adoption of clean cooking.

3.2. Analysis of scenarios

This study proposes several simple scenarios to study the influence of changes in various model variables on adopting clean cookstoves in the Nigerian household sector. The model has considered scenarios in the rural and urban household consumers, bearing in mind that variables we adjusted in the study can be influenced in reality. Thus, variable values used are for experimental purposes, as they could possess different values in real-life applications. Each scenario targeted four variables, with sensitivity analysis carried out on each variable to establish a clear connection between the parameter change and system behaviour (Table. 1).

Fig. 7 and 8 show scenario analyses results for rural and urban household clean cookstove adoption, respectively. In the analysis of scenarios, we have considered sensitivity analysis of the following variables (or leverage points): 1) the first scenario (S1) – household income rate; 2) second scenario (S2) – household size; 3) third scenario (S3) – LPG price per kg; and 4) the fourth scenario (S4) as contact rate (see Table 1). The analysis of scenarios was also conducted based on the influence of leverage points on the i) clean cooking potential adopters; ii) clean cooking adopters; iii) clean cooking adoption rate; and iv) clean cooking rejection rate. This means that the analysis within the stocks and flows captured behaviour and trends due to changes in the leverage points. Sensitivity analysis was done at leverage value of 25% and 50% increase or decrease. The sensitivity value at 25% was labelled as moderate, and the sensitivity value at 50% as optimum.

3.2.1. Analysis of rural scenarios

3.2.1.1. Scenario 1 (S1). Results from Fig 7 show a reduction in both moderate and optimum trends in the total number of clean cookstove potential adopters due to increased household income rates. Moreover, this implies that around 1.04 million households in the moderate trend are yet to adopt clean cookstove. In comparison, approximately 487 thousand rural households would be left to adopt clean cookstove in the optimum run by 2050. This suggests a 75.64% decrease and an 88.59% decrease in the moderate and optimum run compared to the base run. Also, changes in rural household income rate imply that if a moderate change is made in household income, about 8.9 million households will adopt clean cooking. In contrast, in an

Table 1
Description of four scenarios as simulation experiment.

Scenario	Description
Scenario (S1) Household income rate	Scenario 1 tests the effect of an increase in household income compared to the base run and its influence on the potential adopters, adopters, adoption rate and rejection rate.
Scenario (S2) Household size	Scenario 2 tests the effect of a decrease in household size compared to the base run. This scenario addresses how the potential adopters, adopters, adoption rate and rejection rate would evolve due to changes made to the household size.
Scenario (S3) Price of LPG	In Scenario 3, the effect of a decrease in LPG price compared to the base run was carried out. In this case, changes in LPG prices were modelled by considering the impact on the number of rural and urban households that adopt or reject clean cooking
Scenario (S4) Contact rate	In scenario 4, the effect of changed "contact rate" to adopt clean cooking, compared to the base run, was considered. In this scenario, an increase in households' contact rate on adopters was modelled.

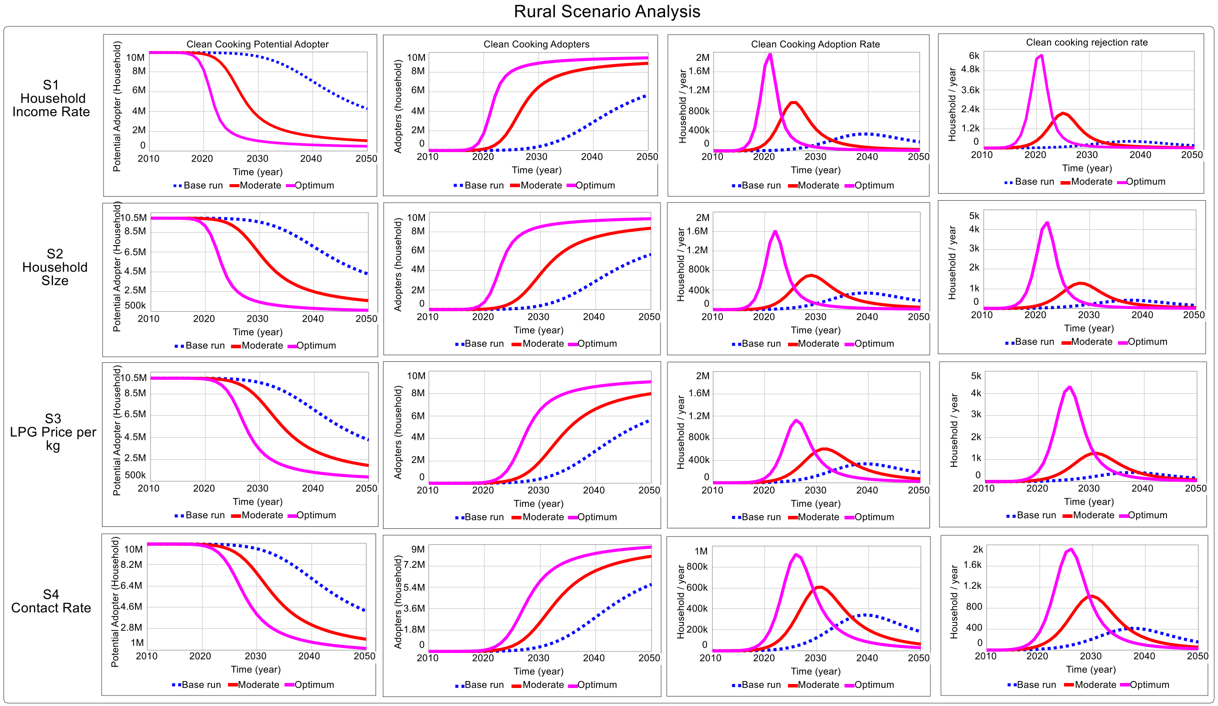

Fig. 7. Behaviour of "Potential adopters", Adopters, Adoption rate and Rejection rate stocks and flow rate (scenario 1 (S1) – increase in household income; scenario 2 (S2): decrease in household size; scenario 3 (S3): decrease in LPG price; and scenario 4(S4): increased contact of rural household clean cooking adoption.

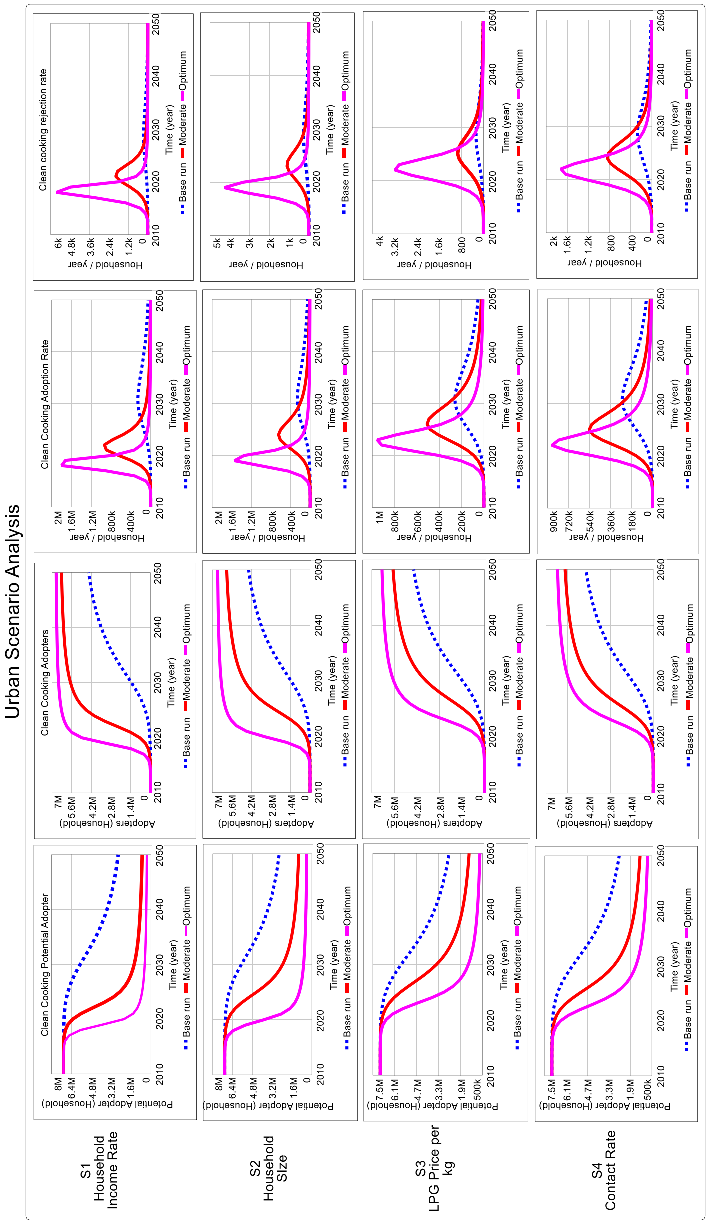

Fig. 8. Behaviour of "Potential adopters", Adopters, Adoption rate and Rejection rate stocks and flow rate (scenario 1 (S1) – increase in household income; scenario 2 (S2): decrease in household size; scenario 3 (S3): decrease LPG price; and scenario 4(S4): increased contact of urban household clean cooking adoption.

optimum run, approximately 9.45 million households would have adopted clean cooking. This growth in adopters can be attributed to the increase in household income. Thus, the more income a household earns, the more likely they are to adopt clean cooking.

Furthermore, the rate at which rural households would adopt or reject clean cooking due to an increase in rural household income is shown in S1. This illustrates that adoption would occur at a rate of 26.50 thousand and 8.83 thousand rural households per year at moderate and optimum household income changes, respectively. This suggests that the adoption rate towards the end of 2050 reduces because few households would be left to adopt clean cookstoves in the long run. Also, in terms of clean cooking rejection rate, about 22.50 and 7.49 rural households at moderate and optimum changes, respectively, would be rejecting clean cookstove per annum. The apparent differences noticed in the changes between adoption and rejection rates could be because, as rural household income increases, more households at the rural level would adopt clean cookstoves at a rate that surpasses its rejection. Similarly, changes in the adoption rate across the two sensitive trends suggest that adoption will occur earlier with increased household income, with more households transitioning to clean cooking in the optimum run than in the moderate run. The decreased rate could further be attributed to the fact that fewer households would be adopting clean cookstove in the future, as the total population of households that are yet to adopt would have reduced.

3.2.1.2. Scenario 2 (S2). Under this scenario, it is assumed that rural household size reduces. In the rural household size scenario, about 1.59 million and 610 thousand households in the moderate and optimum runs, respectively, would remain as potential adopters, representing about 62.75% reduction in the moderate run and 85.71% reduction in the optimum run compared to the base run. This reduction in the total number of households yet to adopt clean cookstoves suggests that, at smaller household sizes, adopting clean cookstoves would be higher with fewer households as potential adopters. The result, therefore, shows that, despite the reduction in the household size, not all potential adopters of clean cookstoves would become final adopters. This could be attributed to why household size changes might not incentivise rural households' total transition to clean cooking. In contrast to the analysis of potential adopters, the analysis for the adopters due to changes in household size shows an adoption rate of about 8.35 million households and 9.33 million households, representing an increase of approximately 47.27% and 64.55% in the moderate and optimum runs, respectively, compared to the base run. The number of adopters' growth due to small household size further suggests smaller household sizes would adopt cleaner cookstoves than larger household sizes because cooking choices and preferences reduce in smaller household sizes.

3.2.1.3. Scenario 3 (S3). For the third scenario, results in Fig 7 show that about 1.95 million and 890 thousand households in the moderate and optimum runs, respectively, would be potential adopters. This means that about 54.54% and 79.25% reduction compared to the base run are households that are yet to switch to clean cookstoves. Conversely, the adoption of clean cooking in the moderate and optimum run shows that about 7.99 million and 9.05 million households would adopt clean cookstoves, representing a 41.17% and 59.89% increase in adopters compared to the base run. The low growth observed in clean cookstoves adoption depicts a small relative change in the moderate and optimum runs despite reducing LPG price. The study argues that the adjustment in LPG price might yield minor changes in the adoption processes of clean cooking, probably due to higher preferences for alternative cookstoves. This scenario further suggests that if income levels are not increased, reducing the price of LPG alone will have little effect on the adoption of clean cooking.

Furthermore, sensitivity analysis on adoption rate due to price changes shows that around 70 thousand and 24 thousand households per annum would be shifting to clean cooking. As a result, about 61.59% and 86.81% decrease per annum is recorded in the moderate and optimum runs, respectively, compared to the base run. This decrease in the adoption rate among simulation runs implies that, as more households shift to clean cookstove, few households would be left to transition in later years. Interestingly, simulation results showed that more households would be shifting to clean cooking due to reduced LPG prices. Simulation results also show that about 78.2 and 38.9 households per annum would reject clean cooking, representing about 49% and 74% reduction in the moderate and optimum runs, respectively, compared to the base run. The lower values observed in the rejection rate suggest that the shift to clean cookstoves would be experienced faster than it would be rejected in later years due to decreased LPG price per kg.

3.2.1.4. Scenario 4 (S4). The fourth scenario, according to Fig 7, represents the effect of contact rate on adopting clean cookstoves in Nigerian rural households. Due to the increased contact rate, around 1.90 million and 1.14 million households are yet to adopt clean cookstoves at moderate and optimum runs. This represents a 55% decrease in the moderate run and a 73% decrease in the optimum run compared to the base run. This implies that less household would remain as potential adopters, with the optimum scoring low in the number of households that are yet to shift to clean cooking. In addition, around 8.03million and 8.80 million rural households would have switched to clean cookstove in the moderate and optimum runs among clean cooking adopters, respectively. This means an increment of about 42% and 55% of households adopting clean cookstoves, compared to the base run at the end of the simulation period. Moreover, additional analysis on S4 (Fig 7) shows that around 64.5 thousand and 30.3 thousand households per year would adopt clean cookstoves. This means that an improvement in contact rate among rural households would reduce the number of households left to shift to clean cooking at a reduced rate of about 65% and 83% household per year in the moderate and optimum runs, respectively, compared to the base run. On the other hand, around 54.6 and 25.6 households per year would be rejecting clean cooking at moderate and optimum runs. However, similar percentage decrease trends were observed in the adoption and rejection rates at the moderate and optimum runs of S4. This suggests that a decrease in adoption and rejection of clean cooking occurs at the same rate at the end of the simulating period but at different quantitative low values of households in the rejection rate.

3.2.2. Analysis of urban scenarios

Fig 8 shows the result of the analysis for urban scenarios. The scenario analysis has followed the same parameters subjected to sensitivity analysis as in the rural scenarios. Model calibration values differ significantly in the urban model.

3.2.2.1. Scenario 1 (S1). In scenario one, the impact of urban household income on those that are yet to switch to clean cookstoves (potential adopters) shows that around 708 thousand and 329 thousand households would be yet to switch to clean cooking by 2050. Thus, about 73% and 87% of households at moderate and optimum runs, respectively, would remain as potential adopters compared to the base run. Urban households that are yet to adopt clean cooking are further clarified by analysing households that have adopted clean cookstoves. In the same scenario, around 6.32 million and 6.70 million households in the moderate and optimum runs, respectively, would switch to clean cookstoves. Compared to the base run, an increase of about 44% households in the moderate run, while an increase of about 52% households in the optimum run would be adopting clean cooking at the end of the simulation period. Compared to adoption in the rural households, an increase in household income yields a favourable shift to clean cooking among the rural household systems than experienced among urban households. However, results from the scenario trends reveal that urban households adopt faster in time and show more households transitioning per time to clean cooking than in the rural households at the end of the simulation period. In addition, results show that urban households' adoption and rejection rates display a similar trend as observed in the rural households where few households refused clean cooking at the end of the simulation period. Analysis results from S1 in the urban households show that an increase in urban household income would encourage clean cookstove adoption.

3.2.2.2. Scenario 2 (S2). In the urban household size scenario, results show that around 1.06 million and 414 thousand households in the moderate and optimum runs, respectively, would become potential adopters at the end of the simulation period. This means about a 60% decrease of the moderate run and an 84% decrease of the optimum run compared with the base run, and this would suggest that, at an optimum run, few households would be left as potential adopters of clean cookstoves by 2050. Besides, around 5.97 million and 6.62 million households at moderate and optimum runs, respectively, would switch to clean cookstoves, resulting in an increase of about 36% in the moderate run and about 50% increase in the optimum run compared to the base run. This suggests that more urban households will transition to clean cooking than those in rural areas. This phenomenon could be due to the relatively small household size in the urban areas compared to rural areas. Furthermore, the result in Fig 8 shows that few households would be rejecting than adopting. This suggests that the adoption rate supersedes the rejection rate at the end of the simulation year.

3.2.2.3. Scenario 3 (S3). For the price scenario, Fig 8 shows the impact of LPG price on clean cookstoves adoption. Around 1.35 million and 662 thousand households would belong to those households yet to switch to clean cooking, which means that about a 49% decrease and a 49% decrease in the moderate and optimum run are observed compared to the base run. This means fewer households will be left as potential adopters, although a close trend is observed among all runs. Besides, around 5.68 million and 6.37 million households in the moderate and optimum runs, respectively, would be adopting clean cooking. The impact of price change on adoption shows close relationships with the trends observed in the rural households' adoption. The price scenario indicates that more urban and rural households will switch to clean cookstoves at a slow pace at a lower LPG price. However, in the optimum run, the adoption rate of around 8.98 thousand and 12.20 thousand households per year in the urban and rural households shows that the impact of changes in LPG price to adoption will be more pronounced among rural households. These changes suggest that more rural households will be willing to switch to clean cookstove at a lower LPG price per kg than urban households at about a 36% adoption rate.

3.2.2.4. Scenario 4 (S4). In this scenario, around 1.27 million and 782 thousand households in the moderate and optimum runs, respectively, would be left as potential adopters at the end of the simulating year. These represent a decrease of about 52% in the moderate run and a reduction of about 70% in the optimum run, compared to the base run. The implication is that few households would be yet to adopt clean cookstoves in the optimum run. Potential adopters across all scenarios have followed relatively similar trends, with different adopting values. Also, around 5.76 million and 6.25 million households would have adopted clean cookstove, which means an increase of about 31% in the moderate run and an increase of about 42% in the optimum run compared to the base run would become adopters of clean cookstoves by 2050. The results suggest that information flow is relevant for more adoption of clean cookstoves.

In addition, results from the adoption rate show that the impact of contact rate is more significant among rural householders than in urban households. This comparison shows a discrepancy of about 33% per year among rural and urban household adopters regarding the number of households reached. Outcomes from S4 on contact rate suggest that more households would have adopted clean cookstoves during the mid-year of transitioning while leaving very few households to either adopt or reject at the end of the simulation year. This shows that more households would have shifted to clean cooking before the end of the simulation year (2050). Urban rejection and rural rejection rates show that adopters in rural households will not be rejecting clean cooking fast if they adopt via word-of-mouth. Analysis of the scenario of contact rate shows that the shift to clean cooking will increase among households with effective communication among potential adopters and adopters.

The results also reveal other significant insights. First, all related scenarios show similar trends. Second, price changes show a slight divergence across trends. Third, more households tend to adopt clean cookstoves than they will reject, i.e., returning to their status as potential adopters. Fourth, the flat trends observed at the beginning of the simulating year suggest that the adoption of clean cooking was slow, but not zero adoption. Adoption processes will be on all through the simulation period, while adoption takes an S-shaped behaviour. The S-shaped behaviour observed across the study outcomes on clean cookstove adoption has manifested the Bass model's adaptability to the study of clean cooking transition dynamics. While systematic review of literature by Lewis and pattanayak on the adoption of improved cook stoves by households in developing countries conducted showed that methods employed by the literature revealed that the influence of fuel availability and prices, household size and gender on clean cook-stoves are unclear (Lewis & Pattanayak, 2012), the current study does not only reveal clear and quantitative impact of household size, income, fuel price and contact rate on clean cooking adoption among rural and urban households but also reveal the dynamics of their impacts.

4. Discussion

The scenario analysis findings show that an increase in urban household income results in faster growth of clean cookstove adopters from 2017 at 448 thousand households, peaking at 6.24 million in 2024. In contrast, the increase in rural household income translates into a sharp growth among rural household adopters in 2028, with 8.71 million and 1.24 million households still belonging to the potential adopters' group. The speed of adoption in the urban areas compared to rural locations implies that as consumers' socio-economic status improves, urban consumers are quicker to switch to cleaner technologies than rural dwellers. The slow and low adoption in the rural areas might be attributed to several factors such as imitation effects, availability of clean cookstove and awareness, which can reinforce a consumer's resistance to new technology. However, more adopters from rural households are likely to emerge in 2043 (Fig 6), which would surpass adopters from the urban household. This could be as a result of the adverse impacts of traditional stoves' continuous use and rural area population growth and thus serve as a driver to adopting clean cookstoves in the future. In the urban areas, the imitation effect is higher as most houses are situated close to each other with frequent interactions among neighbours (Chester, 2013; Haggstrom, 2019; Shabanpour, Shamshiripour, & Mohammadian, 2018). In the theoretical model shown in Fig 3, household income, which falls under economic factors, is an element of the sustainability theory that drives domestic demand for clean cookstoves. The availability of clean cookstoves in urban areas and scarcity in rural areas result in a critical infrastructure challenge that impacts household energy use. Here, infrastructure availability in the urban regions feeds into the economic aspect connected to the social element via domestic demand. Therefore, households' economic power to adopt clean cookstoves is lower in rural areas than in urban locations, as other non-financial factors come into play.

The change in household size also mirrors the outcomes of the S1 in both urban and rural areas. While this is surprising, the decrease in household size can free up disposable income for households to purchase new technologies after a period of high spending. For example, as children get older and move out of their parent's house, the homeowner would have more income to spend on newer fuels or technologies that can save the household cost in the long run (Chester, 2013). Price has a role to play in clean cookstove adoption. Our results show that reducing the price of LPG over the modelling period increases the adoption rate among households in the urban areas compared to rural areas. Here, lower LPG prices alone might not encourage an increase in adoption. Other factors such as location and proximity to refuelling station or LPG refilling shops may be associated with a higher household adoption rate in urban locations than in rural areas (Pye et al., 2020). Lowering the price of LPG as a policy to incentivise a higher adoption rate may not achieve the desired goal if rural consumers have no access to refilling stations or shops. Therefore, they might not be motivated to switch technologies if support systems are not in place. The model shown in Fig 3 shows changes in family size are assumed to drive the increased supply. Simultaneously, the reduction in fuel cost (i.e., LPG) is expected to boost domestic demand and potentially increase the urbanisation rate.

As earlier noted, spreading information via word-of-mouth or imitation effect plays a role in technology adoption, especially clean cookstoves. Our model results show that the contact rate to adopt clean cookstove increased by 42% among urban households. At the same time, 6.25 million households were observed by the end of the simulation period. Spreading the word about improved cooking stove technology might have more impact in the rural areas where most households know each other. However, this might not always turn out to be the case. The topic of discussion among rural consumers might not be how to save cost by using newer technologies if they are low-income earners or have challenges accessing the technology or refilling their tanks, as in the case of LPG stoves. Therefore, urban households tend to have higher adoption than rural consumers as it relates negatively with availability and positively with affordability, as observed in the literature (Bisu et al., 2016). Availability is a significant barrier to clean cookstoves adoption. While affordability is necessary for market penetration, public engagement is vital (Price, 2017) Word-of-mouth, lower LPG prices and higher income alone might not improve the adoption of clean cookstoves in rural areas if the remote communities lack LPG availability to meet demand. On the other hand, suppliers might find it counter-productive to deliver LPG to retail outlets in the rural areas if there are poor access roads. This implies that the results align with our earlier assumption presented in the clean cooking transition management model shown in Fig 3.

This study suggests that policy impact differs by location, with little impact expected in rural areas than in urban locations. This is because consumers' response to market stimuli (such as price policies) and other stimuli (e.g., favourable socio-economic policies) differs across geographical locations. As earlier stated, reaching consumers in rural areas might be considered challenging for sellers of clean cookstoves who may want to balance high logistic costs with marketing costs. However, making clean cookstoves available to rural consumers creates an opportunity to reach a niche market with potentially large customers with fewer competitors than in urban locations (Vigolo, Sallaku, & Testa, 2018). To increase the revenue of sales in regional areas, a high number of sales must be achieved. Government can intervene in this case by providing access roads or introduce policies that encourage the distribution of clean cookstoves to rural areas (Puzzolo, 2019; Quinn, 2018).

Manufacturers of clean cookstoves could introduce marketing strategies such as bundling clean cookstoves with other technologies or services that might induce consumers to take up the technology (Shankar, 2014). Specific examples include after-sales support and a guaranteed supply of gas refill at a fixed price for a given period. This approach can increase consumer value and improve the adoption experience with clean cookstoves. On the other hand, policymakers can increase community outreach programs in rural areas to raise awareness of the technology (Calzada & Sanz, 2018). This can alter consumers' perception and encourage them to switch their traditional stoves with more efficient and sustainable clean cookstoves. This should be done in collaboration with community heads while recognising the role of women who are the primary users of stoves in Nigeria (Onyeneke, 2019).

5. Conclusion and policy implication

This paper has examined the influence of various strategies towards improving clean cooking energy adoption using Nigeria as a case study through the lens of system dynamics. The overarching finding is that the transition to clean cooking energy systems fluctuates and presents a non-linear trend over time. The study also finds that these non-linear trends vary between rural and urban households. Scenarios analyses showed that if income levels are not increased, reducing the price of LPG alone will have little effect on the potential adopters of clean cooking. Furthermore, households with smaller members can transition quicker to clean cooking options compared to larger households. Therefore, the paper infers that one policy strategy would not be enough to promote clean cooking in Nigeria's heterogeneous society.

Prioritising dedicated policies and strategies will be needed to accelerate the transition to clean cooking energy systems. First, enhancing consumer demand by creating awareness, community engagement, and capacity building in local communities is critical in improving demand for the clean cookstove. Nigerian rural households are mainly accustomed to firewood, and convincing them to shift to cleaner fuels might be challenging. While preferences for traditional fuels might be due to an age-long tradition, educating the public on the health and economic benefits can motivate consumers to switch to cleaner fuels for cooking. In this case, local information diffusion channels such as radio broadcast, word of mouth, street-plays, and rural social marketing in village gatherings are often effective. Second, addressing distribution and logistics challenges increases consumer demand for clean cooking by providing them access to clean cookstoves and LPG in their communities. If the vendors are members of their community, the locals may have more confidence in the new technology as the vendors may also serve as repair technicians. Also, access to clean fuels in rural areas is paramount to increasing consumer adoption. Therefore, it is vital to develop local skill capacity and encourage partnership with marketers to supply LPG to outlets in regional areas.

Third, lower LPG and clean cookstove prices mostly favour urban households (based on our model) compared to rural dwellers. There is a need to bridge the gap through finance mechanisms through outlets such as microfinance banks, credit unions, carbon finance and cooperatives or direct government subsidies. The registration process for these credit facilities should be streamlined to ensure households gain access to clean cookstove in a simplified manner. Forth, policymakers should ensure vulnerable people who constitute a majority of the rural households are not left behind in the race to decarbonise the household sector. In conflict zones and off-grid locations in Nigeria, disenfranchised members of the community suffer the most and are often left out in the policy debate. Although donor agencies have played a significant role in meeting the needs of those affected by humanitarian crisis, the Nigerian government should build synergies with manufactures to produce clean cookstoves at a quick scale to meet the basic needs of vulnerable households. This will reduce the unit cost and increase adoption rate in the short term, while Nigerian households gradually decarbonise in the coming years.

Finally, given the dynamics surrounding the clean cooking energy transition, we recommend that various governments and other development agencies employ a multi-sectoral action in improving clean cooking energy access. Public and private stakeholders, including but not limited to decision-makers, executors, and funders, should incorporate clean cooking energy goals into local and international development agendas. Furthermore, all policy frameworks need to carry the consumers along to ensure that all solutions are in tandem with the consumers' social, cultural and gender needs.

We note that our analysis is not without some caveats. First, we used only LPG to represent other modern clean cooking sources. While LPG is a clean cooking fuel, it is worthwhile to mention that it is also a fossil fuel. Consequently, future studies could explore the potential of other clean and climate-friendly cooking energy sources. Second, we explored the influence of household income, house size, price per kg of LPG, and contact rate on adopting clean cooking in Nigeria. In reality, other factors (e.g., educational level, gender of household head, geographic location, and industrialisation) can influence clean cooking adoption beyond the factors considered here. This implies that there is room for further analysis on this subject matter using these other factors. Third, due to the scarcity of Nigeria-specific data, the numerical results presented here should not be taken as exact values but as average expected values since modelling results are intended to be more directional and providing a broad quantitative sense rather than precise forecasts. While acknowledging these limitations, our analysis has shown the overall dynamics surrounding the transition to clean cooking in Nigeria and beyond, thus complementing the existing evidence base for policymaking on the subject matter of our inquiry.

References

Apata, T. G. (2016). Information dissemination and communication strategy using town crier in a traditional context in Southwestern States, Nigeria. *Applied Tropical Agriculture, 20*(2), 78–87. ([Online]. Available) ⟨http://journals.futa.edu.ng/index.php/ATA/article/view/2374/1971⟩.

Ateba, B. B., Prinsloo, J. J., & Fourie, E. (2018). The impact of energy fuel choice determinants on sustainable energy consumption of selected South African households. *Journal of Energy in Southern Africa, 29*(3), 51–65. https://doi.org/10.17159/2413-3051/2018/v29i3a4714 (Aug.).

A.T. Azar. 2012. System dynamics as a useful technique for complex systems, vol. 10, no. 4.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review, 12*(3), 183–210 10.1002/(sici)1099-1727(199623)12:3 < 183::aid-sdr103 > 3.3.co;2-w.

Bass, F. M. (1969). A new product growth for model consumer durables. *Management Science, 18*(8), 14.

Benjamin L Turner, D. F. A., & Kim, Hyunjung (2014). Improving coding procedures for purposive text data: researchable questions for qualitative system dynamics modeling. *System Dynamics Review, 29*(4), 253–263. https://doi.org/10.1002/sdr

Bisu, D. Y., Kuhe, A., & Iortyer, H. A. (2016). Urban household cooking energy choice: An example of Bauchi metropolis, Nigeria. *Energy, Sustainability and Society, 6*(1), 15. https://doi.org/10.1186/s13705-016-0080-1 (Dec.).

Bonan, J., Pareglio, S., & Tavoni, M. (2017). Access to modern energy: A review of barriers, drivers and impacts. *Environment and Development Economics, 22*(5), 491–516. https://doi.org/10.1017/S1355770×17000201 (Oct).

Calzada, J., & Sanz, A. (2018). Universal access to clean cookstoves: Evaluation of a public program in Peru. *Energy Policy, 118*(August 2017), 559–572. https://doi.org/10.1016/j.enpol.2018.03.066

Chalise, N., Kumar, P., Priyadarshini, P., & Yadama, G. N. (2018). Dynamics of sustained use and abandonment of clean cooking systems: Lessons from rural India. *Environmental Research Letters, 13*.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., & Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research & Social Science, 37*(March), 175–190. https://doi.org/10.1016/j.erss.2017.09.015

Chester L. 2013. The impacts and consequences for low-income Australian households of rising energy prices.

Dagnachew, A. G., Hof, A. F., Lucas, P. L., & Van Vuuren, D. P. (2019). Scenario analysis for promoting clean cooking in Sub-Saharan Africa: Costs and benefits. *Energy*Article 116641. https://doi.org/10.1016/j.energy.2019.116641

Danlami, A. H., Applanaidu, S. D., & Islam, R. (2018). An analysis of household cooking fuel choice: A case of Bauchi State, Nigeria. *International Journal of Energy Sector Management, 12*(2), 265–283. https://doi.org/10.1108/IJESM-05-2016-0007

Debbi, S., Elisa, P., Nigel, B., Dan, P., & Eva, R. (2014). Factors influencing household uptake of improved solid fuel stoves in low-and middle-income countries: A qualitative systematic review. *International Journal of Environmental Research and Public Health, 11*(8), 8228–8250. https://doi.org/10.3390/ijerph110808228 (Aug.).

Dioha, M. O. (2020). Nigeria's energy options in the era of climate change: An essay. *Journal of Sustainable Energy, 11*(1), 31–38.

Dioha, M. O., & Emodi, N. V. (2019). Investigating the impacts of energy access scenarios in the Nigerian household sector by 2030. *Resources, 8*(3), 127. https://doi.org/10.3390/resources8030127 (Jul.).

Dioha, M. O., & Kumar, A. (2020a). Exploring sustainable energy transitions in sub-Saharan Africa residential sector: The case of Nigeria. *Renewable and Sustainable Energy Reviews, 117*, Article 109510 (Jan).

Dioha, M. O., & Kumar, A. (2020b). Exploring the energy system impacts of Nigeria's Nationally Determined Contributions and low-carbon transition to mid-century. *Energy Policy, 144*, Article 111703. https://doi.org/10.1016/j.enpol.2020.111703 (Sep.).

ESMAP. 2015. State of the clean and improved cooking sector in Africa. [Online]. Available: ⟨http://documents.worldbank.org/curated/en/385081467992479462/pdf/96499-ESM-P127219-PUBLIC-Box391453B-ESMAP-State-of-Globa-Clean-Improved-Cooking-sector-Optimized.pdf⟩.

FGN. 2016. Sustainable Energy for All Action Agenda (SE4ALL-AA).

W. E. Forum, What 'systems thinking' actually means - and why it matters today | World Economic Forum, The World Economic Forum COVID Action Platform, 2021. ⟨https://www.weforum.org/agenda/2021/01/what-systems-thinking-actually-means-and-why-it-matters-today/⟩ (accessed Jan. 20, 2021).

Geels, F. W., Berkhout, F., & Van Vuuren, D. P. (2016). Low-carbon transitions. *Perspective*(May), https://doi.org/10.1038/NCLIMATE2980

Haggstrom, D. A., et al. (2019). Rural and urban differences in the adoption of new health information and medical technologies. *Journal of Rural Health, 35*(2), 144–154. https://doi.org/10.1111/jrh.12358

Hearne, J. W. (1987). An approach to resolving the parameter sensitivity problem in system dynamics methodology. *Applied Mathematical, 11*(4), 315–318. https://doi.org/10.1016/0307-904X(87)90148-X

Hewitt, J., Ray, C., Jewitt, S., & Clifford, M. (2018). Finance and the improved cookstove sector in East Africa; Barriers and opportunities for value-chain actors. *Energy Policy, 117*, 127–135. https://doi.org/10.1016/j.enpol.2018.02.044 (Jun.).

Horvat, A., Fogliano, V., & Luning, P. A. (2020). Modifying the Bass diffusion model to study adoption of radical new foods-The case of edible insects in the Netherlands. *PLoS One, 15*(6 June), 1–23. https://doi.org/10.1371/journal.pone.0234538

IEA (2017). *World Energy Outlook 2017. Special report: Energy access outlook.* Paris: International Energy Agency (IEA) and the Organisation of Economic Co-Operation and Development (OECD).

IEA (2020). *SDG7: Data and projections.* Paris: IEA. ⟨https://www.iea.org/reports/sdg7-data-and-projections⟩.

Jagger, P., Pedit, J., Bittner, A., Hamrick, L., Phwandapwhanda, T., & Jumbe, C. (2017). Energy for sustainable development fuel efficiency and air pollutant concentrations of wood-burning improved cookstoves in Malawi: Implications for scaling-up cookstove programs. *Energy for Sustainable Development, 41*, 112–120. https://doi.org/10.1016/j.esd.2017.08.007

Johan Schot, G. V., & Kanger, L. (2020). The roles of users in shaping transitions to new energy systems. *Perspective, 1*(2016), 1–7. https://doi.org/10.1038/nenergy.2016.54

Kumar, P., Chalise, N., & Yadama, G. N. (2016). Dynamics of sustained use and abandonment of clean cooking systems: Study protocol for community-based system dynamics modeling. *International Journal for Equity in Health,* 1–8. https://doi.org/10.1186/s12939-016-0356-2

Lewis, J. J., & Pattanayak, S. K. (2012). Who adopts improved fuels and cookstoves? A systematic review. *Environmental Health Perspectives, 120*(5), 637–645. https://doi.org/10.1289/ehp.1104194

F.G.N. Li, E. Trutnevyte, N. Strachan. 2015. Technological Forecasting & Social Change A review of socio-technical energy transition (STET) models, vol. 100, pp. 2014–2016.

LPG Summit, Nigeria LPG summit 2019, 2019. [Online]. Available: ⟨http://www.lpgsummit.com/wp-content/uploads/2019/12/Nigeria-LPGSummit-PSR-2019-04_compressed.pdf⟩.

Maani, K. E., & Maharaj, V. (2004). Links between systems thinking and complex decision making. *System Dynamics Review, 20*(1), 21–48. https://doi.org/10.1002/sdr.281

F.H. Maier. 1998. New product diffusion models in innovation management -A system dynamics perspective, vol. 14, no. 4, pp. 285–308.

Makonese, T., Ifegbesan, A. P., & Rampedi, I. T. (2018). Household cooking fuel use patterns and determinants across southern Africa: Evidence from the demographic and health survey data. *Energy Environment, 29*(1), 29–48. https://doi.org/10.1177/0958305×17739475 (Feb.).

A. Maria. 1997. Introduction to modeling and simulation, Winter Simul. Conf. Proc., pp. 7–13, doi: ⟨10.1145/268437.268440⟩.

Mensah, J. T., & Adu, G. (2015). *An empirical analysis of household energy choice in Ghana. Renewable and Sustainable Energy Reviews*Elsevier Ltd1402–1411. https://doi.org/10.1016/j.rser.2015.07.050 (Aug.).

P.M. Milling, F.H. Maier. 2017. Encyclopedia of Complexity and Systems Science.

Morecroft, J. D. W. (2018). Management attitudes, learning and scale in successful diversification: a dynamic and behavioural resource system view. In O. R. Essentials, & M. Kunc (Eds.). *System Dynamics Soft and Hard operational Research* (pp. 38). Palgrave macmillan.

Naji, R. K., & Hussien, R. M. (2016). The dynamics of epidemic model with two types of infectious diseases and vertical transmission. *Journal of Applied Mathematics, 2016*, 16. https://doi.org/10.1155/2016/4907964

Nwachukwu, C. (2011). Operators blame NLNG for cooking gas scarcity, high cost - Vanguard News. *Vanguard News*. ⟨https://www.vanguardngr.com/2011/01/operators-blame-nlng-for-cooking-gas-scarcity-high-cost/⟩ (accessed Nov. 16, 2021).

Nyankone, B. O. (2018). *Factors influencing adoption of improved cookstoves among households of Thuti Location, Othaya, Nyeri County, Kenya.* University of Nairobi.

Onyeneke, R. U., et al. (2019). Improved cook-stoves and environmental and health outcomes: Lessons from cross river state, Nigeria. *International Journal of Environmental Research and Public Health, 16*(19), 1–13. https://doi.org/10.3390/ijerph16193520

Ozoh, O. B., et al. (2018). Cooking fuels in lagos, Nigeria: Factors associated with household choice of kerosene or liquefied petroleum gas (LPG). *International Journal of Environmental Research and Public Health, 15*(4), 1–13. https://doi.org/10.3390/ijerph15040641

Paudel, D., Jeuland, M., & Lohani, S. P. (2020). Cooking-energy transition in Nepal: trend review. *Clean Energy, 2020*, 1–9. https://doi.org/10.1093/ce/zkaa022 (Dec.).

R. Price. 2017. Clean' cooking energy in Uganda – Technologies, impacts, and key barriers and enablers to market acceleration. [Online]. Available: ⟨https://assets.publishing.service.gov.uk/media/5bae05abe5274a3e019d86ae/191_Clean_cooking_energy_Uganda.pdf⟩.

Puzzolo, E., et al. (2019). Supply considerations for scaling up clean cooking fuels for household energy in low- and middle-income countries. *GeoHealth, 3*(12), 370–390. https://doi.org/10.1029/2019GH000208

Pye, A., Ronzi, S., Ngahane, B. H. M., Puzzolo, E., Ashu, A. H., & Pope, D. (2020). Drivers of the adoption and exclusive use of clean fuel for cooking in sub-saharan africa: Learnings and policy considerations from cameroon. *International Journal of Environmental Research and Public Health, 17*(16), 1–24. https://doi.org/10.3390/ijerph17165874

Quinn, A. K., et al. (2018). An analysis of efforts to scale up clean household energy for cooking around the world. *Energy Sustainable Development, 46*, 1–10. https://doi.org/10.1016/j.esd.2018.06.011

Rahut, D. B., Ali, A., Mottaleb, K. A., & Aryal, J. P. (2019). Wealth, education and cooking-fuel choices among rural households in Pakistan. *Energy Strategy Reviews, 24*, 236–243. https://doi.org/10.1016/j.esr.2019.03.005 (Apr.).

Sana, A., Kafando, B., Dramaix, M., Meda, N., & Bouland, C. (2020). Household energy choice for domestic cooking: Distribution and factors influencing cooking fuel preference in Ouagadougou. *Environmental Science and Pollution Research, 27*(15), 18902–18910. https://doi.org/10.1007/s11356-020-08427-7 (May).

Selvakkumaran, S., & Ahlgren, E. O. (2020). Impacts of social innovation on local energy transitions: Diffusion of solar PV and alternative fuel vehicles in Sweden. *Global Transitions, 2*, 98–115. https://doi.org/10.1016/j.glt.2020.06.004

Shabanpour, R., Shamshiripour, A., & Mohammadian, A. (2018). Modeling adoption timing of autonomous vehicles: Innovation diffusion approach. *Transportation*(0123456789), https://doi.org/10.1007/s11116-018-9947-7

Shankar, A., et al. (2014). Maximizing the benefits of improved cookstoves: Moving from acquisition to correct and consistent use. *Global Health: Science and Practice, 2*(3), 268–274. https://doi.org/10.9745/GHSP-D-14-00060

Shari, B. E., Moumouni, Y., & Momodu, A. S. (2020). Low carbon transition of residential electricity consumption in Nigeria: A system dynamics modeling approach. *International Journal of Energy and Power Engineering, 9*(1), 11–21. https://doi.org/10.11648/j.ijepe.20200901.12

Soltani, M., Rahmani, O., Beiranvand Pour, A., Ghaderpour, Y., Ngah, I., & Misnan, S. H. (2019). Determinants of variation in household energy choice and consumption: Case from Mahabad City, Iran. *Sustainability, 11*(17), 4775. https://doi.org/10.3390/su11174775 (Sep.).

Tian, Y., Lich, K. H., Osgood, N. D., Eom, K., & Matchar, D. B. (2016). Linked sensitivity analysis, calibration, and uncertainty analysis using a system dynamics model for stroke comparative effectiveness research. *Sagepub - Medical Decision Making,* 1–15. https://doi.org/10.1177/0272989×16643940

Vigolo, V., Sallaku, R., & Testa, F. (2018). Drivers and barriers to clean cooking: A systematic literature review from a consumer behavior perspective. *Sustainability, 10*(11), https://doi.org/10.3390/su10114322

Yu, Y., Hu, Y., Qiao, H., & Wang, S. (2019). Co-evolution: A new perspective for business model innovation. *Journal of Systems Science and Information, 6*(5), 385–398. https://doi.org/10.21078/jssi-2018-385-14

X. Zhao, Y. Zhang. 2018. The evolution of renewable energy price policies based on improved bass model: A System Dynamics (SD) analysis, doi: 10.3390/su10061748.