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Energy Access-Development Nexus at National and Local Contexts

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Acknowledgement

To all who have been part of my journey and have contributed to my path in this transient world

Abstract

The enabling role of energy access in meeting the Sustainable Development Goals (SDGs) enshrined in the Agenda 2030 set by the United Nations largely contributes to the increasing support for the implementation of energy access projects globally, especially in developing economies. Moreover, various studies have also established linkages between energy access and the SDGs, mostly using qualitative approaches. However, assessing the nexus between energy access and the SDGs is indeed not straightforward as it involves "complex" systems, whose interactions give rise to unexpected behaviours that are far from being completely understood and characterised.

The inadequate understanding of the complexities of the energy-development nexus in designing, planning, and implementing energy policies and programmes often leads to the assumption that energy access will "automatically" facilitate development. This results in optimistic but unrealistic projections, thus, leading to inefficient, ineffective, and sub-optimal energy policies. The inherent complexities of the energy-development nexus explain the reason some energy interventions lead to significant improvement in livelihood, others only make a limited desirable impact, while some others lead to undesirable impacts. The heterogeneity of the impact of energy programmes calls for the development of tools that will facilitate holistic planning of energy projects given the promotion of their effectiveness to facilitate sustainable development. The study achieved two main objectives, namely:

i. developed a system dynamics model for investigation, evaluation and analysis of various national energisation strategies and roadmaps for an African country (Nigeria),

ii. identified and established the impact pathways between the variables of energy access and those of the other SDGs at the sub-national (rural) level.

Based on the increasing interest in the uptake of renewable energy for energy access in Africa, the study conducted a comparative analysis of renewable energy policies in Nigeria, South Africa, and Egypt, which make up the top three largest economies in Africa and the trio have huge renewable energy resources. South Africa and Egypt provide cases of transformational growth in the uptake of renewable energy driven by market-oriented policies and strategies, while, the Nigerian case typifies policy constraints that limit the optimal exploitation of renewable energy in various countries in Africa. The analysis of the Nigerian case reveals specific challenges in the policy and institutional landscape that impede the uptake of renewable energy and use in the country, which if addressed could catalyse renewable energy integration in Nigeria, among other African countries that are faced with similar challenges. By taking the cases of the three countries, the study analysed the giant strides made in the uptake of renewable energy in Africa and identifies some of the major challenges facing many African countries in developing their renewable energy sectors. Based on the experience of South Africa and Egypt, actionable recommendations that are realistic in the African context are made towards addressing the challenges.

Having gained insight into national energy policies, the study modelled the impact of energy access policies on sustainable development at the national level based on the complex interactions between energy access and other sectors of the economy. Given the multiple interconnections, interlinkages, feedback, time-dependencies, and non-linear behaviours in the energy-development nexus, a system dynamics model was developed. Being calibrated (using the World Bank data for Nigeria) and tested, the model is found to be useful for the formulation, analysis and critical evaluation of various energy policies and plausible impact on sustainable development in Nigeria.

However, national averages hide more than they reveal. Development analysis based on national averaged data is crucial to decision-making at the national level but it does not represent the reality

at the sub-national level especially the conditions of rural livelihood which generally lags behind those in the urban centres. While there is a rapid rate of urbanisation in African countries, the highest share of the population in developing countries live in rural communities. The high development deficit in rural developing countries vis-à-vis the high share of their population who reside in them makes rural communities in developing countries form the largest group of people affected by the global challenges that the SDGs seek to address – 'farthest from behind'. The "leaving no one behind" operating principle of the SDGs to catalyse sustainable development 'starting from the farthest behind' , therefore, makes the case for a new momentum towards rural development in developing countries. Hence, the need for planning tools for energy access policies that would maximise their impact on the SDGs in the rural context. Nonetheless, the development of such planning tools relies on an in-depth understanding of the nexus and the interlinkages between energy access and the SDGs in a rural context.

To provide conceptual tools for modelling the impact of rural energy polices on rural development, the study conducted a detailed analysis of scientific literature on the nexus of energy access and each of the themes of the SDGs. The study presents a detailed descriptive analysis, developed 16 comprehensive causal loop diagrams and crystalises 85 feedback loops of the interlinkages and the impact pathways between energy access and 16 SDGs in the rural context of developing countries. The feedback loops represents the conceptualisation framework for the modelling of system-dynamic models for holistic rural energy planning towards facilitating the realisation of the SDGs in rural contexts of developing countries. Based on the literature analysis, causal loop diagrams and feedback loops, recommendations are made on policies and strategies for energy access towards maximising the impact of energy access on the realisation of the SDGs in a rural context.

CHAPTER ONE

1 Energy Access and Sustainable Development

1.1 Introduction

The coming into force of the Agenda 2030 promoted by the United Nations generated a multi-stakeholder commitment to the realisation of the 17 sustainable development goals (SDGs) enshrined in the agenda. Since coming into force, there has been increasing interest in development paths that help to meet the present needs without reducing the potential and possibility of future generations to meet their needs [1]–[5]. In this pursuit, the role of energy access has been identified both as a sustainable development goal (SDG) and also as a driver of other goals within the framework [6]. Moreover, the sustainability concerns on fossil fuels are leading to a catalysed commitment to the exploitation of renewable energy sources (RESs) across the globe [7], [8]. Africa is at an advantage by nature given the abundant RESs available across the continent [9]. The possibility for decentralised generation of renewable energy (RE) also makes it a good fit for energy access for the huge share of the African populace living in rural and remote communities that are not favoured by the economics of grid extension. Moreover, the environmental friendliness of the generation and use of RE also help nations to reduce their carbon emissions. Thus, contributing to their Nationally Determined Contributions (NDCs) to the Paris Agreement [10]–[14]. However, exploiting available renewable energy resources for energy access comes with multidimensional challenges and addressing them largely depends on the effectiveness of the renewable energy policy [15] and institutional frameworks adopted across nations.

The accelerated growth in renewable energy generation in many nations with relatively low renewable energy resources *vis-à-vis* the slow pace of RE development in nations with abundant potential shows that renewable energy generation requires more than the availability of RESs. As of 2020, the cumulative installed capacity of solar photovoltaic (PV) technology in Africa was 10,581 MW while Europe had a cumulative installed capacity of 152,917 MW with Germany accounting for 53,783 MW; Germany's capacity accounts for about 500% of the African value[16]. Yet, Africa has more solar energy resources compared to Europe [17], [18]. Indeed, the experience of various nations that are advanced in the uptake of renewable energy highlights the crucial role of appropriate policy frameworks and implementation strategies in creating enabling environment that drives the various dimensions of renewable energy development [19].

Hydropower and the traditional use of biomass represent the highest share of renewable energy uptake in Africa yet the continent has abundant solar, wind and biomass energy potentials [20]. The availability of various renewable energy resources for utility-scale exploitation has been demonstrated across many African countries, nonetheless, the diffusion of the associated renewable energy technologies (RETs) requires appropriate policy instrument that will de-risk and incentivise investments in the sector [21]. Therefore, the level of renewable energy development attainable in African countries will be largely determined by the robustness of the policy instruments in increasing the interest and capacity of stakeholders from demand and supply ends [22].

1.1.1 Renewable Energy for Energy Access: Nigeria, South Africa and Egypt

South Africa and Egypt are leaders in renewable energy exploitation with highest installed capacity for renewable energy generation on the continent. South Africa and Egypt account for 57% and 16% of the 10,431MW of total installed solar energy generation capacity respectively on the continent (Figure

1-1) [16]. Moreover, the two countries, also account for 41% (South Africa) and 21% (Egypt) of the 6,479MW wind energy generation capacity in 2019 (Figure 1-2) [16].

South Africa's transformative growth in renewable energy exploitation has been lauded internationally and it provides a model for other African countries. In 2015, the United Nations Environment Programme (UNEP) ranked South Africa among the top 10 countries that attracted the highest RE investment in the world. With a USD 4.5 billion investment in its renewable energy sector, South Africa recorded the 7th highest RE investment in the world in 2015. The investment represents a 329% increase from its USD 1 billion renewable energy investment in 2014 [23]. Similarly, the progress made in Egypt also provides a case of remarkable growth in renewable energy development driven by appropriate market-oriented policy frameworks and transparent implementation strategies with significant participation by private players. Egypt recorded the largest investment in Africa's renewable energy sector in 2017. During the year, twenty-four (24) large scale renewable energy projects summing up to 1.3 GW installed capacity reached financial close totalling a USD 2.6 billion renewable energy investment in the country. Though Egypt missed the rank of "top 10 countries" in the world with the largest renewable energy investments, UNEP called it "next to the top 10 countries" [24].

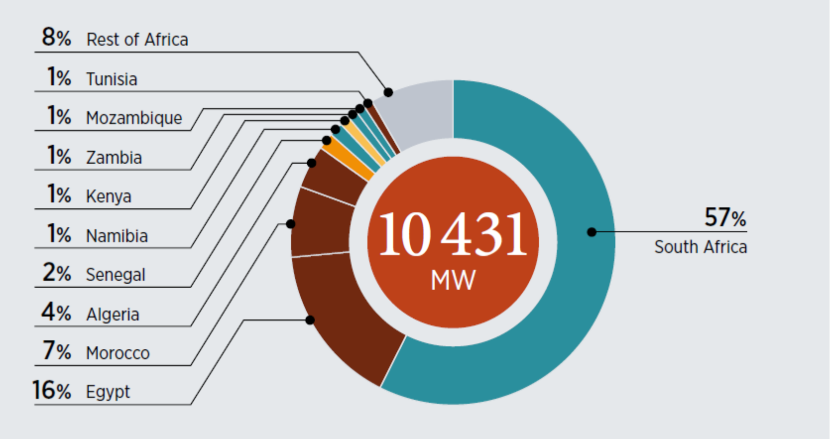


Figure 1-1: Africa's installed solar generation capacity

Source: IRENA, 2021 [16]

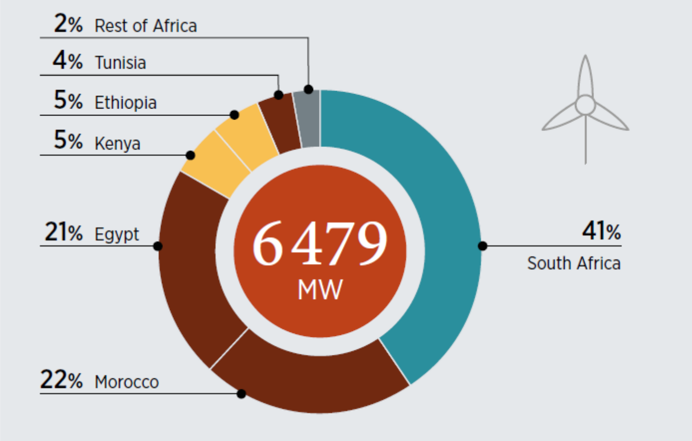


Figure 1-2: Installed wind generation capacity in Africa

Source: IRENA, 2021 [16]

However, Nigeria, South Africa, and Egypt make up the top three largest economies in Africa and the trio have huge renewable energy resources. While South Africa and Egypt have leveraged their renewable energy resources to improve the conditions of energy access in their countries, the exploitation of renewable energy in Nigeria is abysmally low despite the energy poverty vis-à-vis the renewable energy potential in the country. Nigeria ranks as the most populous African country with its population is nearly equally distributed in urban (52%) and rural (48%) settlements. While 84% of its urban population has access to electricity, only 26% of its rural population does, culminating in a 55% national access rate to electricity. The Energy Commission of Nigeria projected that the country requires an additional 100,000MW electricity generation installed capacity for the nation to realise full industrialisation by 2020 [25]. Despite the development of diverse policies and targets, Nigeria has 10,396 MW total installed capacity out of which only 6,056 MW mainly from hydropower (1,938.4 MW installed, 1,060 MW available) and thermal plants (8,457.6 MW installed, 4,996 MW available) driven by natural gas [26] [27] as of 2020. Nigeria was only able to meet about 2.2% of its total electricity demand in 2018 [28]. This huge gap between energy demand and supply indicates the energy poverty of the country. As of 2021, Nigeria ranks as the country with the highest number of people in the world without access to electricity. Moreover, most of the cities and villages with electricity access are largely underserved given the poor attributes of electricity access available to them. This explains the high dependence and use of more than 70 million private electricity generating sets for residential and industrial operations in the country [27]. Yet, the uptake of renewable energy in Nigeria remains low despite its huge potential.

Egypt and South Africa, though still emerging in their renewable energy sectors, have recorded significant progress in their exploitation of renewable energy. The need for Nigeria, among other developing countries, to draw lessons from the pragmatic energy policies and implementation strategies adopted in Egypt and South Africa has been highlighted in the literature and by multilateral organisations [21], [29] [24]. Hence the need for a comparative analysis to facilitate the learning.

1.1.2 Energy access-development nexus at National Context

While it is imperative to develop policies and strategies that would facilitate the uptake of renewable energy for energy access, energy access is not an end in itself.

Although realising sustainable development is promoted as the objective of renewable energy policies, particularly for energy access in developing countries; energy access does not automatically push sustainable development. The assumption that energy access will "automatically" push development in designing, planning, allocating resources and implementing *energisation* programmes is largely due to an inadequate of the understanding of the complexity of energy-development nexus [30]. The assumption leads to simplistic models and relations that results in optimistic but unrealistic projections, and consequently to inefficient, ineffective, and sub-optimal energy policies, programmes and interventions. Riva *et al.* show that the energy-development nexus is not straight-forward, because it involves "complex" systems, whose interactions give rise to unexpected behaviours that are far from being completely characterised and understood [37]. "The dynamics of growth and electrification are complex, involving many underlying forces" [39]. This explains the reason some energy intervention programmes lead to significant improvement on livelihood while others only make limited impact, sometimes with undesirable impacts [31]–[37], [30], [38]. The heterogenous outcomes of energy programmes calls for the development of tools that will facilitate holistic planning of energy projects in view of promoting their effectiveness in facilitating sustainable development.

1.1.3 Energy-Development Nexus in Rural Context

While the focus of energy policies for sustainable development has been mostly on the national level, national averages hide more than they reveal.

Indeed, energy policies and plans based on country-level aggregated data help to guide national development direction for governments among other stakeholders, yet, they do not reflect the realities within the sub-national contexts especially in developing countries with a wide development margin between urban and rural communities. Development analysis for intervention based on national averaged data evades stakeholders' opportunities to understand the reality of the in-country situation and identify the most crucial areas of need. The conditions of livelihood at the sub-national level differ widely between the urban and rural communities in developing countries. In general, the rural population are poorer [40], and has lesser opportunities and access to services than their urban counterparts [41]. Pachauri *et al.*, [42] in an evaluation report for the United Nations Development Programme find that there still exist a wide development margin between rural and urban communities. Ten years into the implementation of the Millennium Development Goals (MDGs), the United Nations [43] found that despite of the achievements of the MDGs, the rural/urban development margin remains daunting in various dimensions including energy access, access to safe drinking water, adequate nutrition, access to quality education among others. On health, the report particularly highlights that *"children in rural areas are more at risk of dying, even in regions where child mortality is low"* and youth in rural areas have lower chances of being aware of HIV/AIDS prevention techniques, hence, more prone to contracting the diseases relative to their urban counterparts. Given their proximity and reliance on nature, rural dwellers also suffer a disproportionate share of the challenges emanating from desertification, biodiversity loss, drought, among other nature-based challenges. Yet, majority of the African populace reside in rural communities.

According to the World Bank database, 58% of people in Sub-Sahara Africa reside in rural communities yet some countries have up to 86% rural population, such as Burundi. According to the World Bank database, more than 50 percent of the population of seven of the ten most populous African countries live in rural communities. This includes Ethiopia (78%), Egypt (57%), Democratic Republic of Congo (54%), Tanzania (64%), Kenya (72%), Sudan (65%), and Uganda (75%), with exception of Nigeria (48%), South Africa (33%) and Algeria (26%) rural population. The high share of population who reside in rural developing countries makes the need to facilitate sustainable development in rural communities more compelling.

1.1.4 Energy-SDGs nexus in a rural context

Given the role of energy in facilitating sustainable development, the high level of energy poverty in rural developing countries has been identified as a major factor that limits the improvement of rural livelihood. Therefore, there has been an increased effort towards the security of energy access in rural communities. The World Summit on Sustainable Development (WSSD) in 2002 identified the crucial role of energy access to the realisation of the MDGs in reducing poverty and facilitating economic development as highlighted in the Johannesburg Plan of Implementation (JPOI) [44], [45]. The acknowledgement of the enabling role of energy in MDGs resulted in an increased commitment of stakeholders across the globe in energy access [46], [47]. The dedication of a goal to energy access within the 2030 Agenda of the United Nations and its role in facilitating other goals within the Agenda set a new trajectory for the global commitment towards the security of energy access for all.

The high development deficit in rural developing countries vis-à-vis the high share of their population who reside in them makes rural communities in developing countries form the largest group of people affected by the global challenges that the SDGs seeks to address – 'farthest from behind'. Therefore, the "leaving no one behind" operating principle of the SDGs to catalyse sustainable development 'starting from the farthest behind' makes the case for a new momentum toward rural development in developing countries. The wide acknowledgement of the pivotal role of energy access towards realising the SDGs [48] made the security of energy access a major priority in the effort to catalyse sustainable development in rural communities. Hence, making a case for the development of tools that could help to maximise the impact of energy access on the achievement of the SDGs in the rural contexts of developing countries. The development of such planning tools relies on the depth of understanding of the interlinkages and interdependences between energy access and the SDGs in the rural context.

1.2 Literature Review

To identify the gaps in literature from which the research derive its unique contributions to knowledge, an in-depth review of the literature was conducted covering on energy access-development nexus at national and sub-national (rural) levels in the context of developing countries.

1.2.1 Energy access-development nexus at National Context

While there is a need to develop policies, strategies and institutional framework that would facilitate the uptake of renewable energy for energy access, it is also crucial to develop tools for the integration of energy access project within the overall development framework to facilitate and maximise the development impact of energy access. Indeed, the dedication of a sustainable development goal to "access to affordable, reliable, sustainable and modern energy for all" in the UN 2030 Agenda is based on its enabling role in facilitating sustainable development [49]. This largely explains the increasing support for the implementation of sustainable energy projects worldwide, especially in developing economies [50], [51]. Nonetheless, the impact on energy access in facilitating the SDGs relies on the level of integration within the SDG framework.

Whereas the SDGs were promoted as "integrated" goals, they probably would be best described, as a set of politically integrated but technically related goals. The 2030 Agenda contains a set of related but separate list of global challenges prioritised by the United Nations. However, since coming into force, there has been a continuous effort towards establishing the inter-linkages among the various goals and targets which are progressively helping towards the scientific integration of the goals.

As an initial effort towards integrating the SDGs, the United Nations Department of Economic and Social Affairs (UN DESA) [52] analysed the first 16 SDGs to assess the extent to which the structure of the goals, through their targets, align with the sectorial integration objective of the 2030 agenda. Goal 17 which is taken as means of implementation of the SDGs, and, all the 62 targets that refer to it throughout the framework were not included in the study. The network of targets was developed based on a matrix linking each of the considered 107 targets to all the goals their "wordings" may refer to (Figure 1-3).

Being based on the interpretation of *wordings* used in the statement of goals and targets, the authors highlight that the approach has some elements of subjectivity as interpretations may differ with researchers. Also, whereas the approach represents a step towards integration of the SDGs, it leaves out systemic linkages between goals that are technically linked but not using wording. For instance, no linkages were established between energy (SDG 7) and climate change (SDG 13), and energy (SDG7) and infrastructure and industrialisation (SDG 10) which have been scientifically identified to be closely linked.

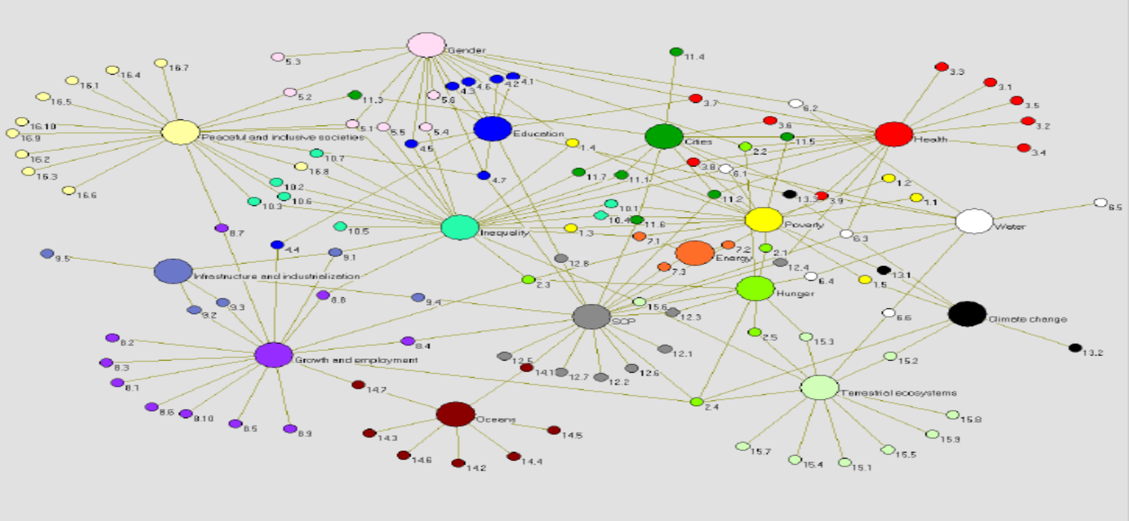


Figure 1-3: Links between the SDGs through their targets

(Source: Blanc 2014) [52]

In the literature, other efforts have been made by researchers to interlink the SDGs using a three-point typology. They categorised the interactions between the SDGs into "*supporting", "enabling" and "relying"* [53], [54].

Another attempt to interlink the SDGs is provided by Nilsson [55], which establishes the *most crucial* linkages between the targets of six SDGs 1, 2, 3, 5, 9 and 14 (which were the SDGs that were selected for review at the 2017 High-Level Political Forum), and those of other SDGs. The interlinks were made through the linkages between selected targets under the six SDGs and the targets of other goals within the framework to highlight the most important interactions between the six SDGs considered in the review and the rest of the SDG framework. The study also considered the institutional implications of the interactions between the SDGs. The assessment of the linkages was based on the seven-point typology developed by Nilsson [55], [56] which categories and assigns values +3 to -3 to the interactions between the SDGs. While the + and - sign shows the direction of the influence, the numbers show the strength. The typology assigns values to the linkage between a target "X" to target "Y" depending on whether progress in target "X" is indivisible (+3), reinforcing (+2), enabling (+1), neutral (0), constraining (-1), counteracting (-2) or cancelling (-3) the progress of target "Y".

There has also been an effort towards the integration of SDG 7 and other SDGs. Because of filling the knowledge gap on the interactions between the targets of SDG 7 and those of other SDGs, McCollum *et al.* apply the seven-point typology in the review of the literature to establish a qualitative relationship between SDG 7 and other 15 SDGs (taking SDG 17 as a means of implementation of the SDGs) [57]. Using the seven-point typology, the authors finds that there are positive and negative linkages between SDG 7 and other SDGs but the positive linkages are more in number and magnitude. The typology range from indivisible (+3), reinforcing (+2), enabling (+1), consistent (0), constraining (-1), counteracting (-2), cancelling (-3). The application of the framework for mapping the SDGs interactions to health, energy and the ocean reveals that the interactions are context-specific, depending on the geographical context, resource endowments, time horizon and governance [58]. McCollum *et al.* conducted a qualitative analysis that presents a narrative of the nature and strength of the linkages between SDG 7 and 1, 2, 3 6, 8 and 13 at the target level [59]. By analysing the voluntary national reviews of six countries in 2016 and 2017, Tosun and Leininger find divergence in the understanding of the linkages between SDGs and perspectives towards policy integration [60]. The divergence result from the domestication process of the SDGs for policy-making and the implementation strategies [60].

So far, all the approaches described are limited to qualitative analyses. Indeed, they are helpful as they increase the understanding of stakeholders on the linkages between the SDGs and their targets. Nonetheless, the progress made can make only limited contributions towards integration and policy coherence for the simultaneous achievement of the goals. The approaches used are subjective, and qualitative, thus, insufficient to support policy actions.

Because of supporting national governments in policy design, formulation and assessment; the Millennium Institute (MI) developed a system dynamics-based modelling tool (integrated Sustainable Development Goal - iSDG) which models the non-linear causalities and feedback relationships between the SDGs capturing the time delays involved in their interactions. The iSDG model is a system dynamics-based simulation tool for analysing, evaluating and testing complex systems, and it has been applied in various fields including business operations, logistics, and shipping, among others.

The Millennium Institute's iSDG modelling tool contains over 1000 "stocks/levels" – viz. the system dynamics representations of integrals in mathematical terms – and "flows" – viz. derivatives in mathematics. The stocks/levels are connected through several thousands of feedback loops covering all the 17 SDGs and 78 indicators covering 30 sectors; 10 for each of the economic, social and environmental main sectors [61]. The development of the iSDG model tool represents a major improvement in the efforts toward integration of the SDGs and policy coherence in the implementation of the SDGs based on the synergies and trade-offs for simultaneous achievement of the SDGs. Using the system dynamics approach, the iSDG captures the systemic linkages and causalities including the mathematical relations which provides for quantitative evaluation and analysis for identifying, analysing and evaluating effective integrated national development policies towards realising the SDGs [61], [62]. But the model fails to meet some requirements such as the availability of open-source software. Similarly, there are calls for open access and sectorial modelling tools that deepen the variables of each sector and their impact on the SDGs. The development of such a sector-based model with the capacity to evaluate its impact on other sectors will set a new paradigm for system planning and evaluation of sector-based intervention projects and their impact on the SDGs.

1.2.2 Energy Access-Development nexus in a rural context

There is a need for the development of the planning tools that would maximise the impact of energy access on the SDGs to facilitate sustainable development in rural communities whose conditions of livelihood are '*hidden*' by national averages in developing countries.

Studies establish the differentiated dynamics of energy access-development nexus between rural and urban communities. Based on the analysis of a nationally representative data in India from 1987-2010, the authors find that household expenditure on electricity and LPG increased over the years, yet, the increase is not connected to an increase in household income [63]. Examining the impact of attributes of electricity access in rural and urban communities, Alkon *et. al.* find both electricity access and availability positively impact health and education outcomes in rural India, while only availability of electricity positively impact education and health outcomes in the urban centres [64]. This further highlights disparity between energy-development dynamics in rural and urban centres which are not visible from national aggregated data and evaluation. Krey *et al* find the evaluations of the economic implication of the energy use requires differentiation of urban and rural households [65]. This shows that the dynamics of energy-development dynamics differs between rural and urban communities.

There are no major studies found to have attempted to establish the linkages and impact pathways between energy access and SDGs in the rural contexts of developing countries. Nonetheless, there has been a diverse effort by researchers, among other stakeholders towards deepening the understanding of the energy access-development nexus in the rural context of developing countries. While some deepen the understanding of rural energy poverty, others examine the linkages between energy access and the various themes of development (such as poverty, health, education, and employment, among other themes) in a rural context. Other researchers examined the approaches to the implementation of energy access projects in rural developing countries.

1.1.1.1 Rural Energy Poverty

Through a survey of 10,000 households from 200 villages in India, Agrawal, *et. al* find that rural household energy use is nearly half of India's national average residential electricity use[66]. The study finds that a 1% increase in the duration of electricity supply from the grid results in a 1.245% increase in electricity use. This shows that an increase in electricity supply could have a high impact on rural livelihood[66]. Balachandra [67] reviewed major rural energy access policies and programmes spanning 1957-2006 vis-a-vis the high deficit of modern energy access in rural India. The authors argue that the high share of the population without modern energy access in rural India is due to the low effectiveness of government policies and programmes, and that poorer households account for the highest number of those without access to modern energy[67]. This highlights the need to develop tools that will help to improve the effectiveness of policies for rural energy access and their impact on the overall improvement of rural livelihood.

Based on a survey of 1128 households, Niu *et. al.* find that per capita income, diversity of electrical appliances, their cost of acquisition, and household size are closely related and are major determinants of residential electricity use[68]. The study also finds that the level of electricity use also positively impacts the quality of life and lifestyle of the users hence its recommendation for improved availability of electricity to facilitate improvement of livelihood especially in the worse off communities[68].

1.2.2.1 Energy Access and Labour Productivity

Salmon and Tanguy [69] examine the impact of rural electrification in Nigeria on the household supply of male and female labour, with a focus on spouses. The joint evaluation shows that rural electrification only increased the working hours of the husband, while separate evaluation shows that electrification increases the working hours of both husband and wife. The study finds that labour decisions of a spouse significantly impact that of the other such that rural electrification results in increased working hours for men at the expense of their wives given the need for home management [69].

1.2.2.2 Energy Access, Income and Economic Development

Rural households are satisfied with electricity from solar energy based on the duration and reliability of electricity access it provides [48]. However, their desire to increase electricity consumption is not only dependent on their satisfaction with solar electricity but also on their income, levels of education, and financial support mechanisms[48]. Meanwhile, the study also finds that subsidies offered to support rural households in securing electricity access do not promote sustainability of electricity access because it fails to improve the fundamental and structural characteristics of rural livelihood [48]. Similarly, electricity provided by philanthropic services is mostly provided at a limited capacity that is insufficient to bring about economic development, hence, usually has mainly welfare impact [70]. Electricity access that will be sufficient to bring about economic development through productive use [70] requires a mechanism that would increase the financial capacity of the people [71] towards ensuring affordability of electricity. This highlights "affordability of electricity access" as a major consideration in the provision of electricity access [36] and explains the reason the wealthier villages gain electricity access (by grid extension) before their poorer counterpart[70]. Given that public funds are rarely sufficient to meet electricity access needs, stakeholders have highlighted the need for a public-private partnership to drive energy access, among other infrastructural development [70].

Moreover, in terms of impact, Pueyo and DeMartino [72] employ a difference-in-difference approach for ex-ante and ex-post comparison of electrified and unelectrified communities two years after the implementation of a solar mini-grid in rural regions of Kenya. The study finds that there was neither significant increase in electricity consumption nor was there significant impact on the performance of rural businesses that could facilitate increase in income for poverty reduction. The authors highlight the need for proper sizing of electricity access projects and implementation of complementary actions that contributes to agricultural productivity (which is the primary socioeconomic activity) and the opening of external markets[72]. A major objective of providing energy access is to drive its productive use, however, there could be a trade-off between electricity access and electricity consumption [73]. Nock *et al.* find that the pursuit of equal electricity access could result in a high access rate but lower overall electricity consumption, while indifference to equality of electricity access yields a lower access rate but higher overall electricity consumption. While electricity access is crucial, there is a need to evaluate such trade-offs and adopt complementary policies to reduce the undesirable impact on electricity consumption [73].

1.2.2.3 Energy Access and Environment

Energy access has several complex linkages with poverty reduction [71] among other socio-economic challenges [74], however, the pursuit of energy access to facilitate socio-economic transformation in rural communities has implications for the environment[70] [74]. The evaluation of a 70-year old supply of LPG which replaced fuelwood as cooking fuel in rural Brazil reveals that LPG is a viable alternative to fuelwood and provides an antidote to the associated environmental impact [70]. The consumption of fossil fuel and the emissions of CO_2 strongly depends on differentiated labour productivity in rural and urban areas. Different development pathways require varying shares of fossil fuel in household energy consumption hence varying shares of the population depending on fossil fuel and its undesirable impact on health [65]. As found by Coelho and Goldemberg, energy access for poverty reduction can be achieved simultaneously with other themes of development including the environmental impact [70]. Nonetheless, realising this relies on an in-depth understanding of the energy-development nexus.

1.2.2.4 Implementation Approach

The inadequate understanding of the energy-development nexus in the design, planning and implementation of rural energy access projects largely explains the heterogeneous results reported on energy access projects[75]. While some energy access projects resulted in significant improvement in livelihood, some led to only marginal contributions to livelihood while others negatively impact and undermine the overall progress of development in target communities. Many rural energy access projects in rural communities fall short of their objectives and the expectations of their stakeholders on the impact on rural livelihood. Studies show that some rural energy projects do not make the intended impact on increasing the income of rural dwellers [34], [35].

An impact evaluation of electricity access to poor and rural households in Brazil reveals that there was an immediate social impact of electricity access on electrified households, however, no significant increase in income was recorded in the short term[36]. Given the heterogeneity of the impact of energy access, stakeholders have continued to wonder "if electricity 'per se' - particularly in rural areas and isolated communities that cannot be reached by the grid - can be a prime factor in promoting development, this is still an open question [70]".

Moreover, the implementation approach of the energy access project is crucial to its impact, particularly, the level of integration of the project with the livelihood and overall development of the target communities [36]. While localisation of dissemination strategies is crucial to the adoption of energy technologies and electricity connection [76], integration of energy projects in overall rural development is crucial to its impact. Coelho and Goldemberg find that rural electrification that is not integrated within the rural development framework can have but limited impact [70]. Many renewable energy projects in rural communities fail due to considering the social and cultural contexts of the target communities, hence, such projects do not meet the needs and interests of the users [77]. Nygaard concludes that development initiatives such as energy access are better developed and integrated into the existing structure rather than being implemented as a new and isolated initiative [78]. Similarly, Ahmad *et al.* recommend electrification should be implemented within an integrated multidimensional ecosystem that could facilitate human development [64].

In addition to the impact on livelihood, energy access for productive activities that utilise local resources, integrates technical functions and organisational framework are also found to impact policy and governance [78]. Obermaier *et al.* also recommends that government and other stakeholders on rural electricity access need to integrate rural electrification within a broader rural development strategy to facilitate electricity use as an input into other sectors of the rural economy to achieve the long term impact of electricity on economic development[36].

Indeed, there have been projects that attempts to integrate energy access projects within the overall development of target communities. By gathering evidence and expert views of over 1000 stakeholders from 70 countries, Smart Villages Initiative suggest bottom-up strategies to increase rural energy access in a way that would facilitate rural development [79]. Urmee and Md developed a framework that enables the evaluation of community attitudes and needs using various factors that should be considered at various stages of the project lifecycle [77]. Mainali *et al.* developed the energy sustainability index (ESI) which integrates thirteen technical, environmental, economic, and social sustainability factors. The application of the index to China, India, South Africa, Sri-Lanka, and Bangladesh assessment covering 1990 - 2010 shows that improvement in ESI in the countries was mainly due to increasing rural electricity use and cleaner cooking [81].

In addition to the multidimensional impact of energy access, a recent effort of researchers to improve the understanding of stakeholders on the rural energy-development nexus reveals that the energy-development nexus is not unidirectional as assumed previously in the literature [75]. Through analysis of survey data covering 2010-2011, Bridge *et al.* find that electricity access influences income, so also does income impact electricity access, a bi-directional relationship [82] as opposed to the unidirectional relationship that is mostly considered. Diverse literature finds that the energy-development nexus is multidimensional, non-linear and complex dynamics of several underlying linkages of several factors and comprises diverse feedback mechanisms whose impacts are delayed in time[75][26][36]–[38]. The inadequate understanding of the complexity of relationships between energy access and various aspect of social and economic development results in poor projections of electricity demand, hence, resulting in inadequate sizing of electricity projects. Moreover as highlighted in section 1.1.2 the inadequate understanding of the complexity of energy-development dynamics also leads to the assumption that rural energy access automatically push improvement in livelihood in target communities[85]. Lessons learnt from field experience by multilateral and development organisations projects across diverse countries and continents also highlight that rural energy access does not automatically push improvement in livelihood in target communities. Therefore, realising and maximising the impact of energy access on local development requires an integrated implementation approach that captures the complexity of energy access-development in rural context of developing countries.

Meanwhile, there has been increasing commitment towards increasing rural energy access to catalyse the realisation of sustainable development goals in rural communities of developing countries. Globally, the number of people with access to electricity via mini-grid increased by more than 100% from 5 million in 2010 to 11 million in 2019 while access to off-grid solar energy solutions grew from 85 million people in 2016 to 105 million in 2019, 45% of which reside in Sub Sahara Africa [15]. The global access to clean cooking fuels and technologies grew from 63% to 66% in a year (2018-2019). In Africa, the total installed capacity of solar mini-grids rose from 1,756MW (out of 17,246 MW globally) in 2009 to 280,386 MW (of out 362,130 MW globally) in 2018. For the first time, the number of people who gained access to electricity in the Sub-Sahara Africa surpassed the population growth between 2017-2019. Within the same period, the rate of access to electricity outpaced population growth in rural areas.

To maximise the impact of the renewed commitment to rural energy access on the realisation of the SDGs in the rural context of developing countries, there is a need to increase the understanding of stakeholders on the nexus of energy access-SDGs nexus to guide the planning and implementation strategies of rural energy access projects.

1.3 Objectives

Based on the identified gaps in the literature discussed above, the research

i. developed a system dynamics model for investigation, evaluation and analysis of various national energisation strategies and roadmaps for an African country (Nigeria),

ii. identified and established the causal linkages and impact pathways between the variables of energy access and those of the SDGs at the sub-national (rural) level.

1.4 Structure of the thesis

The thesis is divided into three main parts. The first part (which covers chapters 2-5) presents a multidimensional overview of renewable energy exploitation for energy access in Africa with three case studies for South Africa, Egypt and Nigeria. The second part (chapter 6) presents a system dynamics model developed for the investigation, evaluation and analysis of various national energisation strategies and roadmaps for Nigeria. The third part (chapters 7-8) presents the causal linkages and impact pathways between the variables of energy access and those of the SDGs in the sub-national (rural) context of developing countries.

Chapter 9 provides the conclusions and limitations of the research as well as future works that would build on the research.

Part One

Part 1 - Multidimensional Overview of Renewable Energy Development for Energy Access in Africa: Lessons and Policy Recommendations from South Africa, Egypt, and Nigeria

Nigeria, South Africa, and Egypt make up the top three largest economies in Africa and the trio have huge renewable energy resources. By taking the cases of the three countries, the study analysed the giant strides made in the uptake of renewable energy in Africa and identifies some of the major challenges facing many African countries in developing their renewable energy sectors. South Africa and Egypt provide cases of transformational growth in the uptake of renewable energy driven by market-oriented policies and strategies, while, the Nigerian case typifies policy constraints that limit the optimal exploitation of renewable energy in various countries in Africa. The analysis of the Nigerian case reveals specific challenges in the policy and institutional landscape that impede the uptake of renewable energy and use in the country, which if addressed could catalyse renewable energy integration in Nigeria, among other African countries that are faced with similar challenges. Based on the experience of South Africa and Egypt, actionable recommendations that are realistic in the African context are made towards addressing the challenges.

CHAPTER TWO

2 Renewable Energy Development for Energy Access: The case of South Africa

Abstract

The commitment of the government of South Africa to the exploitation of renewable energy was in pursuit to reposition its electricity sector by diversifying its energy mix to reduce its reliance on coal and nuclear energy, reduce GHG emissions, and increase energy access to off-grid communities. South Africa moved from an insignificant renewable energy contribution to its energy pool in 1998 to 9638.7 MW total installed capacity of renewables in 2020 by tapping into diverse renewable energy sources available in the country, mainly, solar, wind and hydro and a limited growth in biomass. The exploratory study reveals that in addition to the availability of renewable energy resources, renewable energy development is based on the adoption of market-oriented policies coupled with legislation that provides enabling environment for private and foreign investment for on-grid and off-grid renewable energy investment coupled with significant public investment in the sector. The remarkable growth in renewable energy exploitation is predicated on the development and implementation of strategic programmes and initiatives to realise the aspirations of the policies. The review of policy evaluation and realignment of policies and programmes are crucial to the growth of renewable energy development in the country. The development of large scale and on-grid renewable energy projects resulted from the development of dedicated programmes that address the challenges of large scale renewable energy investment. The government made Power Purchasing Agreements for up to 20 years and the assurance of payment from the National Treasury of South Africa in case of default in payment of electricity by the public utility company, Eskom. This, coupled with the guarantee of the payment of sponsors of IPPs in case of early termination of independent power project (IPP) projects reduced investment risk, hence, facilitating large scale renewable energy investment in the country which helped to diversify the South African electricity sector from one generating company to a multi-player sector led by the private sector. This resulted in the award of 112 IPPs in South Africa which has generated 110,000 direct jobs. The development of utility-scale IPPs also helped to improve social equality among the poor black population who had been marginalized in access to services over the years [86]. Moreover, the mandatory contribution of IPP developers to the development also facilitated the improvement of human livelihood in host communities [87]. The development of the off-grid Rural Electrification Programme with an investment of about USD 24 million resulted in the installation of more than 95,000 solar home systems especially across regions that have been initially marginalised in the provision of access to electricity among other public services [88]. This also resulted in the installation of a cumulative 44MW solar home systems without incentives from the government. These contributed to the increase in access to electricity from 60% in 1998 to 85% in 2019.

2.1 Renewable Energy Resources and Potential

Electricity generation and use in South Africa dates back to 1860 for lighting through 1881 when the first set of streetlights was installed in the country [89], [90]. Consequently, the increased productivity in mining and railway operations led to the development of South Africa's first power plant in 1889 after the discovery of gold in 1886. A concession from the government to private players saw the development of the first coal-powered plant which transmitted high-voltage electricity to mines and neighbouring towns [91]. This was followed by unprecedented growth in electricity generation in the country, however, with high electricity costs due to limited capacities and efficiencies of the power plant. As of 1915, South Africa has thermal power plants with a cumulative of 160MW capacity led by private investors [92]. The Power Act was enacted to allow for the expropriation of privately-owned electricity companies to the government after 35 years. The government also enacted the electricity act in 1922 which led to the establishment of the Electricity Supply Commission (ESCOM) in 1923 which saw to the development of power plants while acquiring independent power plants towards building a centralised electricity system while a department for rural electrification was established in 1951[93]. The growth in the South African electricity sector continued till it was negatively impacted by drought in 1983 which among other factors increased electricity prices. The restructuring of ESCOM (renamed "EKSOM")[94] and the amendment of the electricity act and setting up of a National Electricity Regulator (which replaced a 15-man Electricity Council initially set up to oversee EKSOM's operations) helped to improve the efficiency of the sector as well as increase customer base thus partly addressed EKSOM financial crisis. Based on a projected in electricity supply, a revamp of power generation capacity was recommended, the neglect of which resulted into consistent electricity shortages in 2007. This resulted in increasing disruption in electricity supply despite an increasing demand, including accidents in coal-fired plants due to proximity to their end of service life [95], hence, the attention on the exploitation of renewable energy potential in the country.

Renewable energy development in South Africa is aimed at diversifying its energy mix to reduce its reliance on coal (and nuclear energy), reduce emissions in compliance with international treaties and agreements, and increase modern energy access in rural communities.

2.1.1 Solar energy

Approximately 194000km^2 land area in South Africa receives high radiation from the Sun which represents one of the country's most abundant renewable energy sources [96]. Northern Cape in South Africa is one of the world's best sites for solar energy resources [97]. Although the expensive price of the solar modules which represents up to 50% of utility-scale solar PV projects (Figure 2-1) constituted a major barrier to solar energy generation, the diffusion of solar PV technologies has been catalysed by the falling price of solar photovoltaic (PV) [98] which contributed to South Africa's 5989.60 MW installed capacity for solar energy as of 2020.

2.1.2 Wind energy

Unlike solar energy resource that is available in various African countries at significant measure, wind energy potential is relatively low in Africa and available in only a few countries [99]. South Africa's wind energy resource represents one of the highest in Africa which is being exploited and estimated to be sufficient to power 56,000MW electricity generation installed capacity of a wind turbine [100]. Based on its additional 700MW wind energy installed in 2017, South Africa ranked among the top 10 countries with the highest additional installed capacity for wind energy and the only African country that increased its wind energy generation capacity in the year [101] (Table 2-1). Though its cumulative installed capacity for wind energy generation stood at 9MW from two pilot projects in 2010, the country increased its capacity to 2100MW from more than 20 wind energy projects in 2017 [101], [102].

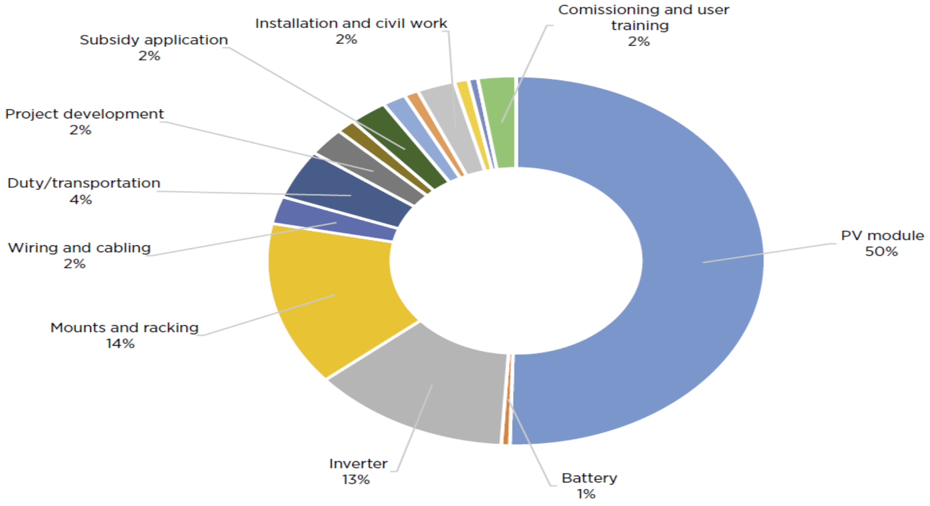
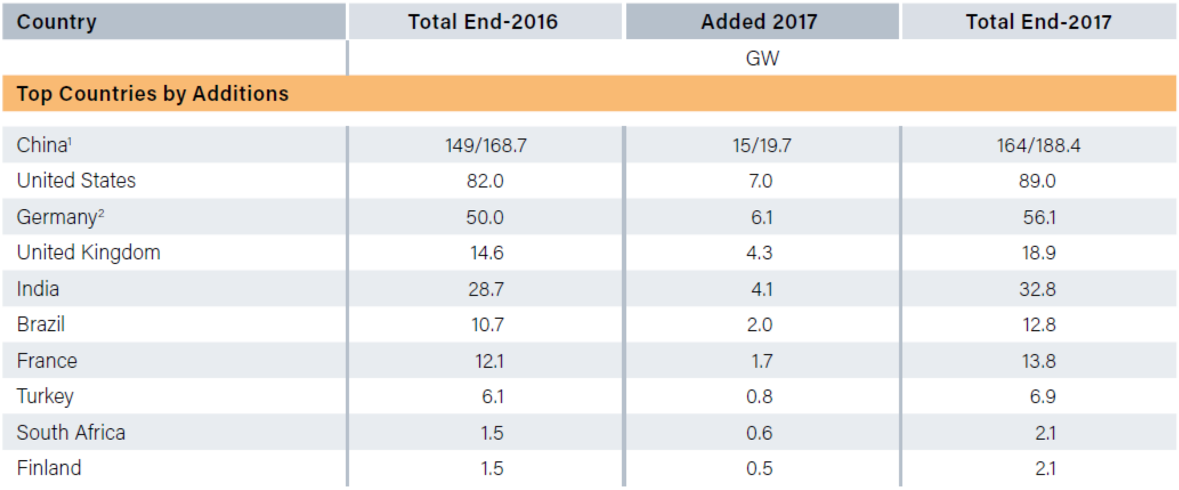


Figure 2-1: Share of total cost of an Large-scale Solar Photovoltaic project in Africa

Source: IRENA, 2018 [103]

Table 2-1: Increase in wind energy installed capacity in 2017 in the top 10 countries



Country	Total End-2016	Added 2017	Total End-2017
		GW	
Top Countries by Additions			
China[1]	149/168.7	15/19.7	164/188.4
United States	82.0	7.0	89.0
Germany[2]	50.0	6.1	56.1
United Kingdom	14.6	4.3	18.9
India	28.7	4.1	32.8
Brazil	10.7	2.0	12.8
France	12.1	1.7	13.8
Turkey	6.1	0.8	6.9
South Africa	1.5	0.6	2.1
Finland	1.5	0.5	2.1

Source: REN21, 2018 [101]

2.1.3 Hydropower

Hydropower generation in South Africa dates back to 1892 when gold mines were powered by two 6kW hydro turbines [104]. A report from South Africa's department of energy shows that as of 2015, there were six utility-scale hydropower projects developed as integrated power projects (IPPs), out of which three were developed under the Renewable Energy Independent Power Producer Procurement (REIPPP) programme and being fed into the grid. An aggregated 247MW hydroelectricity potential exploitable through small hydropower projects has also been identified especially in the Eastern Cape, Free state, and Kwazulu-Natal parts of the country [88]. According to the African Energy Portal being managed by the African Development Bank, the total installed capacity for hydropower generation in South Africa stood at 747.20MW in 2019 [105] from large and small-scale hydropower plants.

2.1.4 Biomass

The traditional use of biomass constitutes a high proportion of energy use in Africa, especially in the rural communities[106], [107]. South Africa has 42 million hectares of natural woodland and 1.35 million plantations and trees which produces 1.2 million tons of fuelwood which indicates a significantly high potential for energy generation from biomass[108]. For instance, in 2010, 80% of rural homes in South Africa relied on traditional wood fuel while charcoal accounted for 10% of its total primary energy use. However, there has been adoption and diffusion of biomass energy technology which enables clean and more efficient use of biomass. The two major industrial applications of biomass energy technologies in South Africa are power generation for paper packaging companies and sugar mills, both generating 201GWh of electricity from biomass annually. There are, also, diverse small-scale biogas plants generating heat for cooking from animal wastes and a few industrial-scale plants generating biofuel from municipal organic waste, sewage, and animal waste [109].

However, competition for land for food production and the need for diversity in crop production to protect land quality are two major concerns against plantations for energy generation from biomass. As of 2006, South Africa had 4300 km^2 (430,000 hectares) and 13,000km^2 (1,300,000 hectares) land area of sugar cane plantation[1] and forest respectively [110]. Apart from REIPPP, the government also commenced working on a Biomass Action Plan in 2014. This resulted in an increase in its installed capacity for biofuel and energy generation from waste from 246.0 MW which generated 280.3GWh of electricity in 2012 to 264.7MW that generated 350.9GWh in 2019 [105].

The implementation of the renewable energy policies and strategies resulted in transformational growth in renewable energy exploitation, especially solar energy, in South Africa which provides a *'model'* for other African countries.

2.2 Renewable energy policies and strategies

South Africa's White Paper on Energy Policy published in 1998 [111] sets the policy foundation for the country's renewable energy development. Before the adoption of the policy, 60% of the South African households had been electrified out of which more than a 2.4million were electrified between 1991-1997. The Paper established the interest of the government in the uptake of renewable energy. Before 1998, South Africa made no significant commitment to exploit its renewable energy potential due to the excess generating capacity (39,000MW) of its national utility company (ESKOM) which was above the national electricity demand of 28,330MW in 1997 [112]. The integration of the South African science and research community in the policy development architecture for renewable energy exploitation in the country enabled the government towards making realistic projections which informed its policy decisions. The white paper envisions that renewable energy technologies will be cost-effective and cost-competitive in the future as it is fast becoming in the present day. Renewable energy technologies were identified as the least expensive energy alternatives (especially with the

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[1] Sugar cane is one of the sugar-rich biomass with established conversion technology for production of biofuel **[109]** by burning bagasse (substrate of sugar cane).

inclusion of social and environmental costs) for delivering energy to remote areas that are not favoured by the economics of grid extension.

In 2003, the government developed the Working Paper on Renewable Energy (WPRE) which charted the course for the nation's energy transition with the first specific target (medium-term, 2003-2013) for the share of renewable energy in its energy mix. It also highlighted governance, finance, technology, education and research as five support pillars for meeting the targets. The government envisioned the development of solar, wind, biomass, and small hydropower plants with a cumulative capacity of 1,667MW (about 4% of the projected 41,539MW electricity generating capacity for 2013) to contribute 10,000GWh electricity to its projected final electricity consumption in 2013 [113]. The technical and financial support of development partners and the commitment of the government at the 2009 Copenhagen Conference of Parties (COP) to cut its emissions by 34% in 2020 and 42% by 2025 led to the massive roll-out of renewable energy projects across the country [114]. Also, the National Climate Change Response White Paper (NCCRWP) that was published in 2004 sets out the agenda of the government to reduce GHG emissions in strategic sectors. Given the domination of its energy sector by the fossil fuel and the depreciated plant efficiencies, the energy sector was the highest emitter of GHG emissions in the South African economy [115], thus, providing another thrust for renewable energy uptake in the country.

Moreover, the effort to reposition the South African electricity sector against the backdrop of the electricity 'blackout' (electricity crisis) experienced in 2008 generated additional motivation for South Africa's commitment to renewable energy uptake [116]. In addition to its commitment to off-grid renewable energy projects, in 2009, the government launched the Renewable Energy Feed-in-Tariff (REFiT) which attracted private sector investment for large scale renewable energy (on-grid) development by drawing on the experience of Germany in promoting the development of its renewable energy sector. This culminated in a competitive tendering scheme which has been identified as a strategy for affordability for consumers while ensuring profitability for investors [114], [117].

The government designed an Integrated Resource Plan (IRP) in 2010 which defined its long term (20 years) electricity generation plan by exploiting its various energy resources [118]. IRP outlines the vision of the government to add 17,800 MW of renewable energy-based electricity generation capacity to its energy mix by 2030. In 2012, South Africa adopted the Renewable Energy Independent Power Producer Procurement (REIPPP) programme. REIPPP programme was adopted to reduce the country's reliance on coal and nuclear energy by developing large scale renewable energy projects using various technologies with a total installed capacity of 17,800MW between 2012-2030, hence, reducing the country's emissions trajectory [87]. Through '*Ministerial Determinations*' which is being promoted by the 2016 Electricity Regulations Act [119], the government an envisions additional installed capacity of 3,275 MW by 2016, 3,200MW by 2020 and 6,300MW by 2025 (that is, 30% of its electricity mix) as intermediate additional targets because of realising its target of adding 17,800MW renewable energy generation capacity by 2030.

2.3 Policy Impact on Renewable Energy Development

The REIPPP programme, through a competitive bidding scheme, catalysed the development of grid-connected RE projects in South Africa [87]. Beacause the adoption of the REIPPP programme, the government selected, through competitive bidding (setting the tariff in the REFiT as the cap), twenty-eight (28) private investors to add more than a 140MW renewable energy generation capacity with an investment of USD16billion in 2011. An additional 36 renewable energy-based IPPs were also selected in 2013, also, through a bidding process such that by 2014, South Africa had approximately 1000MW of on-grid solar energy installed capacity that generated 213 GWh/month of electricity. Also, in 2014, South Africa had about 600MW on-grid wind energy installed capacity that produced 130 GWh/month and the projects are fairly distributed across the country (Figure 2-2 and Figure 2-3). As of 2015, 56 out of the IPPs that were selected through the bidding scheme added 2902 MW of electricity generating capacity from renewable energy to the grid resulting from an investment of more than R200billion (approximately USD14 billion) [120] constituting an additional 1902 MW in one year, about 190% increase from 2014.

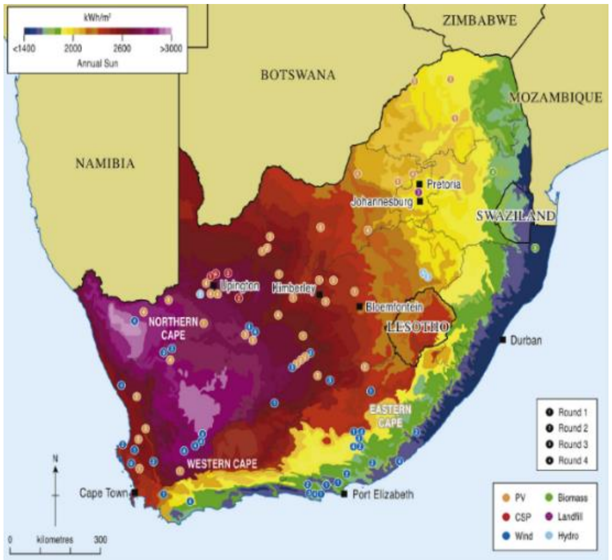

Figure 2-3: Distribution of renewable energy projects in South Africa

Source: McEwan , 2017 [97]

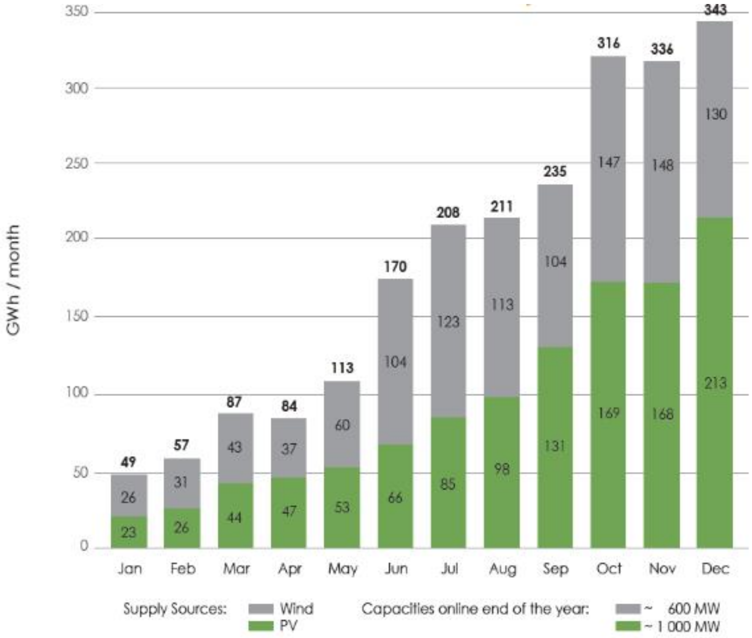

Figure 2-2: REIPPP growth in energy produced during 2014
Source: DoE, 2015 [88]

The REIPPP programme helped to diversify the South African electricity sector from one generating company to a multi-player sector led by the private sector [87], [98]. The development of utility-scale IPPs also helped to improve social equality among the poor black population who had been marginalized in access to services over the years [86]. Moreover, the integration of socio-economic development into the programme also facilitated the improvement of human livelihood in host communities [87]. The IPPs are required to contribute to social and economic development in communities within a 50 km radius from their respective plants, an initiative that has generated about 110,000 direct jobs. The development of the IPPs attracted over R53 billion (about USD3.7 billion) of foreign investment and financing out of which R35billion (about USD2.4 billion) is equity. The R35 billion foreign equity from the four rounds of bids through the REIPPP programme represents one-third of the total foreign direct investment (USD8.2 billion) in South Africa in 2013 [88]. The provision of guarantees by the government also reduced payment risks hence improving the bankability of the projects. All the IPPs, under the REIPPP programme, sell electricity to Eskom, the South African public utility company, and Eskom is required to pay for the electricity sold by the IPPs through Power Purchasing Agreements (PPAs) for up to 20 years. In the case that Eskom defaults, the payment guarantee by the government provides that the National Treasury of South Africa (NTSA) purchases and pays for electricity from IPPs. The second guarantee provides that the government pays the sponsors of IPPs in case of early termination of the projects by the government. The various support mechanisms and strategies for large scale project development of renewable energy projects resulted in the award of up to 112 IPPs in South Africa [121].

In addition to utility-scale projects, the total installed capacity of solar home systems (SHS) increased by 44MW without incentives from the government. In 2001, the government initiated the Rural Off-Grid Electrification Programme with an investment of more than R350million (approximately USD24 million) in the bid to achieve universal household electrification by 2012. Through the programme, more than 95,000 SHS were installed especially across regions that have been initially marginalised in the provision of access to electricity among other public services [88]. This represents a major contribution to increasing access to electricity in rural households in South Africa. In 2013, the government adopted a New Household Electrification Strategy with the vision to provide off-grid energy systems aimed at electrifying 300,000 households to attain 97% household electrification by 2025 [122], [123].

Whereas the development of renewable energy has contributed to local economy in the country especially with the requirement for IPPs to contribute to social and economic development in communities within 50 km radius from their respective plants, the South African renewable energy policies do not particularly integrate strategic and quantitative mechanism to facilitate and maximise the impact of renewable energy development on sustainable development in the country.

CHAPTER THREE

3 Renewable Energy Development: The Case of Egypt

Abstract

While its annual population and economy grow by 2.2% and 3% respectively, its electricity demand increases by 7% annually requiring an annual 2 GW increase in generation capacity, thus posing a challenge to the Egyptian energy landscape due to its limited fossil fuel reserve [124]. The limited fossil fuels vis-à-vis the increasing energy requirement in the country (due to the growing population and the need to power the Egyptian economic expansion) propelled the effort of the government to tap into the self-replenishing renewable energy sources available to the country. In this pursuit, the government developed and is implementing various policies and strategies that are facilitating plurality in its energy mix by exploiting renewable energy sources in the country especially solar and wind energy.

Despite generating 50-60% of its electricity from hydropower until the 1970s, the relative increase in the development of fossil-powered plants reduced the share of renewable energy from its energy mix. The high cost of electricity generation and the associated subsidy to boast affordability as well as the dominance of the energy sector in carbon emissions renewed the interest of the Egyptian government in renewable energy. Egypt has huge energy potential from various renewable energy sources, notably hydropower, solar, wind, and biomass. While a significant share of Egyptian hydropower is being exploited, the government revised existing laws, enacted a new law, adopted new policies as well as initiated programmes and strategies to catalyse the exploitation of solar and wind energy in the country with the aspiration that both energy sources will contribute 50% to its energy pool by 2050. In addition to its investment in the sector, the government provided an investment guarantee by the Egyptian Central Bank, power purchase agreement, revised import duties, reduce subsidies on fossil fuels, and increase electricity tariffs among other incentives to create enabling environment to attract renewable energy investment. The resulting private sector investment and foreign investment including the support of international finance corporations especially for large scale solar and wind energy projects resulted in significant progress in the exploitation of renewable energy in the country. As of 2019, renewable energy accounts for 5,972.3 MW of the 64,586.30MW cumulative installed capacity for electric power generation in the country. This comprises 2,850.80MW hydropower, 1,668MW solar, and 1,375.0MW wind energy installed capacities while diverse large scale projects remain under construction. The significant increase in renewable energy project development has increased the scale and scope of the renewable energy industry in Egypt given the development of human capacity, and patronage of local businesses, among others. Given the focus of the government on solar and wind energy, the exploitation of biomass energy has been limited to the effort of donors and non-governmental organisations as biomass are yet to be included in any of the government's programmes. The limited growth in the exploitation of biomass for electric power production despite the huge available resource versus the remarkable development of solar, wind and hydropower brings to the fore the crucial role of the government in facilitating the exploitation and use of renewable energy sources. Indeed, the sourcing of materials, components, and labour for the development of renewable energy projects locally led to an increase in the number of solar PV companies, creation of employment opportunities through sub-contractors in the long term for the operation and maintenance of renewable energy projects have altogether helped to boost the local economy. However, the Egyptian renewable energy policies do not integrate strategic and quantitative

mechanisms to facilitate and maximise the impact of renewable energy development to accelerate sustainable development in the country.

3.1 Renewable Energy Resources and Potential

The Middle East, and North African (MENA) region receives 22-26% of the total global solar radiation which is sufficient to generate solar energy per square kilometre per year equivalent to 1-2million barrels of oil [125]. Moreover, countries such as Morocco, Egypt, and Turkey also have the abundant potential for wind energy [126]. Despite the available potential, the progress in renewable energy exploitation in the region is relatively slow except in Egypt, Tunisia, Morocco, Jordan and Iran [127].

The effort towards increasing renewable energy generation in Egypt is largely in pursuit of diversifying its energy sector as a strategy to address several challenges within its energy sector. Namely, the high cost of electricity generation as 94% of its electricity is generated from fossil-power generation plants, high investment in energy subsidy, and increasing electricity demand especially at peak load [128] vis-à-vis to its limited fossil fuel reserve. Hence, the increased exploitation of renewable energy is to improve energy security in the country.

3.1.1 Hydropower

The concentration of about 94% of the Egyptian population the River Nile provides an insight into the significance of the river to the development and livelihood of the country. Until the 1970s, the hydropower generation from the River Nile accounted for 50-60% of total electricity generation in the country [103]. Egypt is estimated to have 3,664MW potential capacity and 15,300GWh electricity production per annum exploitable hydropower in Egypt [100]. While there is a perception that 95% of the Egyptian hydropower potential has been exploited, a recent study reveals that Egypt has sites for mini and micro-hydropower projects that are yet to be exploited. Based on the analysis of eight (8) selected sites using daily hydraulic data for 2017, the generation of an additional 200GWh of hydropower per annum was found to be technically feasible from the sites[128]. This may indicate the possibility of unidentified hydropower potential that is yet to be unexploited in the country.

3.1.2 Solar Energy

The location of Egypt in the global sunbelt makes it receive high solar insolation within its territories throughout the year which indicates an enormous potential for solar energy exploitation. Egypt receives an estimated 2900-3200 h annual sunshine hours and direct power density ranging between 1970-3200 kWh/m^2 [129], [130]. With uninhabited desert accounting for 94% of the country's 1,000,000 km^2 land area [131], Egypt is not limited by the land size requirement for the development of solar energy projects. This also provides the possibility of the development of large solar farms in the country especially along the North Coast [132].

3.1.3 Wind Energy

While many African countries are endowed with huge potential for solar energy, wind energy resource is not as widely distributed as the potential for solar energy. However, Egypt is one of the African countries with significant potential for wind energy exploitation. An evaluation of Egypt's potential for wind energy based on a 20-year (1973-1994) data collected from 15 anemometer meteorological stations distributed across the country reveals that Egypt has a high potential for wind energy uptake across the Red and Mediterranean Sea coasts and a lower potential in some interior locations[133].

Egypt has a significantly high wind speed ranging from 8-10.5m/s at 25m altitude and power intensity between 300-600W/m^2 which has been estimated to be sufficient to power more than 20,000MW wind energy installed capacity [130], [132], [134].

3.1.4 Biomass

Biomass is another renewable energy resource that is available in abundance from various sources in Egypt. Studies show that 15.3 million tons of municipal solid waste was produced in the country in 2001 (three-quarter being produced in the urban areas), 27 million tons of crop residue was generated in 2003 while 2 million tons of sewage was generated in 2008 [100]. Being Africa's largest producer of rice[22], Egypt could add significant electricity contribution to its energy pool using rice straw. Abdelhady shows that 3.1 million tons of rice straw produced in Egypt per annum is sufficient to generate 2,447GWh and reduce CO_2 emission by 1.2Mtons CO_2 annually in the country [135].

3.2 Renewable Energy Policies and Strategies

The Egyptian government began its effort towards renewable energy exploitation in the 1970s which culminated in the adoption of a renewable energy strategy and the setting up of the New and Renewable Energy Authority (NREA) in the 1980s [124]. Electricity generation in Egypt has been fossil-dominated [136] as 89% of the Egyptian electricity supply is generated from fossils fuels while renewables account for 11%, with hydropower representing 6-8% [137]. While its annual population and economy grow by 2.2% and 3% respectively, its electricity demand increases by 7% annually requiring an annual 2 GW increase in generation capacity, thus posing a challenge to the Egyptian energy landscape due to its limited fossil fuel reserve [124]. It has been estimated that only 1.5 billion barrels of the Egyptian oil reserve will be left by 2030 [136]. The limited fossil fuels vis-à-vis the increasing energy requirement in the country (due to the growing population and the need to power the Egyptian economic expansion) propelled the effort of the government to tap into the self-replenishing renewable energy sources available to the country. In this pursuit, the government developed and is implementing various policies and strategies that are facilitating plurality in its energy mix by exploiting renewable energy sources in the country especially solar and wind energy.

A Renewable Energy Master Plan financed by the European Union shows that with appropriate incentives, renewable energy, particularly wind and solar, could constitute 50% of the Egyptian energy pool by 2050. This may partly explain the commitment of the government to numerous renewable energy policies, strategies, and incentives. In its New National Renewable Energy Strategy published in 2008, the Egyptian government declared its ambition to produce 20% of its electric power from renewable energy sources by 2020 [124]. Of this proportion, 12% is designated to be generated from wind energy which is equivalent to 7200MW on-grid wind energy generating capacity. The targets were revised and set at 20% of its electric power from renewable energy sources by 2022 and 42% by 2035 [103]. Similarly, the government published its *solar plan* in 2012 which is aimed at adding 3,500MW installed capacity for solar energy generation (700MW of solar PV and 2800MW of CSP) by 2027 [138]–[140].

While the majority of the renewable energy generation capacity is envisioned to be developed through private investment, one-third is to be funded by the government with the support of international finance corporations. The Strategy outlines the plan of the government to attract foreign private players through the Competitive bidding scheme with the aim that the respective Feed-in-Tariff will be determined through the bidding scheme. The strategy also allows private investors to develop private renewable energy projects for private consumption and/or uptake to the national grid through Power Purchasing Agreements. The implementation of the Competitive Bidding Scheme resulted in the development of large scale renewable energy projects by private players through public finance supported by international financial organisations. Zero import duty for all renewable energy equipment and device, a long term power purchase agreement spanning 20-25years between the government and developers of independent power projects guaranteed by the Egyptian Central Bank among other strategies were adopted to de-risk private investment, thus attracting investors to the sector. The Strategy also layout the interest of the government to have renewable energy projects participate in Carbon Credit Scheme while setting up a dedicated public fund to subsidise the investment cost of private players while ensuring affordability for energy consumers. The Strategy also highlights the commitment of the government to research and development to increase the country's human and knowledge capitals on renewable energy.

While the Egyptian Electricity Transmission Company (EETC) has responsibility for the competitive bidding scheme, the provision of land for projects is domiciled with the New and Renewable Energy Authority (NREA). To demonstrate its readiness for investment and guide investors' decision-making, the government earmarked a 7600km^2 land area of the desert for RE projects and issued the permit for the land area to the NREA [103]. The government also conducted an environmental impact assessment of wind projects on the reserved land area.

In 2015, the government, through a Presidential Decree (No. 17/2015) reviewed its Investment law (No. 8/1997) to attract investment (including renewable energy) to the country. The law also provides for the provision of land at no cost or discounted fees for renewable energy projects [141]. By the revised law, the importation of renewable energy devices was set to attract a 2% duty while sales tax was reduced to 5%. In addition, the new energy investment law also committed the government to subsidise technical training programmes and provide for social insurance for employees of electricity producers to improve human capacity development in the energy sector.

Table 3-1 presents the relevant public stakeholders in the Egyptian renewable energy sector and their respective mandates. As the implementing agency, the NREA promotes electricity generation from renewable energy sources except for hydroelectricity which is being coordinated by the Hydro Power Plants Executive Authority (HPPEA). Because of ensuring quality control for standard installation, NREA developed a certification programme for solar PV installers which has already produced 100 PV installers in the country [124], [142]. Similarly, since the agency was set up by the government, several indoor and outdoor testing facilities have been established for quality assurance of renewable energy devices and equipment being allowed into the Egyptian renewable energy market [103].

Table 3-1: Institutional Framework of Renewable Energy Development in Egypt

Role	Institution	Specific Role
Planning	Supreme Council of Energy	Development of strategies for the energy sector and reports directly to the Egyptian Presidency
	Ministry of Electricity and Renewable Energy	Meeting the national electricity demand.
Regulation	Egyptian Electric Utility and Consumer Protection Regulatory Agency (EgyptERA)	Regulates the cost of electricity based on the interest of all stakeholders and ensures transparency in the electricity sector
Execution	Egyptian Electricity Holding Company (EEHC)	Deals with electricity supply to the consumers

	Egyptian Electricity Transmission Company (EETC)	Has the mandate for the operation and management of the transmission grid, and it operates with the electricity distribution company.

Based on Elkhayat, 2016 [124]

Towards cost competitiveness of renewable energy in Egypt

The substantial amount of subsidy on electricity and fossil fuels negatively impacts the cost-competitiveness of electricity generation from renewable energy[131]. Until the enactment of Law 203/2014, electricity tariff in the country was not cost-reflective. According to the World Bank, Egypt's energy subsidy accounted for 22% of the government's budget while subsidy on fossil fuels amounted to 7% of its GDP, more than the sum of the expenditure on health and education (5%) in 2013 [143].

The huge sum committed to the electricity sector as a subsidy had an adverse effect on the country, which necessitated the development of a self-sustaining electricity industry that ensures profitability for investors, and affordability for energy users. In this pursuit, the government announced, in 2014, an increase in electricity tariffs for various users because of reducing and ultimately phase out electricity subsidies within five years [142]. The domestic users will have a 10-20% increment annually (with the exemption of the lowest energy consuming user category), commercial users, about 7% while industrial users will have more than 20% increment every year till 2018. The government also increased the prices of various fossil fuels. The gradual reduction and eventual removal of subsidies on electricity were aimed at improving the cost competitiveness of renewable energy in the country.

3.3 Policy Impact on Renewable Energy Development

The remarkable growth in renewable energy exploitation in Egypt is traceable to the laws and strategies implemented by the government.

The significant growth in renewable energy investment in Egypt provides some indications of the impact of the various laws, policies and implementation strategies employed in the country. While the Egyptian renewable energy infrastructure built over 25 years has been estimated to be USD 1.3 billion, NREA awarded renewable energy (340 MW of wind farm and 60 MW Solar PV) contracts to the sum of USD 500million in the first six months of 2015.

The following presents the impact of laws, policies and implementation strategies adopted on renewable energy sources in Egypt.

3.3.1 Hydropower

Until the 1970s, hydropower generation from the River Nile accounted for 50-60% of the total electricity generation in the country [103]. Despite the increasing installation of hydropower (Figure 3-1), its share in the electricity mix declined over the years to 12% in 2012 [100] and 7.3% in 2016 [144] due to the more rapid development of gas-fired thermal generation power plants to meet the growing electricity demand. Out of the 3,664MW potential capacity and 15,300GWh electricity production per annum exploitable in Egypt [100], the country has developed 2,800MW installed capacity generating 13,545GWh mainly along River Nile (Table 3-2 and Figure 3-1) as of 2016. Hydroelectricity generation is mainly generated from five major hydropower projects that were developed on River Nile, namely High Dam (2100MW), Aswan I (280MW), Aswan II (270MW), Esna (85MW) and Naga Hamadi (64MW).

Table 3-2: Hydroelectric Power Plants and their capacities in Egypt

Station	Capacity (MW)	Annual Electricity Generation (GWh)
High dam	2,100	9,484
Aswan 1	280	1,578
Aswan 2	270	1,523
Esna	86	507
Naga Hamady	64	453
Total	2,800	13,545

Source: IRENA (2018) [103]

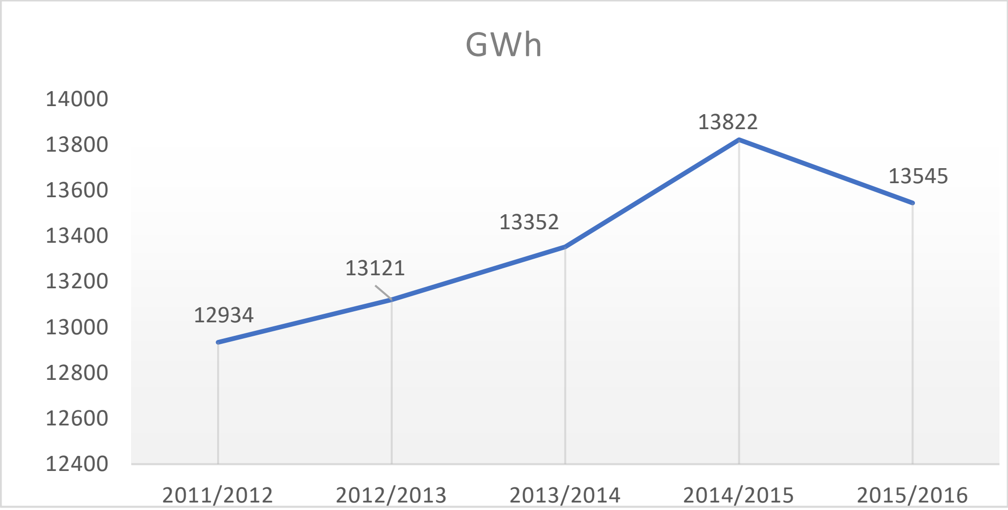

Figure 3-1: Electricity Generation from Hydropower between 2011 - 2016

Source: EEHC, 2016 [144]

3.3.2 Solar energy

Egypt has been a major target country for solar energy investment in recent years due to the high solar energy resource available to the country and the various policies and initiatives of the government. The adoption of concentrated solar power (CSP) technology in Egypt dates back to 1910 when an industrial scale set of solar parabolic collectors were installed in Cairo for water pumping for irrigation[132], while, the uptake of solar energy through the solar PV commenced in the country in the 1980s [103]. Since then, solar PV technology has been deployed for lighting, refrigeration, water pumping, and desalination among others applications in the country [145], [146].

The government launched various initiatives to support the deployment of small scale solar PV installations in the country [103]. The Cabinet of Ministers (CoM) Initiative mandated the installation of grid-connected solar PV on the rooftop of public buildings. Since the commencement of the initiative in 2013, 30 solar PV systems totalling 840kW have been installed. The total installed capacity of small solar PV in the country was estimated to be 6MW in 2013, of large scale plants was 30MW in 2016 [103] while the total installed capacity for solar energy rose to 1,668MW in 2019[147]. In addition, about 6,000 rooftop solar PV systems have been implemented in remote areas around the country [124].

In line with the New National Renewable Energy Strategy adopted in 2008, Egyptian Electricity Transmission Company (EETC) opened an auction for four renewable energy projects totalling 520MW (200 MW Solar PV, 250 MW Wind, and 50MW CSP at West Nile and another 20MW at Kom Ombo) generating capacity in 2015. Table 3-3 provides information about the various solar energy projects being developed under the Build-Own-Operate (BOO)[2], Engineering, Procurement and Construction (EPC)[3] and Integrated Power Project (IPP)[4] schemes and planned to be on-stream by 2023.

Table 3-3: Solar Photovoltaic Projects in view towards 2023

Project	Type	Status	Size	Contact
Kom Ombo	PV	Binding	200MW	BOO Scheme
West Nile	PV	Binding	600MW	Sky Power and EETCC BOO
West Nile		Binding	200MW	EETC BOO
West Nile		Binding	600MW	BOO scheme
FIT		Operational	50MW	EETC PPA
FIT		Under Development	1,415MW	EETC PPA
Hurghada		Tendering	20MW	NREA-JICA EPC scheme
Zaafarana		Under development	50MW	NREA-AFD EPC scheme
Kom Ombo		Under development	26MW	NREA-AFD EPC scheme
Kom Ombo		Under development	50MW	NREA-AFD EPC scheme

Note: BOO = build, own, operate; EETC = Egyptian Electricity Transmission Co.; PPA = power purchase agreement; NREA = New and Renewable Energy Authority (Egypt); JICA = Japan International Cooperation Agency; EPC = engineering, procurement and construction; AFD =French Development Agency (Agence Française de Développement).

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[2] Build-Own-Operate is a model for development of renewable energy project which involves the issuance of a right to construct a renewable energy project based on agreed specification and operate the same within an specific duration.

[3] Engineering, Procurement and Construction is a construction contract which allows the private organisations to take responsibility for the designing, procurement, implementation and commissioning of renewable energy project and hand it over to the government.

[4] Integrated Power Project is an non-government-funded power projects that generates electricity and sells to utilities and end-users

Source: IRENA, 2018 [103]

Through the UAE Rural Electrification Initiative, Egypt added 32MW to its cumulative solar PV installed capacity; comprising of 30MW cumulative capacity of centralised PV projects, and 2MW from 6942 stand-alone PV systems.

Since its launched the first tenders for large scale private renewable energy-based electricity under the BOO scheme in 2009, EETC has opened tenders for a cumulative capacity of 200MW of solar photovoltaic in 2013; 250MW wind, 200MW solar photovoltaic and 100MW CSP in 2015. The adoption of the New National Renewable Energy Strategy in 2015 followed the enactment of the Renewable Energy Law by Presidential Decree (Decree No. 203/2014) [148] which empowers the bidding mechanism for Build-Own-Operate (BOO) contracts. The Egyptian Electricity Regulatory Agency also developed regulations to reduce the risk and boost investors' confidence in the sector. The IPPs built under the BOO contracts with purchasing power agreements (PPAs) are allowed to sell electricity to EEHC or directly to electricity distribution companies. Due to the declining cost of renewable energy generation, the government adopted the competitive bidding (auction) procedure in 2017 for wind and solar energy projects. Projects can be implemented as a state-owned EPC contract or as IPP through PPA with EEHC using the BOO scheme [18], [103]. The BOO and IPP schemes catalysed the development of large scale renewable energy power plants with bidding opened for more than 1000MW capacity for solar and wind energy through the BOO scheme and three wind, solar and CSP projects with cumulative 1700MW installed capacity through the competitive bidding have been approved by the government [103].

Also, the Feed-in-Tariff (FiT) scheme was developed in 2014 to facilitate the development of small and large scale renewable energy projects towards achieving 2,000MW installed capacity each from solar and wind energy [124], [149]. The maximum capacity under the scheme for each project is set at 50MW with PPA for 20years for wind and 25years for solar energy projects. The FiT scheme catalysed the development of grid-connected PV systems (which also covers wind energy) such that a total of 10MW solar PV capacity was added to the grid at the end of the first phase of the FiT scheme in 2016. The scheme has now been revised and extended to large solar PV plants.

Through these various programmes and initiatives, the government received over 20bids for the development of various on-grid solar energy projects totaling 20,000MW capacity within 2years. In addition to the solar PV, Egypt has also developed a 140MW solar thermal combined power plant. This comprises 20MW of solar thermal capacity and 120MW from a gas-fired combined-cycle plant which altogether generated 164GWh of electricity in 2015/2016. The solar component of the project is estimated to save 10,000 tons of conventional fuel annually, hence, cutting 20,000 tons of CO_2 emissions [103].

3.3.3 Wind energy

As highlighted in the elucidation on the uptake of solar energy in Egypt; the FiT, Auction and Competitive Bidding schemes cover both solar and wind energy which are the two priority renewable energy sources of the government. Therefore, having discussed the schemes above, this section will be limited to the growth in wind energy uptake in Egypt.

Egypt commissioned its first wind farm with a 5.2MW total installed capacity in Hurghada in 1991. Another 63MW wind energy project was commissioned in 2000 and connected to the grid the following year. In 2006, the government developed a wind atlas which stratifies the country into regions based on their wind speeds [150]. The development of the atlas helped the government to identify viable locations for wind energy exploitation across the country. The capacity of the Hurghada wind farm was also increased to 305MW in 2007 and is now being expanded to add 1100MW to the Egyptian energy mix [100], [130], [151], [152].

In 2011, a series of large-scale wind energy farms (545MW) was commissioned in Zafarana. An additional 200MW capacity was installed in the Gulf of El Zayt in 2015 which was developed in cooperation with four European countries using the EPC scheme [100], [103], [144], [152]. The progressive growth in wind energy investment increased electricity generation from wind energy by approximately 790% in 4years, that is, from 260 GWh in 2011/2012 to 2058 GWh in 2015/2016. This resulted in increased savings of conventional fuel from 58Mtoe to 432Mtoe and CO_2 savings from 143,000 tons to 1.131 million tons within the same period [144].

Figure 3-2 shows the progression of electricity generation from wind energy while Table 3-4 provides an overview of proposed wind energy projects till 2023.

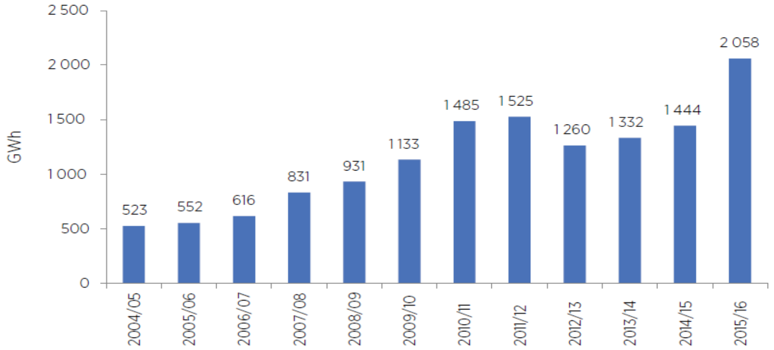

Figure 3-2: Electric power generation from wind energy (2004/05 - 2015/16)

Source: IRENA, 2018 [103]

Project	Technology	Status	Size	Contract
Gulf of Suez	Wind	Under development	250MW	NREA-KfW, EIB, AFD EPC Scheme
Gulf of Suez	Wind	Under development	250MW	GDF Suez, Toyota, Orascom BOO Scheme
Gulf of Suez	Wind	Under development	200MW	NREA-Masdar EPC scheme
Gulf of Suez	Wind	Under development	200MW	AFD-KfW EPC scheme
Gulf of Suez	Wind	Under development	2,000MW	Siemens EPC scheme
Gabal El Zayt	Wind	Under construction	220MW	NREA-Japan-JICA EPC scheme
Gabal El Zayt	Wind	Under construction	320MW	Italgen BOO scheme
Gabal El Zayt	Wind	Under construction	120MW	Spain-NREA
West Nile-1	Wind	Under development	250MW	Boo scheme

West Nile	Wind	Under development	200MW	Japan EPC scheme
West Nile	Wind	Tender-bidding Phase	600MW	NREA IPP scheme

Table 3-4: Proposed wind energy till 2023

Notes: AFD = Agence Française de Développement; EIB = European Investment Bank; JICA = Japan International Cooperation Agency

Source: IRENA, 2018 [103]

3.3.4 Biomass

Despite its abundant biomass potential, there are no records of significant exploitation of biomass for clean energy generation. Though the government has demonstrated an appreciable commitment to renewable energy development, through policies and initiatives, the focus has been on solar and wind energy in addition to increasing its hydropower generating capacity which has been in its

electricity mix over decades. Therefore, exploitation of biomass energy has been limited to the effort of donors and non-governmental organisations as biomass is yet to be included in any of the government's programmes. The limited growth in the exploitation of biomass for electric power production despite the huge available resource versus the remarkable development of solar, wind and hydropower brings to the fore the crucial role of the government in facilitating the exploitation and use of renewable energy resources.

3.4 Impact of renewable energy policies and strategies on sustainable development

The FiT scheme and the resulting increase in the development of large scale renewable energy projects (Table 3-5) in Egypt have made a significant positive impact on the development of the country. The sourcing of materials, components, and labour for the development of renewable energy projects locally led to an increase in the number of solar PV companies, creation of employment opportunities through sub-contractors in the long term for operation and maintenance have altogether helped to boost the local economy. The dedication of the desert for large scale RE projects has resulted in increased population density in the desert regions, hence, attracted social facilities and services like schools, hospitals, roads, and water supply in addition to electricity supply to the interior part of the country which had been previously unserved by social services. This is contributing to the decongestion of cities especially with the migration of skilled labours while increasing the economic profile of villages and towns around the areas where projects are being implemented.

Table 3-5: Ongoing Renewable energy projects

Capacity (MW)	Technology	Scheme	Scale
Wind	2,000	FiT	Utility
Wind	250	BOO	Utility
PV	2,000	FiT	Utility
PV	300	FiT	Rooftop
Wind	200	EPC	Utility
Wind	200	EPC	Utility

Source: Elkhayat, 2016 [124]

While there has been no empirical study that analyzed the employment benefits of the recent progress on renewable energy projects implemented in Egypt, findings from similar studies may provide some knowledge on the impact of the RE policies and strategies on employment in the country. Based on a study conducted by Estela Solar in 2008, the development of every 100MW solar thermal plant creates new 400 jobs in manufacturing, 600 jobs through contracts and installation and 30 annual jobs for management of the projects. Particularly, a scale-up investment plan designed by the World Bank and the African Development Bank for the MENA region shows that the development of 5 GW of CSP by 2020 in Egypt, Algeria, Jordan, Morocco, and Tunisia will generate employment for 64,000-79,000 people in these countries by 2025 [153].

Whereas the development of renewable energy has contributed to the local economy in the country especially in the desert region, the Egyptian renewable energy policies do not particularly integrate strategic and quantitative mechanism to facilitate and maximise the impact of renewable energy development on sustainable development in the country.

CHAPTER FOUR

4 Renewable Energy Development: The Case of Nigeria

Abstract

Nigeria has abundant resources for renewable energy generation available across its territory particularly, solar, hydro and biomass resources while its potential for wind energy generation is mainly within its middle belt region. Despite the availability of the resources, renewable energy exploitation in Nigeria remains low relative to its potential. The Nigeria electricity sector has undergone various institutional reforms towards improving the effectiveness of the sector and bridge the energy gap in the country. Diverse policies have been adopted and masterplan drawn with various provisions and incentives that could catalyse renewable energy development in Nigeria to address the energy access deficit in the country. However, the relative lack of the policies makes the challenges they were designed to address to persist. Since 1971 when hydropower contributed 83% of Nigeria's electricity generation, the share of hydropower generation in the Nigerian electricity mix has consistently declined largely due to the increasing development of the thermal plant in the country. The recent development of renewable energy projects has been mostly on solar energy solutions, mainly solar mini-grids, and solar home systems, nonetheless, solar energy uptake in the country remains low. Nigeria's first wind energy project in the middle belt has remained uncompleted more than 12years after its commencement while biomass is yet to receive major attention within government programmes.

4.1 Renewable Energy Resources and Potential

4.1.1 Hydropower

Nigeria has high technical and economic viabilities for hydropower generation. In addition to the potential for large hydropower plants mainly on River Niger, Nigeria has an estimated potential for 3500MW for small hydropower by tapping on diverse rivers in Nigeria [154], [155]. Studies have shown that Nigeria has the potential for a 12,954.2 MW hydroelectricity installed capacity that is yet to be exploited [27], [155], [156].

4.1.2 Solar

Nigeria receives solar radiation of 3.5–7.0 kWh/m^2-day for 5-6 hours/day throughout the year [157], [158]. Studies show that with state of the art of solar PV technology, the installation of PV on 1% of Nigeria's total surface area will be sufficient to generate 1,850,000 GWh of electricity per annum [159], [160]. Though the uptake of solar energy in Nigeria remains insignificantly small relative to the available potential, solar PV represents the most deployed renewable energy technology in the country apart from hydropower.

4.1.3 Wind energy

Unlike solar energy potential which has been proven to be sufficient for electricity generation across the country, the exploitable wind resource in the country is mostly in the middle belt region [161]. Nigeria has a wind speed ranging from 1.9 - 8m/s. To date, there is no significant exploitation of wind energy in the country.

4.1.4 Biomass

Nigeria has abundant biomass potential from fuelwood, crop residue, and municipal and solid waste among other sources which account for its 144 million tons of biomass potential annually[162]. Studies show that Nigeria uses 43.4million metric tons/year of fuelwood which has been estimated to have 6.0 x 10^6 MJ energy content. However, only 5-12% of the energy content is being converted to useful heat energy for cooking and other domestic applications based on the efficiencies of the technologies being employed [163]–[165]. The resulting fast loss of the vegetation induces various environmental concerns. Solid waste also constitutes a major energy resource that has remained largely untapped in Nigeria, especially in the major cities with high rates of waste generation. Lagos, with its over 21 million estimated population [166], is the most populous city in Nigeria and Africa, and produces over 9,000 metric tons of waste daily. Apart from contributing to Nigeria's energy pool, energy generation from solid waste will also reduce environmental pollution [167].

4.2 Renewable energy policies and strategies

The Nigerian Electricity Power Authority (NEPA), the successor of previous national electricity companies (Table 4-1), was the sole player in the Nigerian electricity sector with mandates for the generation, transmission, and distribution of electricity until 2005. In a bid to improve the effectiveness of the Nigerian electricity sector, the government enacted the Electric Power Sector Reform Act (EPSRA) in 2005 which mandated the unbundling and privatisation of the sector [168], [169]. The Act established the Power Holding Company of Nigeria (PHCN) and the Nigerian Electricity Regulatory Commission (NERC). While PHCN was established as a transient company through the period of the privatisation and handing over of the sector to private players, NERC was established to have the regulatory oversight of the sector.

The Energy Commission of Nigeria (ECN) developed the National Energy Policy (NEP) [170] to increase energy security by diversifying the Nigerian energy mix. The policy envisions the exploitation of renewable and non-renewable energy resources including energy efficiency strategies to facilitate sustainable development and achieve a 75% electrification rate by 2020. The policy promotes the need to increase the contribution of renewable energy to the Nigerian energy mix. ECN drafted the first edition of the policy in 1993 and revised it in 1996, an effort led by the Ministry of Science and Technology. While the policy was awaiting approval, the dynamic change in the economic landscape that has erupted over time, necessitated the revision of the 1996-revised version of the policy by an inter-ministerial committee. The revision was aimed at making the provisions of the policy attract private investment to the sector. The participation of the private sector is believed to be crucial to increasing investment in the sector while their profit-making objective would help to improve the managerial inadequacies in the sector. The policy was approved in 2003 and revised twice in 2013 and 2016 [171].

Table 4-1: History of the Nigerian electricity sector

Year	Reform
1886	A colony of Lagos installed two small power generating sets
1951	Electricity Corporation of Nigeria (ECN) Act of Parliament was established
1962	Niger Dams Authority (NDA) was established for the development of hydroelectric power: First 132 KV line
1972	ECN and NDA were merged and formed National Electric Power Authority (NEPA)
1990	Commissioning of Shiroro power station

2005	Power Sector Reform Bill was signed into law by President Olusegun Obasanjo, to enable private companies to participate in the electricity sector
2005	Establishment of the Power Holding Company of Nigeria (PHCN)
2005	Government commissioned independent power projects (IPPs) to generate and sell electricity to PHCN by increasing foreign participation in the electricity sector
2006	The six private generating companies and eleven private distribution companies were established
2006	Approval of construction of four thermal power plants with a combined capacity of 1,234MW
2013	Unbundling of the electricity sector, the dissolution of the PHCN and the establishment of the Nigerian Electricity Regulatory Commission (NERC) to monitor and regulate the electricity sector

Source: Ebhota and Tabakov, 2018 [154] (revised by author for the research)

The first Rural Electrification Strategy and Implementation Plan (RESIP) was developed for the Power Sector Reform team of the Bureau of Public Enterprise in 2006 and it outlines the rural electrification plan of the country till 2040 [172]. The plan outlines the vision of achieving a 75% electrification rate by 2020 which would necessitate annual electrification of about 471,000 households in rural communities till 2020 and over 513,000 households every year from 2020 to 2040. This was envisioned to be achieved through small- and large-scale energy projects from renewable and non-renewable energy sources.

By drawing on the first RESIP that was published in 2006 among other policies, including outcomes of workshops and consultations; the Nigerian Rural Electrification Agency (REA) developed a new RESIP [173]. The Plan was approved in July, 2016 for further implementation of the EPSRA that was enacted in 2005 and the Rural Electrification Policy prepared in 2005 and approved in 2009. The plan is to be implemented with the Rural Electrification Fund which is to be provided by the government among other stakeholders. The Fund will provide part-funding for renewable energy projects in rural communities. The government envisions attaining 75%, 90% and universal (100%) electrification access by 2020, 2030 and 2040 respectively through on-grid and off-grid solutions with not less than 10% electricity consumption being generated from renewable energy sources. Based on the plan, achieving these goals will require the annual electrification of additional 1.1 million rural households from 2015-2020 and 513,000 rural households from 2020-2040. This is projected to require total energy investments of USD 0.836–1.38 billion[5] from 2015-2020 and an equivalent of USD 1.33-2.18 billion (NGN 507.2 – NGN 830.2 billion)[6] from 2020-2040. This put the required total investment from 2015-2040 to achieve universal electrification by 2040 at USD 2.17–3.68 billion (NGN 825 billion and NGN 1.4 trillion).

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[5] The projected investment NGN 317.8 – NGN 525.8 billion is stated in the Nigerian local currency, Naira (NGN) and has been converted at an exchange rate of NGN 380 = USD 1 sourced from the Central Bank of Nigeria as of October 23, 2020. The same rate has been used for subsequent conversions

[6] at an exchange rate of NGN 380 = USD 1 of the Central Bank of Nigeria as of October 23, 2020

In 2012, the Renewable Energy Master Plan (REMP) was developed to exploit renewable energy resources in the country to increase energy access, especially in rural communities. The plan envisions the provision of energy access for the economic, social and environmental development of the nation [155]. The Plan also outlines fiscal incentives such as zero import duty on equipment for the manufacturing of renewable energy devices, and ten (10) years of tax holidays for new renewable energy companies while existing companies are to be charged 50% of the prevailing tax rate. The plan provides zero import duty on the importation of components for the development of Solar PV projects. The incentives also include a minimum of 10% tax rebates for individuals and organisations (that are subject to income and profit tax) who adopt renewable energy technologies at their private costs.

Moreover, the Nigerian Electricity Regulatory Commission (NERC) adopted the Multi-Year Tariff Order (MYTO) 1 in 2008 which outlines electricity prices to be charged by electricity-generation companies. The Multi-Year Tariff Order (MYTO) 2, the successor of MYTO 1, came into force in 2012, as amended in 2015 and was active till 2018 [174]. It outlines a new Feed-In-Tariff (FiT) for electricity produced from renewable energy and supplied to electricity distribution companies (DISCOs). The FiT is denominated based on the various energy technologies (onshore wind, ground-mounted solar PV, small hydro that are less than 30MW and biomass) to be cost-reflective and are subject to minor review once in six months based on local and international economic factors (such as local inflation rate and Naira-USD exchange rate) and major reviews once in five years. Based on the provisions of the Order (MYTO 2), considerations on the FiT will be given to companies that can demonstrate that the economic implications of their generation differ from the assumptions of the MYTO 2.

Also, because of decreasing the country's reliance on the importation of refined petroleum products, the government developed the Biofuel Blending Mandate in 2013 [175] which outlines the commitment of the government to the blending of petrol with up to 10% ethanol and diesel with 20% biodiesel.

To provide a specific policy structure for stakeholders with particular interests in renewable energy and energy efficiency (EE) policies, the Nigeria Renewable Energy and Energy Efficiency Policy (NREEEP) was developed mainly as an extraction from the Nigerian Energy Policy (NEP). NREEEP was approved in December 2015 and it outlines various targets for various renewable energy sources (Table 4-2) and various incentives to be provided by the government towards meeting the targets [176]. As strategies for overcoming the challenges of renewable energy development in Nigeria, the policy outlines various fiscal and financial incentives of the government covering the interests of investors and energy users in the country. Some of the fiscal incentives include:

i. Minimum of 10 years tax holidays for new renewable energy companies and 50% profit tax reduction for existing ones

ii. 10-25% tax rebate for individuals and organisations that acquire renewable energy technologies from their private funds (but the rebate should not be more than 10% of the total cost expended on renewable energy technologies)

iii. Zero import duty on imported renewable energy equipment and components

The financial incentives outlined in the policy include:

i. Provision of low-interest loans (not exceeding 5% interest) for renewable energy and energy efficiency projects from development financial agencies

ii. Provision of subsidies that covers up to 30% of the upfront cost of renewable energy and energy efficiency projects implemented as personal and organisational projects.

Table 4-2: Targets and timelines for electricity generation from renewable energy

S/N	**Resource**	**2012**	**Short Term (2015)**	**Medium Term (2020)**	**Long Term (2030)**
1	Hydro (LHP)	1,938.00	2,121.00	4,549.00	4,626.96
2	Hydro (SHP)	60.18	140.00	1,607.22	8,173.81
3	Solar	15	117.00	1,343.17	3,211.14
4	Biomass	-	55.00	631.41	3,211.14
5	Wind	10	50.00	57.40	291.92
All Renewables plus LHP		1,985.18	2,438.00	8,188.20	23,134.80
All Energy Resources (On-grid power plus 12,500MW of self-generated power)		21200	24,380	45,490	115,674
% of Renewables plus LHP		23%	10%	18%	20%
% RE Less LHP		0.8%	1.30%	8%	16%

Source: Ministry of Power, 2015 [176]

To attract investment for electricity generation from renewable energy sources, NERC put into force FiT for electricity generated from renewable energy sources. The new regulation also mandated electricity distribution companies (DISCOs) to procure 50% of electricity from renewable energy plants while the counterpart 50% should be procured from Nigeria Bulk Electricity Trading (NBET) Company. The regulation also grants automatic integration of electricity generated from small[7] renewable energy plants and the commission intends to adopt the bidding scheme to facilitate the implementation of large renewable energy projects.

In 2016, NERC developed the Mini-Grid Regulation [177] to boost investors' confidence by *'de-risking'* mini-grid investment in the country. The regulation categorised mini-grid projects into Isolated and Interconnected mini-grid projects. The difference is that inter-connected mini-grids are connected to distributions lines of a licensed DISCO covering the area. Also, interconnected mini-grids are operated in underserved communities while isolated mini-grids operate without connection to a distribution grid and are operated in unserved communities. An isolated mini-grid project with installed capacity below 100kW can either be operated as a 'Registered' mini-grid or mini-grid 'with Permit' while the development and operation of a mini-grid project with installed capacity above 100kW (100kW – 1MW) required the acquisition of Permit.

Mini-grids operated with permits are required to be developed and operated based on specified codes and standards, and operators must meet other associated requirements as stipulated by NERC. This includes that the tariff for electricity consumers should be calculated using the Multi-Year Tariff Order

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[7] a plant with capacity ranging from 1MW to 30MW

(MYTO) methodology. However, mini-grids operated as registered mini-grids are not required to meet the standards. The possession of a Permit assures the advantage of the recovery of investment cost should the electricity distribution company covering the area extend its network to the community being served by a mini-grid with a permit. The registration of the mini-grids, on the other hand, only helps the government to be able to track the evolution of mini-grids operating in the country. The regulation requires that potential operators who want to operate as Mini-Grid Permit Holders are required to confirm the eligibility of an unserved community and ascertain that there is no plan for the distribution company in the area to extend the grid to the target community within the following five (5) years after the implementation of the proposed mini-grid.

Apart from isolated mini-grids which are developed in unserved (off-grid) communities, the regulation also makes provisions for interconnected mini-grids that may be developed in underserved (connected but the low-quality of supply) communities. Each interconnected mini-grid is required to be operated "with Permit" and a require tripartite agreement between the developer, the community and the distribution company operating in the area. Table 4-3 summarises the various renewable energy policies, plans, and strategies that have been developed in the country.

Table 4-3: Summary of renewable energy policies in Nigeria

S/N	Policy Document	Highlight
1	Rural Electrification Strategy and Implementation Plan (2006)	• Attain a 75% Electrification rate by 2020 - Electrify 471,000 households annually in rural communities till 2020 • Attain universal electricity access by 2040 - Electrify 513,000 households annually in rural communities from 2020 - 2040
2	Electric Power Sector Reform Act (2005)	• Establishment of Power Holding Company of Nigeria (PHCN) in the interim of privatisation of the sector
3	Multi-Year Tariff Order (MYTO) I (2008-2013)	• Fed-in Tariff for Generating Companies (GENCOs) (2008 – 2013)
4	Nigeria Renewable Energy Master Plan (2011)	• Targets: renewable energy to contribute 13% of total electricity generation in 2015, 23% in 2025 and 36% by 2030 • Small-hydro: 600 MW in 2015 and 2, 000 MW by 2025; • Solar PV: 500 MW by 2025; • Biomass: 50 MW in 2015 and 400 MW by 2025; • Wind: 40 MW for wind energy by 2025;

		• Fiscal and Market Incentives
5	Multi-Year Tariff Order (MYTO) II (2012-2017)	• Provided Feed-in Tariff for renewable electricity subject to biannual minor reviews and major reviews once in five years
6	National Renewable Energy and Energy Efficiency Policy for Nigeria (2015)	• Interest of the government in RE development for large scale • Highlight fiscal and market incentives
7	Nigerian Electricity Regulatory Commission Mini-Grid Regulation (2016)	• Catalyse mini-grid development • De-risk the sector • Licensing: Registered and Mini-Grids with Permit
8	Nigeria Feed-in Tariff for Renewable Energy Sourced Electricity (2016)	• Feed-in Tariff for RE electricity

Source: Authors' elucidation

4.3 Policy Impact on Renewable Energy Development

Despite the development of various policies, strategies and regulations; the growth of renewable energy exploitation is slow relative to the available renewable energy sources and the energy deficiency in the country (Figure 4-1). Apart from large hydropower projects that were implemented over decades, the development of renewable energy projects in Nigeria has been largely limited to small scale solar energy applications. The following sections discuss the levels of exploitation of the various renewable energy potential in the country.

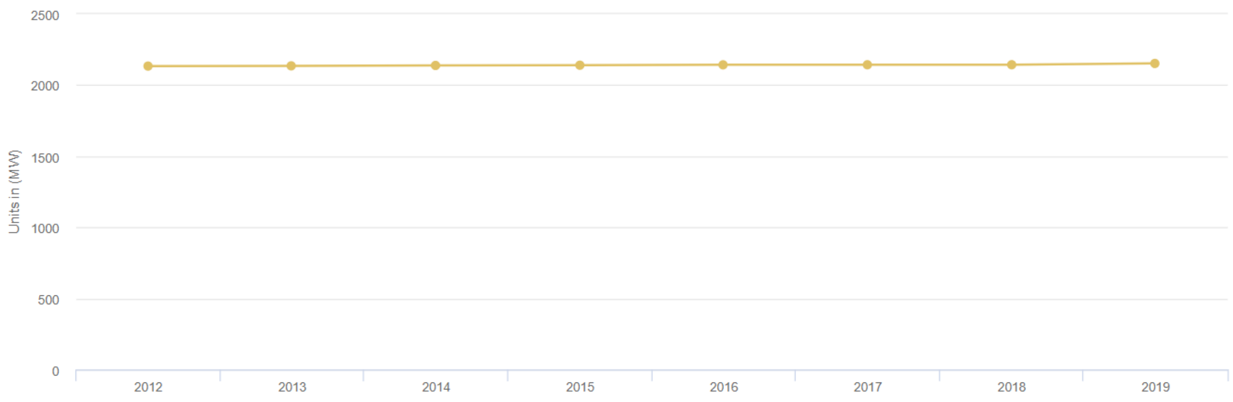

Figure 4-1: Renewable energy generation capacity in Nigeria

Source: African Energy Portal (managed by the African Development Bank), 2020

4.3.1 Hydropower

Since 1971 when hydropower contributed 83% of Nigeria's electricity generation, the share of hydropower generation in the Nigerian electricity mix has consistently declined largely due to the increasing development of the thermal plant in the country (Figure 4-2). Despite the high technical and economic viabilities for large and small hydropower generation in Nigeria, the total installed hydropower generation capacity stands at 1,938.4MW mainly from Kainji (760MW), Jebba (57.80MW) and Shiroro (600MW) dams on river Niger. Only 64.2MW out of the 3,500MW estimated potential for small hydropower in Nigeria has been exploited [154], [155]. Currently, Nigeria generates 6,985 GWh of electricity annually which represents about 21% of its proven potential. However, the development of a 3050MW Mambilla hydropower project which would have boosted hydropower generation in Nigeria commenced in 1982 [178] but has remained uncompleted to date (2022). Indeed, there is an increasing effort towards exploiting renewable energy potential in the country, yet, there is a limited effort on hydropower projects. Nonetheless, studies reveal that Nigeria has the potential for a 12,954.2 MW hydroelectricity installed capacity that is yet to be exploited [27], [155], [156].

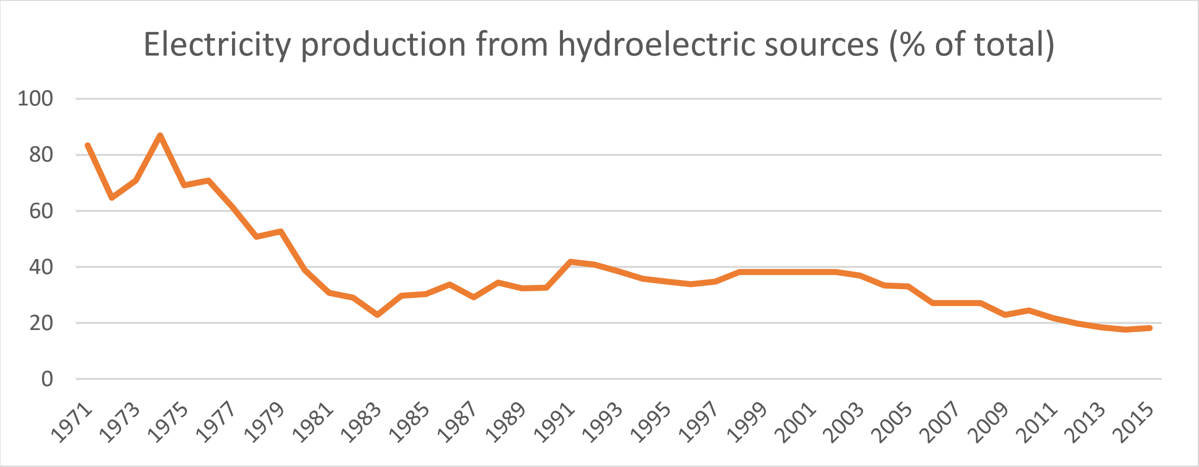

Figure 4-2: Electricity production from hydroelectric sources (% of total)

Source: African Energy Portal (managed by the African Development Bank), 2020

4.3.2 Solar energy

There has been increasing support for the deployment of solar PV for distributed energy generation in the country by development partners and multilateral organisations. Currently, several mini-grid projects have been developed in rural communities in Nigeria mostly not exceeding 100kW installed capacity. Also, in addition to solar home systems, street lighting, and, refrigeration of vaccines in hospitals are other common applications of solar PV technology in Nigeria. According to the African Development Bank, Nigeria has 29.95MW of Solar PV as of 2019 [179] relative to 427,000MW [160] estimated potential. There have been several Memorandum of Understanding (MoU) signed between foreign investors and the government for the implementation of large-scale renewable energy projects but are rarely developed years after the agreements were signed. For instance, a US-based energy company signed an MoU with the University of Ilorin in Kwara state of Nigeria to develop a 500MW solar energy plant worth USD 2.3 million. The project was planned to commence in May 2016 and to be completed by October 2016, six months after commencement[180]. To date, the project is yet to be developed. In 2012, the government of Kaduna state, one of the states in the northern part of Nigerian signed MoU with a German company to develop a 30MW solar energy plant worth 50 million

Euro in the state[181]. Similarly, the state also signed another an MoU with an Indian solar energy company to develop a 100MW solar energy plant in the state [182]. None of the projects have been developed to date. These are typical of several large scale renewable energy projects planned to be developed in various parts of the country by foreign private investors that are yet to be developed. This may suggest concerns on the policy environment and the administrative bottlenecks on large scale renewable energy investments in Nigeria.

However, the renewable energy sub-sector recently began to receive a boost with funding for rural electrification from the government, the World Bank and the Africa Development Bank [183]. This has resulted in the development of two public-funded solar hybrid projects in two public universities in the country; namely 2.8MW at Alex Ekwueme Federal University and a 7.1 MW at Bayero University. The projects were developed within the Energizing Education Programme by the Rural Electrification Agency which aims to develop 28.5MW of solar hybrid projects during its first phase with a target of 89.6 MW during its second phase[184]. Moreover, the federal government also commissioned a 1.52MW solar power plant to generate electricity for three Federal ministries, namely; the Ministry of Works and Housing, the Ministry of Environment and the Ministry of Lands in the nation's Federal Capital Territory.

4.3.3 Wind energy

The government commenced the development of Nigeria's first major wind energy project with a capacity of 10MW in Katsina state but the project has remained uncompleted 10years (2020) after its commencement of the project [100]. The various reasons identified by stakeholders for the non-completion of the project highlight the need to reduce the coordination and administrative bottlenecks in the implementation of renewable energy projects as well as the state of security in the country [185], [186].

4.3.4 Biomass

Biomass constitute approximately 80% of total primary energy in Nigeria [162] but mostly through traditional and inefficient energy technologies such as a three-stone fire place. Despite its huge biomass potential in Nigeria, the aspirations of Nigeria in renewable energy generation from biomass are relatively insignificant compared to other renewable energy resources in the country (Table 4-4). The four electricity supply aspirations from various fuel sources developed based on electricity's four GDP growth rates: 7%, 10%, 11.5% and 13%, reflect a neglect of electricity generation from biomass as presented in the National Energy Master Plan[187]**.** For instance, based on the scenario that the GDP grows at 7%, Nigeria envisioned a cumulative 3MW, 16MW, 35MW, and 54MW electricity generation capacity from biomass as against, its aspiration for 1369MW, 3455MW, 7000MW, 25917MW total installed capacity for solar energy respectively in 2015, 2020, 2025 and 2030 respectively.

The low ambition of the government in exploiting biomass for renewable energy is also reflected in the relative neglect of biomass in government action for renewable energy development in the country. Apart from several small scale pilot projects, most effort for renewable energy generation from biomass is largely laboratory works in Nigerian universities [28] and the effort of small scale businesses and non-governmental organisations.

Table 4-4: Electricity supply projection by Source (MW): for GDP growth rate at 7%

Fuel	2009 (Base Year)	2015	2020	2025	2030
Coal	0	1850	6527	7545	10984
Electricity import	0	0	0	0	31948
Gas	3803	18679	33711	61891	80560
Hydro (Large and small)	1930	3043	6533	6533	6533
Nuclear	0	1000	1500	2500	3500
Small Hydro	20	172	409	894	1886
Solar	0	1369	3455	7000	25917
Wind	0	19	22	25	29
Biomass	0	3	16	35	54

Source: National Energy Master Plan [187].

CHAPTER FIVE

5 Comparative Analysis of Renewable Energy Policies for Energy Access in South Africa, Egypt and Nigeria

Abstract

Nigeria, South Africa, and Egypt make up the top three largest economies in Africa and the trio have huge renewable energy resources. By taking the cases of the three countries, the study analyses the giant strides made in the uptake of renewable energy in Africa and identifies some of the major challenges facing many African countries in developing their renewable energy sectors. South Africa and Egypt provide cases of transformational growth in the uptake of renewable energy driven by market-oriented policies and strategies, while, the Nigerian case typifies policy constraints that limit the optimal exploitation of renewable energy in various countries in Africa. The analysis of the Nigerian case reveals specific challenges in the policy and institutional landscape that impede the uptake of renewable energy and use in the country, which if addressed could catalyse renewable energy integration in Nigeria, among other African countries that are faced with similar challenges. Based on the experience of South Africa and Egypt, actionable recommendations that are realistic in the African context are made towards addressing the challenges.

5.1 Motivation for Comparative Analysis

Diverse studies have examined various themes on renewable energy development in Nigeria, South Africa and Egypt in separate case studies with various recommendations for the respective countries [188]–[194]. Most of the studies on renewable energy development in the selected countries have analysed renewable energy development in each of the countries in separate studies. There are also several comparative studies, some comparing of one of the countries with other non-African countries, others compared the countries with other African countries, and others are focused on a particular renewable energy technology or scale. However, there are limited review and comparative studies that compare renewable energy development in one or more of the three countries to facilitate learning. The analysis of comparative studies in multiple countries that include one or more of Nigeria, South Africa, and Egypt is presented in Table 5-1 to identify the gaps in literature from which this study derives its unique contributions.

Table 5-1: Relevant Comparative Analysis and Review

S/N	Author	Objective and Methodology	Countries Examined	Relevant Findings and Recommendations
1	Amandine Nakumuryango and Roula Inglesi-Lotz, 2016 [195]	compares South Africa's renewable energy development with those of OECD and other African countries by analysing their respective renewable energy generation, use and share in the energy mix	South Africa, Other African countries, OECD countries	despite the high share of fossil in its energy mix, South Africa leads renewable energy development in Africa, however, it ranks below OECD countries, hence, has room for improvement

2	Akintande et al., 2020 [196]	using a Bayesian Model Averaging approach, the authors developed a model for renewable energy consumption in Africa's top five most populous countries	Nigeria, South Africa, Egypt, Ethiopia and the Democratic Republic of Congo	increase in population, energy demand, electricity use, and development of human power are major factors that influence renewable energy use in the selected countries
3	Olanrewaju et al., 2019 [197]	conducted a panel data analysis to examine the pattern of renewable energy consumption in the top five most populous and largest economies in Africa.	Nigeria, South Africa, Egypt, Ethiopia and the Democratic Republic of Congo	- natural gas rent is positively correlated with RE generation and use while energy and carbon intensities, oil rents and coal rents have negative correlation with the exploitation and use of renewable energy - recommends a higher tax rate on fossil fuels to subsidise renewable energy development
4	Lakshmi Pathak and Kavita Shah, 2019 [198]	compares the renewable energy resources, polices and energy deficiencies in the five developing countries among the top 10 energy-consuming countries in the world (BRICS countries)	Brazil, Russia, India, China and South Africa (BRICS countries)	-While South Africa is coal-rich and needs to improve on its policies, it has made remarkable progress in renewable energy development and provides examples for other. - A catalysed commitment to renewable energy generation started in South Africa in 2014 with the target to reduce its carbon emissions - renewable energy development could further be catalysed by paying attention to on-conventional renewable energy sources in the country including the provision of subsidies and tax exemptions
5	Abubakar Kair Aliyu Babangida Modu Chee Wei Tan, 2018 [22]	review of the development of renewable energy in South Africa, Egypt and Nigeria	South Africa, Egypt and Nigeria	- highlighted the need for appropriate technology, skills and awareness are crucial to renewable energy development - identified policy regulation as a factor for the varying

				level of growth in the renewable energy sectors of the three countries - Focused on the technology-related challenges to highlight the need for improved energy efficiency, an extension of the grid, advanced technologies for energy storage and seasonality changes to increase renewable energy generation
6	Abdullahi Abubaka Mas'ud Asan Vernyuy Wirba Jorge Alfredo Ardila-Rey, 2017 [199]	review wind energy potentials and development in Cameroon and Nigeria, and drew lessons from wind energy development in South Africa	South Africa, Cameroon and Nigeria	- the commitment of the government and private sector is crucial to wind energy exploitation and development - there is a need to secure more donor funding - project failure can be minimised by ensuring effective project procurement strategies and the development of feed-in-tariff for wind energy
7	I.M. Bugaje, 2006 [200]	reviews energy policies in South Africa, Egypt, Nigeria, and Mali; and how they are contributing towards addressing their respective energy challenges	South Africa, Egypt, Nigeria, and Mali	- deployment of solar PV technology to meet non-industrial energy uses such as schools, clinics, and homes - need for policy development to drive the diffusion of solar thermal technologies for heating and cooking - development of local capacities for the local manufacturing of improved cookstoves - establishment of centres for information dissemination and guidance on energy appliances and use

8	Tyeler Matsuo, 2019 [201]	examined the impact of their varying approaches and results in diverse auction designs of large scale renewable energy projects and the development of the renewable energy industry in the two countries	South Africa and Mexico	- the development of renewable energy comes with a trade-off hence the need to develop strategies would minimise the undesirable impact of the trade-off - While the increasing attention on renewable energy would facilitate the path to decarbonisation, it will also increase reliance on foreign renewable energy value chain if renewable energy development is implemented without complementary effort to develop local capacities.

Source: Authors' elucidation

Indeed, the existing literature made contributions to knowledge but mostly focused on technology and economic dimensions of renewable energy. Some of the factors of focus and recommendations in the studies include seasonality and unreliability of renewable energy resources, high upfront cost, prevailing prices of conventional energy sources including taxes and subsidies, energy and carbon intensities, and trend of energy demand, among other technology and economic factors [195] [196] [197] [198].

A number of the studies highlight policy and regulation as a crucial factor that influences the progress in renewable energy development [22],[200]. However, there still exists a dearth of knowledge on detailed and comparative analysis of renewable energy policies, regulations and institutional frameworks in the selected countries, a need the study addresses. Based on the detailed analysis of the policy and regulatory frameworks conducted in chapter 2 (for South Africa) chapter 3 (for Egypt) and chapter 4 (for Nigeria), the study also makes a unique contribution to the extensive review and comparative analysis of the institutional frameworks of the three countries.

5.2 Policy Implications

Despite the existence of various policies among other regulatory instruments, the uptake of renewable energy resources in Nigeria has been minimal relative to the potentials available in the country. Several authors have identified that the barriers to renewable energy development in Nigeria are typical of the challenges of renewable energy sectors in other developing countries, especially in Africa. Meanwhile, the approaches of South Africa and Egypt provide some successful models ('*best practices*') which could provide actionable strategies to fast-track renewable energy development in Nigeria among other African countries. Based on the approaches and experience of South Africa and Egypt, the following strategies were identified to have been crucial in catalysing renewable energy integration, and, could provide guideposts for Nigeria among other African countries:

i. **Timely approval and implementation of policies:** Extended delays in the approval of policies pose challenges to the relevance of the policies and their effectiveness. As found in the Nigerian case study, Nigeria's first National Energy Policy was developed in 1993 and reviewed in 1996 while awaiting approval. Due to the extended delay in the approval of the policy, changes in the economic dynamics necessitated another review of the policy before it was approved in 2003. A related challenge to the delays in approval is the delay in the implementation of the policies. Despite the approval of the Nigeria Renewable Energy and Energy Efficiency Policy (NREEEP), there has been no significant implementation of the policy, hence, the challenges the policy seeks to address persist in the sector. The NREEEP which was approved in 2015, provides for various incentives such as zero import duty, tax holidays for new actors in the sector and a 50% reduction from the prevailing tax rates for existing actors, among others. Due to a lack of implementation, the impact of this policy is yet to be visible in the sector. This aligns with findings by Sesan [202] for the Nigerian case, who highlights that there is a poor effort towards policy implementation in Nigeria. Indeed, various regulations, policies and incentive mechanisms for energy access have been developed to address the barriers to renewable energy development in many African countries. However, the barriers subsist due to the lack of implementation of those policies and incentives.

The analysis of renewable energy development in South Africa and Egypt emphasises the need for effective coordination of various institutions of the government with mandates on renewable development in African countries. This is crucial to ensure timely approval of policies, and removal of delay in policy implantation that has constituted barriers to the development of large scale renewable energy projects in many African nations. In addition, the participation of civil society organisations (CSOs) in the sector is needful to pressurise the government for policy actions and follow-up on the implementation.

ii. **Intermediate review of policies:** The Nigerian case shows that some of the policies and regulatory instruments in the Nigerian renewable energy sub-sector were reviewed within their lifespan, however, some of the reviews became necessary due to extended delays in the approval of the policy. As presented in the Nigerian case study, the Nigerian Energy Policy (NEP) which was drafted in 1993 has been reviewed four times. Two of the reviews were carried out before the approval of the policy due to the approximately ten-year delay in its approval while the other two reviews have been conducted after its approval in 2003. MYTO 2, which came into force in 2012 was also amended in 2015 and active until 2018.

The experience of South Africa and Egypt highlight the relevance of intermediate reviews of policies during their lifespan. Many times, real-life realities differ from the assumptions which form the basis for policy design, hence, the need for intermediate reviews of policies and implementation strategies to re-orient the policies to fit into current realities to make more realistic projections. Such reviews should be based on the impact of the policies, lessons learnt, and the new realities of the sector and the economy at large at the local and global levels. This will help to ensure the effectiveness of renewable energy policies and strategies employed in the sector.

iii. **Integration of socio-economic development into renewable energy projects:** The relationship between energy access and development is multi-directional. Not only does energy access facilitate the development of other sectors, the development of other sectors of the economy is also crucial to energy access projects. Nigeria's first major wind energy project is a 10MW wind farm in Katsina state which has remained uncompleted for more than 10years (2020) after its commencement. Whereas there is no official report from the government on the reasons for the delay, media interviews with the contractor highlight that inadequate coordination of the project between the national and the sub-national (state) governments, and, the kidnapping of expatriates are some of the reasons for the incompletion of the project.

However, the REIPPP programme in South Africa mandates developers of IPPs to contribute to the development of communities within a 50km radius from their sites. As discussed in the South African case study, the strategy catalysed the development of the communities where large scale renewable energy projects have been developed. Such an approach, if adapted to the contexts of other African countries, would also help to improve the relationship between project developers and the host communities in African countries. This would help to build a sense of ownership in the host communities, thus, ensuring the commitment of target communities and fostering the security of the project facilities and the contractors working on the project.

iv. **Development of standard codes, testing facilities and training courses:** The deployment of low-quality renewable energy components and equipment has been identified to be a reason for the early failure of renewable energy systems in Nigeria which led to mistrust of solar PV technology, especially at the early stage of the adoption of the technology in the country [203]. This calls for the development of standard codes, testing facilities and training of professionals for quality assurance of the renewable energy devices and equipment imported into the country. In addition to the poor quality of products, the poor technical know-how of engineers and technicians leads to poor installation and inadequate maintenance are two other factors that also contribute to the early failure of renewable energy projects. This may suggest the need for the development of courses to improve the competencies of the renewable energy workforce in Nigeria. Indeed, several organisations that offer training for solar PV installers in Nigeria. For instance, the Nigeria Energy Support Programme (NESP) being implemented by GIZ has supported several private organisations to offer some renewable energy courses.

The Egyptian strategy for renewable energy development is complemented by quality assurance and human capacity building. The development of testing laboratories and training courses in Egypt helped to prevent the diffusion of renewable energy devices and equipment of poor quality in the country while the courses helped to raise the renewable energy workforce with adequate competencies in the country. A high level of quality assurance is crucial to building confidence and trust in adopters and users of renewable energy technologies for sustainable uptake and integration of renewable energy in the African energy mix. Similarly, the development of certification training for installers of renewable energy technologies as well as the development of degree programmes on renewable energy within the Nigerian university system will be of significant contributions to renewable energy development in the country. These will help to prevent the infiltration of low-quality renewable energy products and also raise human capital with adequate capacity and competence of renewable energy engineers and technicians for the development and maintenance of renewable energy projects.

v. **Enactment of renewable energy laws:** The development of renewable energy in Africa requires not only policies and strategies, but also laws that will enforce the implementation of the policies and the associated strategies. The adoption of the Egyptian New National Renewable Energy Strategy in 2015 followed the enactment of the Renewable Energy Law by Presidential Decree (Decree No. 203/2014) which put into force the build-own-operate (BOO) mechanism that catalysed large scale renewable energy project development in Egypt.

Also, the government of Egypt, through a Presidential Decree (No. 17/2015), reviewed the Investment Law (No. 8/1997) through which the Egyptian government reduced various import duties and taxes including the provision of subsidies to attract renewable energy investment to the country. The Nigeria Renewable Energy and Energy Efficiency Policy (NREEEP) and Renewable Energy Master Plan (REMP) also make similar provisions for various incentives such as zero import duty, tax holidays for new actors in the sector and a 50% reduction from the prevailing tax rates for existing actors, among others. However, the provisions are yet to make an impact in the sector due to delays in their implementation. Drawing on the Egyptian approach, the enactment of laws that would foster the implementation of the various mechanisms, provisions, and incentives embedded in NREEEP and REMP will help to facilitate the development of renewable energy in Nigeria. Moreover, the implementation of policies may also be affected by changes in government, therefore, the enactment of laws to enforce renewable energy policies would ensure the sustainability of policies, thus, promoting investors' confidence in the policies given the long term nature of renewable energy investments.

vi. **Grid reliability:** The high upfront initial financial commitment for the development of renewable energy especially solar PV technology constitutes a strong barrier to the uptake of renewable energy in Nigeria, among other developing countries. However, the cost of batteries constitutes a high share of solar PV projects, especially with the need for the replacements of the batteries at intervals during the lifecycle of the projects. As discussed in previous sections, the cost of battery constitute up to 57% of the lifecycle cost of solar mini-grids. Therefore, the development of on-grid solar energy systems would result in a decline in the investment costs of solar energy systems for investors and increase the affordability of tariff by consumers. Despite the advantage of grid-connected solar energy systems, the low reliability of the Nigerian electricity grid network poses a barrier to the development of such systems in the country, hence, the need for improvement in the reliability of the national grid. There is a need to improve the reliability of the electricity grid in African countries as this would facilitate investment in on-grid renewable energy project thus eliminating the cost of batteries in renewable energy development.

vii. **Large scale renewable energy investment:** There is a need for the adoption and implementation of dedicated policies, strategies and incentives targeted at the development of large scale renewable energy projects in Nigeria. This may also include an improvement in the coordination of the institutional framework on renewable energy in Nigeria. In addition to the large hydropower plants that have been developed decades ago, investment in renewable energy in Nigeria has been largely limited to solar home systems and solar mini-grids mostly not exceeding 100kW capacity. There have been several Memorandum of Understanding (MoU) signed between foreign investors and the government for the implementation of large-scale renewable energy projects but none has been developed years after the agreements were signed. For instance, a US-based solar energy company signed an MoU with the University of Ilorin in Kwara state of Nigeria to develop a 500MW solar energy plant worth USD 2.3 billion. The project was planned to commence in May 2016 and to be completed by October 2016, six months after commencement [204], [205]. To date, the project is yet to be developed. In 2012, the government of Kaduna state, one of the states in the northern region of Nigerian signed an MoU with a German company to develop a 30MW solar energy plant worth Euro 50 million in the state[181]. Similarly, the state also signed another an MoU with an Indian solar energy company to develop a 100MW solar energy plant in the state [182]. However, none of the projects has been developed to date. These are typical of several large scale solar energy projects planned to be developed in various parts of the country by foreign private investors that are yet to be developed.

An improvement in the coordination between the various institutions with mandates within the energy sector in African countries may also be considered. The Nigerian Federal Ministry of Power has the mandate to develop energy policies while the Energy Commission of Nigeria (ECN) has the responsibility to implement the policies and energy planning [206]. The coordination of ECN by the Ministry of Science and Technology may impede effectiveness in its interactions with the Ministry of Power in coordinating the sector.

In Egypt and South Africa, on the other hand, the governments emphasised their commitments to large scale renewable energy project through the various policies and implementation strategies targeted at large scale renewable energy investment. The implementation of the policies and strategies contributed largely to the increasing growth in large scale renewable energy investments in the two countries.

viii. **Diversification of renewable energy uptake:** There is a need for the Nigerian government among other stakeholders who are active in renewable energy exploitation to diversify their interest to tap into other renewable energy resources to address the energy access deficit in the country. While the policies and institutional framework developed cover various technologies required to exploit the renewable energy sources in Nigeria, most of the programmes and support mechanisms by the government, multilateral organisations, and development partners, among other stakeholders have been focused on solar PV technology for the exploitation of solar energy. There is no significant effort toward the exploitation of other renewable energy sources in the country. However, the ability of Nigeria to reduce the energy supply deficit in the country will largely depend on its effort to tap the diverse renewable energy sources available in the country.

South Africa and Egypt have benefited from diversifying their renewable energy mix. The governments of the two countries adopted and implemented support mechanisms covering the various renewable energy sources that are available in their countries. The support mechanisms provide the bedrock for simultaneous exploitation of various renewable energy sources in the two countries and as a result, both countries have recorded significant progress in the uptake of renewable energy, especially from solar, wind and hydropower[8].

5.3 Conclusion

The 600 million people without access to electricity across Africa depict the deficiency of the African energy architecture. The availability of huge and diverse renewable energy potential provides alternative energy resources that could be exploited o fast track energy access across the continent. However, electricity generation in Africa has been dominated by fossil fuels, therefore, the integration of renewable energy sources in the African electricity mix requires a new paradigm in its energy sector.

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[8] The generation of energy from biomass is also growing in South Africa especially with the development of small scale plants while the uptake of energy from biomass in Egypt is limited to the effort of donors and non-governmental organisations as biomass has not being included in any of the programmes of the Egyptian government.

Being unconventional energy sources, the exploitation of renewable energy sources comes with multidimensional challenges especially in developing economies.

The study analysis renewable energy exploitation and use in Africa by taking the case of South Africa, Egypt, and Nigeria which are the three largest African economies and all possess abundant renewable energy sources. South Africa and Egypt provide cases of transformational growth in the uptake of renewable energies driven by market-oriented policies and strategies with active support and contributions of the government that cover the various dimensions of renewable energy development. The Nigerian case, on the other hand, exemplifies multidimensional constraints faced by many African countries that limit the optimal exploitation of their renewable energy sources. Based on the significant progress made in renewable energy development recorded in South Africa and Egypt, the study discusses the various policies and programmes including the implementation strategies guiding the renewable energy sector in the two countries. By drawing from the experience, approach and results in the two countries, recommendations were made for other African countries, taking the case of Nigeria, which, if adapted to their local context, could facilitate renewable energy development, especially through private sector investment for utility-scale renewable energy projects. It is crucial to highlight that the thesis is not intended to compare whether the effectiveness of large and small scale renewable energy projects in facilitating the uptake of renewable energy.

In summary, the study highlights the need for a holistic and system-wide institutional and regulatory instrument for the deployment and diffusion of renewable energy technologies. Such instruments should also include actionable strategies for the underlining fiscal and financial instruments required to mobilize investment to the sector, without forgetting the relevance of capacity building to required manpower.

Publication:

The review and comparative analysis of renewable energy development in South Africa, Nigeria and Egypt has been published as a chapter (Chapter 10) in the peer reviewed, Scopus and web of science indexed book, *"Renewable Energy for Sustainable Growth Assessment"*.

Adeleke, F. Inzoli, and E. Colombo, "Renewable Energy Development in Africa: Lessons and Policy Recommendations from South Africa, Egypt, and Nigeria," in *Renewable Energy for Sustainable Growth Assessment*, Scrivener Publishing LLC, 2022, pp. 259–300. ISBN: 9781119785361

Part Two

Part II - Energy Access and Sustainable Development in National Context

The 2030 Agenda was promoted as an 'integrated' framework based its inclusion of the economic, social and environmental dimensions of sustainable development. Since the adoption of the agenda, there has being continuous effort towards establishing the inter-linkages between the economic, social and environmental dimensions. Meanwhile, energy access has been widely acknowledged as pivotal to facilitating sustainable development. As a contribution towards facilitating the energy planning that maximises impact on overall sustainable development at the national level, a system dynamics model was developed for investigation, evaluation and analysis of various national energisation strategies and roadmaps for Nigeria and plausible impact on sustainable development in Nigeria. The model will facilitate the formulation of appropriate energy policies, resource allocation of energy intervention funds, and budgetary allocations in determining optimum energy mix and high leverage complementary actions that can promote the effectiveness of energy access programmes and strategies.

Having gained insight into national energy policies, the study modelled the impact of energy access policies on the sustainable development at the national level based on the complex interactions between energy access and other sectors of the economy. Given the multiple interconnections, interlinkages, feedback, time-dependencies, and non-linear behaviors in energy-development nexus, a system dynamics model was developed. Being calibrated (using the World Bank data for Nigeria) and tested. The results shows the ability of the model to capture the observed historical behaviour of the system showed by data with 9.86% (highly accurate) and 11.55% (good) Mean Average Percent Errors for total energy demand (input) and the GDP (overall output of the model) respectively. Further testing by the disintegration of the of the Mean-Square-Error (MSE) into bias, unequal variation and unequal covariation using the theil statistic further affirms the usefulness of the model for the formulation, analysis and critical evaluation of various energy policies and plausible impact on sustainable development in Nigeria.

CHAPTER SIX

6 Modelling Policies for Energy Access and their impact on the Sustainable Development Goals (SDGs) in National Context

6.1 Materials and Method

While realising sustainable development is being promoted as the objective of renewable energy development, particularly for energy access in developing countries; the review of national renewable energy policies and strategies in Nigeria, South Africa and Egypt reveals no strategic integration of other themes of sustainable development in their national renewable energy policies. Indeed, South Africa mandated developers of renewable energy-based independent power producers (IPP) to 'contribute' to the development of communities located within a 50km radius from the location of their plants. Yet, this does not provide a plan and strategic integration of renewable energy projects in the overall sustainable development framework of the country.

Nigeria has been a target country for various support programmes aimed at improving the Nigerian energy sector. The USD 200 million loan from the African Development Bank [207], the Germany-EU funded Nigeria Energy Support Programme, World Bank's USD 486 million grant to improve electricity transmission and ESMAP's USD 150 million from the World Bank for off-grid energy access are a few examples. Many of the intervention funds have been dedicated to rural electrification especially through mini-grids to provide electricity for household and productive use to facilitate sustainable development in rural communities. In 2013, a private energy company commissioned a 6kW mini-grid project in Nigeria that has been operational and sustained over time [208]. Since then, there has been various mini-grid projects developed across the country mostly powered by solar energy. Whereas northern Nigeria receives more solar radiation (9.0kWh/m^2/day) than the south with a minimum solar radiation of 3.5kWh/m^2/day [209], the sustainability of various mini-grid projects developed across the country has proven the technical viability of solar mini-grids in all parts of the country. To date, more than 11 mini-grids [206] have been developed in Nigeria to provide energy access in unserved off-grid rural communities with various funding initiatives for energy access in Nigeria. Other funding supports are targeted at supporting the government to strengthen the capacity of the national electricity grid such as the World Bank's USD 486 million grant to Nigeria to improve electricity transmission in the country.

Given the increasing attention of the government, international organisations and development partners, among other stakeholders towards improving the conditions of energy access in Nigeria, the study contribute by developing an open-source model to support the planning and design of effective and sustainable energy policies that will ensure efficient and effective resource allocation and use of the available funds to maximise the development impact of energy access projects. The overall objective is to support sustainable development in the country by enabling the development of effective energy polices, hence, the model integrates nine other sectors of the Nigerian economy. Given the various evidence from the literature on the need for complementary actions to maximise the impact of energy intervention projects [36], the intended use of the model is also to test various resource allocation strategies which consider the use of a share of the available energy funds to support complementary actions in other sectors that are crucial for the effectiveness of the impact of energy access.

Given the multiple interconnections, time-dependencies, and non-linear behaviours in the energy-development nexus, a system thinking approach supported by a simulation-based tool is advised [210].

As identified section 1.1.2, the energy access-development nexus is a complex systems whose interactions are non-linear, characterized by feedbacks and delays between interventions and impact. Complex system are generally defined as systems who characteristics are not defined by the summation those of its interconnected components, which are free to act unpredictably [211][212]. The interconnection of the components of the system facilitates the adaptive ability of the system to exogenous factors [213]. System Dynamics and Agent-based Modelling are two major modelling approaches to complex systems, each with its peculiarities which determines the suitability of their use [212].

System Dynamics is a modelling tool for capturing, visualizing, investigating, analysing, and evaluating the non linear behaviours of complex systems over time horizon leveraging the causal relationships and feedbacks within the systems. Stock (or levels), flows (or rate), converters and connectors are the four building blocks of a system dynamics model. The stock accumulates the difference between inflows and outflows, hence responsible for the delay in the system while flows are functions of the stocks. While inflows are rate of increase of the stock, outflows are rates of its depletion. The converters integrates appropriate parameters in the model while the connectors are information transmitter connecting elements in the model [212]. Agent-based Modelling (ABM) is a dynamic modelling approach with an ability for learning, adaptive capacity, heterogeneity, autonomy, local interaction, bounded rationality and non-equilibrium dynamic characteristics. ABM is an effective cross-scale modeling approach that combines time dimension with space dimension and characterized by heterogeneity, space discretization, time discretization, and discrete states [212]. A major draw back on the adequacy of ABM for the study is that ABM ignores the feedback between the components in complex system, which is a characteristic feature of energy-development. Energy-development nexus is multidimensional, non-linear and a complex dynamics of several underlying linkages of several factors and comprises of diverse feedback mechanisms and whose impacts are delayed in time[75][26][36]–[38]. Moreover, while the model being developed is aimed at analysing and projecting the impact of energy access on development over a long term, ABM is not suited for simulation over a long period. ABM is implemented with programming languages (such as C, and Java) or specialized tool kit (such as NetLogo), thus, increasing the technicality of the approach and the level of specialty its requires [212].

System Dynamics is a simulation-based tool for characterising complex systems that captures the characteristic non-linearity, time delays and feedback. As presented in the literature review, system dynamics has been applied in modeling the interdependencies in complex systems in development interventions including business operations, among other sectors. The approach was also employed in modelling endogenous complexities between rural electrification and socio-economic development in rural communities as a PhD thesis by Fabio Riva [210] in the department of energy (Politecnico di Milano). While Fabio's work examined the complexity of energy access-development at the sub-national level (in Tanzania), the thesis in view builds on this path by modelling energy access-development at the national (Nigeria) context. Therefore, System Dynamics was selected as the simulation-based tool to critically investigate, evaluate, and analyse different energisation strategies and roadmaps for Nigeria, to inform future energy policy options to support sustainable development at the national level.

Based on the model development process as categorized by Sterman [215], the model development can be divided into a five-step procedure, namely; problem scoping, conceptualisation, formulation, testing and validation, and policy design and evaluation.

6.1.1 Problem Scoping

This covers activities aimed at understanding the background or context of the system to define the problem. While this is covered through the review of literature discussed above in this study, problem scoping in other contexts, such as organisations and businesses, could involve engagement of clients, workshops, focus group discussions, and interviews among others. The entire model captures 10 sectors, namely; Energy, Health, Education, Land, Infrastructure, Finance, Gross Domestic Product (GDP), Population, Households, and Government.

The following section describes the model conceptualisation which captures the linkages and causalities between the sectors endogenously integrated into the model. The formulation process transformed the causal loop diagrams into the model by integrating the underlying integral, differential and algebraic equations. The model is also calibrated using Nigerian data collected from the World Bank database.

6.1.2 Model conceptualisation

This entails the selection of key variables, definition of the model boundary (the scope of the model), selection of time horizon, the description of the historical behaviour of the (reference modes) of the key variables and conceptualisation of the feedback loops through the feedback diagrams. A crucial outcome of the model conceptualisation process is the feedback loop diagrams which determine the dynamics of the model.

A causal loop diagram (CLD) provides a pictorial view of the interactions between the key variables in the system relevant to the problem to be modelled. CLD comprises variables and their causal linkages represented by arrows. The arrows connect independent variables (variables at the tail of the arrow) to the dependent variables at the arrowhead (at the arrowhead). Each arrow has either a positive (+) or negative (-) sign, which indicates the kind of relationship between the independent and dependent variables. A *positive (+) sign* represents that a change (increase/decrease) in the independent variable will lead to a change in the *same* direction (increase/decrease respectively) in the dependent variable than what it would have otherwise been. Conversely, a *negative (-) sign* indicates that a change (increase/decrease) in the independent variable will lead to a change in the *opposite* direction (decrease/increase respectively) in the dependent variable than what it would have otherwise been.

Causal Loops diagrams are developed based on the modellers' understanding of the problem garnered from various sources. Such sources include literature, policies, case studies, focus group discussion, news stories, and documentaries, including stakeholders' experience and expert judgement that provide a descriptive and in-depth understanding of the problem. Feedback loops, which are traced out from the causal loop diagrams, present the descriptive dynamics that will underline the model. For instance, the following descriptive analysis on the dynamics of renewable energy, consumption of crude oil and GDP are three of the feedback loops that underscore the dynamics of the model as presented in Figure 6-1.

The nature of the feedback in each loop is indicated with a Loop Identifier. A Loop Identifier starting with a loop identifier **R** indicates a Reinforcing Feedback Loop while **B** represent a balancing Loop. The causal linkages in a loop is Reinforcing (positive) if a change in a variable travels across variables

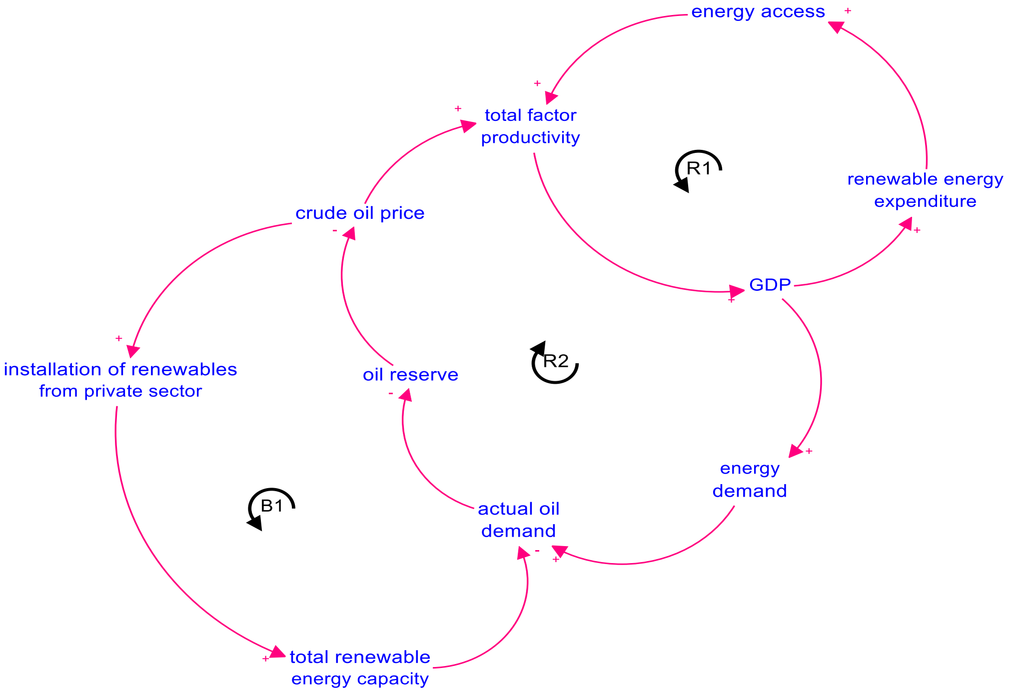

Figure 6-1: Causal Loop Diagram showing the dynamics of renewable energy, consumption of crude oil and GDP

in the loop and returns to the variable causing it to further change in the same direction. Conversely, a loop is Balancing (negative) if a change in a variable travels through the chain of the causal relations and returns to the same variable with a change in the opposite direction.

The validity of the dynamics presented in Figure 6-1 is established in the literature. Based on an analysis of data using cross-sectional autoregressive distributed lags (CS-ARDL) in 25 countries, Sohag *et al* [216] report that investment into renewable energy uptake for new energy market contribute to the total factor productivity (energy access →total factor productivity), with emphasis that a higher share of renewable energy promote total factor productivity in the long run. Arazmuradov *et al* also report that, total factor productivity positively impact the gross domestic product (total factor productivity → GDP) [217] and indeed, the higher the GDP, the more the availability of resources to expend on renewable energy (GDP → renewable energy expenditure).

Mishra et al [218] finds that gross domestic product positively impact energy consumption [218], with energy consumption being influenced by energy demand (GDP → energy demand). An increase in energy demand will increase the demand for oil in an oil-dependent economy like Nigeria (energy demand → oil demand). Increased oil production to meet the energy demand negatively impact oil reserve as it reduces the volume of oil reserve(energy demand → oil reserve). A decrease in oil reserves reduces the supply of oil which, according to Alfred Marshal's law of demand and supply, increases the price of oil (oil reserve → crude oil price). The price of crude oil has a positive or negative impact on productivity depending on whether the country is an exporter or importer of oil respectively. Jumbri and Managi [219] established that the price of oil impacts the overall economic productivity(crude oil price → total factor productivity). An increase in crude oil price increases revenue for oil-exporting countries which boosts their economic productivity.

In a study on the impact of oil prices on renewable energy investment in African countries with an energy deficit, Tambari and Failler [220] find renewable energy investment has a positive response to oil shock. That is, an increase in oil price leads to spur energy investment into the installation of renewable energy to increase the contribution to the overall energy demand (crude oil price → installation of renewables from private sector →total renewable energy capacity → actual oil demand) which aligns with economic principles, being competitive commodities.

Figure 6-1 presents three causal loop diagrams which show the causalities between key energy variables and those of the national gross domestic product (GDP). The causal loop diagrams show the qualitative integration of renewable energy into the energy mix impacts energy consumption and the gross domestic product (GDP).

R1 (Reinforcing loop): energy access → total factor productivity → GDP → renewable energy expenditures → energy access

Increasing energy access increases the total factor productivity, that is, the efficiency of a combination of factors of production, thereby increasing GDP which increases the share of resources available for renewable energy investment thus increasing energy access.

R2 (Reinforcing loop): GDP → energy demand → actual oil demand → oil reserves → crude oil price → total factor productivity → GDP

An increase in GDP increases the size of the economy (e.g businesses) which requires more energy hence an increase in the demand for crude oil thereby reducing the oil reserves. Following the law of demand, the price of oil increase as the available reserve of oil decreases hence necessitating improvement in technology of production to facilitate an increase in productivity, hence, an increase in GDP.

B1 (Balancing loop): Installation of renewables from private sector → total renewable energy capacity → actual oil demand → oil reserve → crude oil price → Installation of renewables from the private sector

Investment in renewable energy increases the total renewable energy capacity thus reducing the volume of crude oil required for energy generation. The reduction in oil demand reduces the amount of oil exploration (thus increasing the amount of oil in the reserve) thus reducing oil price. The reduction in oil price leads to an increase in the interest in oil for energy production thus reducing renewable energy installation.

The three loops show the causalities between energy access, GDP, Oil reserves, and how renewable energy interventions affect the dynamics. R1 and R2 reflect the fossil fuel-dominated energy sector in Nigeria showing a continuous increase in GDP by increasing energy access, however, leading to continuous depletion of the oil reserve which is finite in nature, hence unsustainable. The balancing loop B1 explains how the renewable energy intervention could be used to achieve an increase in GDP by increasing energy access yet reducing the depletion of oil reserves.

6.1.3 Model formulation

Feedback loop shows the nature of the qualitative impact (increase or decrease) of one variable on another by polarity, however, the formulation phase helps to specify it is crucial to know 'at what rate' and 'by how much' which are specified at the formulation stage. The formulation of the system dynamics model describes the process of transforming the feedback loops into *stock* and *flow* diagrams (SFD) with algebraic, differential and integral equations including the use of *parameters* required to specify the mathematical structure of the model.

Figure 6-2: Stock and flow diagram

Models are abstract of realities, therefore, problems are modelled, not the system, if not. the model will be as complicated as the system it seeks to abstract. Hence, the need to identify model boundary in terms of limiting the variables of the system to be included in the model. In principle, in transforming the feedback loops (which include only key variables) into stock and flow diagrams, the variables that directly influences the key variables are modelled endogenously while the indirect variables which impact the key variable through the direct variables are taken exogenously, hence, becomes the enveloping variables.

The formulation stage resulted in 363 variables and 250 equations which has been detailed in the Appendix. In addition, the set of equations below present the mathematical principle which underline the formation of the equations. Moreover, given that the GDP requires the integration the Cobb Douglas Production function, the details of the formulation of the equations for GDP is also provided below to further present the formulation phase of the modelling process. The complete equations are presented in the Appendix.

Stocks are variables in the systems dynamics model which accumulates over time, while the flows (inflow and outflow) are rate of change (differential) of the stock. While the inflow is the value by which the stock increase per unit time, the outflow is the value by which the stock decreases per unit time. Therefore, the value of the stock at any given time, is the integral of the net flow (inflow minus outflow) added to the initial value of the stock, that is Stock (0) [221] as presented in equations 6-1 and 6-2

$$S\,(t) = S\,(t_0) + \int_{t_0}^{t} [I(s) - O(s)]ds \qquad 6\text{-}1$$

$$\frac{d\,[S(t) - S(t_0)]}{dt} = I\,(s) - O(s) \qquad 6\text{-}2$$

S = Stock

t_0 = initial time

I = Inflow

O = Outflow

t = any given time within the model horizon

In addition to stocks and flows, auxiliary variables are commonly used in system dynamics models to aid the formulation of flow equations. The formulation of many flow equations in system dynamics model encapsulate many principles or concepts, thus, capturing multiple principles in a single flow equation makes it complicated and confusing. As a rule of thumb, every equation in a system dynamic model is supposed to represent only one principle: hence the need for Auxiliary Variables. They are used in formulating complex rate equations thus helping in model clarity. The auxiliary variables ('helping' variables) are incorporated in the model as they are needed to help to break down the complicated rate equations into several variable equations such that each variable captures only one principle.

The complexity of system dynamic models makes it complicated to be solved using analytical methods, hence, system dynamitists employ computer simulation to approximate the model behaviour given its ability to perform iterative computations in a discrete short time.

The simulations of the model are performed by applying Euler's integration method using STELLA Architect software. While the simulations are carried out by the software, it is crucial to understand the underlining mathematical principles:

Net flow is a derivative of the stock (S) over time (t), that is, a function of the value of the stock and time as presented in equation 6-3.

$$Net\ Flow = \frac{dS}{dt} = f(S,t) \qquad \text{6-3}$$

Mathematically,

$$\frac{dS}{dt} = \lim_{\Delta t \to 0} \frac{\Delta S}{\Delta t} \qquad \text{6-4}$$

that is, for a very small time step

$$\frac{\Delta S}{\Delta t} = \frac{S_k - S_0}{t_k - t_0} = f(S_0, t_0) \qquad \text{6-5}$$

Therefore,

$$S_k = S_0 + f(S_0, t_0)(t_k - t_0) \ (k) \qquad \text{6-6}$$

Where S_k and S_0 are the values of the stock at time t_k and t_0 respectively and

$$\Delta t = (t_k - t_0) \tag{6-7}$$

which should be a short discrete time.

Therefore, the first iteration from the time t_0 is

$$S_1 = S_0 + f(S_0, t_0) \cdot \Delta t \tag{6-8}$$

The second iteration from time t_1 based on the first iteration, till final time t_k

$$S_2 = S_1 + f(S_1, t_1) \cdot \Delta t \tag{6-9}$$

Subsequent iterations continue till the last iteration at time t_k

$$S_k = S_{k-1} + f(S_{k-1}, t_{k-1}) \cdot \Delta t \tag{6-10}$$

Therefore, the number of iterations n is given by

$$n = \frac{t_k - t_0}{\Delta t} \tag{6-11}$$

Euler's integration method is applied in the model using the Stella Architect software which solves all the equations in the model for every discrete time-step *dt* specified in the model (Table 6-1)

Table 6-1: Model settings

Time unit	**Year**
Time step $\boldsymbol{\Delta t}$	1/16 (=0.0625)
Start time $(\boldsymbol{t_0})$	1990
Final time $(\boldsymbol{t_k})$	2015

As an illustration of the stock and flow diagrams and the underlying equations in the model, Figure Figure 6-3 shows the Stock and Flow diagram for the energy sector which presents the dynamics of the oil price, investment in renewable energy and energy access.

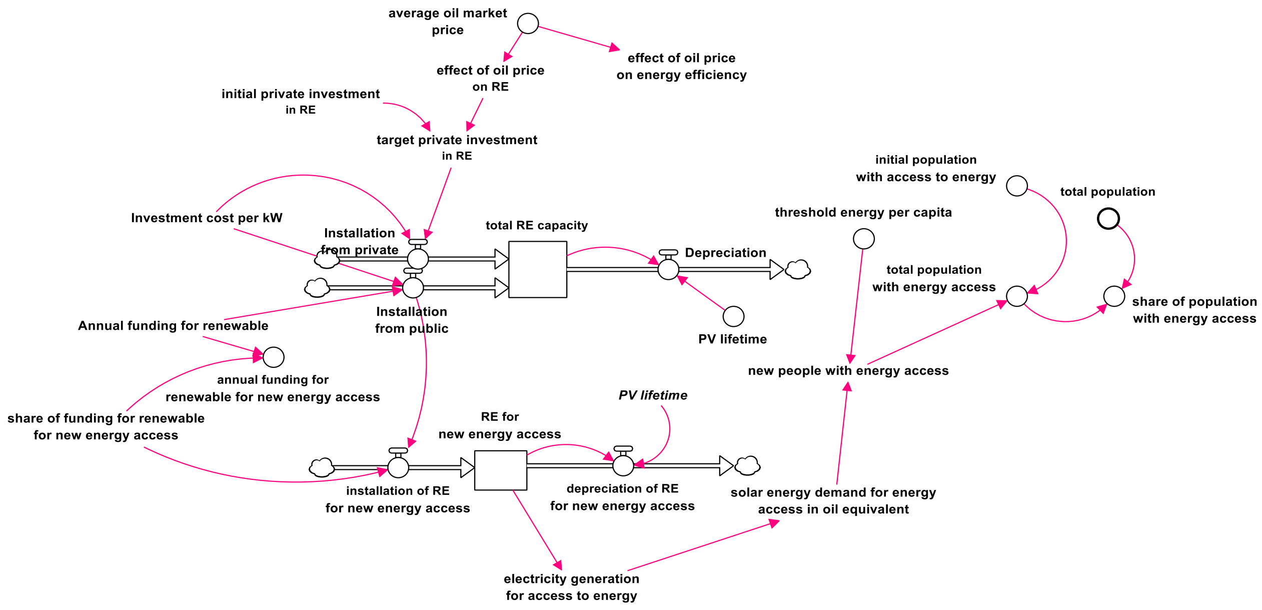

Figure 6-3: Formulation of the stock-and-flow model for the energy sector

An example of mathematical formulation is represented below:

Total Renewable Energy Capacity ("Total RE Capacity") is given by:

$$C\ (t) = C\ (t_0)\ + \int_{t_0}^{t} \left[I_v(t) - I_p(t) \right] dt \qquad \text{6-12}$$

C = total installed renewable energy capacity ("Total RE Capacity")

C = total installed renewable energy capacity ("Total RE Capacity")

I_v = rate of installation of renewable energy capacity from private sector

I_p = rate of installation of renewable energy capacity from public sector

t_0 = initial time in the time horizon of the model

t = any time t over the time horizon of the model

$$\frac{\boldsymbol{d\ [C(t) - C\ (t_0)]}}{\boldsymbol{dt}} = \boldsymbol{I_v(t) - I_p(t)} \qquad \text{6-13}$$

The rate of installation of renewable energy capacity from the private sector ("installation from private") is given by

$$I_v(t) = \frac{\mathrm{I}_{p.max}\ (t)}{P_{kW}\ (t)} \qquad \text{6-14}$$

I_v = rate of installation of renewable energy capacity from private sector

$I_{p.max}$ = target private investment in renewable energy

P_{kW} = investment cost per kW$C\ (t) = C\ (t_0)\ + \int_{t_0}^{t} \left[I_v(t) - I_p(t)\right] dt$ 6-15

$$\frac{d\ [C(t) - C\ (t_0)]}{dt} = I_v(t) - I_p(t) \qquad \textbf{6-16}$$

C = total installed renewable energy capacity ("Total RE Capacity")

C = total installed renewable energy capacity ("Total RE Capacity")

I_v = rate of installation of renewable energy capacity from private sector

I_p = rate of installation of renewable energy capacity from public sector

t_0 = initial time in the time horizon of the model

t = any time t over the time horizon of the model

The rate of installation of renewable energy capacity from the private sector ("installation from private") is given by

$$I_v(t) = \frac{I_{p.max}\ (t)}{P_{kW}\ (t)} \qquad 6\text{-}17$$

I_v = rate of installation of renewable energy capacity from private sector

$I_{p.max}$ = target private investment in renewable energy

P_{kW} = investment cost per kW

Annual funding for renewable energy for new energy access ("annual funding for renewable energy for new energy access") =

$$f_{r.e}\ (t)\ = f_r(\mathrm{t}) * s_{f.e}\ (t) \qquad 6\text{-}18$$

$f_{r \cdot e}$ = annual funding for renewable for new energy access

f_r = annual funding for renewable

$s_{f.e}$ = share of funding for renewable energy access

The "total population with energy access" is given by

$$P_e(t)\ = P_{0.e}\ (t)\ + P_{n.e}\ (t) \qquad 6\text{-}19$$

P_e = total population with energy access

$P_{0.e}$ = initial population with access to energy

$P_{n.e}$ = new people with energy access

"Share of population with energy access" is given by

$$s_{p.e}\,(t) \;=\frac{P_e\,(t)}{P_e\,(t)} \qquad 6\text{-}20$$

$s_{p.e}$ = share of population with energy access

P_e = total population with energy access

P_t = total population

Figure 6-4 presents the dynamics variables from various sectors and their impact on the Gross Domestic. Product (GDP)

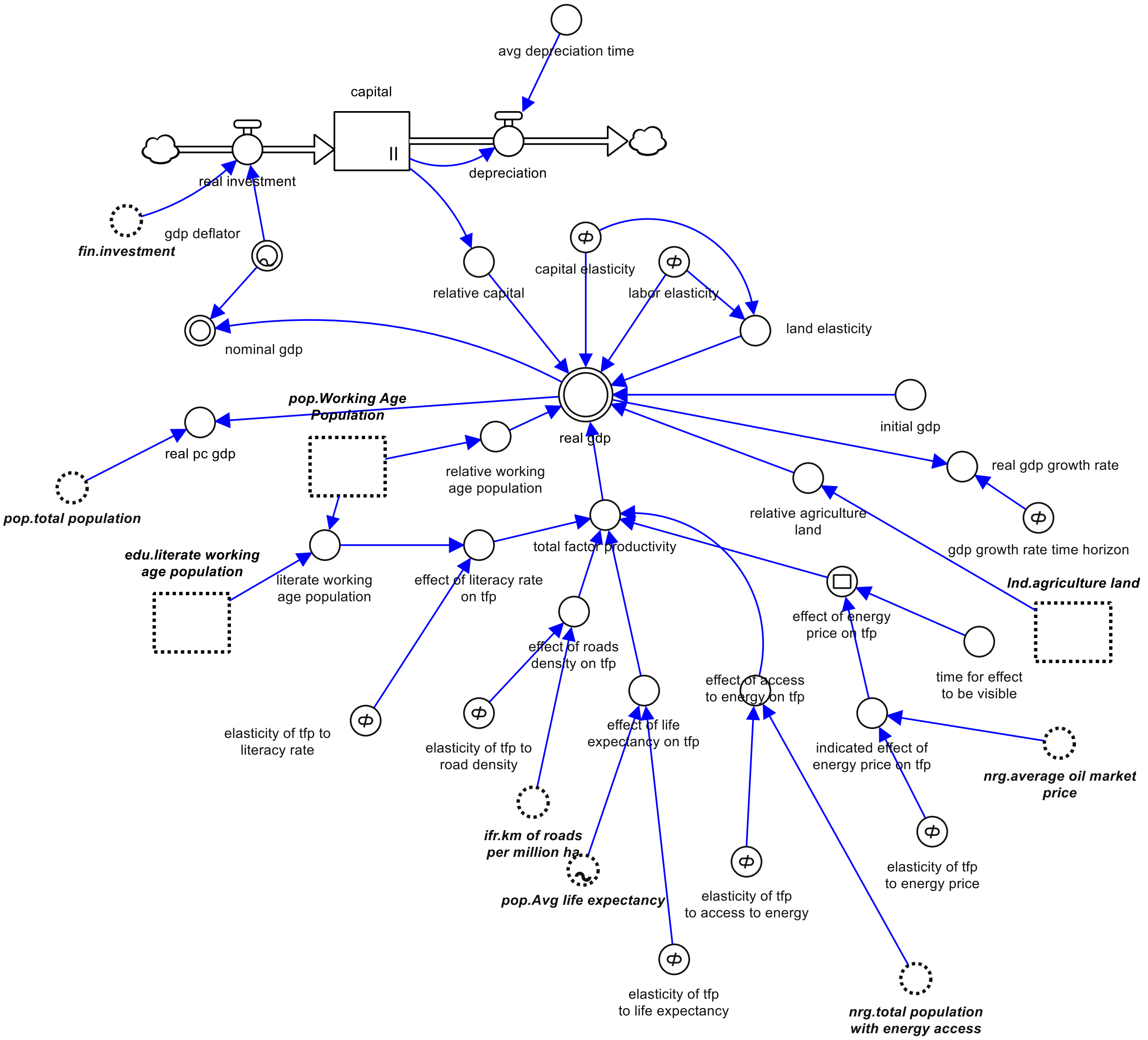

Figure 6-4: Formulation of the stock-and-flow model for the GDP sector

Figure 6-4 presents the economic dynamics showing how changes in various economic input impact the total factor productivity (tfp) and their overall impact on the gross domestic product (GDP). In the field of economics, Production Function is usually employed to express mathematical relations capturing the various factors of production and the technology of production which represents the efficiency of the combination of the factors. Using the Cobb Douglass production function, the output is expressed as a product of the production function and all the inputs with each input raised to the power of its respective elasticity. The elasticity of output Y to input X expresses the degree of responsiveness of the output Y to a unit change in input X. The generic Cobb Douglass function is expressed as:

$$Y = A \prod_{i=1}^{n} X_i^{\varepsilon_i} \tag{6-21}$$

Where X_i represents the input *i*, ε_i is the elasticity of the output Y to input *X* and A is the total factor productivity (tfp) which captures, in the GDP, the effect of the changes in all the economic inputs based on their respective elasticities.

"Effect of access to energy on tfp" is given by

$$eff_{\mathrm{e.tfp}} = \left[\frac{P_e}{P_{0.e}}\right]^{\varepsilon_{\mathrm{tfp.e}}} \tag{6-22}$$

$\mathrm{eff}_{\mathrm{e.tfp}}$ = effect of access to energy on tfp

P_e = total population with energy access

$P_{0.e}$ = initial population with access to energy

$\varepsilon_{\mathrm{tfp.e}}$ = elasticity of tfp to access to energy

Total factor productivity ("tfp")

$$A = E_{road.tfp} * E_{life.tfp} * E_{edu.tfp} * E_{ep.tfp} * E_{ene.tfp} \tag{6-23}$$

A = total factor productivity (tfp)

$E_{\mathrm{road.tfp}}$ = effect of roads density on tfp

$E_{\mathrm{life.tfp}}$ = effect of life expectancy on tfp

$E_{\mathrm{edu.tfp}}$ = effect of literacy rate on tfp

$E_{\mathrm{ep.tfp}}$ = effect of energy price on tfp

$E_{\mathrm{ene.tfp}}$ = effect of access to energy on tfp

Gross Domestic Product ("GDP")

$$gdp = A * G_0 * C^{\varepsilon_c} * W^{\varepsilon_w} * L^{\varepsilon_l} \qquad 6\text{-}24$$

A = total factor productivity

G_0 = Initial GDP

C = relative capital

ε_c = capital elasticity

W = relative working age population

ε_w = labour elasticity

L = relative agriculture land

ε_l = land elasticity

6.1.4 Model calibration

Models are abstract of the reality. Model Calibration is an essential phase in the modelling process that modellers use to assess how well the structure of the model is able to replicate historical trend, hence, building confidence in the model in its ability to project into the future. Nigerian data (1990-2015) were sourced from the World Bank database and used in calibrating the model while the calibrating the parameters were collected from various sources including the World Bank data. The figures below show some of the results of the calibration process.

Key variables were selected in various sectors and tested to ensure they reproduce the historical behaviour using data from the World Bank. Given that the purpose of the model is to analyse the impact of energy access on the overall development of Nigeria, energy demand is the primary input of the model, while GDP which captures the overall output of the model given that all the 10 sectors captured in the model impact the GDP and development of the country. Hence, evaluating the model by testing the input (energy demand - Figure 6-5) and the overall output (GDP - Figure 6-6) suffices to give an overall assessment of the model.

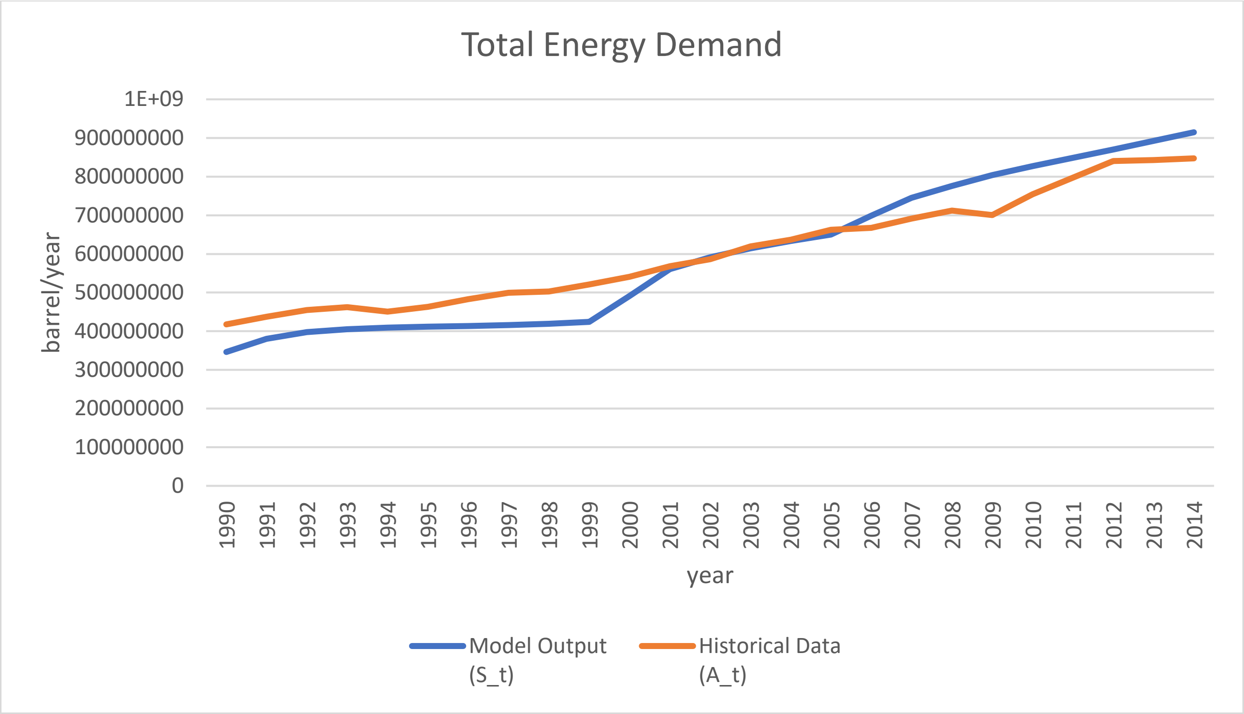

Figure 6-5: Model result (Total energy demand) versus data

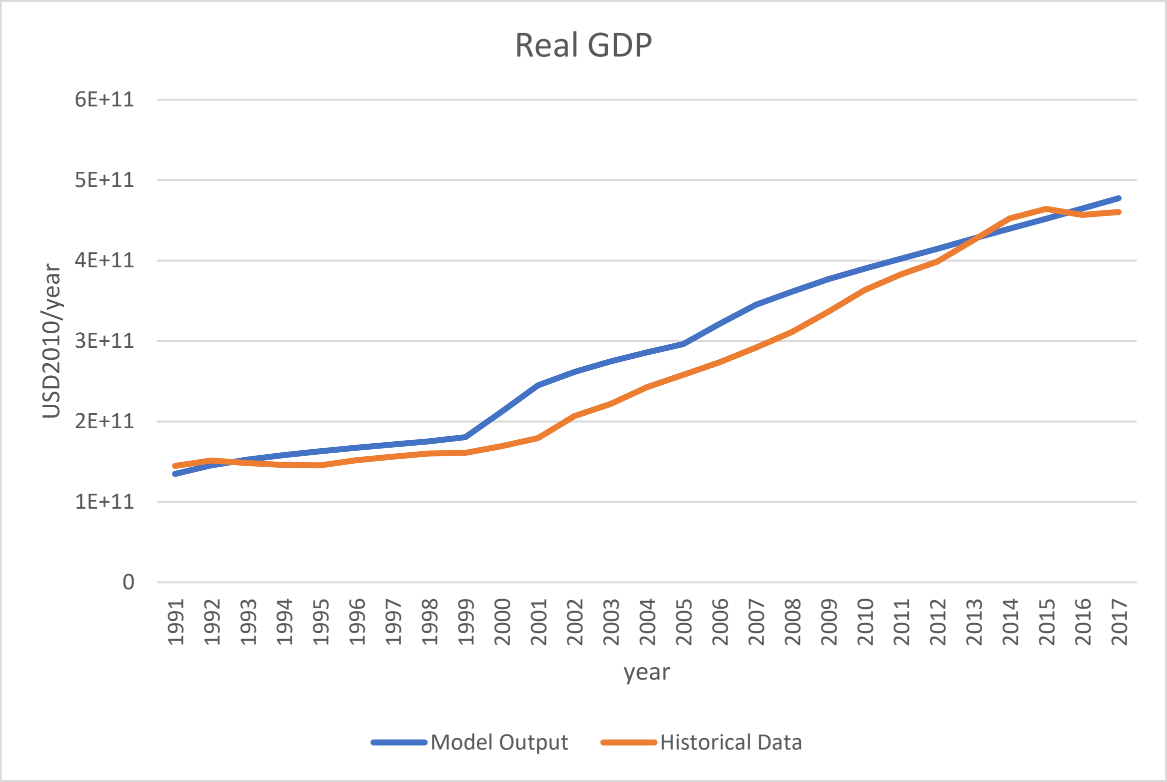

Figure 6-6: Model result (real GDP) versus data

The results shows the ability of the model to capture the observed historical behaviour of the system showed by data with 9.86% (highly accurate) and 11.55% (good) Mean Average Percent Errors for total energy demand and the GDP respectively [222], [223]. Table 6-2 presents the interpretation of MAPE values.

Table 6-2: Interpretation of MAPE values

MAPE (%)	Interpretation
<10	Highly accurate forecasting
10-20	Good forecasting
20-50	Reasonable forecasting
>50	Inaccurate forecasting

Source: Moreno *et al.*, 2013 [222]

The results show the ability of the model of capturing the observed historical behaviour of the system showed by data. The result after calibration was presented at the "Energising the SDGs Conference" at the De Montfort University in the United Kingdom[9].

6.1.5 Model Testing and Interpretation

However, historical fitness is a required but not sufficient test to evaluate the usefulness of a model. It is easy to fit a set of data to any degree of precision, hence, making fitness of system dynamics simulation to historical data a weak test. Moreover, system dynamics model is often assessed by those who require formal measures of goodness of fit.

Generally, there is no single test that can establish the absolute validity of a model. Forrester states that the evaluation test and procedure of the validity of a model should be dependent on the purpose of the model [224]. A model is useful when it is able to meet the purpose for which it was developed. The procedure for testing a model for short term prediction will differ from that that is meant for long term policy analysis.

Similarly, there can be no objective tests of validity. t- statistic has been used to assess the validity of models by econometricians such that a significant t-statistic establishes the validity of a model while an insignificant t-statistics invalidate the model. However, t-statistic in the context of the standard single equation least-squares repression model are based on some assumptions ("maintained assumptions") which are unverified[225]. The fact that the underlying (maintained) assumptions are not verified makes t-statistic not a test of validity. Accepting t-statistic as a test of validity means that the maintained assumptions are accepted to be true without verification [225]. For instance, while econometricians holds that an insignificant t-statistic value indicates an insignificant relationship thus invalidating the model, an insignificant value may indicate one of the maintained hypothesis is violated. While some tests have been developed to test the maintained assumptions, such tests also invoke other maintained hypothesis.

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[9] A. Adeleke, F. Riva, F. Tonini, and E. Colombo, "Policy coherence to enable effective energy strategies and promote sustainable development: toward developing an integrated simulation model for Nigeria," in Energising the SDGs through appropriate technology and governance, 2019, no. July, pp. 90–99.

This points to the fact that the validity of a model is rather subjective as it depends on the social context and background of the model developer and users. The perspective of the validity of the model will also differ from an "observer" (e.g researcher) to "operator" (policy maker). Therefore the validation of a model is a social process, thus, making all tests of validity for models subjective. Therefore, validity of models has been better captured and replaced by the level of confidence model builder and users place in the model to serve the purpose of developing it. Hence, "useful", "illuminating", "convincing" or "inspiring confidence" are more appropriate words than "validated" in referring to a model. *"A point of view, or a model, is realistic to the extent that it can be adequately interpreted, understood, and accepted by other points of view"* [225].

Moreover, common statistical tools for testing are not appropriate for system dynamics models. The behaviour of a real complex system is determined by relevant systemic and random forces (factors) that happen due to historical circumstances. The randomness represent those aspect of decision-making that are weakly coupled to the (real) system (that is, least relevant to the model) and have not been modelled. The inadequacy of common statistical tools for testing for system dynamics models are because:

1. The errors between simulated data in system dynamic model and historical data is often more than in regression models because system dynamics does not employ standard statistical estimation procedure that ensures a minimum sum-of-squared errors.

2. The use of exogenous, dummy variables and the historical data to determine the value of parameters helps to minimise errors in regression models. Therefore, given that the parameters in system dynamic model are not determined by using the exogenous variables, dummy variables, and historical data makes system dynamic models have larger errors than regression models.

3. System dynamics models are developed for specific objectives, hence, may not capture some modes of behaviour which, though are present in the real world (data), are not relevant to the purpose of the model. Therefore, system dynamics models often exhibit larger errors than regression models.

These explains that the coefficient of determination or R^2 (which measures the fraction of total variable explained by the model) which is mostly used as summary statistic to assess the goodness-of-fit in regression models is not suitable for system dynamic models. This also explains that larger errors in system dynamic models relative to regression models does not necessarily compromise system dynamic models or that confers lack of confidence in their results.

A common measure of forecast error is the Mean-Square-Error (MSE), which is employed for rigorous evaluation of the total error between simulated and actual data [225]. MSE has the advantage that the larger the errors, the heavier they are weighed; and that errors in opposite direction do not cancel one another. However, the Root-Mean-Square (RMS) Error is often taken as it provides the same unit as the unit in the data, that is the variable being analysed. A normalised measure of error, such as the Root-Mean-Square Percent Error (RMSPE), provides a common and dimensionless measure of forecast error.

In addition to estimating the error, it is often important to know the sources of error in a system dynamic model. For instance, as stated above, there may be large errors in a model if some behaviours of the real world being model is considered irrelevant to the purpose of the model, hence, not captured in the model. Also, disparity between the simulation and historical data may be due to poor model or presence of a large degree of randomness in the historical data. There are several statistical methods of disintegrate the error: systematic error and error due to randomness in the historical data. Theil statistic presents an approach to disintegrate Mean-Square-Error (MSE) [225] which allows the error due to individual behaviour modes to be analysed. Model Testing is the analysis of the error due to individual modes. Theil statistic breaks down the MSE into bias, unequal variation and unequal covariation.

$$\frac{1}{n}\sum(S_t - A_t)^2 = (\bar{S} - \bar{A})^2 + (S_S - S_A)^2 + 2(1 - r)S_S S_A \qquad \text{6-25}$$

where

n = number of observations (t = 1, …., n),

S_t = simulated value at time t

A_t = actual value at time t

$\bar{A}$ and $\bar{S}$ are the means of actual and simulated data

S_A and S_S are the standard deviations of actual and simulated data

r is the correlation coefficient between simulated and actual data

$(\bar{S} - \bar{A})^2$ measures the bias between simulated and actual data while $(S_S\text{-}S_A)^2$ measures the degree of unequal variation in the two series. It is the component of the mean-square-error that is due to a difference in the variances of the two series. $2(1\text{-}r)S_S S_A$ measures the degree to which the changes in the simulated series fails to match the changes in the actual series on a point by point basis. It is the part of the error due to incomplete covariation between the two series. Therefore, the mean-square-error is due to bias, unequal variance and unequal covariance respectively.

Dividing each of the components of the error by the total (mean-square-error) gives the "inequality proportions" which gives a reflection of the share (contribution of each of the causes of the error to the total mean-square-error).

$$U^M = \frac{(\bar{S} - \bar{A})^2}{\frac{1}{n}\Sigma(S_t - A_t)^2} \qquad \text{6-26}$$

$$U^S = \frac{(S_S - S_A)^2}{\frac{1}{n}\Sigma(S_t - A_t)^2} \qquad \text{6-27}$$

$$U^C = \frac{2(1-r)S_s S_A}{\frac{1}{n}\sum(S_t - A_t)^2} \tag{6-28}$$

Therefore, $U^M + U^S + U^C$ should be equal to 1

U^M – Average Error is a systematic error

U^S – Trend Error and could be a systematic or random error depending on the behaviour of the model vis-à-vis the purpose of the model

U^C – Random or Cyclic Error is a random error

Conducting the test on the model yields:

Table 6-3: Testing results

	U^M	U^S	U^C	$U^M + U^S + U^C$
Total Energy Demand	0.022898363	0.796322454	0.180779183	1
Gross Domestic Product	0.531084536	0.00505426	0.463861204	1

6.1.6 Interpretation

While the summation of the disaggregated errors in the Total Energy Demand and Gross Domestic Product equals 1 as expected, there is need for interpretation on the error distribution:

Total Energy Demand: U^M and U^C are close to zero while the U^S accounts for the highest share of the error. The model result and the historical data have the similar means but the U^S is large and at least one of the two series is near constant (which makes U^C to be small as their standard deviations are small). This indicate random noise or a cyclic mode in one of the series that is absent in the other. Given that the model was developed to analyse the long-run behaviour that abstracts from the short term cycles, the failure to generate the cycle will be mean a random noise which is unimportant given the purpose of the model [225].

Gross Domestic Product: U^C and U^S are small and U^M account for the highest share of the error. A bias indicated by a large U^M while U^S and U^C are small is a translation of one of the series by a constant at all points. A bias indicated by large MSE and U^M are large shows systematic errors between the model and reality. Errors due to bias could be due to errors in specifying the parameters, including initial values. Bias error may also be caused by acceptable simplifying errors which does not compromise the model [225].

6.2 Limitations and Future Works

The results of a modelling process shows that the model captures the dynamics of the energy sector (fossil fuels, renewables, and access to energy) with ten major sectors of the Nigerian economy. The model results capture the non-linearity delays and feedbacks of the system which allows us to link different sectors, thus, avoiding “black-box” exogenous relations and approaches in designing energy policies. The model allows us to increase our knowledge of the energy-development dynamics in the

Nigerian context by serving as a holistic and integrated quantitative tool for understanding how energy variables interact and impact the variables of other sectors of the Nigerian economy.

The endogenous generation of the behaviour of model, and its fitness with historical data, and the error test, disintegration and analysis presented demonstrates the appropriateness of the structure and behaviour of the model. The summary statistics analysed and interpreted above demonstrate the ability of the model to reproduce historical behaviour of the system endogenously, thus, building confidence in the model. In addition, the model has been verified for structural appropriateness to ensure that all equations are dimensionally consistent without the use of parameters without real-world counterpart (dimensional consistency) and structure of the model is consistent with real-life description of the system (structural verification). Indeed, "the true test of a model is its ability to reproduce historical behaviour endogenously, with the structure and parameters that are consistent with descriptive knowledge of the system" [225].

Building on the work carried out so far, future work will be focused on policy analysis which will be predicated on extreme and surprise policy test of the model to ensure that the model behave properly when subjected to extreme policy. For the policy analysis, a review of Nigeria energy policies particularly, an analysis of the annual budget of the government on energy relative to the GDP over time to ascertain inputs for the policy analysis.

The model will be fit to evaluate various scenarios of energy policies such as energy investment, resource allocation of energy intervention fund and budgetary allocations vis-à-vis their respective plausible impact on sustainable development. The model will also help in determining, analysing and evaluating optimal energy mix from crude oil and renewables sources and their impact on energy access, GDP, health, education, among other sectors captured by the model. The model will be a tool to evaluate the impact of various scenarios of energy investment, intervention fund and budgetary allocations on household income (SDG 1), education (SDG 3), health (SDG 4), energy access (SDG 7), economic growth (SDG 8) and infrastructure development (SDG 9). The model will also be a tool to identify necessary complementary actions and their effectiveness in maximising the impact of energy interventions to facilitate sustainable development in Nigeria. Users of the model would be able to compare the impact of various resource allocations including ascertaining what level of investment are required in other sectors for effective impact of energy investment.

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Part Three

Part III - Energy Access and Sustainable Development in Rural Context

While development analysis and planning based on national averaged-data are crucial to decision-making at the national level, national averages hide more than they reveal. National energy planning does not reveal the energy reality at the sub-national level especially the conditions of rural livelihood which generally lags behind the experience in the urban centres. Yet, the highest share of the population in developing countries live in rural communities. Indeed, there has been a renewed commitment to facilitating rural development in developing countries through the lens of the SDGs in pursuit of the 2030 Agenda. In realising this, the security of energy access in rural communities of developing countries have been identified as a catalyst to facilitating the realisation of the SDGs in rural context. Hence, the need for the development of tools for investigating policies for energy access that would maximise impact on the SDGs in rural context. Nonetheless, the development of such planning tools relies on an in-depth of understanding of the nexus and the interlinkages between energy access and the SDGs in rural context. Therefore, the study conducted a detailed analysis of scientific literature on the nexus of energy access and each of the central themes of the SDGs. The study presents a detailed descriptive analysis, and developed 16 comprehensive causal loop diagrams which crystalises 85 feedback loops of the interlinkages and the impact pathways between energy access and 16 SDGs in the rural context of developing countries. The feedback loops represent the conceptualisation framework for the modelling of system-dynamic models for holistic rural energy planning towards facilitating the realisation of the SDGs in rural contexts of developing countries.

The disproportionate share of the challenges to universal energy access borne by rural dwellers are largely due to the peculiarities of rural livelihood and the energy-development dynamics in rural context of developing countries. Therefore, realising universal energy access for all in such context requires comprehensive energy policy approach that is based on an in-depth understanding of energy-development dynamics in rural context and encapsulate strategies that addresses the various peculiarities of rural livelihood which pose barriers to energy access and use in rural communities. Based on the literature analysis in the previous chapter, recommendations are made on strategies that could catalyse rural profitable investment that provides high-tier of affordable energy access that embraces plurality of technologies towards universal energy access in rural communities. Moreover, energy access-SDGs dynamics comprises of synergies that facilitate the impact of energy access on the SDGs in rural context. Nonetheless, there also exist trade-offs in the nexus that offer constraints which limits, weakens and counteract the overall impact of energy access on the SDGs. Therefore, policies aimed at providing rural energy access requires complementary policies that prevent or minimises undesirable trade offs in the energy access-SDGs dynamics. With the realisation of the SDGs at the rural context of developing countries, diverse policy constraints to the impact of energy access in facilitating the achievement of the SDGs that are identified in the literature analysis are discussed, with policy recommendations on how they could be prevented or at least mitigated.

CHAPTER SEVEN

7 Energy Access for Sustainable Development Goals in Rural Contexts of Developing countries

Abstract

While development analysis and planning based on national averaged-data are crucial to decision-making at the national level, national averages hide more than they reveal. National energy planning does not reveal the energy reality at the sub-national level especially the conditions of rural livelihood which generally lags behind the experience in the urban centres. Yet, the highest share of the population in developing countries live in rural communities. Indeed, there has been a renewed commitment to facilitating rural development in developing countries through the lens of the SDGs in pursuit of the 2030 Agenda. In realising this, the security of energy access in rural communities of developing countries have been identified as a catalyst to facilitating the realisation of the SDGs in rural context. Hence, the need for the development of tools for investigating policies for energy access that would maximise impact on the SDGs in rural context. Nonetheless, the development of such planning tools relies on an in-depth of understanding of the nexus and the interlinkages between energy access and the SDGs in rural context. Therefore, the study conducted a detailed analysis of scientific literature on the nexus of energy access and each of the central themes of the SDGs. The study presents a detailed descriptive analysis, and developed 16 comprehensive causal loop diagrams which crystalises 85 feedback loops of the interlinkages and the impact pathways between energy access and 16 SDGs in the rural context of developing countries. The feedback loops represent the conceptualisation framework for the modelling of system-dynamic models for holistic rural energy planning towards facilitating the realisation of the SDGs in rural contexts of developing countries.

7.1 Materials and Methods

In order to identify and establish the impact pathways between the variables of energy access and those of the other SDGs at sub-national (rural) level, the analysis employs a descriptive analysis and causal loop diagrams (CLDs) of the causal relationships between variables of energy access and those of the SDGs in rural contexts of developing countries. Causal Loop Diagrams (CLDs) are conceptual models employed for visual description of the causal relationships, impact pathways and feedback between variables in complex systems which represent the formulation stage in the development of system dynamics models.

Indeed, the SDG framework provides 232 unique indicators many of which are being employed to monitor and assess progress in the realisation of the SDGs in the run up to 2030. While such indicators could have been apt as variables for the analysis, the indicators are not specific, measurable, and relevant to the rural context of developing countries. Measurability and methodologies for data collection were some of the basis for selection of SDG global indicators and the same factors influence the number of indicators adopted by governments for national SDG frameworks. Yet national SDGs frameworks are not applicable for the rural context in developing countries [226] particularly due to the wide divergence between development realities at the sub-national level, particularly between rural and urban communities. Nonetheless, there is need for policies and strategies that captures the peculiarities of rural context to facilitate the realisation of the SDGs in rural developing countries which are the farthest from behind for many of the SDGs as discussed in previous sections.

The review of scientific literature for case studies on rural energy access-SDGs nexus was employed to explore insights on rural energy access-SDGs nexus and identify variables that are specific, measurable and relevant to the context of rural developing countries. Search strings such as "energy access and SDG X" returned near zero response for almost all the SDGs on Science Direct and Scopus databases. This highlight that paucity of scientific research on rural energy access towards facilitating the realisation of the 2030 Agenda is the rural context of developing countries. However, search strings on rural energy access and the central themes of each of the SDGs such as "rural energy access and poverty" for SDG 1, "rural energy access and health" for SDG 3, among others returned several literature on the same platform.

The selection of literature for the analysis was primarily focused on scientific literature that present case studies and reviews of case studies on the nexus of rural energy access and the central themes of each of the SDGs. The focus was primarily on literature that provide qualitative analysis of the casual relationships between energy access and the central themes of the SDGs at the rural context. The focus on scientific literature of case studies on rural development is aimed at ensuring that the variables that are selected for the SDGs have established scientific methodologies for data collection at the rural context which is a major underlying principle for selection of global SDGs indicators. In addition, use of such scientific literature on case studies from rural energy-development studies helps to ensure the variables in the CLD are specific, measurable, and relevant to rural context of developing countries.

The harmonisation of the insights garnered from the literature provides a descriptive analysis of energy access-SDGs linkages and causalities. The analysis provides causal relationships, impact pathways and feedback between the variables of energy access and those of all the SDGs in the rural context of developing countries. The only exception is for SDG 12 on "responsible consumption and production" for which no literature was found on the theme in the rural context. Based on the descriptive analysis, causal loop diagrams (CLDs) were developed for the nexus of energy access with each of the 16 SDGs covered in the analysis. The descriptive analysis and CLDs also highlights the complementary actions required to facilitate and maximise the impact of energy access on each of the 16 SDGs and vice versa.

Each CLD is a network of several linkages between variables with a positive or negative sign to indicate the nature of the causality. A→B with a positive "+" sign means that a change in variable A in a direction (increase/decrease) will result in a change in variable B in the same direction as the direction of change in variable A (increase/decrease respectively) relative to what it would have been. The same link with a negative "-" sign means that a change in variable A in a direction (increase/decrease) will result in a change in variable B in the opposite direction as the direction of change in variable A (decrease/increase respectively) relative to what it would have been. Feedback loops, which are traced out from the causal loop diagrams, presents the descriptive dynamics that will underline the model dynamics when developed.

The repetition of several variables and causal linkages in a number of energy access-SDGs causal loop diagrams indicates indivisibility, interconnectedness, interdependencies, cross- and inter- sectoral linkages between the SDGs. The numerous overlaps indicate two kinds of interdependencies; namely, synergies and trade-offs that needs to be identified, analysed and modelled that could be leveraged for policy coherence and simultaneous achievement of the goals. Synergies shows interdependences that could be leveraged to facilitate and maximise the impact of energy access, while trade-offs presents interdependences that constitute policy constraints and undesirable impact of energy access that needs to meet minimised.

For instances, variables and linkages of cooking are crucial to realising SDG 2 (agriculture and food production, and hunger), SDG 3 (health), SDG 4 (education), SDG 5 (gender), SDG 7 (energy) and SDG 13 (climate change) in rural context. Similarly, variables and linkages of water resources are common to SDG 3 on health, SDG 5 on gender, SDG 6 on water, and SDG 7 on energy, among others.

7.2 Impact pathways of energy access and the SDGs in rural contexts

7.2.1 SDG 1 – No Poverty

SDG 1 seeks to end poverty in all forms. The analysis of scientific literature shows that the impact of energy access on rural poverty and vice versa have been measured mainly by income. Therefore, the energy access-SDG 1 nexus focuses on the variables and causal linkages of energy access and income in the rural context of developing countries.

7.2.1.1 Income

The access, use and impact of electricity on income is influenced by the economic profiles and capacities of the users prior gaining access to electricity[227]. The economic profile of respective potential users influences the security of electricity access given the crucial role of ability to pay (for electricity access) in the decision matrix of energy investors to ensure the sustainability and profitability of energy investment. Despite the prioritisation of the poor households in rural electrification projects in Indian villages and the zero connection fee [228], many poor households remained unconnected to electricity due to their inability to afford the electricity tariffs [228], [229]. In addition to access, the level of use and impact of electricity also vary with the existing economic profile [230], and, such impact begins at the household and enterprises levels before culminating to community impact [1][2][227][230]. Wealthier rural dwellers and communities gain access to electricity before their poorer counterparts and also benefit more given their high ability to pay for electricity. Also, wealthier electricity users are already operating or able to start new enterprises for productive use of electricity, and have access to complementary supports such as loans for scaling productive activities [230]. The impact of electricity use, in turn, contributes to increased income in electrified communities [230], thus, increasing their financial capacity to spend more on electricity (feedback loop) [227] [230] [231]. Also, modern energy access has been largely associated with decrease in energy cost [230] [232], for instance, elimination of recurrent cost of fossil fuel [233]. However, whether or not the decrease in energy costs leads to poverty reduction depends on the share of energy cost in the overall cost of operations for household expenditure and enterprises [230]. The recurrent cost of fossil fuel to operate generators is generally high in rural communities due to their higher prices in rural communities given the high cost of transporting the fuels from cities, limited supply, elongated supply chain (middle men) among other factors. Therefore, the provision of energy access from renewable energies usually reduce electricity expenditure for rural households and business especially those who are already using fossil-powered alternatives before gaining access to renewable energy.

The most versatile application of electricity access is lighting, however, a large share of rural enterprises also put it to productive and economic use [227] [230]. Enterprises with low income have low propensity to invest in electricity equipment for productive use. Therefore, they prefer to acquire appliances for lighting, comfort among other with low energy-intensive applications [227] while high energy-intensive applications remains manually operated. Nonetheless, the type, level and extent of use is a major determinant of the impact of electricity on income [227]. Entrepreneurs that use electricity for enterprise and services are able to make it into higher income category while there are only a marginal difference in the income levels of those using the electricity for lighting, entertainment, comfort or communication and those who do not have at all [227]. Meanwhile, lighting may also have significant economic impact depending on the nature of business. Lighting enables enterprises and home-based income-generating activities to extend workhours by allowing them to work at night [30]. While this enables service-providing enterprises to attend to more customers, producing businesses are able to produce more products thus generate more income [227], [232]. Meanwhile, weather conditions also contributes to low patronage at night. Difficulty in travelling home for those living distant from their business location and limited flexibility of staff[10] also influences the ability of businesses to extend their workhours. Streetlights, which is often not installed as part of many energy access projects largely address these challenges as the provision of streetlighting enables businesses and customers to operate and travel at night thus increasing active workhours (effective day). Moreover, the adoption of improved technologies reduce the time requirement of house chores (e.g. cooking). This frees-up time, therefore, increasing possible workhours and income, especially for women. However, ensuring the extension of workhours translate to economic impact requires access to finance for increased production and higher social network to increase demand for the product access from external market [227]. The opening of external market has been identified to be crucial to improving social economics of rural communities and the lack of it partly explains the reason some electrified enterprises do not record significant increase in their income level [227]. The SDG 5 on gender looks further expatiate into this.

7.2.1.2 Labourforce, Employment and Wages

Agriculture and agro-processing, non-agricultural productive activities, welfare grants by the government [234] and remittances[230] are the four major sources of income for rural livelihood. Government provides most of the formal employment, such as teaching, clinical staff, in rural communities. However, the income from such formal employment have only limited impact on rural livelihood as most of the government employees live outside the villages where they work [234]. The receipt of remittances is also associated with reduction in the rural workforce especially as those who migrate to the cities are majorly youth [230].

7.2.1.3 Training, Economic Diversification and Non-Agricultural Activities

Increased income has been identified to result in the demand for non-basic commodities (such as hairdressing, and cold drinks) [230] hence contributing to economic diversification. However, the possibility to produce the '*new*' and non-basic commodities depends on the financial capacity of rural enterprises. Meanwhile, the cost of procuring the required electric equipment is often beyond the capacity of rural micro-credit scheme, where it exist, yet many of the formal credit facilities are not fitting into rural contexts especially due to the informal settings of rural enterprises [230]. The establishment of new enterprises complementary to energy access projects necessitate the training and employment, hence, provides income generation for staff (rural dwellers) and profit for the enterprises for their sustainability and scaling[235].

7.2.1.4 Water and Solar Water Pump

River is one of the most common water sources for drinking, food preparation, bathing, home sanitary use, irrigation and animal husbandry in rural communities. Livestock often suffer attacks when ranged to drink water from rivers infested with animals, such as crocodile, leading to loss of wealth (livestock and dairy products) thus decreasing the income of livestock farmers [235]. Solar water pump provides cleaner water for livestock which eliminates or reduces the need for ranging to the river for water drinking, therefore, reducing economic loss to livestock farmers[235]. Similarly, solar water pump provides water source at close proximity for irrigation, hence, promotes subsistence and commercial crop cultivation (food production) for household consumption and income generation. This reduces household dependence on government support grant [235].

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[10] as both customers and entrepreneurs close early during winter due to cold (as their shops are usually open and poorly insulated in rural communities)

7.2.1.5 Fuelwood and Improved Cookstoves

The adoption and use of improved cookstoves reduces fuelwood requirement for cooking using improved cookstoves (relative to three-stone stove) reduces the cost of fuelwood (especially for cooking-based income-generating activities - IGAs). The reduced frequency of trips for fuelwood collection also free-up time which can be used for IGAs [236].

7.2.1.6 Complementary Action: Access to market

The productive use of electricity does not automatically increase income. Despite the high level of productive use of electricity by users of over 100 rural electrification projects in various countries in the global south, only one out of every three projects resulted in increased income yet the increase were limited [232]. Facilitating the impact of productive use of electricity on income for poverty reduction requires investment in electrical equipment [230] [3], among other complementary actions. Electric equipment increases operational efficiency thereby reduces the production time per unit, thus, saving time for increased production [227]. Increased production may also be caused by market entrance by new actors (sequel to electricity access) from outside the village who may have more skills hence take over a large share of the market[237]. The increase in production reaches a peak when the market is saturated, hence, consequent reduction in price. Consequently, the initial economic gains of the electricity access such as increased income, job creation and increased workhours may be lost due to the 'super saturation' of the local markets [227]. Therefore, increased production could only sustainably impact income if there is increase demand, unfortunately, most rural enterprises are limited to the market within their communities [227] further highlighting the need for external market. Inadequate start-up capital, limited business skills and techniques and poor communication and transportation facilities limit the abilities of rural enterprises to access external market[227][234]. Also, selling to external markets often requires that the products meet higher quality and standards than required in local market and such standards are often determined by the target market[227]. Therefore, maximising and sustaining the economic impact of energy access require creating access to finance to increase the capacities of enterprises to procure new and more efficient electrical equipment, skill acquisition on improved operation techniques and access to external market to increase demand for their increased production [232], [30], [234] [227]. However, improved transportation facilityto facilitate access to external market could also encourage rural dwellers to access cheaper products in bigger communities hence reduce their patronage of local products especially for everyday products[234] [227]. Nonetheless, rural dwellers will prefer local products when convenience of access to such products is of priority [234] [227].

Figure 7-1 presents the pictorial view of the energy access-SDG 1 causal linkages above and the intervening feedback loops in a Causal Loop Diagram

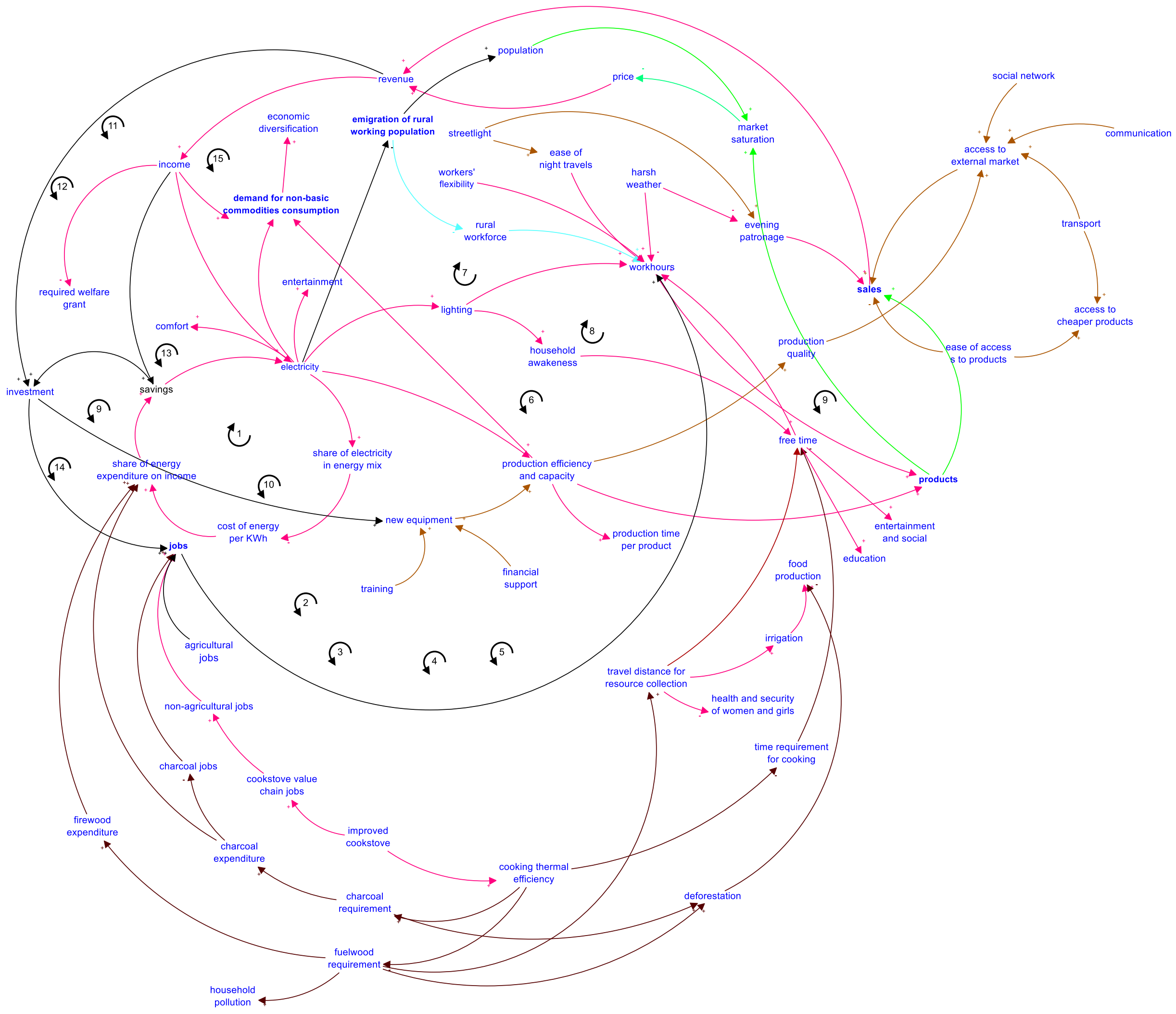

Figure 7-1: Causal Loop Diagram - Energy Access and SDG 1

7.2.2 SDG 2 – Agriculture and Food Security

SDG 2 seeks to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture". Therefore, the energy access-SDG 2 nexus focuses on the variables and causal linkages between energy access, agriculture and human nutrition in the rural context of developing countries.

7.2.2.1 Agricultural Production: Crop Production and Animal Husbandry

The proximity of rural communities to nature vis-à-vis the various dimensions of poverty that characterise rural livelihood in developing countries makes rural dwellers depend heavily on nature for sustenance. Rural communities often rely on river water sources for irrigation and animal husbandry, among other applications. In cases where such rivers are infested with dangerous animals such as crocodile, livestock often suffer attacks while being ranged to the river to drink water. The resulting loss of livestock leads to reduction in the production of meat and dairy products, which leads to increase in their prices in response to the forces of demand and supply [235]. The installation of solar water pumps provides clean water for animal husbandry at closer distances hence eliminating or reducing the need for animal ranging to the river thereby reducing attacks by sea animals. Solar water pump also provides water for irrigation thus promoting crop production at both subsistence and commercial scales thereby increasing food availability and sustaining agricultural practice [235].

While complementary actions are recommended to maximise impact in some cases, they are requirement to facilitate impact in others. The development of large energy access projects often require the construction of roads which also creates access to external markets for rural enterprises [32]. Meanwhile, access to external market could result in a decrease in the food production as more farmers may divert their interest in cash crops as it would yield more income in the long term [32]. For instance, following the development of Belo Monte hydroelectric dam in a rural community in Brazil, the average annual cocoa production per household increased from 426kg in 2005 to 5055kg in 2015 [32]. However, the forces of demands and supply balances this in the long term. Though the price of cash crops is influenced by international (external) price, it also responds to local production levels. As the production of cash crops increases, cash crop farms are extended to soil with lower fertility hence produces lower yield and revenue for the farmers. The decrease in revenue from cash crops may therefore increases interest in food production.

Moreover, farmlands with direct access to highways are less productive due to lower soil fertility though such access facilitate ease of linkage to the market. Farmlands in the interior on the other hand benefit from higher soil fertility which result in high yield, however, produce evacuation is slower, expensive and more difficult especially during rainy season due to worsening road condition. It is also crucial to note that soil fertility is an important factor in the decision matrix for financial support for farming especially from banks. Therefore, it may be helpful to site cash crops in the interior while lands with proximity to the road may serve as pastures for livestock.

Electricity access rarely significantly impact rural agriculture, however, high quality electricity access facilitates the opportunity for value addition on agricultural produce which increases farmers' income. Due to its limited capacity for cocoa processing, Africa account for only 5% of the USD 100 billion global market for chocolate despite producing 75% of the global cocoa beans [238]. Therefore, the more the quality of electricity, the more the ability of farmers to process their produce and the more they maximise the value of their produce for more income.

7.2.2.2 Nutrition and Education

Continuous exploitation of fuelwood without commensurate afforestation policy leads to progressive decline in forest population, thus, results in increase in the price of forest wood[236]. The resulting increase in the price of fuelwood and charcoal forces a reduction in meal sets to meals requiring minimal cooking time and fuel[236]. This negatively impact nutrition available to affected households yet the nutritional status of children have positive correlation with total years of schooling [239]. Some households may also avoid boiling water for bath even when it is essential to reducing contraction of water-borne diseases and cold-related sickness. Therefore, the lower fuelwood requirement of improved cookstoves enables food selection from wider varieties and previously avoided meals [236]. The possibility to regulate cooking temperature of some improved stove also allow for cooking previously avoided food variety due to high time requirement and risk of spoilage by excessive heat. Money and time saved from the use of cookstove could be diverted into access to more nutritious food and embrace better food preparation practices [236].

7.2.2.3 Agricultural Land and Productivity

Flooding for hydropower generation results in loss of agricultural lands which often make farmers to resettle in areas with less fertility [32]. Also, fuelwood collection and charcoal production contribute to deforestation[240] which promote soil erosion, leaching of soil resources thus increasing soil destabilisation [32], land degradation, desertification and loss of watershed functions[236]. Moreover, the burning of wood for charcoal production kills soil organisms which reduces soil fertility and agricultural productivity, thus, aggravating food scarcity while reducing income in the agricultural value chain [236]. Also, coal production chamber (kiln) occupies space thus reducing agricultural land.

The development and operation of the small hydropower plants (SHPs) decreases the river flow for irrigation which exacerbate during dry season as most rural farmers depend on natural irrigation[30]. The fencing of some land area for hydropower projects may also constitute conflict of interest with pastoral farmers (herders), which could result in social tension. Such conflict often result from inadequate or lack of community consultation and participation in the development of such project [30].

7.2.2.4 Rural and agricultural workforce

Economic diversification resulting from electricity access often leads to a decline in agricultural workforce [32] as rural dwellers especially the youth take advantage of opportunities for non-agricultural income-generating activities (IGAs) that results from electricity access[38]. Sequel to the development of Belo Monte hydroelectric dam in Altamira region of Brazil, 85.8 percent of the households in the Altamira region attested to the scarcity of labour to employ for agricultural activities[32]. Similarly, More than half of the households stated that household labour is insufficient for their farming operations, 33.33 percent reported a reduction in the number of household labour available for agricultural activities[32]. However, reduction in agricultural workforce could also be result from migration for employment, education, among other factors. This negatively impact agricultural practice especially food production, thus, constituting an undesirable impact of electricity access [38]. Meanwhile, most of the direct jobs provided by energy access projects are temporal and retaining only a small fraction after the project development phase given the low operation and maintenance requirement of renewable energy projects which is mostly developed for energy access in rural communities of developing countries.

However, energy generation from biomass attract a high level community participation and support as it sustains and strengthens the predominant occupation in rural communities. Energy generation from biomass helps to sustain and increase agricultural workforce especially for energy crops. The preference for the production of energy crop over food crop may also be influenced by the relatively higher and stable prices of energy crops (largely determined by international market) [38]. Some biodigesters use cow dung and water to generate biogas while the residue from the process (bioslurry) provides fertiliser for soil fertility [236]. Similarly, energy generation from energy crops requires consistent production and supply of energy crops [32] such as sunflower, hence, provides ready market for energy crops thus sustaining the direct agricultural jobs it provides. Nonetheless, the production of energy crops competes for land, labour among other resources with food production. Meanwhile, emigration and importation of better-processed food products from the township into rural communities also contribute to the decrease in food production in rural communities. However, preference for locally-made product (due to natural flavours, for instance) helps to sustain the demand for some specific food crop.

Figure 7-2 presents the pictorial view of the energy access-SDG 2 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

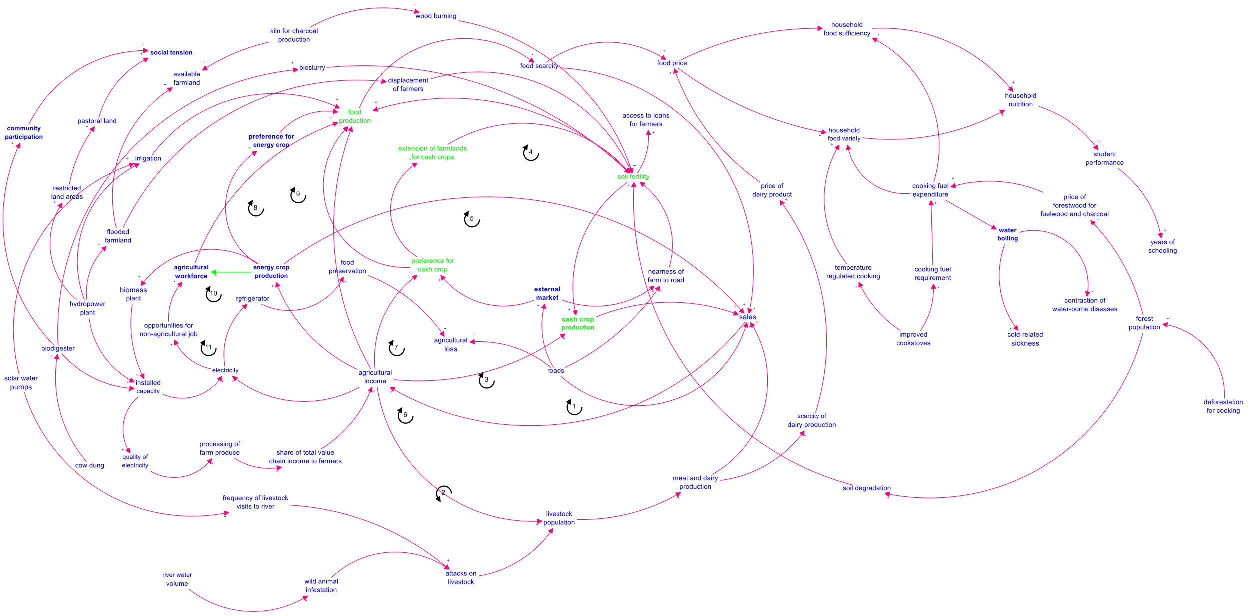

Figure 7-2: Causal Loop Diagram - Energy Access and SDG 2

7.2.3 SDG 3 – Health

SDG 3 seeks to "ensure healthy and promote well-being for all at all ages". Therefore, the energy access-SDG 3 nexus focuses on the variables and causal linkages between energy access and health in the rural context of developing countries.

7.2.3.1 Health and Security Hazards

The traditional role of women and children in sourcing for fuelwood and water makes them prone to various security and health hazards [236]. Therefore, the lower fuelwood requirement of improved cookstove due to its higher thermal efficiency (relative to traditional stoves) reduces the exposures of women and children to these risks [236], [241]. Moreover, traditional cooking methods using firewood is a major source of indoor air pollution. Therefore, the use of improved cookstove which produces less smoke generation reduces indoor pollution, thus, reduces the risk of adverse pregnancy outcomes and contracting diseases caused by air pollution, thereby increasing life expectancy [236].

Similarly, exposure to mosquito bites in the bush especially in regions with high temperatures or during summer causes infections. The installation of solar water pump within residential areas of rural communities reduces their traversal of forests to source for water, hence, reducing mosquito bites [235]. [61] Water pump provides safe drinking water which reduces the risk of contracting water-borne diseases thus increasing rural life expectancy [61]. However, where electricity is generated from hydropower dam, the reduction in water flow or stagnancy of water provides breathing grounds for diseases-carrying bacteria. Some riverine communities drink and use water from such river without treatment, thus aggravating the negative impact on their health [32]. Also, the immigration of people from neighbouring communities to benefit from energy access could also increases the incidence of vector-borne diseases [32].

7.2.3.2 Electric cooking and its limitation

While electricity is preferred for convenient and zero-smoke cooking [234] [61], electric cooking is largely limited by its high electricity intensity vis-à-vis the affordability of the associated cost. This in addition to traditional preferences makes fuelwood remain the primary fuel for cooking in rural communities, and also for traditional preferences while electricity is limited to cooking that require short time such as water-boiling. However, many rural dwellers do not boil water fetched from unprotected sources despite their awareness of water-borne diseases neither do they boil feeding bottles for babies. This is based on the perception that growing up in such environment (rural locality) immunes them against pathogens and spiritual beliefs that only God knows who will fall sick and when [234].

7.2.3.3 Electricity and medical facilities

Electricity access facilitate acquisition of electric medical facilities for improved health care [61] [233] [226]. Such improved medical services include such as x-tray, medical scans, sterilisation, and advanced medical tests and laboratory operations instead of their preliminary alternatives such as basic but non-confirmatory malaria test [61] [233] [226]. Electric lighting could also increase the workhours of medical centres [61] while refrigerator preserves and increases the lifespan of vaccines[61] [233] [226]. These increase health outcomes, thus increasing life expectancy in rural communities. Moreover, electric lighting in households reduces household hazards (accidents) especially in the nights, heating during cold and cooling during heat especially summer particularly in hot regions.

In addition, electricity access provides opportunities to use refrigerators for food preservation hence reducing contamination rate and increasing availability of food varieties which boost human nutrition [61] thus improving health outcomes. Similarly, rural electrification also replaces the use of diesel generators hence reducing air and noise pollution from diesel generators [233] [230].

7.2.3.4 Linkage to Education

Access to electricity also facilitates the diffusion and use of information and communication technologies (ICT) such as television and internet facilities which increases exposure to health education [242]. This induces a positive attitudinal change towards health care in rural communities, thus reducing the contraction rate of diseases. Healthy students have better chances in school attendance, study, performance and have more years of schooling [61]. Moreover, school-going children experience less eye irritations and respiratory tract infections when studying at night with electric lighting compared to paraffin lamps which produces soot and vapour [235].

Figure 7-3 presents the pictorial view of the energy access-SDG 3 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

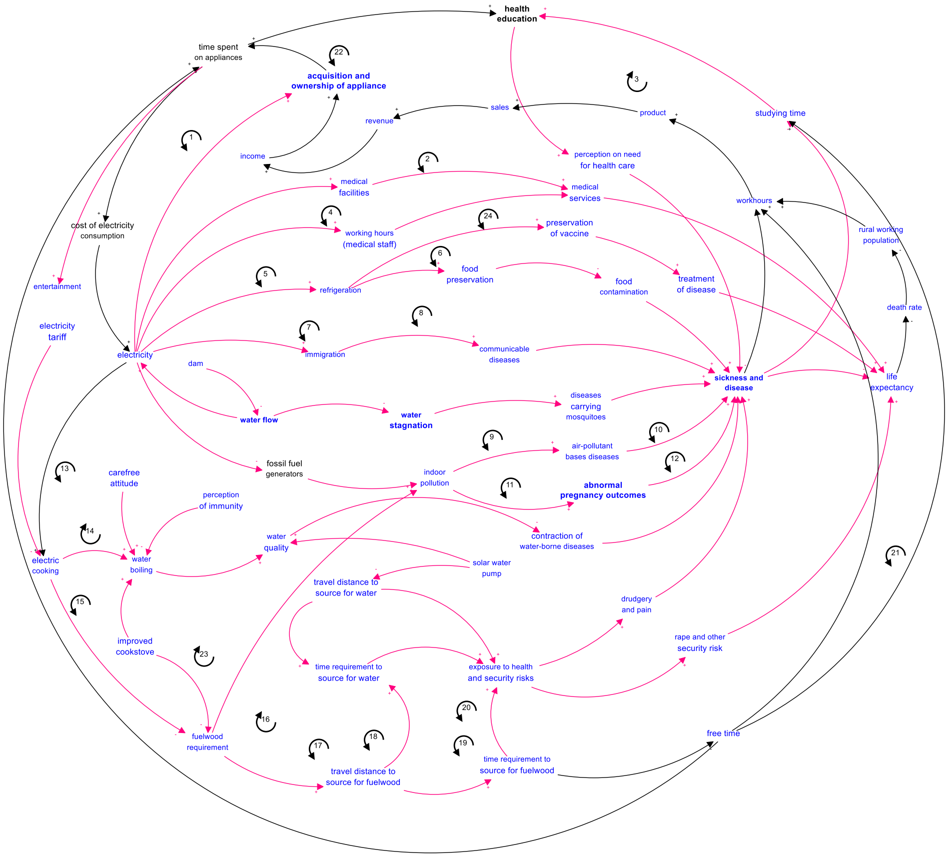

Figure 7-3: Causal Loop Diagram - Energy Access and SDG 3

7.2.4 SDG 9 – Rural Innovation, Industrialisation and Economic Diversification

SDG 9 seeks to "build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation". The analysis of scientific literature, the relevant development themes to the goal in the rural context of developing countries are rural innovation, technology diffusion and changes, industrialisation, and economic diversification.

Despite the various opportunities that follows electricity access, electricity access may not result in rural industrialisation assessed based on diffusion of technologies, economic diversification and business innovations [243]. A number of studies have employed the acquisition of new appliances as a metric of the impact of electricity access, however, acquisition of new appliances do not in itself constitute an improvement on livelihood. However, the acquisition of such equipment is only a step towards the impact of electricity on livelihood [227].

7.2.4.1 Agricultural Workforce

While economic diversification is crucial to facilitating sustainable development in rural communities, it usually have negative impact on agriculture which is, mostly, the primary productive activity in rural communities. [32] The development of rural energy access project attract a significant share of rural workforce as construction workers which temporary boasts rural economy [30], however, reducing the manpower available for agriculture [32]. While most of the direct jobs created by energy access are lost at the completion of its development phase, rural dwellers seek to take advantage of entrepreneurship opportunities that accrue from energy access for indirect job opportunities which often lead to a long term reduction in agricultural workforce. Sequel to the development of Belo Monte Dam in Brazil, 33.33% of households reported a reduction in the number of household labour in the Altamira region available for agricultural activities[32]. Yet, more than half of the households in the region stated that household labour is not enough for their farming operations while 85.8% of the households attested to the scarcity of labour to employ for agricultural activities [32]. Nonetheless, emigration, education, among other factors, also contribute to the decrease in the rural workforce that are available for agriculture.

Conversely, energy generation from energy crops retain and sometimes increase rural commitment to agriculture hence increasing agricultural workforce[38].

7.2.4.2 Innovative use of waste

The generation of biogas from organic waste using biodigester represents an innovative approach for waste management and energy generation. [167] A biodigester generates biogas from organic waste for cooking and occasionally for lighting and refrigeration in rural households. Therefore, the biodigester represent an innovative approach for waste management that serves a dual purpose of reducing environmental pollution from organic waste and also increasing energy access [167].

7.2.4.3 Economic diversification and entrepreneurship

In addition to energy access, the establishment of new businesses is largely influenced by the economic characteristics of target communities; the wealthier population have more capacity to establish businesses than their poorer counterpart[227]. Rural dwellers who establish businesses sequel to gaining access to electricity are those who have stable income including those that benefit from remittances, among other sources. In addition to financial capacity, the number and nature of non-agricultural productivity activities established also depend on proximity to market, exploitable resources[230] [30], among other infrastructure[167], services and amenities available in the rural communities. For instance, businesses established in a rural communities close to high-traffic roads may include metal works for cars, construction and tyre repairs. More and diversified enterprises exist in communities closer to the road than those in the interior where enterprises are few and mostly related to agriculture [230]. Also, increased workhours and the use electric equipment result in increased output which translate to increased income if there is increase in access to market (customers) to secure sales of the outputs [167]. Similarly, villages that are close to the township have a more and diversified enterprises than those in the interior while villages with higher income levels and more demands for diversified services such as tourism also use more electricity. Therefore, proximity to exploitable resources also affect the extent of economic diversification as the available resources play significant roles in the type of enterprises that could be established [230]. Also, the lack of skills for market development such how to seek opportunities for market expansion and the role of energy access in market expansion pose a major limitation to rural entrepreneurship [230].

7.2.4.4 Quality of energy access and technology diffusion

Access to electricity catalyses the diffusion of electrical equipment and appliances in rural communities which facilitate improvement in the quality of rural livelihood, promotes economic diversification and rural industrialization [227]. Electricity access with high income facilitates the acquisition and ownership (diffusion) of electrical appliances such as television, radio and cassette player which increases opportunities for entertainment and education [226][229][30]. The increase in entertainment could also increase social bonding. For instance, the use of radio facilitates dance programmes in schools which increases education (cultural education) [230], entertainment [229] including social awareness (such as politics) [229]. However, the use of electrical appliances and equipment increases electricity consumption [30] thus increasing electricity expenditure which raises the challenge of affordability. Also, sustained power outages and voltage fluctuations limit the use of electrical equipment, thus, have negative impact on business (mostly non-agricultural) operations especially the electricity-dependent enterprises. Also, fluctuations in voltages causes damages to electrical equipment while power outages (low reliability) halts some business operations. Low quality of electricity supply reduces the acquisition and diffusion of electrical appliances and increased risk for those who already have them. Therefore, the quality of electricity supply, which is determined by the installed capacity of the project [230] vis-à-vis the electricity use, influences the level of impact that electricity access can make. While there are negative impacts of low reliability of electricity on rural businesses, businesses that are significantly financially stable are able to mitigate the negative impact given their capacity to provide alternative electricity supply for instance through private electricity generating sets [227]. Also, electricity access comes with a perception of civilisation which motivates electricity users to also adopt modern cooking technologies [230].

Figure 7-4 presents the pictorial view of the energy access-SDG 9 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

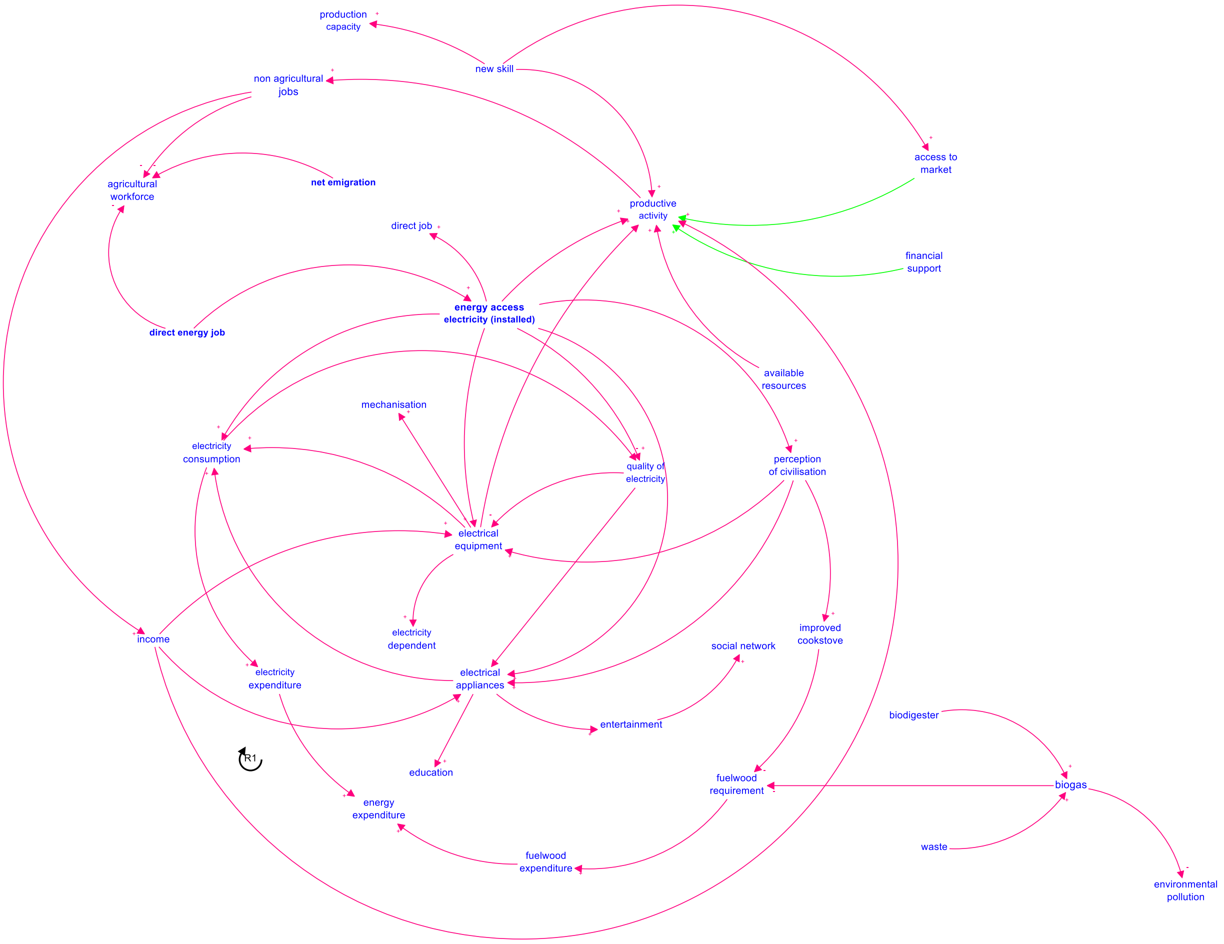

Figure 7-4: Causal Loop Diagram - Energy Access and SDG 9

7.2.5 SDG 4 – Education

SDG 4 seeks to "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all". Therefore, the energy access-SDG 4 nexus focuses on the variables and causal linkages of energy access and education in the rural context of developing countries.

7.2.5.1 Electric lighting and Studying

Electric lighting provides better illumination compared to traditional sources which is also associated with health hazards such smearing eyes, eye irritations and respiratory tract infections [229] [235]. Therefore, Electric lighting could facilitate increased reading hours [235], [241], [61], [30] [38] [229]. However, the impact of electric lighting on studying is dependent on the personal diligence of the students which is influenced by personal ambition to escape the hardship associated with low level of education and the encouragements of their parents [234].

7.2.5.2 Electric lighting and rural attractiveness to teachers, Employment

Moreover, many teachers serving in rural communities are unwilling to serve in rural communities, thus seek opportunities for service transfer and emigration which adversely impact the quality education delivery in the rural communities. However, electricity access increases the perception of civilisation, [61] facilitate increased comfort and enables the teachers to generate additional income by organising evening classes [226] which altogether increases teachers' willingness to serve in rural communities (rural attractiveness) [61]. The increase in teachers who are serving in rural schools including the evening classes helps to improve educational outcome of the students in rural communities. Nonetheless, the opening of job opportunities facilitated by energy access often constitute a distraction to the youth from education to pick up jobs to earn 'quick money' hence reduce their commitment to education (average years of schooling) [61].

7.2.5.3 Information and Communication Technologies: Socialisation and entertainment

Meanwhile, the acquisition and use of electrical appliances could either positively or negatively impact education outcomes in rural communities depending on their applications. Students' personal diligence contribute to the extent to which students use electricity for studying relative to its social and relaxation applications. The acquisition of electrical appliances such as television and satellite dish facilitates the establishment of new schools within the neighbourhood for school-age children [235]. Such appliances also provides access to information, thus, increasing knowledge on various subjects for youth and adults[230]. Children are also likely to start schooling younger due to the proximity of the school to their homes, while, some electric appliances also increase school attractiveness to children. Also, electricity also facilitates the teaching of '*new*' subjects such as ICT education which are not taught prior securing electricity access [241], [61] including extracurricular activities for education and entertainment [229]. The increased access to quality education facilitated by these appliances in rural communities reduces rural-urban migration for education [167].

Conversely, the use of some electrical appliances may constitute a distraction for youth hence negatively impact education outcomes in rural communities. Sequel to electricity access, students may spend more time on socialisation and entertainment after school hours [234]. Household and streetlight lighting also motivates strolling round the village till late hours. Matinga et al. finds that school-going boys and girls in rural South Africa spends 3-5hours daily watching television often till or beyond midnight thus reducing the time spent on studying [234], [46], [244], [61].

7.2.5.4 Improved Cookstove and Gender

The reduced fuelwood requirement of improved cookstoves helps to reduce the operation cost of school feeding programme which increase school attractiveness and increase educational outcomes among children from poor homes [236]. Energy access impact education of both sexes, however, with different level of impact. Khandker et al. find that whereas electricity access increased the years of schooling by 0.13year for boys, the year of school for girls increase by about 1year in Vietnam [245]. The lower fuelwood requirement of improved cookstoves reduce time requirement for fuelwood collection and cooking, thus, free-up time for educational activities especially for women and girls [236]. However, the time saved could also be spent on entertainment and socialisation which reduces educational outcomes.

Figure 7-5 presents the pictorial view of the energy access-SDG 4 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

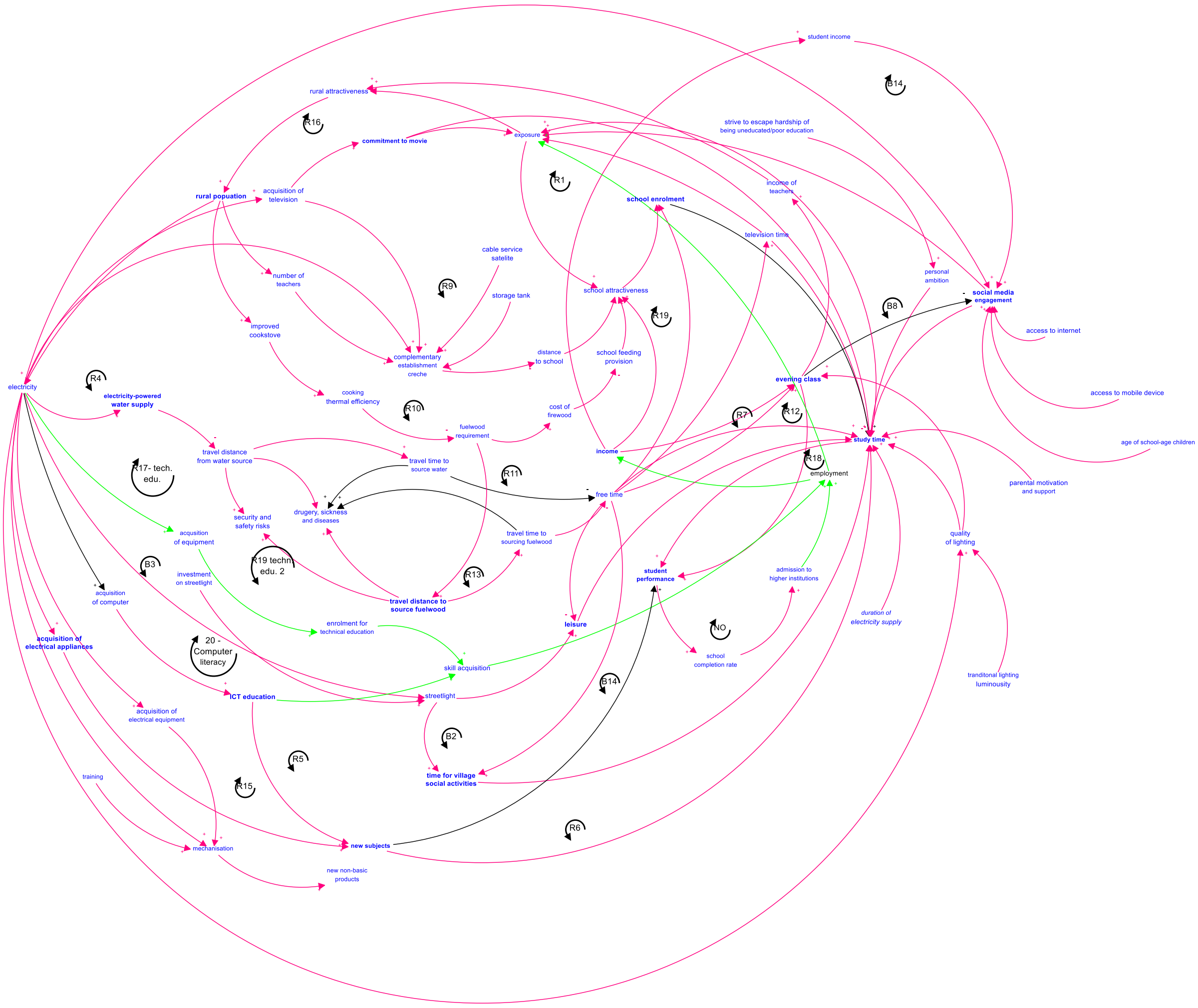

Figure 7-5: Causal Loop Diagram - Energy Access and SDG 4

7.2.6 SDG 5 – Gender

SDG 5 seeks to "achieve gender equality and empower all women and girls". Therefore, the energy access-SDG 5 nexus focuses on the variables and causal linkages of energy access and gender equality, inclusion and empowerment in the rural context of developing countries.

7.2.6.1 Lighting, cooking and productive activities

Freeing up time is one of the most significant impact of electricity access for women in rural communities [230] though this also applies to men but it is relatively insignificant to that of women [232]. The traditional role of women and girls in cooking makes them recipient of a disproportionate share of the negative impact of sourcing fuelwood and cooking [236] [232] [246]. The time investment on fuelwood sourcing and cooking reduces the time available to women and girls to commit to education and IGAs [236] [232]. Studies show that women in Kenya spends an average of one hour daily to source for fuelwood [236]. Therefore, the provision of improved cookstoves, clean cooking fuels [167] and electric cooking [246] [232] reduces the time and labour requirement for sourcing fuelwood, thus, free up time and labour that could be deployed for productive activities [40]. Electric lighting also provides opportunity to carry out domestic activities in the night, thus, allowing women to increase their workhours by spending more than on productive activities during the day [30]. The saved time increases women participation in IGAs employment [246] including home-based production and marketing services [232]. [243] Such increase in women labour force is, however, often associated with a decrease in female wages and income [243] in response to the forces of demand and supply [243]. [230] However, the saved time from house chores may also be expended on other non-productive activities [230]. Also, the manufacturing, distribution and sales of improved stoves could provide employment for women. Also, women's participation in the improved stove value chain and role in decision-making on cooking facilitates adoption and sustained use of the cookstoves [236]. While the use of improved cookstoves reduces the exposure of women and girls to health hazards and security risks [232] [236], electric lighting also improves the perception of security and safety, hence, increase mobility of women at night [30] [226],[247].

Terrapon-Pfaff *et al.* [232] finds that a 15% increase in electricity access in a rural district in South Africa made women work for additional 8.9 hours per week which represents a 3.5% increase in their workhours. This resulted in 30-35% increase in female employment amounting additional 15,000 women employment in the electrified communities. However, jobs facilitated for women by electricity access are mostly informal, temporal, unpaid, flexible self-employment, and are taken up by family members if it requires more than one employee [230]. This may be due to the scale of small scale of operations and low economic profile that characterises rural livelihood [230]. Hence, the need to complement energy access with financial support to increase the capacities of rural dwellers to maximise the entrepreneurial and employment opportunities provides by electricity access [232] in view of providing permanent and sustainable jobs for women. Indeed, an important strategy for improving the livelihood of rural women is by providing access to finance. However, access to such support often require that women organise themselves into 'self-contained cohesive groups' with shared socio-cultural and economic interests and perspectives [248]. This helps to leverage the strong social relations amidst rural women for social pressure that would help to ensure repayment in case of micro-credit as defaulting may put beneficiaries and their families in shame and ridicule [248].

7.2.6.2 Gender Differences in Productive Use

There are gender differences in the application of electricity for productive uses; men often use more electricity compared to women in productive activities[230]. Access to modern energy access increases opportunities for female entrepreneurship, income-generation, gender equity, autonomy and reduce drudgery [30][246]. Most of the men-dominated enterprises are highly energy-intensive such as carpentry and metalwork while women are more involved in productive activities that are less electricity dependent [40],[230]. However, the mechanisation of energy-intensive productive activities powered by modern energy access increases the ease and cost of operating some of the men-dominated productive activities thus facilitating participation of women in such businesses [230],[227]. However, the impact on operation cost depends on the share of energy cost in the overall operation cost of such IGAs [230]. Similarly, electrifying manually-operated productive activities also free-up time, reduces workload for women, thus, reducing drudgery and increasing productivity and income [30] [230].

7.2.6.3 Business Location

Electricity access is a motivation for citing business location, however, women (and people of lower caste) are less flexible in the locating their businesses than men, hence, are limited in their abilities to access higher quality of electricity supply in cases where electricity access with varies attributes are supplied in different areas of their community [227]. [230] The flexibility in operation of enterprise depends on the location of the enterprise relative to the household especially for women given the need to combine productive activities with home-making [230]. Therefore, where applicable, women may be limited in citing their business in locations with high quality of electricity supply for their businesses.

7.2.6.4 Social Education and Culture

Electricity access facilitate acquisition and use of ICT for exposure, education, and entertainment which improves social attitudes such as reducing gender-based violence, gender equality, family planning [246] among other subjects. Conversely, such social education could also erodes traditional cultures and values in rural communities. Nonetheless, the acquisition and use of ICT is limited by level of income, hence, their ownership is largely limited to rural households that are financially better-off.

7.2.6.5 Cooking and Health

Traditional cooking methods is one of the major sources of in-door pollution in rural households. Based on its relatively high thermal efficiencies, improved cookstoves produces less smoke hence reduces the exposure women and girls (who are primarily responsible for cooking in rural households) to indoor air [236] [232]. This reduces their risk of contracting diseases such as respiratory diseases, chronic obstructive pulmonary disease, eye irritation, cataract, headaches and burns, thus, reducing deaths linked to indoor air pollution [236] [246]. Clean cooking also help to reduce the risk of still birth and low child weight, among other adverse pregnancy outcomes.

Figure 7-6 presents the pictorial view of the energy access-SDG 5 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

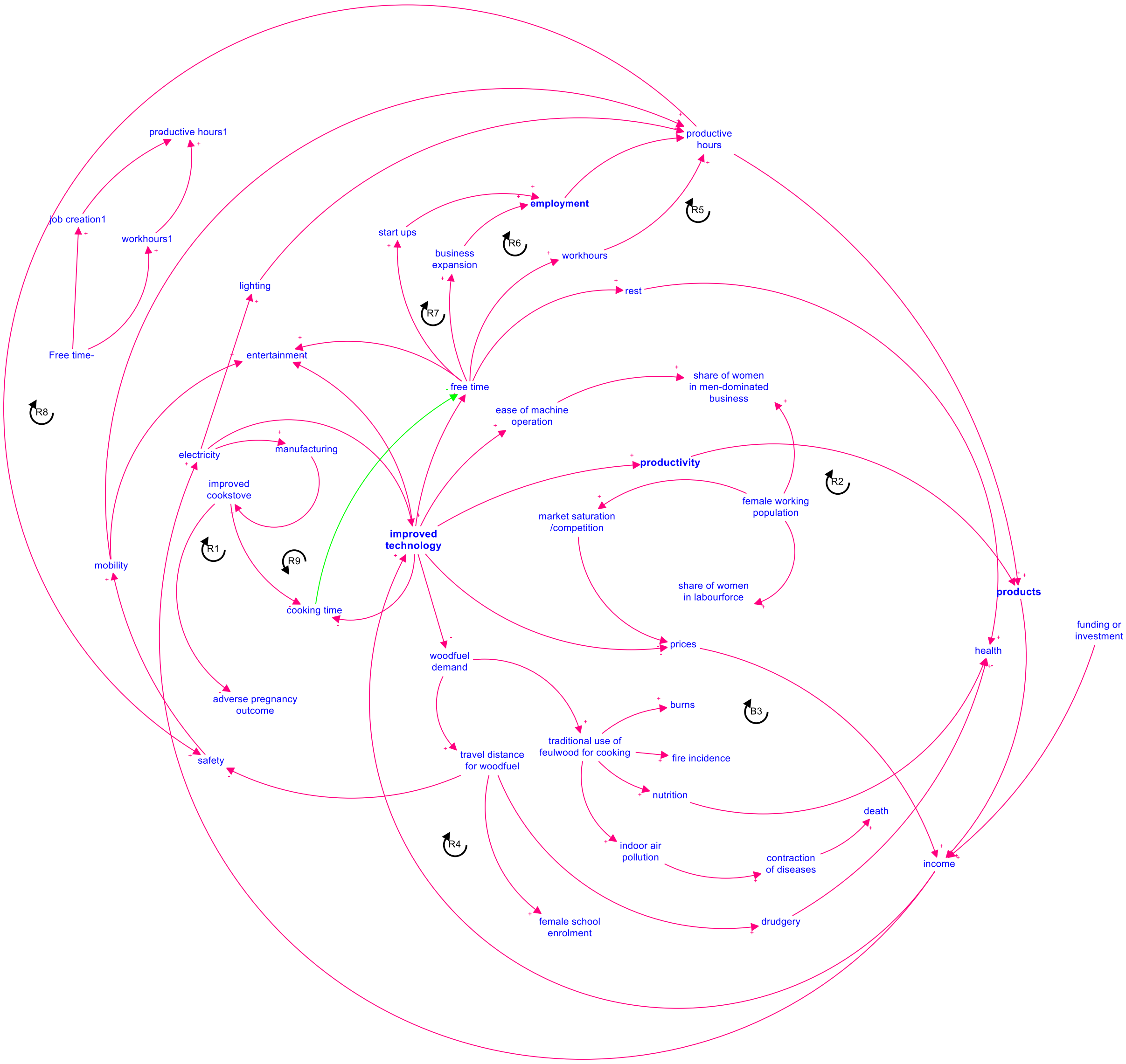

Figure 7-6: Causal Loop Diagram - Energy Access and SDG 5

7.2.7 SDG 6 - Water and Sanitation

SDG 6 seeks to “ensure availability and sustainable management of water and sanitation for all”. Therefore, the energy access-SDG 5 nexus focuses on the variables and causal linkages of energy access, water access and use, waste management and sanitation in the rural context of developing countries.

7.2.7.1 Solar Water Pump

Rural livelihood is characterised by high dependence on ‘open and unprotected’ water sources that are unsafe for drinking without treatment among other uses due to their high level of contamination. The consumption of untreated water from open and unprotected sources is a major cause of diseases such as fever and diarrhoea, among rural dwellers. Indeed, lack or inadequate awareness of the health risks and hazards related to the consumption of unsafe water is a reason rural dweller do not treat water from unprotected and unsafe sources. However, many rural households neither boil water fetched from unprotected sources nor use other treatment mechanisms [234] despite having a significant level of awareness of water-borne diseases. This is common in riverine communities given their perception of immunity from water-borne diseases due to their history of drinking water from such sources [234]. However, in addition to the electricity cost which limit water boiling, traditional beliefs and perceptions of immunity against water-borne diseases also limit the impact of electrification on access to clean and safe water. However, the installation of solar water pumps within the residential areas of rural communities helps to provide clean and safe water without the need for boiling [247]. While the impact of electricity access for water boiling may be limited by perception of "automatic immunisation", solar water pump is not [240]. Moreover, solar water heaters also provides hot water for bathing [240].

The dependence on water from river for drinking also impact animal husbandry. The infestation of river with dangerous sea animals such as crocodile makes livestock prone to attack during ranging for water drinking. Livestock are also susceptible to water-borne diseases such as anthrax, paratuberculosis, black quarter, rinderpest and actinomycosis which all mostly affect cattle and sheep [249] which could lead to their death. However, the installation of solar water pump within residential areas of rural communities provide cleaner and safe water for drinking for livestock [240] and also reduces the risk of attack of livestock by sea animals and the associated ranging distance and time [240]. This shows that the diversification of energy technologies to include solar water pump and heaters in energy access projects provides rural communities with clean and safe water without the need for boiling [235],[61].

7.2.7.2 Water Dam and Hydropower Generation

The development of the dams manipulates the river flow which affects human livelihood in various dimensions. Due to reduced water flow, upstream of river course becomes waterlogged while the downstream suffers water scarcity [32]. Moreover, due to the flooding of the site for the dam, agricultural lands are lost leading to the displacement of farmer who often resettle in areas with less fertility, hence, reduced productivity [32]. However, the integration of hydropower projects with water milling facility provides water supply for drinking [226] , [247] food production and promoting health. The integration of electricity-dependent productive activities also decreases electricity wastages, thus, fostering profitability and sustainability of energy projects [226]. The fencing of close land area of hydropower plants also reduce grazing land creating tension between the developer and extensive livestock farmers. This result from lack or ineffective of community participation and consultation in energy access projects[30].

7.2.7.3 Waste and Sanitation

Biodigesters generate biogas for cooking, lighting and refrigeration from organic waste, thus, serving a dual purpose of energy generation and waste management which reduces environmental pollution [167].

Figure 7-7 presents the pictorial view of the energy access-SDG 6 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

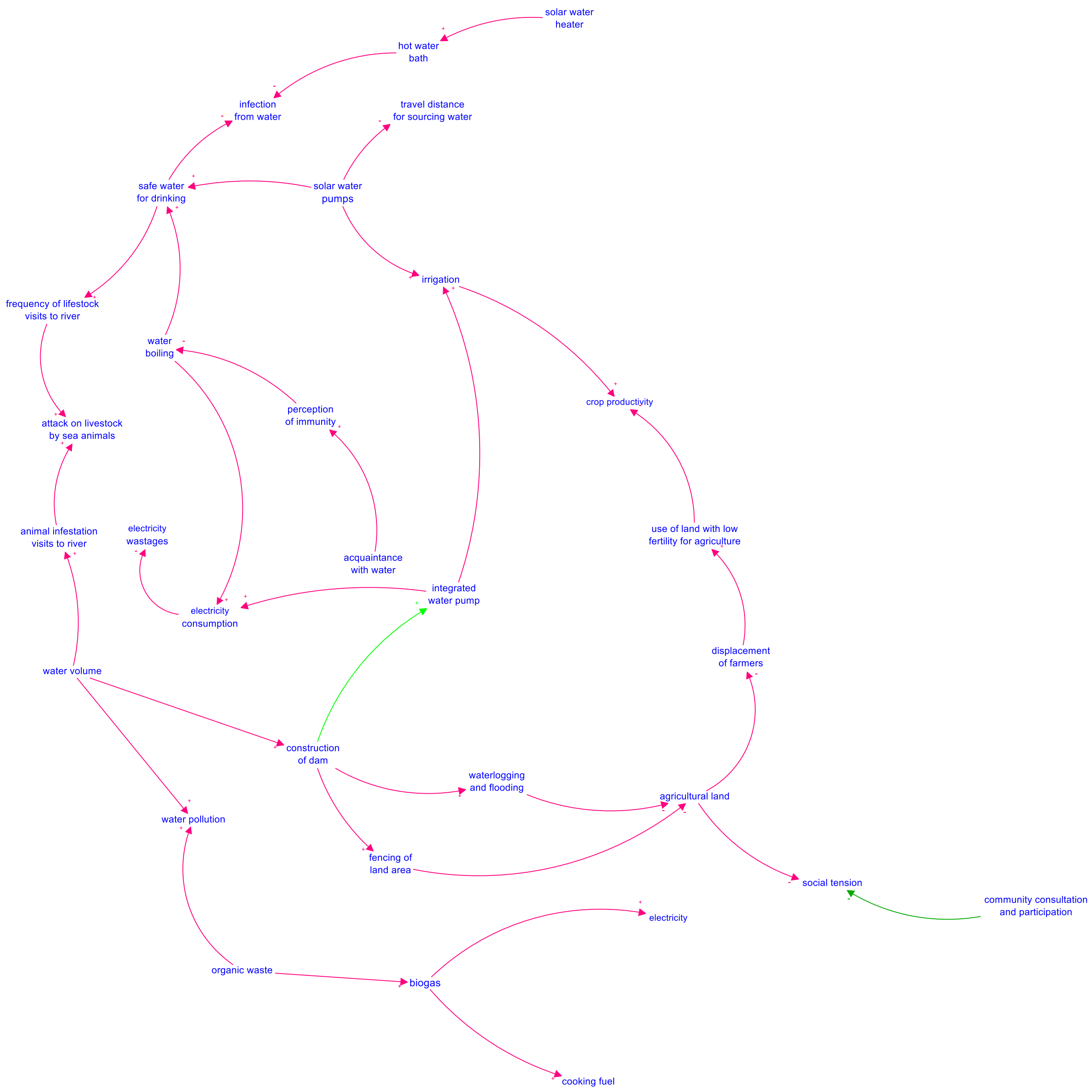

Figure 7-7: Causal Loop Diagram - Energy Access and SDG 6

7.2.8 SDG 7 – Energy

SDG 7 seeks to "ensure access to affordable, reliable, sustainable and modern energy for all". While energy access is a crucial part of SDG 7, the scope of the goal is broader than energy access. The energy access-SDG 7 nexus focuses on the variables and causal linkages of energy choices, its determinants, the peculiarities of energy access, its attributes, use and impact in view of realising the SDG 7 in the rural context of developing countries.

7.2.8.1 Energy access and peculiarities of rural livelihood

Electricity access in rural communities is crucial given its enabling role in facilitating development especially in rural communities of developing countries with high level of development deficit. Electricity access facilitates establishment and citing of businesses [227] (especially electricity-dependent businesses) including other socioeconomic infrastructure to stimulate rural development. Conversely, the presence of businesses also attracts electricity access due to increased willingness and capacity to pay for electricity use. Market potential, energy use, ability to pay for electricity consumption, proximity to cities [228], nearness to road networks [230] and proximity to existing electricity-dependent infrastructure [30] are crucial factors in the decision matrix of energy investors [230]. Therefore, the remote location and high level of poverty in many rural communities of developing countries make them unattractive for energy projects. As a result, many utility companies reckon rural communities as 'burden' rather than a market base for investment [230]. This explains the reason such communities suffer a disproportionate share of energy poverty [230].Therefore, if investment decisions for rural energy access in developing countries is subjected to market forces on a business case, a high percentage of the global rural population will not have access to modern energy in a near future, thus, reducing the chances of meeting the 2030 target for universal energy access [230]. Therefore, there is the need for the development and implementation of energy access strategy which captures the peculiarities of rural livelihood, thus, highlighting the collaborative role of government, the private sector and development organisations [228] [167] in the rural energy development dynamics. Such strategy could provide for financial support to utility companies to offset some of their cost hence increase their interest and the profitability of providing electricity access to rural communities [230], and, provide incentives such as subsidies both at the energy supply and demands sides [228]. This is particularly important in developing countries with high rural population.

7.2.8.2 Energy choices and challenges

The technology choice for rural energy access should consider available energy resource, expertise and history of target communities [226]. For instance, hydropower generation may be an appropriate option for a rural community with hilly topography with run-off water bodies [226] while biomass may be the best option for regions that can grow energy crops and frequently generates significant volume of waste. Moreover, energy access projects that promote, strengthen and support existing economic activities in rural communities have been identified to benefits from high community support [230]. Energy generation from biomass has some unique peculiarities in this regard. Biodigesters generates biogas for cooking among other applications from wastes serves a dual purpose of reducing environmental pollution and energy production [167]. Generally, the attraction of rural youth to opportunities for non-agricultural productive activities sequel to gaining energy access often results in a decline in agricultural workforce. However, the cultivation of energy crop for biofuel helps to, rather, retain and sometimes increase rural commitment to agriculture. Nonetheless, the cultivation of crops for energy generation competes on land for food production, thus, increasing food scarcity and prices [38]. This call for policy coherence on agricultural production and energy generation especially on the allocation of agriculture land for energy and food crops to ensure sufficient food production while promoting the cultivation of energy crops.

The diversion of water for hydropower generation reduces the volume of water available for traditional watermill business, and upsets traditional irrigation systems, hence negatively impact milling operations which often generate reactions from residents and farmers [30]. While stakeholders on such hydropower projects often offer compensation to those who lose their livelihood due to the development of hydropower plant, the implementation of such compensation scheme is always not effective [32]. The affected farmers are always resettled in areas with lower quality of life, especially soil fertility, relative to their original settlement. This results in lower agricultural productivity and poorer access to infrastructure to rebuild their livelihood [32].

Apart from the required wind speed required to drive wind turbine, electricity generation from wind is also limited by the "not at my back yard" attitude due to the perceived related visual intrusion, negative impact on birds and noise pollution from wind energy plants [38]. Moreover, effective community engagement and participation provide panacea for such challenges [30]. Nonetheless, relative to fossil-based energy generation, energy generation from renewable energy sources are environmentally friendly which may serve as an added advantage for other economic activity such as tea production [30].

7.2.8.3 Energy attribute and use

The attributes of energy access determines the type, level and diversity of its use and impact [227]. The assessment of energy access was largely assessed based on a binary approach of whether there is access to energy or not until the development of the Multi-Tier Framework by the World Bank among international stakeholders in 2015 [250]. The quality of energy access is crucial to its impact, particularly in rural context. In rural India, while 16% increase in electricity connection only increased household income by 9% from non-agricultural activities, a 32% increase in the quality of electricity resulted in a 29% increase in household income from non-agricultural activities in in rural India [251]. However, due to economic metrics among other factors, many utilities do not supply higher tier of electricity to rural communities, which limits rural productive activities to performing preliminary processing in their produce value chain[230]. The inability of rural enterprises to perform sophisticated value addition on their produce makes them loose a great share of the economic benefits of their produce to the cities or foreign nations with processing and value addition capacities[238].

While securing access to electricity and acquisition of electric appliances are indicators of potential use, the impact depends on the duration and frequency of use [227] [30], among other attributes. Power outage and fluctuating voltage cause damages to machines and products, disrupts business operations, thus reducing the diffusion of electrical appliances and increased risk for those who already have them[227]. Electricity access with low attributes may force poorer enterprises out of business while those with significant financial stability may be to provide alternative electricity supply using individual generating sets [227].

Nonetheless, the level (duration and frequency) of electricity use does not constitute an appropriate measure of the scale of operation of electrified businesses [227], [235]. Studies show that enterprises with low income have low propensity to invest in electricity appliances for productive use, therefore, they prefer to acquire appliances for low-energy intensive activities such as lighting, comfort , among others [227]. Such productive activities employ non-electric (manual) means for energy-intensive aspects of their operations [227], [235].

7.2.8.4 Electricity Access and Agriculture

Electricity access in rural communities rarely have direct impact on agriculture which is the predominant occupation in rural communities especially as farmlands are mostly located in far distances from rural settlements where electricity projects are mostly implemented. Nonetheless, electricity support agro-processing which are often carried out within the residential areas of rural communities, where such activities exist. In addition, electricity also support diversified productive use of electricity for pre-existing and new productivities that emerge sequel to gaining access to electricity such as metal works and communication services in wealthier communities [230].

7.2.8.5 Energy Transition

The rural energy mix in developing countries is characterised by inefficient and unclean use of traditional fuels for various energy needs and applications to support rural livelihood. Therefore, an effective energy intervention effort aimed at ensuring "access to affordable, reliable, sustainable and modern *energy* for all (SDG 7)" in rural context would provide holistic approach by providing modern energy access for various rural energy needs and services. Given the pivotal role of energy access in rural livelihood, provision of affordable, reliable, sustainable for lighting, cooking, water pumping [230] among other applications and services has implications for various dimensions of rural livelihood.

7.2.8.5.1 Energy transition for cooking

Also, the adoption and use of modern cooking fuels and technologies has multidimensional impact on time, health and safety, drudgery among other impacts especially for the feminine gender. Despite gaining modern energy access, electric cooking remain largely limited by the associated high electricity cost. Rural households adopt improved cookstoves where provided, however, wealthier households complement the improved cookstoves with LPG [30], largely motivated by the perception of civilisation that accompanies security of modern energy [230]. Fuelwood which are mostly sourced at no cost [229], often remains cooking fuel for poorer households, on the other hand. However, developers of energy access project often offer electric stoves and heaters to electricity users at no cost in order to increase electricity consumption to boast their profitability. Nonetheless, the users do not use the electric cookers and heaters upon discovery that their use escalates their electricity expenditure [30]. However, the pattern of change in cooking technology could differ with productive activities especially with electric cooking as more food businesses are able to adopt electric cooking. While there are a few instances of electric cooking especially for food-related businesses in rural communities[40]; LPG, improved cookstoves, solar water heater, among others are most adopted cooking energy technologies in rural developing countries.

The adoption of modern cooking technologies such as improved cookstoves and electric cooking reduce the undesirable impacts of traditional cooking methods. Similarly, the installation of solar water pumps within residential areas reduce travel distance, drudgery and the associated health and safety risks of fetching water for irrigation thus freeing up time for education and other productive activities [230].

7.2.8.5.2 Energy transition for lighting

Studies show that many energy access intervention projects in rural communities have been limited to electricity access. However, electricity does not usually have direct impact on some of the essential dimensions of rural livelihood such as agriculture while the extent of its impact on other dimensions is limited by diverse factors. Such factors include affordability (income level vis-à-vis the cost of electricity), installed capacity of the electrification plant, technical and business expertise of rural dwellers, and, level of economic diversification among others. Indeed, some energy project generates more electricity than the actual electricity demand, while, others generate less. Depending on the installed capacity among other technical factors, electricity users may experience occasional blackouts and unable to use energy-intensive applications such as welding [229]. This partly explains the reason lighting has been identified as the most significant application of electricity in rural communities [229]. Nonetheless, electric lighting eliminate or reduce the use of kerosene lighting which is the primary lighting fuel in many rural households thus reducing indoor pollution and the associated health and safety implications [40]. For instance, a 100kW small hydropower plant in Gauhati (a rural community in India) saves 60 litres of kerosene for lighting applications annually sequel to their transition from kerosene lamps to electric lighting [30].

7.2.8.6 Complementary actions for productive use

Lighting appears to be the most significant impact of energy access when energy access is limited to electricity [40] [229]. This is largely due to the generation capacity [229] [40], affordability of electricity tariff (including connection fee in some cases),and, limited technical and financial capacity of rural dwellers to increase their production capacity, among other factors. The factors limit the extent and dimensions of rural economy that is impacted by electricity access which ultimately affect the revenues of rural enterprises [227]. However, where electricity access enables increase in production, this may not automatically translate to significant impact on income [227] due to limited access to external market to facilitate the uptake of the increased products [40]. A study conducted on rural enterprises in some Kenya communities where mini-grid projects have been implemented reveal that 88% of their customers are within the village where the businesses where domiciled while 10% were from the same county [40]. Also, Kooijman-van Dijk finds that the impact of electricity access on income of small scale enterprises in rural Indian Himalayas was low due to limited access to market as rural dwellers have lower social network to facilitate access to markets outside their communities [227]. This highlight the need to complement rural energy projects with increase in access to external market by increasing the social network of rural dwellers to increase their customer base.

Moreover, the projected growth in electricity demand is often more than reality partly due to the assumption that electricity access will automatically and immediately facilitate development which will result in rapid growth in electricity use [30] [40]. This leads to oversizing electricity generation plants and consequent electricity wastages which negatively impact the revenue, profitability and sustainability of energy projects [167]. This is particularly the case for many solar energy projects as electricity consumption during the day offers relative financial advantage compared to the evenings. Once the storage facility is fully charged, electricity generation during the day are either consumed or wasted. Therefore, the integration of energy project with other productive equipment for creating a small-scale industry [226] such as milling equipment for grains, and financial support for rural businesses to procure electrical equipment offers a significant economic advantage [226]. Such complementary inputs increase electricity consumption thus, reducing electricity wastages, revenue and profit on electricity investment, and enterprises in the community. Electricity consumption for productive uses may also be increased by adopting financial models that provides offers cheaper electricity tariff for productive uses during the day relative to the evening.

7.2.8.7 Limitations to Productive Use

While access to electricity offers diverse advantages, electricity tariff often increase the energy expenditure for rural dwellers especially those that have not been using electricity from fossil fuel generators prior gaining access to electricity [167] [227]. Therefore, newly electrified households often expend significantly higher energy cost (than unconnected households) [229] which may negatively impact the interest in securing electricity access. However, the energy cost for households that use private generators is generally cheaper as fossil fuels are usually higher in rural communities due to their limited supply, cost of transportation of the fuels from the city, elongated supply chain among other factors. Therefore, the provision of electricity access from renewable energies usually reduces electricity expenditure for such households and business. Therefore, the richer class gain electricity access and benefit more from electricity use than their poorer counterparts [40] due to the affordability of initial connection fees, payment of tariff and financial capacity to acquire electric equipment to increase the productivity of their business operations[167] [227], among other factors. However, electricity access results in decrease in energy cost for the financially better-off who uses generator prior gaining electricity access and consequently overall operation cost for productive activities [234] especially for electricity-dependent IGAs given the productive use of energy which increase their income. While productive use of electricity may be majorly limited to agro-processing in poor villages, there are more diversified productive uses in the wealthier villages both to support pre-existing activities and new activities that emerge sequel to securing the access to electricity [230]. This shows that maximising the impact of electricity access requires complementary actions that boost the economic profile of target population [226].

Figure 7-7 presents the pictorial view of the energy access-SDG 7 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

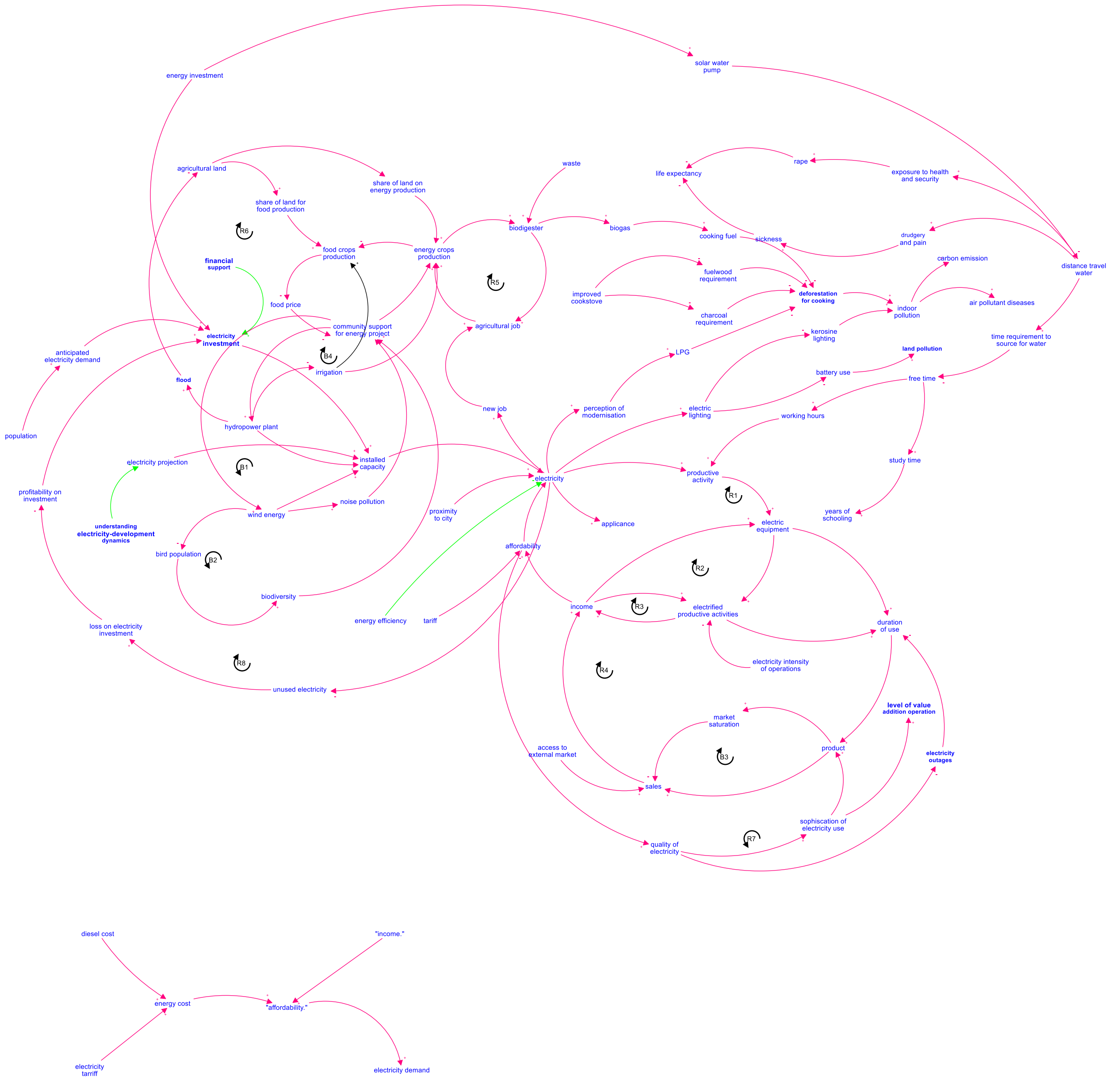

Figure 7-8: Causal Loop Diagram - Energy Access and SDG 7

7.2.9 SDG 8 – Decent Work and Economic Growth

SDG 8 seeks to "promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all". Therefore, the energy access-SDG 8 nexus focuses on the variables and causal linkages of energy access and jobs in the rural context of developing countries.

Access to modern energy have both direct and indirect impact on some existing productive activities as well as facilitate the emergence of new productive activities [241][234], thus, creating jobs in rural communities , however, access to modern energy also result in closing down other existing productive activities. Modern energy access impact productive activities through the adoption and use of modern technologies that increase production efficiency and lighting which increases workhours. The adoption of modern technologies also reduces the time-intensity of household chores thereby freeing-up time and labour for productive activities, among other impact pathways. The increase in productive activities leads to increase in employment opportunities which increases income, thus reducing poverty (SDG 1) [241].

The development of rural energy intervention projects aimed at facilitating rural development requires baseline and needs assessment to the determine the most appropriate businesses to be supported. The assessment helps to identify the available resource base that could be exploited and leveraged for the development of small-scale industry in target communities. This is crucial as studies show that energy projects that support existing activities and tapping into the resources in the host communities attract more community participation and support hence more sustainable. For instance, enabling the establishment of agricultural processing facilities enables value addition processes on the agricultural produces which significantly increase the share of agricultural revenue that is retained in the rural economy [226].

7.2.9.1 Productive use

Based on its higher thermal efficiency relative to the traditional cooking methods, improved cookstoves reduces the time and fuelwood requirement for cooking, thus, reducing the operation cost for cooking-related business such as fish-smoking[232]. Also, the installation of solar water pump within the residential areas reduces the travel times for sourcing for water relative to fetching from open river sources. Similarly, the adoption and use of improved cookstoves reduces fuelwood requirement for cooking. These reduces the travel times to source for fuelwood and water [232]. The resulting increase in labour supply and workhours [30] affect both sexes, however, the impact is more on women given the traditional role of rural women in home-making [243].

Electric lighting enables rural dwellers to carry out household chores late in the night, hence, can devote more time to productive activities during the day [167] [30]. However, the impact of electricity access on enterprises and employment will be limited if its application is limited to lighting [230].

Energy access interventions that are limited to electricity access rarely make significant impact on agriculture which is the predominant occupation in most rural communities of developing countries [30]. Rural electrification does not have direct significant impact on irrigation, protection of livestock, among other agricultural activities [235] which are mostly located far from the residential areas of rural communities. However, electricity access support existing businesses which are mostly operated within the residential areas of rural communities and facilitate the establishment of new productive activities [232] [230] [226] [234]. The use of electric machines improve the efficiency of business operations which decreases the time requirement per unit of production hence freeing-up time. The saved time and increase in workhours can be use to scale production to generate more revenue provided there is commensurate increase in the demand for the goods and services [230]. Sequel to gaining electricity access, some of the existing businesses extend their operating hours while others increase their range of products with new products especially electricity-reliant products such as frozen chicken[234].

A common challenge of rural energy developers is the shortage of electricity demand over supply hence leading to electricity wastages especially during the day. In order to increase electricity consumption, rural energy developers employs various strategies such as distribution or facilitating the diffusion of energy-intensive appliances which often does not yield intended results as the rural dwellers stop using the appliances on discovery of the resulting drastic increase in their electricity expenditure. However, integrating the establishment of new electricity-dependent business in rural energy access project offers a more effective strategy to boast electricity consumption[226]. Such integration increases electricity consumption (thus, reducing electricity wastages) while generating returns for the investors (energy and integrated business), thus increasing the profitability of the energy project [226]. Conversely, there are also cases where the use and type of application of electricity access is limited by the installed capacity of the plant, thus limiting productive use and possible economic diversification and rural industrialisation [243].

7.2.9.2 Direct and Indirect Jobs

The provision of modern energy access creates both direct and indirect jobs opportunities including opportunities for capacity building [232] and the number of such jobs is limited by the capacity of the energy projects [167]. The direct jobs include employment that directly serves the development, operation and maintenance of the energy projects. The indirect jobs cover jobs created from productive activities that takes energy access as input and leveraging opportunities created by the energy access [32]. This also includes job opportunities created by other infrastructural development to serve the increased population due to energy access [32]. Nonetheless, some of the indirect jobs created are unpaid, flexible and such that are taken up by family members which may be due to the small scale of operations and low economic capacity of the businesses [230].

Indeed, many of the direct jobs created during the development phase of rural energy access project boast rural economy, nonetheless, such impact are short-lived as only a small fraction of such jobs are retained in the long term [30], [32] [230]. This is due to the low maintenance requirement of renewable energy technologies which are mostly adopted for energy access in rural developing countries. The adoption of remote control and monitoring system in the operation and maintenance of the energy plants further reduce the labour requirement in on the site while creating jobs outside the target community[38]. The development phase of a 208MW wind farm created 150 direct temporary jobs for 10months but only 12 direct permanent jobs in the community at the completion of the development phase and the end of the two-year warrantee period on the project[38]. A 1MW solar PV project provided 10 direct temporary jobs during the development phase but only one in the long term of the project [38]. However, the generation of biofuel provides relatively more direct and permanent jobs. Modern generation of bioenergy (from energy crops) depends on the consistent supply of raw materials from farmers, thus, provides a ready market for their produce, hence sustaining and increasing agricultural jobs. For instance, a biofuel plant with annual production capacity of 50,000 tonnes created 23 direct jobs which were taken up by the youth in the host community mostly those with technical or university education. The project developer also established 4522 contracts for the supply of raw materials (sunflower seeds) in one year which resulted in about 200 direct and indirect jobs[38]. Therefore, the use of endogenous resources (agricultural produce) in bioenergy projects makes it to strengthen the primary occupation in the community, therefore, enjoy high level of community participation and stakeholder engagement which enhances its impact [38]. In addition to providing ready market, energy crop could also attract more revenue (especially as their prices are largely influenced by the global market) than food crops which altogether leads to a preference to cultivate energy crops over food crops [38].

Moreover, livestock farmers in rural communities often depend on free ranging of their livestock to source for feed and water. Therefore, livestock suffer attack during ranging to rivers infested with dangerous sea animals such as crocodile. The loss of animals reduces income and sustenance of livestock farming [235]. The provision of solar water pumps addresses this challenge by providing water for animals without the need for ranging to river banks hence reducing the loss of livestock, therefore sustaining livestock agricultural jobs. Besides, the solar water pump also provided water for irrigation purposes, hence, promoting the crop cultivation at commercial scale which could serve as new income-generating activity thus enhancing agricultural jobs [235].

More so, modern energy access also provides opportunity for capacity building which position the beneficiaries for employment. The development and operation of energy access projects often requires capacity building of some rural dwellers to manage the project. In addition, projects especially those implemented in a more holistic approach, integrate empowerment of rural dwellers for productive use of electricity which leads to establishment of businesses and employment [235].

Conversely, rural electrification projects especially based on renewable energy system also come with trade-offs on employment and income generation. This is common with energy access projects that are mainstreamed to electricity access which results in loss of jobs yet creating limited direct and permanent jobs. For instance, the provision of renewable energy access may cause generator technicians and gasoline dealers to lose their jobs, traditional watermills may go out of business due to the diversion of water for hydropower generation while those dealing in fuelwood and charcoal experience reduced income sequel to the diffusion and use of improved cookstoves [30] [236]. A field assessment for this research in a local community where renewable energy project had been implemented in Nigeria shows that many of the generator technicians left the community due to the loss of patronage as generators were no more in use. Only one of the technicians remained in the village who started making a living in helping owners of generators to sells their generating sets to dwellers in other communities.

Enshrining plurality in the technology mix of energy access programmes would help to provide more direct jobs especially with clean cooking. The improved cookstove value chain (design, manufacturing, distribution and sales) offers employment opportunities that could provide decent and highly skilled jobs for income generation[236]. GIZ reports to have generated 1000 jobs in 2016 across the cookstove value chain. Nonetheless, while improved cookstoves create jobs, it also leads to a decline in fuelwood and charcoal consumption hence negatively impact jobs along their value chains which employs a significant share of population in developing countries [236]. About 13 million people earn their living across the charcoal value chain in Sub-Sahara Africa, while 635,000 people are employed across the fuelwood and charcoal sector in Kenya, contributing about USD 1.6billion annually to its economy. It is estimated that the charcoal value chain provides 200-350 jobs per TJ of charcoal; and charcoal and fuelwood activity constitute a significant part of informal economy rural communities [236].

Therefore, an important consideration in planning rural energy intervention is to ensure that strategies and measure are deployed for job creation and increased income to ensure that the intervention provide sufficient jobs to at least offset the job losses that may result due to the energy intervention. This often require complementary actions that provides economic catalysts (such as access to finance) that would incentivise job creation at least to at least offset job losses or reduced income due to the modern energy intervention [236].

7.2.9.3 Complementary Actions

Studies show that energy access projects that leads to significant impact on productive use do not 'just' trigger the productive use automatically or by coincidence. Rather, productive use is integral to the planning and design of such projects [232] and the intended impact on productive use does influence the nature and capacity of the energy intervention including the complementary actions.

As found by various studies, wealthier businesses benefits from electricity access than the poorer counterpart [235] [40]. The ability of wealthier businesses to leverage their capital base and network to increase their production capacity and quality demonstrates the essential role of access to finance in maximising the impact of electricity access.

Financial Support: While electricity access facilitate the establishment of new businesses, such establishments require access of finance [234] as a complementary action. Matinga and Annegarn reports that, due to lack of start-up finance and business skills, no new shops were established in Tsilitwa village in South Africa sequel to gaining electricity access while the existing shops were owned by rural dwellers with stable income[84]. Moreover, such new business face more challenges than their existing counterpart due to lack of experience and early saturation of such new business[230][38]. As more entrants leverage on electricity access to start new business such lines of business are saturated early with supply over the demand hence the prices and profitability drop leading to a crowding-out effect. Moreover, maximising the impact of energy access for improving rural economy and job creation requires provision of access to finance as a complementary action to increase the capacities of existing businesses. Large transfer of funds to rural household has been identified to increase employment opportunity for young adults and women in rural communities [243] .

Access to finance often require that rural dwellers organise themselves into groups (social networks) with shared socio-cultural land economic interests and perspectives[248]. This helps financiers (creditors) to leverage social pressure among rural groups to gain confidence that micro-credits provided will used responsibly and returned, thus preventing defaults. Women are particularly more advantaged than men as they are accounted more reliable than men and such provision of financial support has been identified as an important strategy for improving livelihood for women [248]. However, men may be more advantaged to receive loans for farming than women as men own more lands than women in rural communities and are often more active in farming. In general, complementary actions should seek to create indirect jobs by integrating the energy access projects into rural socioeconomic structure. Studies show that the number of indirect jobs created depends on the economic profile of the community [230] and the level of integration of the energy projects into the rural socioeconomic structure (especially primary economic sector-agriculture) [38].

Market Expansion: In addition to enabling the flexibility of workhours[230], electric lighting also increases length of effective day (number of active/productive hours) which makes an endowment effect that result in an increase in the demand for all normal goods [243]. Nonetheless, maximising the benefit of the increase in workhours for economic impact requires complementary actions. This includes increased labour force [243] and other production capacity (e.g. equipment [167]) for new and existing products especially non-basic goods and services. However, this will only result in increased in sales and revenue if there is an increase in customer base[40]. Hence, the need to create access to external market which often requires increased in social network. The markets for basic goods are usually saturated such that increase in demand from an enterprise majorly follows from a decrease in the demand from a competitive enterprise in poorer villages and the demand for luxury goods are low in such communities. In wealthier communities, economic growth result in increase in demand for luxury goods and services such as repair of vehicles, refrigerated drinks and welding [230]. However, the demand for some commodities are seasonal, therefore, their demand generally increases during the peak seasons for the enterprises and electricity use contribute to their ability to generate and meet such demands[230].

Figure 7-7 presents the pictorial view of the energy access-SDG 8 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

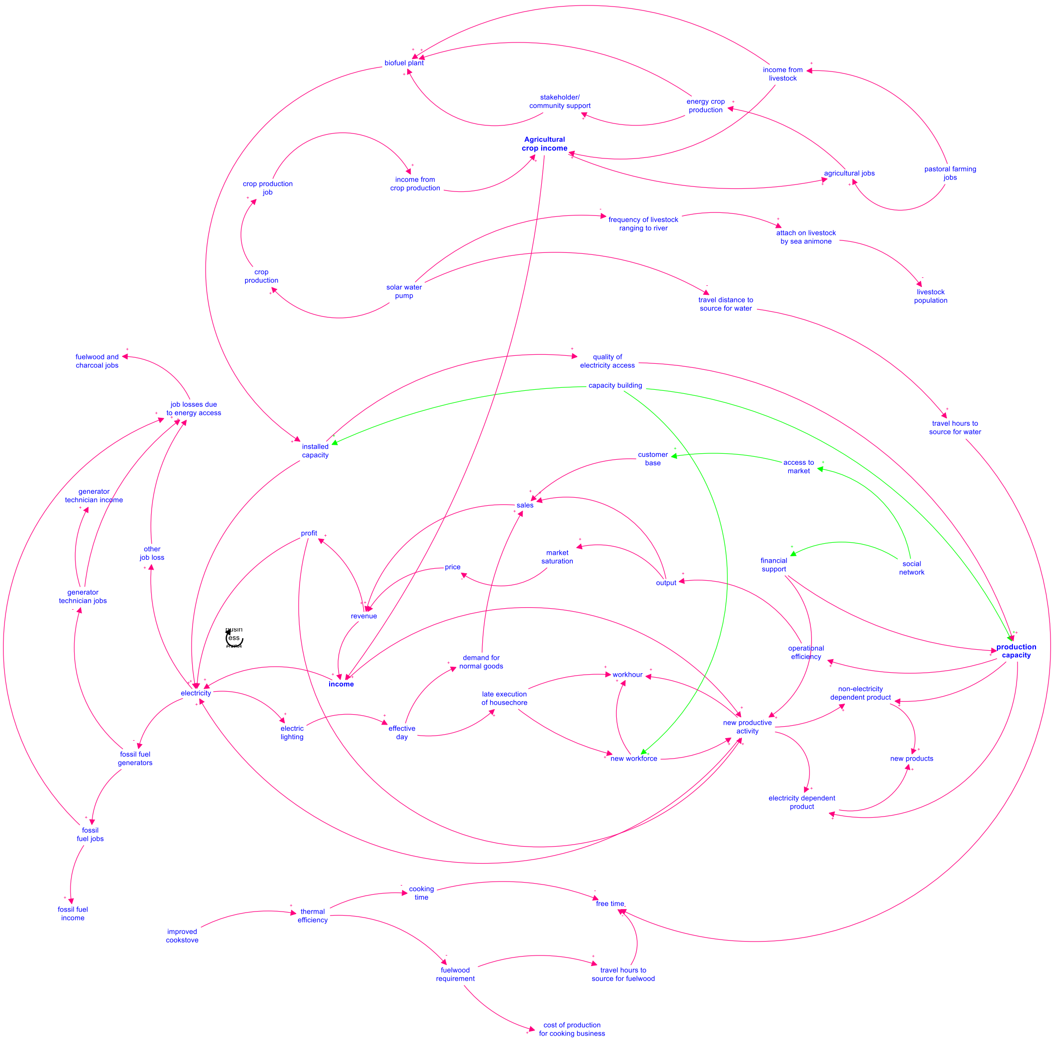

Figure 7-9: Causal Loop Diagram - Energy Access and SDG 8

7.2.10 SDG 10 – Inequalities

SDG 10 seeks to "reduce inequality within and among countries". Given the focus of the study on the impact of rural energy access on the SDGs in rural context, relevant literature are studies on the impact of energy access on inequality and vice versa within target rural communities. Therefore, the energy access-SDG 10 nexus focuses on the variables and causal linkages of energy access and inequalities in the rural context of developing countries.

Several studies highlight the high level of inequality between livelihood in rural and urban communities. However, there also exist inequalities within rural communities especially based on gender, race, caste, income level, rights to ownership of lands, individuals, among other factors. While the energy access and use represent indicators of inequality in rural communities, it also influences other indicators of inequalities. Therefore, this section explores the interactions between energy access with inequalities within rural communities.

Energy access could both increase and decrease inequality in rural communities by influencing various variables of rural livelihood. As such, the causalities need to be understood so as to strengthen the linkages that reduces inequalities while weakening those that increases the same. Wealthier rural population benefit more from energy access given their ability to pay for electricity use and expand their productive activities. The ability of richer rural population to acquire electrical appliances and pay for more electricity use enable them to benefit from social impact of energy access such as entertainment [226] unlike their poorer counterpart who are limited by their financial capacity to basic and economic electricity services. However, the poorer households may also benefit from social energy services as their income increases especially in cases where complimentary supports are provided and targeted at stimulating productive activities of the poorer rural population. The ownership of electrical appliances often become a 'status symbol', thus, may serve as an indicator of extreme poverty in the village such that those who do not have electrical appliances had a sense of exclusion [242]. However, the social bonding that characterise rural livelihood could also enable poorer households to benefit from social energy services from the richer counterparts. For instance, members of poorer households could go to see movies and television programmes with their friends from richer households [242]. Nonetheless, social pressure and the role of children as major influencers also creates another motivation for poorer parents to acquire electrical appliances for social services (entertainment) [242]. This further emphasis the reason complimentary support should give priority to poorer class in rural communities as a strategy towards reducing inequality among the rural population. As poorer households acquire electrical appliances, their perception of inferiority, exclusion, and inequality reduces. The resulting decrease in inequality increases social networking and inclusion especially sharing common stories, and experience. For instance, their access to political awareness through seeing television programmes could lead to sharing updates which increases time spent in social networking.

The increased access to television increases their awareness about politics and governance, hence, increasing their interest to participate and also help them make more informed position in voting during elections, thus increasing political empowerment (social inclusion) [242]. The development of rural energy access from renewable energy sources often increase more participation of rural dwellers in decision-making especially if the project is managed by the village or at least the village is involved in the management [246], thus increasing social inclusion.

However, seeing movies and television programme (including access to urban centres and education) exposes rural dwellers [242] especially women to social norms that negate the belief and traditional systems in rural communities. These may also include human rights, gender equality, abortion rights, teenage sex, and pregnancies. This aligns with findings that learnings from television increased the rate of separation and divorce [252]. Also, La Ferrara et al. find that watching television programmes could lead to decrease in fertility rate through education on family planning [253]. Therefore, social exposure due to electricity access to may negatively impact the adherence to rural culture and beliefs [242].

The female gender suffers a disproportionate share of the impact of rural energy poverty, hence, benefit significantly when energy access results in technology adoption that makes their roles easier. The adoption and use of improved cookstoves reduces the fuelwood and charcoal requirement of rural households, [236]. The resulting reduction in time requirement for sourcing for fuelwood, and cooking free-up time for education for girls and productive activity for women which reduces the inequality between their male-female access to education, income generation [242], and consequently decision-making capacity.

Access to quality electricity supply influences the citing of new businesses [227]. However, while men may be have more freedom to cite their businesses to benefit from electricity access, women are often not able to benefit as much as their male counterpart given their cultural and traditional role in homemaking which limits their freedom to work away from home [227]. Electric lighting, especially streetlights, allows members of households stay longer outside their households increasing social networking while it may also reduce the social bonding as some rural dwellers return home early to see television programmes and movies [242]. The increase in time spent at home, however, improves family life [242].

Figure 7-10 presents the pictorial view of the energy access-SDG 10 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

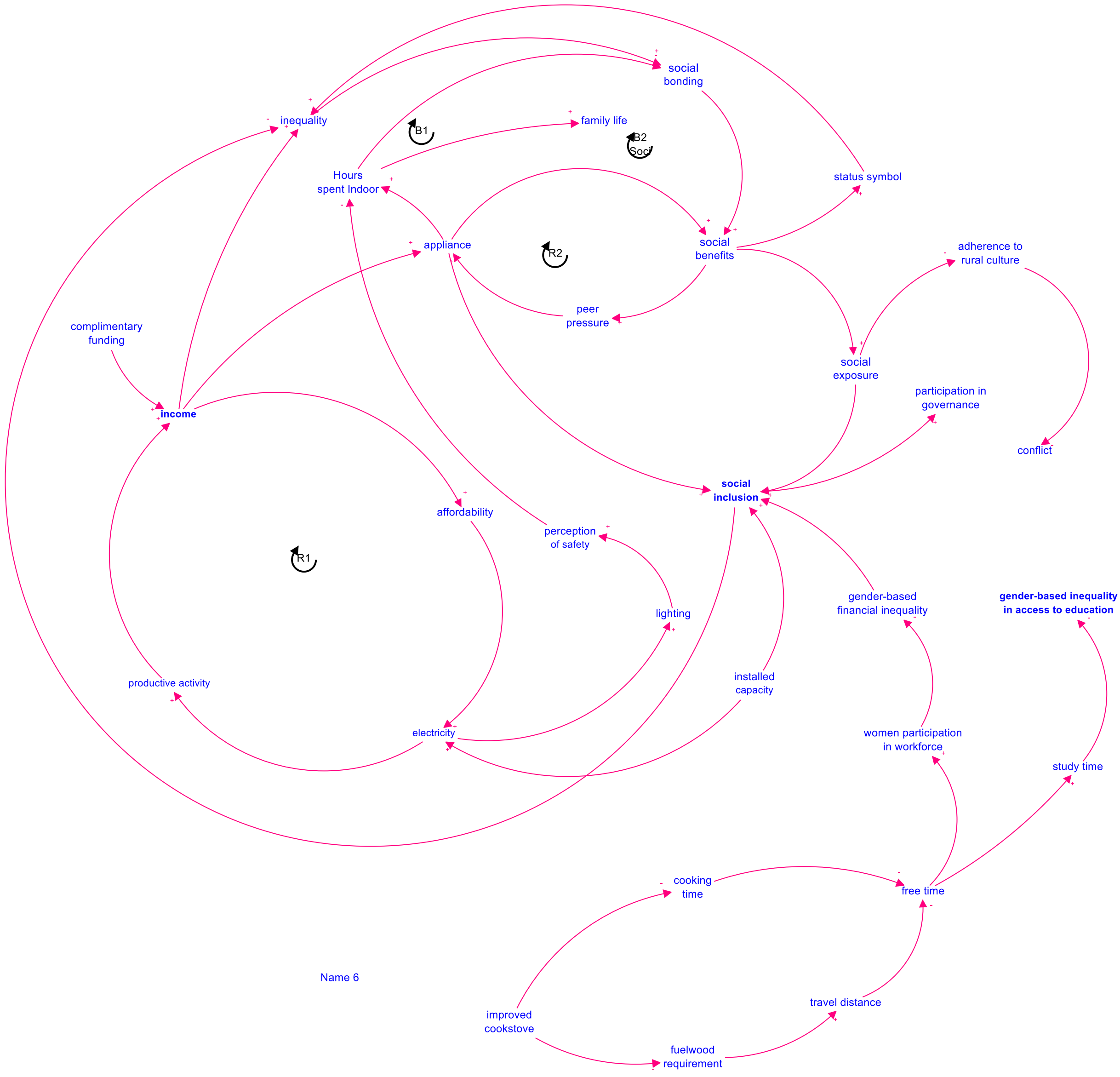

Figure 7-10: Causal Loop Diagram - Energy Access and SDG 10

7.2.11 SDG 11 – Sustainable Cities and Communities

SDG 11 seeks "make cities and human settlement inclusive, safe, resilient and sustainable". The relevant themes found in literature in relation to energy access in rural context of developing countries include pollution, erosion and flood.

Increase in modern energy access through renewables or grid connected sources reduces the use of fossil-powered individual generators which reduce air and noise pollution in the rural communities, thus, making the community more habitable [246]. The increase in anthropogenic activities in rural communities also result in increase in commuting between rural communities and the urban centres hence increasing the frequency of public transport facilities and movement. The increase in transport by automobiles, motorcycles among other fossil-powered means of transportation increases carbon emissions which increases air pollution. Improved cookstoves has relatively higher thermal efficiency relative to the traditional cookstoves, thus, generate less smoke which reduces air pollution. The use of improved cookstove also reduces fuelwood and charcoal requirement thus slows down the loss of vegetation thereby reducing erosion and flood.

Batteries is one of the energy sources for lighting in off-grid communities which are often indiscriminately disposed, thus, contributing to environmental pollution. [230]. Therefore, access to electricity for lighting and appliances reduces the use of batteries, thus, reducing environmental pollution[230]. Also, electricity access gives a sense of civilisation which often motivate attract other improvement in livelihoods both from the rural dwellers and from external stakeholders [229]. While the perception of civilisation spur rural dwellers to acquire new appliances and equipment such as LPG cookers, television and DVDs; it also attracts opportunities and support from external stakeholders [229]. The perception of civilisation also decreases rural-urban migration [38] as rural population especially youth have increased opportunities in rural communities, thus contributing to the development of rural communities.

Figure 7-11 presents the pictorial view of the energy access-SDG 11 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

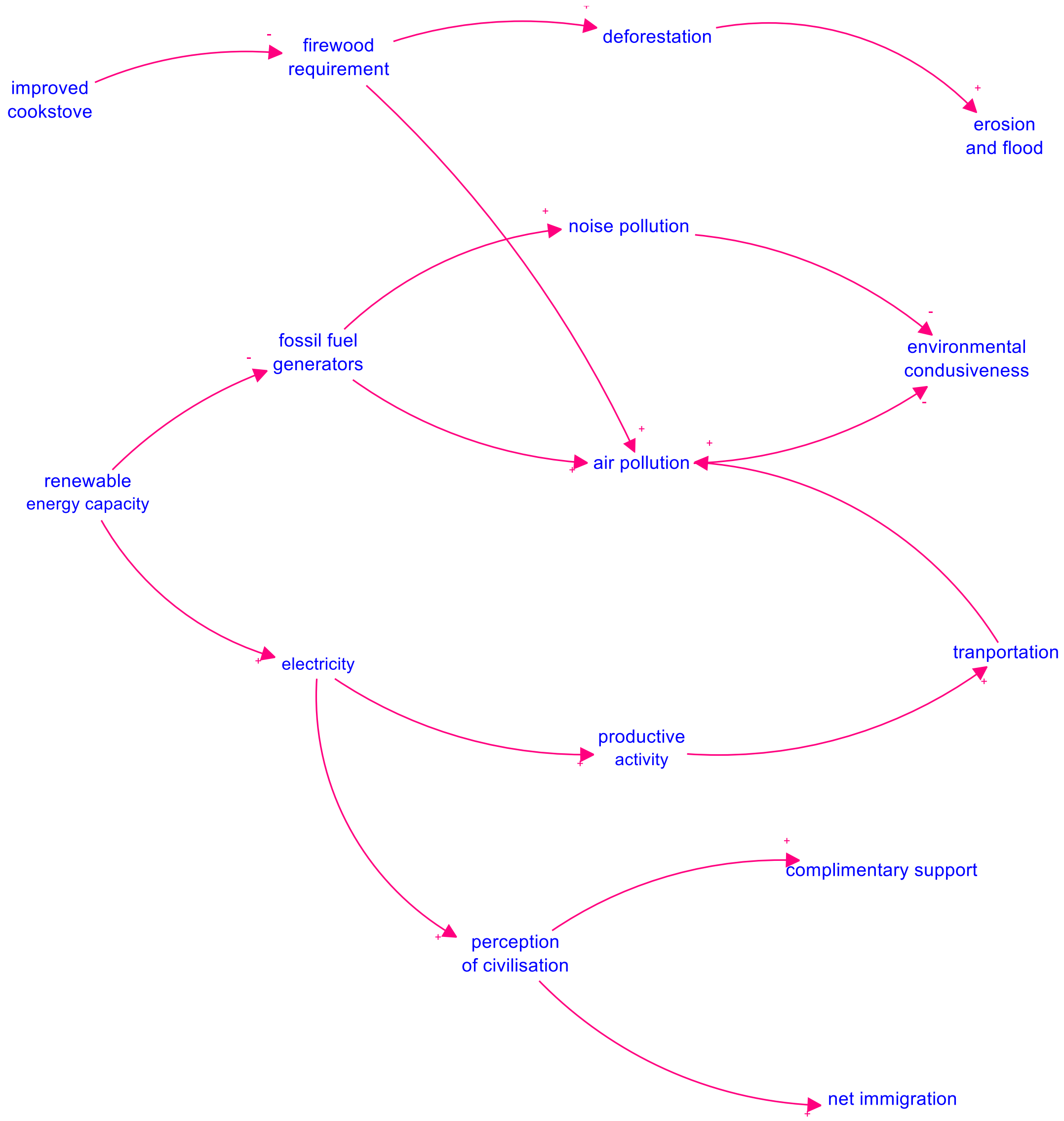

Figure 7-11: Causal Loop Diagram - Energy Access and SDG 11

7.2.12 SDG 13 – Climate Change

SDG 13 is aimed at taking “urgent action to combat climate change and its impacts”. The relevant theme found in literature in relation to energy access in rural context of developing countries include carbon emission and capture.

The impact of modern energy access on climate change might not be significant at the household and community level given the relatively small level of anthropogenic activities at such levels. Moreover, the long delay in the impact of changes in greenhouse gas (GHG) emissions on the climate, among other factors also makes some of the global and national indicators for climate change inapplicable in rural context. Therefore, proxy indicators that may be measurable at the rural levels such as fuelwood consumption, indoor pollution, among others have been considered in discussing the impact of energy access on climate change.

7.2.12.1 Cooking

Cooking for households and businesses is women-dominated and represent a major source of carbon emissions in rural communities given the domination of fuelwood and charcoal as cooking fuels [40]. Indeed, electricity access provides opportunity for electric cooking. However, electric cooking is limited by the high energy intensity of electric cookers vis-a-vis the affordability of the resulting electricity expenditure. This indicates a major limitation of rural electrification project in reducing carbon emissions, thus, highlighting the need for diversification of energy technologies if energy access projects are to contribute to reducing carbon emissions. The inclusion of improved cookstoves in energy access projects facilitate a significant impact of energy access on reduction of carbon emission which is also linked to health. Also, electricity access gives a perception of civilisation which motivates rural dwellers to improve on others areas of livelihood. This spurs wealthier rural households to adopt the use of LPG for cooking [230] thus reducing use of fuelwood and consequently, carbon emission. While some employ modern cooking technologies to complement the traditional cooking, others completely transit from traditional cooking methods [230].

The adoption and use of the various modern cooking technologies reduces greenhouse gas (GHG) emissions due to their relative higher thermal efficiencies which also makes them have low fuel consumption characteristics [236], [30]. The reduction in carbon emissions reduces indoor pollution and the associated diseases especially to the eyes and lungs [30]. The reduced fuelwood requirement also reduces deforestation thus increasing forest population, thereby increasing absorption of carbon by the forest. The increase in forest population reduces the rate of soil erosion and degradation, thus preserving and nourishing soil fertility which further reinforces forest population [236]. Studies show that various model of improved cook stoves reduces energy fuelwood consumption by 25-60% relative to the traditional three-stone stove which is common in rural households [236]. The use of fuelwood for cooking also reduces during rainy season when the trees are wet and are not able to burn sufficiently for cooking. Solar water heaters also reduces traditional use of biomass for water heating for bath, thus reducing household air pollution and improving the contraction of water-borne diseases [235]

7.2.12.2 Renewable energy and carbon emissions

Wealthier homes in unelectrified communities often generates electricity using fossil powered generators which contributes to carbon emissions. Therefore, electricity access from renewable energy reduces carbon emission [40], [167], [230]. However, there are concerns on the CO_2 emissions from hydropower dam in the long term. Biomass flooded into hydropower dam are not usually removed before from the dam before it is filled of water which makes them decompose over several years hence generating significant level of methane and CO_2 [32].

Figure 7-12 presents the pictorial view of the energy access-SDG 13 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

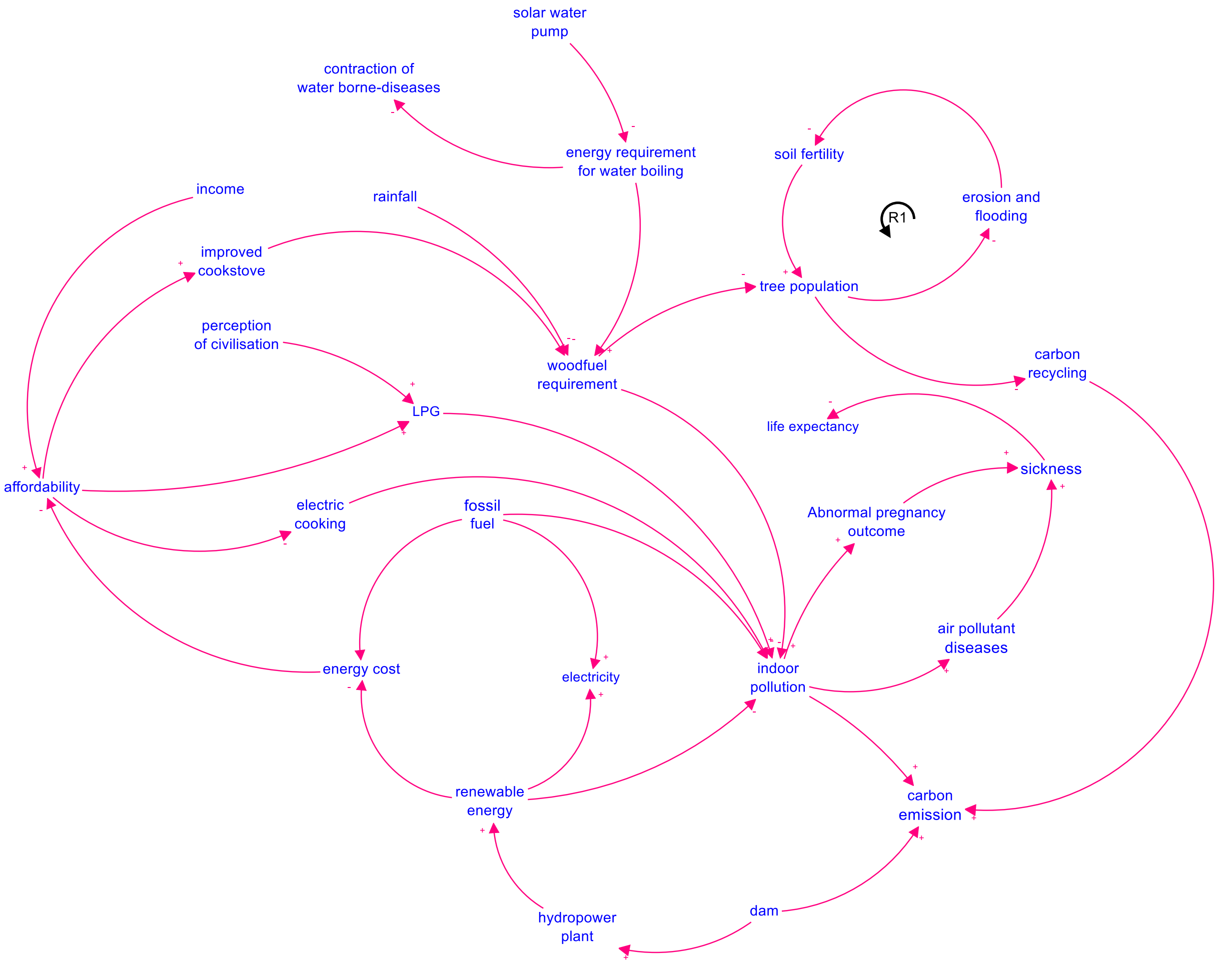

Figure 7-12: Causal Loop Diagram - Energy Access and SDG 13

7.2.13 SDG 14 – Life Below Water

SDG 14 is aimed at taking “conserve and sustainable use the oceans, seas and marine resources for sustainable development”. The relevant themes on marine ecosystem found in literature in relation to energy access in rural context of developing countries include fishery, fish population and water pollution.

The development of the dam manipulates the river flow[32]. The upstream is waterlogged, while, the downstream suffers from water scarcity due to reduced flow of water, thus negatively impact crop cultivation and rural livelihood [32]. The reduction in soil fertility and land suitability for farming due to flooding and waterlogging cause relocation of farmers to locations often with lower soil fertility hence negatively impact food production and prices.

As discussed in SDG 13, hydropower dams generates methane and CO_2 [32]. Also, fishes are limited in their search for feed as the physical infrastructure of dams which prevent them from migrating to feeding grounds, negatively impacting the fish population and leading to deterioration of fish habitats [32]. Given that fishery is usually a predominant occupation in riverine communities, therefore, the resulting decrease in fish population negatively impact the income of fish farmers and subsequently the community.

Due to the low level of environmental awareness and education, rural communities are characterised by high level indiscriminate deposition of waste which are eventually washed into the water bodies. Therefore, energy generation from biomass therefore helps to reduce waste disposal into the water bodies hence reducing water pollution.

Figure 7-13 presents the pictorial view of the energy access-SDG 14 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

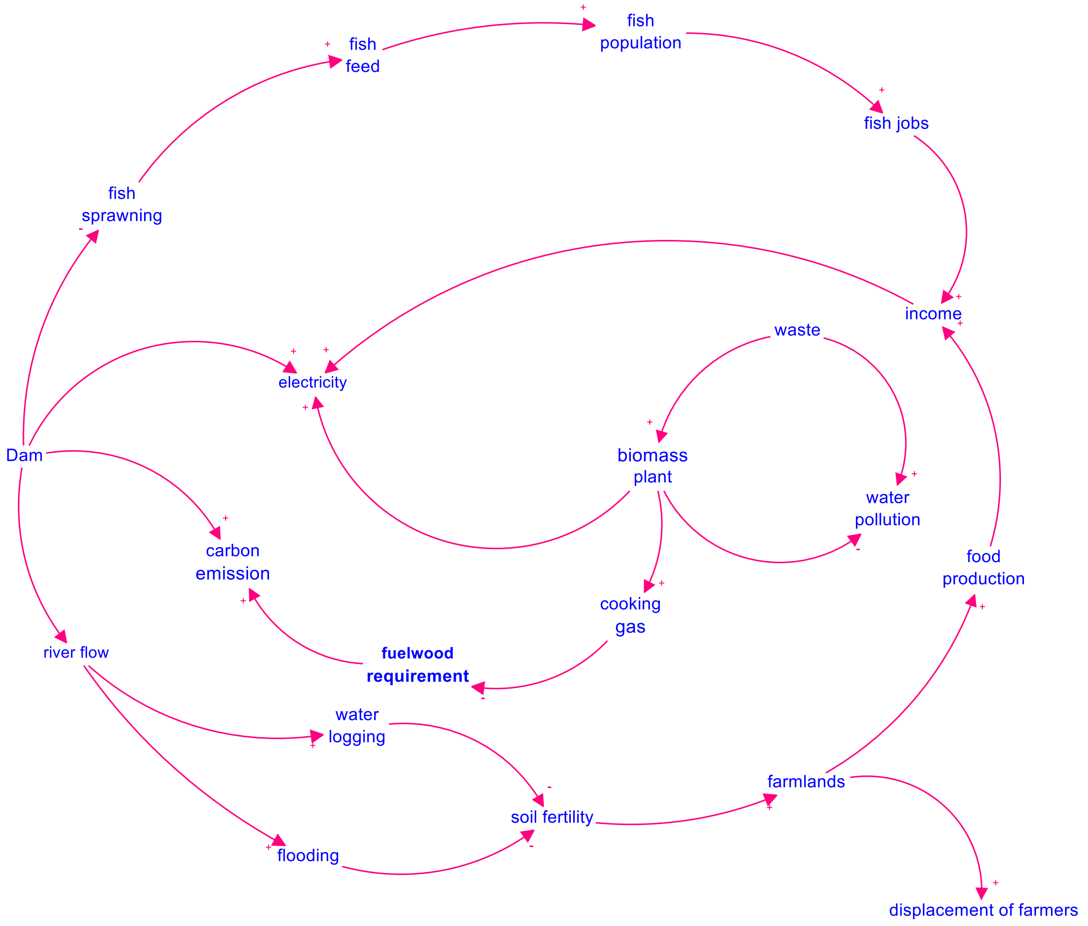

Figure 7-13: Causal Loop Diagram - Energy Access and SDG 14

7.2.14 SDG 15 – Life on Land

SDG 15 seeks to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss". Therefore, the energy access-SDG 15 nexus focuses on the variables and causal linkages of energy access, biodiversity, natural ecosystem, and forestry in the rural context of developing countries.

The use of fuelwood as cooking fuel, which is the predominant cooking fuel in rural communities, [254] is largely used in two major forms, directly as fuelwood and as charcoal. This constitutes a major factor responsible for deforestation in rural communities. In addition to the prevalent use of fuelwood in rural communities, there is a significant use of charcoal for cooking in cities which are sourced from rural communities. Studies show that various model of improved cookstoves reduces energy fuelwood consumption by 25-60% relative to the traditional three-stone stove which is common in rural households[236]. Therefore, improved cookstoves reduces deforestation, increases landcover, reduces erosion, reduces leaching of soil nutrient and soil degradation, which ultimately reinforces forest population fosters sustainable management of forest [241] [30]. The reduction in deforestation and loss of plant species and biodiversity, contributes to the increase in soil nutrients, wildlife population and again reinforces the forest population as new trees sprout up. This further reduces land degradations and loss of soil nutrients[236].

Moreover, the production process of charcoal from fuelwood has other impact on the ecosystem [254]. Kara and Plateau are two regions in Togo with high volume of charcoal production. Between 2004-2008, charcoal production decreased in the two regions by 92% and 50% due to the loss of vegetation to consistent charcoal production. This highlights that charcoal production has high potential to alter the natural ecosystem and aggravate the loss of biodiversity [255]. Deforestation for charcoal production does not exempt trees from protected areas and they are often produced from fresh wood felled from national park (forest) [254].

Burning of wood for charcoal production kills soil organisms hence reduces humus formation (soil nutrients) [256]. The construction of Kiln (charcoal-production chamber) decreases land available for agriculture while the burning activities involved in charcoal production adversely alter soil properties. The burning increases soil pH value and bulk density of the soil under the kiln [254] while decreasing soil microbial population and action. The impact affects to 15m radius of soil in the vicinity of the kiln in Savana region and 5m radius for semi-deciduous forest.

On the other hand, wind turbine leads to killing of birds thus increasing biodiversity loss [38] while the construction of reservoir for hydropower plants requires flooding of a large expanse of land which leads to deforestation [32]. Due to the loose of forest cover, soil minerals are depleted while the soil is exposed to degradation[32]. Deforestation also adversely hampers the recycling function of the forest in converting CO_2 to Oxygen, carbon retention, and preserving the biodiversity.

Figure 7-14 presents the pictorial view of the energy access-SDG 15 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

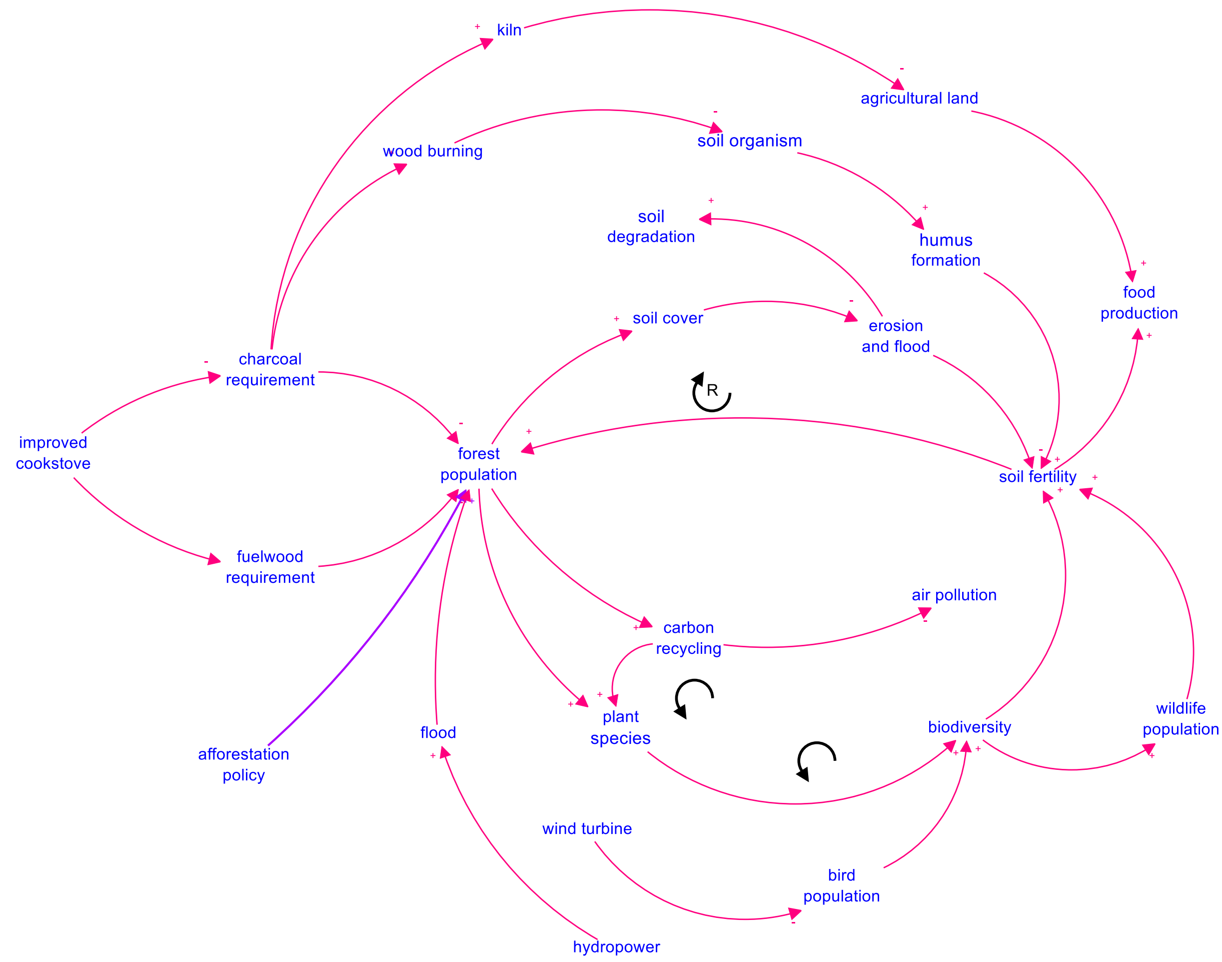

Figure 7-14: Causal Loop Diagram - Energy Access and SDG 15

7.2.15 SDG 16 – Peace, Inclusive Society, Governance and Justice

SDG 16 seeks to "promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive". Therefore, the energy access-SDG 16 nexus focuses on the variables and causal linkages of energy access, social inclusion, equity, community cohesion, bonding and networking, security and safety, and inclusive governance. income in the rural context of developing countries.

Access to electricity in households make rural dwellers stay awake than they do prior gaining access to electricity especially due to increased time spent on entertainment. Some electricity users spend more time in the house watching television, among other forms of entertainment [234], thus, increasing the time family spend relating together which improves family life thus increasing peaceful societies. However, seeing movies and television programme (including access to access to urban centres and education) exposes rural dwellers [242] especially women to social norms that negate traditional beliefs and systems in rural communities. These may also include human rights, gender equality, abortion rights, teenage sex, pregnancies, and family planning. This aligns with findings that learnings from television increased the rate of separation and divorce [252]. Seeing television programmes could lead to decrease in fertility rate through education on family planning [253]. Therefore, social exposure facilitated by electricity access may negatively impact the adherence to rural culture and beliefs [242].

Also, various opportunities result from energy access increases girls' and women's engagement in education and productive activities. For instance, electric lighting enables them, especially women, to carry out their house chores at night while others are able stay longer outdoor with friends due to the increase in the perceptions of safety in electrified communities especially in the cases where street lighting is provided. Household lighting including security lighting [234], streetlighting and the consequent increase in the time that rural dwellers are awake (effective day), also reduce the chances of robbery attacks on households, shops among other structures in electrified communities as people are more at alert. However, the impact of electricity for household, security and street lighting may only improve the perception of security as there could still be burgling and theft after gaining electricity access. Modern energy access may also have some undesired impact on peace in rural communities [234]. The acquisition of new electrical equipment which may be articles of ostentation and 'status symbol' in rural communities also may increase theft. Also, the influx of visitors especially those from nearby villages for electricity services who could also indulge in theft as they are not easily traceable since they do not live in the communities. Nonetheless, the increase in social networking could spur community policing to improve safety and security in such communities.

Provision of access to finance such as micro credits is an important complementary action to energy access to facilitate improvement in rural livelihood [248] especially women. However, gaining access to such financial support mechanism requires that rural dwellers organise themselves into 'self-contained cohesive groups' with shared socio-cultural and economic interests and perspectives [248]. The formation of such groups and associations also contribute to inclusive governance (SDG 16) as members are able express their perspectives of various community subject which can be presented to the community leadership as the position of the groups and associations.

Figure 7-15 presents the pictorial view of the energy access-SDG 16 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

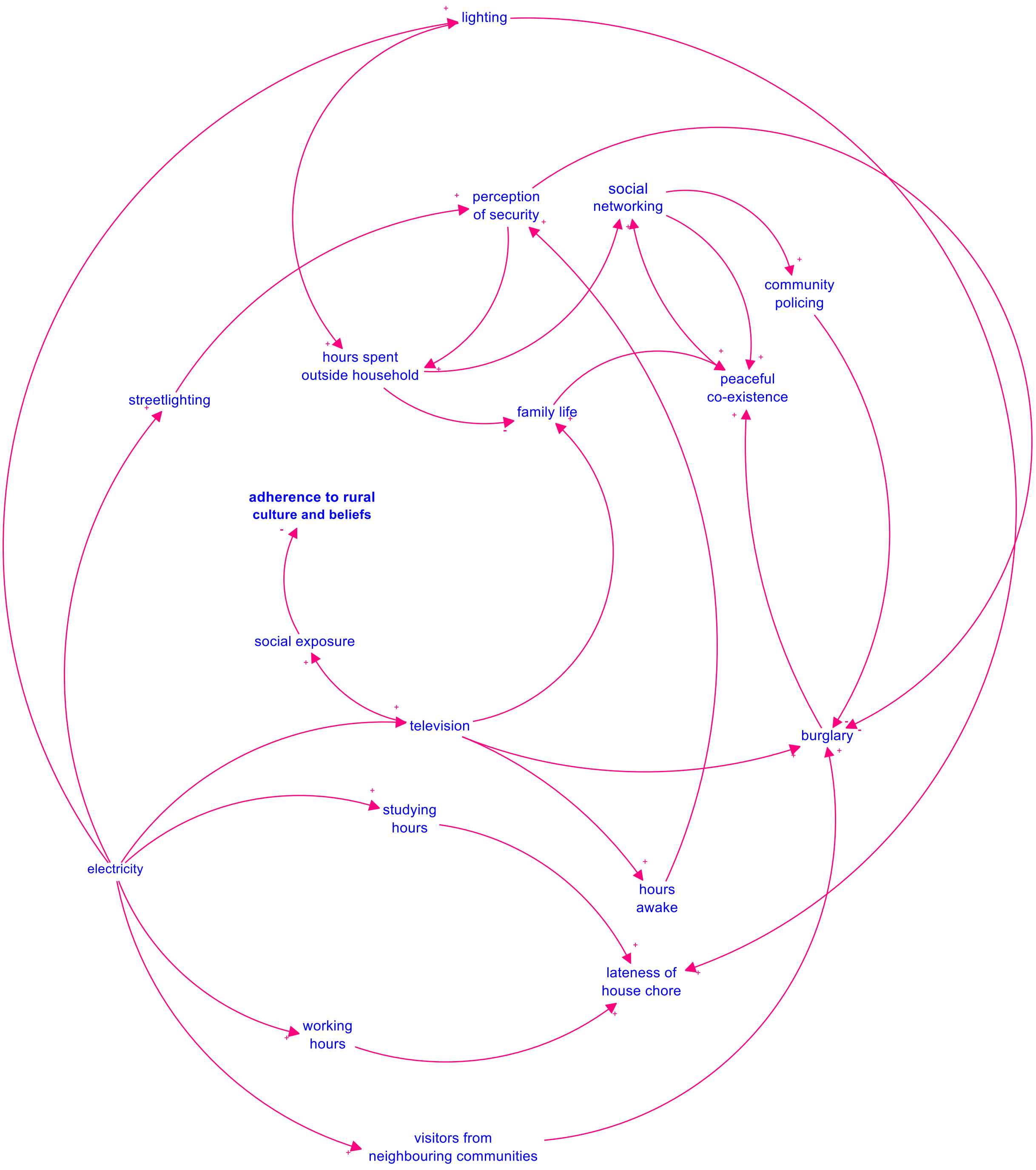

Figure 7-15: Causal Loop Diagram - Energy Access and SDG 16

7.2.16 SDG 17 - Partnership

SDG 17 seeks to "strengthen the means of implementation and revitalise the global partnership for sustainable development".

The seventeenth goal in the UN 2030 Agenda focuses on "partnership" as an implementation strategy for all the goals. Partnership in rural context of developing countries is crucial to the implementation of rural energy access projects. The development and implementation of rural energy access project often requires the contribution of various stakeholders for effectiveness, sustainability, impact, replication and up-scaling of the projects. The need to integrate the various dimensions of energy access in rural energy projects further strengthens the need for the contributions of various stakeholders within and outside the target community. Studies show that energy access intervention projects implemented only as technological intervention by energy companies without collaboration with other organisations often fail ahead of the expiration of their service life[167]. This has led to the acknowledgement of the role of other stakeholders including the government towards an holistic and multi-dimensional approach to the implementation of energy access projects [167] to facilitate the sustainability and impact of the projects. Of the projects Based on a study on the impact of small energy projects implemented in various developing countries, Terrapon-Pfaff reports that 73% (about three quarter) of the projects created new, strengthen or extended existing network (partnership) [257]. The provision of access to finance such as micro credits complementary to energy access facilitate improvement in rural livelihood [248] especially for women. However, gaining access to such financial support mechanism requires that rural dwellers organise themselves into 'self-contained cohesive groups' with shared socio-cultural and economic interests and perspectives [248]. The formation and existence of strong social relations within such groups boast financiers' confidence and assurance that the credits will be returned [248]. This is because rural dwellers who benefits from micro credits offered through a group are under social pressure to pay back to enhance possibility micro-credit facility could be available for other women [248] and reduce the possibility of defaulting, as such put them and their families in shame and ridicule.

The role of partnership and network building transcend the planning and implementation phase of the project as they are also essential to creating pathways for the dissemination of the impacts and lessons learnt on the projects [257]. As annotated on the various other SDGs, the need for complementary actions to maximise the synergies and reduce the trade-offs also enshrines the role of partnership.

Figure 7-16 presents the pictorial view of the energy access-SDG 16 causal linkages above and the intervening feedback loops in a Causal Loop Diagram.

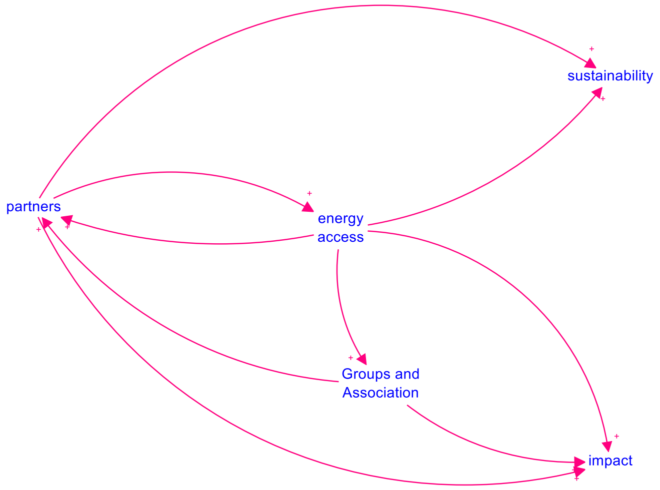

Figure 7-16: Causal Loop Diagram - Energy Access and SDG 17

CHAPTER EIGHT

8 Rural Energy Access from a Systems Perspective: Essential Pillars

Abstract

The disproportionate share of the challenges to universal energy access borne by rural dwellers are largely due to the peculiarities of rural livelihood and the energy-development dynamics in rural context of developing countries. Therefore, realising universal energy access for all in such context requires comprehensive energy policy approach that is based on an in-depth understanding of energy-development dynamics in rural context and encapsulate strategies that addresses the various peculiarities of rural livelihood which pose barriers to energy access and use in rural communities. Based on the literature analysis in the previous chapter, recommendations are made on strategies that could catalyse rural profitable investment that provides high-tier of affordable energy access that embraces plurality of technologies towards universal energy access in rural communities. Moreover, energy access-SDGs dynamics comprises of synergies that facilitate the impact of energy access on the SDGs in rural context. Nonetheless, there also exist trade-offs in the nexus that offer constraints which limits, weakens and counteract the overall impact of energy access on the SDGs. Therefore, policies aimed at providing rural energy access requires complementary policies that prevent or minimises undesirable trade offs in the energy access-SDGs dynamics. With the realisation of the SDGs at the rural context of developing countries, diverse policy constraints to the impact of energy access in facilitating the achievement of the SDGs that are identified in the literature analysis are discussed, with policy recommendations on how they could be prevented or at least mitigated.

8.1 Introduction

Indeed, there has been a renewed commitment to facilitating rural development in developing countries through the lens of the SDGs in pursuit of the 2030 Agenda. In realising this, the security of energy access in rural communities of developing countries have been identified as a catalyst to facilitating the realisation of the SDGs in rural context.

The previous chapter presents an in-depth understanding of the dynamics of energy access and the SDGs in the rural context of developing countries. The analysis:

i. identified and reviewed the relevant and measurable variables of energy access and those of the SDGs in the rural context of developing countries that

ii. analysed and discuss the causal linkages and impact pathways between the variables of energy access and those of the SDGs,

iii. identified the synergies and trade-offs within the energy access and SDGs dynamics

iv. identified the complementary actions required to leverage on the synergies and trade-offs to maximise the desirable impact of energy access on the SDGs while minimising undesirable impact

v. developed the linkages, causal linkages and impact pathways into Causal loop Diagrams as conceptual models for rural energy access-SDGs and identify the intervening feedback loops

Based on the literature analysis, the study highlight the following strategies, policies recommendations and complementary actions for rural energy access that maximises its impact towards the realisation of the SDGs in rural context of developing countries.

8.2 Strategies for rural energy access:

The disproportionate share of the challenges to universal energy access borne by rural dwellers are largely due to the peculiarities of rural livelihood and the energy-development dynamics in rural context of developing countries. Therefore, realising universal energy access for all in such context requires a comprehensive energy policies that is based on an in-depth understanding of energy-development dynamics in rural context and encapsulate strategies that addresses the various peculiarities of rural livelihood which pose barriers to energy access and use in rural communities.

1. **Catalysing rural energy investment:** Rural communities which host a high share of population in developing countries usually rank low in decision matrices for energy investments. Therefore, a high share of the global population will be without modern energy access should rural energy investment be subjected to market forces on a business as usual scenario, thus, making unrealistic the 2030 target for universal energy access. This highlights the need for the development and implementation of dedicated rural energy access strategies that captures the peculiarities of rural livelihood. The effectiveness of such strategy will depend on the collaborative roles of government, development organisations, the private sector, non-governmental organisations (NGOs) and community-based organisations (CBOs) in the rural energy development dynamics. Such strategy could provide incentives both for the energy supply and demands sides particularly in developing countries with high rural population. Financial support should be provided to utility companies to offset some of their cost to increase their interest and the profitability of providing electricity access to rural communities. Moreover, the sustainability of rural energy projects necessitates the development of local technical capacity for effective operation and maintenance and residents of those communities should be the target beneficiaries of training.

2. **Profitability and sustainability of rural energy investment:** A common challenge of rural energy investment is the shortfall of actual energy demand over the projected energy demand and the energy generation, which results in electricity wastages. This often result from an inadequate understanding of the energy-development dynamics which result in the assumption that energy access will facilitate immediate and automatic development which will result in rapid growth in electricity use. An effective rural energy planning and design will be based on a holistic and multidimensional analysis that adequately captures energy-development dynamics of target rural community in order to prevent the challenge of oversizing of energy projects which negatively impact the profitability and sustainability of energy projects. Similarly, the integration of electricity-dependent productive activities with rural energy projects by energy companies and/or in partnership with other investors helps to reduce energy wastages while creating jobs and generating income. Electricity consumption for productive uses may also be increased by adopting financial models that provides offers cheaper electricity tariff for productive uses during the day relative to the evening. These together will reduce electricity wastages, thus, foster profitability and sustainability of rural energy investment.

3. **High Tier of Electricity Access:** Often, rural dwellers are often provided with lower tier of electricity (due to their limited ability to pay for higher tiers of electricity) which

limits its economic application to preliminary processing in their produce's value chain. The inability to perform sophisticated electricity-reliant value addition activities makes rural producers (such as farmers) loose a disproportionate share of the economic benefits of their products to the cities and foreign nations[238]. Similarly, power outages and fluctuations due to lower tier of electricity also damages equipment, and negatively impact business operations. The provision of low tier of electricity access among other factors makes electric lighting the most common electricity applications in many rural communities. Governments and development organisations should support a share of the investment cost of rural energy investors to enable them supply high tier of electricity. High tier of electricity, in addition to other complementary support, will facilitate mechanised value adding productive activities that will increase the revenue and promote economic diversification (SDG 9). Similarly, providing varying tier of electricity access in varying parts of rural communities have negative impact on the empowerment of women (SDG 5) and people of lower caste. Given the roles of women in homemaking, proximity to household is crucial in the location of their business hence they are limited in locating their productive activities in locations with better electricity access but far from their homes, thus, exacerbating inequality in rural context (SDG 10). This further strengthen the need for the provision and security of high teir of electricity across the rural community to maximise its impact on gender empowerment (SDG 5) and inequality (SDG 10).

4. **Affordability of Electricity Cost:** While electricity access offers several benefits, electricity costs constitute significant increase in energy expenditure especially for households who have not being using fossil fuel generators. This negatively impact electricity use by the poorer rural dwellers given their limited ability to pay for electricity use and acquire electrical equipment for productive use. This makes their richer counterpart benefit more from electricity use and further increasing rural inequality (SDG 10). This calls for complimentary actions including access to finance and capacity building for productive use of electricity that would increase the affordability of electricity expenditure. Such support should prioritise the economically worse off so as to reduce the level of inequality (SDG 10) in rural communities. Electricity users also need to be exposed to energy efficiency measures to minimise their energy cost while maximising its impact.

5. **Plurality of energy technologies (Energisation, not electrification):** The mainstreaming of energy access to electricity access limits the dimensions of impact of rural energy intervention. There are a number of SDGs that will not be impacted where energy access is limited to electricity access (e.g. SDG 6 on water). The installation of solar water pump provides access to clean safe water (SDG 6) within residential areas of rural communities thus reduces the traversal of forests to source for water. The resulting reduction in mosquito bites among other health and security risk improves health outcomes (SDG 3). Similarly, the installation of solar water pump also eliminates or reduces loss of livestock to sea animals during ranging to drink water. This reduces economic loss of livestock farmers, sustaining livestock agricultural jobs (SDG 8), and reducing poverty (SDG 1). While electricity cost and perception of automatic immunity to water borne diseases limit water boiling, solar water pump provides clean safe water without boiling (SDG 3 and 6). It also provides water source at close proximity for irrigation, hence, promotes subsistence and commercial crop cultivation (food production - SDG 2) for household consumption and income generation. The overall

impact on income generation (SDG 1) reduces household dependence on government support grant.

Moreover, the relatively higher thermal efficiency of improved cookstoves also generate relatively less smoke, hence, reduces exposure of women and girls to indoor pollution and the associated health (SDG 3) implications and contributions to carbon emissions (SDG 13). The reduced fuelwood requirement decreases loss of biodiversity (SDG 15), decreases cost of fuelwood for cooking, thus increase savings and investment to combat poverty (SDG 1), allows for cooking previously avoided food due to cooking fuel requirement (SDG 2). Similarly, the manufacturing of improved cookstoves could provide decent and highly skilled direct jobs (SDG 8) especially if complemented with training and capacity development for local manufacturing of the stoves (SDG 4 and SDG 8).

These highlights the diversified impact on SDGs that are missed when 'energisation' is limited to electrification. Therefore, rural energy access intervention should be implemented with plurality of energy technologies for rural energy projects to maximise the dimensions of their impact and the contributions to the 2030 agenda.

8.3 Policy Constraints

Energy access-SDGs dynamics comprises of synergies that facilitate the impact of energy access on the SDGs in rural context. Nonetheless, there also exist trade-offs in the nexus that offer constraints which limits, weakens and counteract the overall impact of energy access on the SDGs. Therefore, policies aimed at providing rural energy access requires complementary policies that addresses or minimises undesirable trade offs in the energy access-SDGs dynamics. Below are the diverse policy constraints to the impact of energy access in facilitating the achievement of the SDGs that are identified in the analysis with policy recommendations on how they could be prevented or at least mitigated:

1. **Leveraging Endogenous Resources**: Leveraging endogenous resources strengthens existing productive activities and jobs while facilitating new ones. The provision of job opportunities resulting from the provision of modern energy access usually result in a decline in agricultural workforce (SDG 8), especially the youth, hence reducing food production (SDG 2). Moreover, most of such jobs are temporal and are lost at the completion of the development phase of the energy projects. Meanwhile, biomass projects (from energy crops), being dependent on consistent supply of energy crops (SDG 2 &7) provides and sustain agriculture jobs (SDG 2 & 8). The residue from energy generation from biomass provides fertilizers for crop production (SDG 2), reduce wastages and environmental pollution and health (SDG 3). Nonetheless, the land requirement and the relatively higher and stable revenues from energy crops set it at competition with food crops with tendencies to negatively impact food security (SDG 2). This necessitate policies that ensures a reserved proportion of agricultural land for food production with possible incentives in order to encourage and sustain food security in rural communities where energy is being generated from biomass.

2. **Agriculture:** Hydropower generation also have undesirable impact on water security (SDG 6), agriculture and food security (SDG 2). The development and operation of dams for hydropower generation manipulates river flow, thus reducing water volume for traditional watermill business (SDG 8). It also causes waterlogging of the upstream and water scarcity at the lower course of river regime which decreases river flow for irrigation (SDG 2) including the flooding of the site for the dam. This results in loss of agricultural lands with diverse impact on income, agriculture

and food production, employment and peace (SDGs 1, 2, 8 and 16 respectfully). The fencing of rural hydropower project sites also reduces grazing land for pastoral farmers which negatively impact peace (SDG 16). This highlights the need for developers of hydropower projects to work with governments to provide new agricultural lands for farmers who may be negatively impacted by hydropower projects while CSOs and CBOs support with effective consultation engagement and participation of target communities in energy projects.

3. **Job Creation and Income**: The use and maintenance of private fossil-powered electricity generators by wealthier rural populace provides job and income for fossil fuel dealers and mechanics. However, the provision of community-wide electricity access negatively impact such vocations and productive activities (SDG 8) and their livelihood (SDG 1) including ripple undesirable impact on SDGs 2-5. Traditional watermills may go out of business due to the diversion of water for hydropower generation while those dealing in fuelwood and charcoal experience reduced income sequel to the diffusion and use of improved cookstoves. Therefore, stakeholders involved in rural energy investment should be implemented such that it provides jobs and increased income that at least offset job losses and income reduction that accrue due to the energy intervention project**.**

4. **Community Participation and Engagement**: The location of wind energy generation could be met with opposition, that is the "not at my back yard" attitude, due to the perceived related visual intrusion, negative impact on birds and noise pollution from wind energy plants. This further highlights the need for effective community engagement and participation including effort to accelerate biodiversity especially bird species in wind energy projects.

5. **Personal Diligence, Parental Control and Social Values:** The acquisition and use of electrical appliances could either positively or negatively impact education outcomes and social attitudes in rural communities depending on their applications. Students' personal diligence play a crucial role in determining the extent of electricity use for studying relative to its social and entertainment applications [234]. Hence the need for parental control among other effort to direct the students to beneficial use of electrical appliances. Similarly, social education on gender-based violence, gender equality, family planning including abortion, teenage sex among other subjects through ICT could also erode traditional cultures and values (SDG 16) in rural communities. Hence, the need for CBOs to intensify effort in teaching and dissemination of desirable traditional and cultural values (SDG 16). Personal diligence [234], parental control and motivation are also crucial to educational outcomes of students and guiding them against the abuse of ICT.

8.4 Complementary Actions

The need for complementary actions to facilitate and maximise the impact of energy access to drive the SDGs in rural context highlights the need for multistakeholder approach to rural energy intervention.

1. **Boasting Security (SDG 10 and 16):** Electric lighting enables users to be active indoors at night doing house chores, and, stay longer outdoor especially where projects incorporates streetlighting[234]. The increase in active hours (effective day) increases the perception of safety and security (SDG 16) hence reduces the chances for robbery and theft. Nonetheless, the acquisition of electrical appliances by the wealthier households may increase the sense of inequality (SDG 10) thus making the appliances articles of ostentation and 'status symbol' in rural context which may increase incidence of theft which disturbs peace in energised communities (SDG 16). Also influx of visitors especially those from nearby villages for electricity services who could also indulge in theft as they are not easily traceable since they

do not reside in the communities. Hence, the need for rural communities to leverage social networking for community policing to improve safety and security in their communities.

2. **Complementary actions to maximise saved time (SDG 5):** Most of the energy access project are mainstreamed and limited to electricity access. While electricity is the most versatile form of energy, the high energy intensity of electric cooking vis-à-vis affordability of associated electricity cost limits electric cooking. The adoption of improved cookstoves provides an alternative with multiple benefit, mostly for women and girls. The lower fuelwood requirement of improved cookstoves reduce time expended in fuelwood collection and cooking, especially for women and girls (SDG 5). While the freed time provides opportunity for improve education outcomes of the girlchild, however, such impact are often marginal. Realising significant impact on education requires complementary actions such as building of schools, recruitment of teachers, including awareness creation on the benefit of educating the girlchild.

   Similarly, the possibility of women to productively use the saved time depends on their ability to access funds to set up new productive activities or scale up existing ones. Hence, the need for government and international organisations to complement rural energy investments by creating access to finance to complement energy access project. Given the forces of demand and supply, the increased availability of women for productive activities and the resulting increased production leads to market saturation and further increase in supply of women to labour market result in the reduction of prices which reduces income and wages (of women) [243]. Hence, in addition to financial support, government and international organisation should support rural productive activities by creating access to external market for their produce. However, securing a share of external market often require meeting some level of standards and value addition above those required in rural markets. Hence, the need for government and development organisations to create dedicated funds and initiatives that increase the capacity of rural productive activities to carry out value addition activities on their products.

3. **Afforestation Policy (SDG 15):** The use of improved cookstoves reduces deforestation which reduces biodiversity loss, land degradation (SDG 15) including the associated undesirable impact. Nonetheless, improved cookstoves still require fuelwood. Hence, the need for an afforestation policy that both sustains the forest ecosystem, their fuelwood collection and charcoal business. Such policy should that mandate a specified number of tree seedling to be planted for every tree cut down to further enhance nature conservation and the sustainability of the ecosystem. Such a policy should be complemented with awareness and education of the stakeholders who are active in the fuelwood and charcoal business value chain.

4. **Impact on gender empowerment requires change in technology (SDG 5 and 8):** Diverse electricity access projects prioritise the impact on gender in their objectives. However, most of the energy access projects, especially when limited to electricity access, have mainly welfare impact on women especially in freeing up time. Electrification can only impact female employment if it is accompanied with change in the technology for time-intensive household activities such as cooking. There should be transition from traditional cooking to modern cooking, thus, emphasising the need for holistic approach in energy access from electrification to 'energisation', that is the plurality of energy technologies for energy access projects. Furthermore, facilitating gender (empowerment) impact of energy access also

highlight the need for complementary actions. Most of the energy-intensive productive activities are men-dominated in rural communities given their physical advantages for manual operation. However, the mechanisation energy-intensive productive activities enabled by energy access increases the ease and cost of operating some of the men-dominated productive activities thus facilitating participation of women in such businesses and jobs. This highlight that gender empowerment impact of energy access requires plurality in energy technologies and complementary actions which could be achieved in collaborations with government, development organisations and NGOs. Such complementary support includes increasing women education, training and skill sets, access to finance among resources, access to market, and, participation in decision-making.

5. **Local recruitment and retention of formal employees:** Agriculture and agro-processing, non-agricultural productive activities, welfare grants by the government and remittances are the four major sources of income for rural livelihood. Government provides most of the formal employment, however, the income from such formal employment have only limited impact on rural livelihood as most of the government employees live outside the villages where they work. In order to facilitate the impact of income from formal employment in rural communities, government should ensure that formal employees who are recruited to work in rural communities are from those who are resident in such communities. This will ensure that their income contributes to the rural economy of their place of service.

   While electricity access already increases the perception of civilisation, and facilitate increased comfort, opportunities that enable formal employees to maximise comfort and make additional such as teachers generating additional income by organising evening classes altogether increases their willingness to live and serve in rural communities (rural attractiveness).

6. **Acquisition and use of electrical equipment (SDG 1, 2, 3, 4, 8, 9, and 10):** While electricity access could facilitate transformation of rural economy and livelihood, a great deal of the impact depends on their adoption of use of modern and electrical technologies. Access to electrified equipment facilitates the production of 'new' and non-basic commodities which promote the diversification of rural economy (SDG 9). The acquisition of electrical equipment such as television and satellite dish facilitates the establishment of new schools within the neighbourhood for school-age children (SDG 4). Electrical equipment also facilitate teaching of new subjects among other contributions to improving educational outcomes (SDG 4) and facilitates access to information thus increasing knowledge on various subjects for youth and adults. Acquisition of electrical medical facilities improves medical services (SDG 3) including refrigerators for preservation of food at human nutrition (SDG 2) and vaccines (SDG 3).

   The diverse impact of electrical equipment on multiple SDGs explains the development potential that are left untapped when electricity access is not complemented by acquisition and use of electrical equipment. However, given the limited capacity to invest in electrical equipment, many rural productive activities are not able to experience a significant increase in their income that is sufficient to change their income levels. Nonetheless, the wealthier productive activities are able to invest more in electrical equipment are able to perform sophisticated value addition which facilitate a significant change in their income level, thus, exacerbating rural inequality (SDG 10). Governments and development organisations need to facilitate and/or provide financial support for rural businesses to procure electrical equipment to set-up new electricity-driven productive activities and scale-up existing ones. This will help to increase their income (SDG 1), provide jobs (SDG 8) and facilitate economic diversification (SDG 9). Such support should prioritise the economically worse off so as to reduce the level of inequality (SDG 10) in rural communities. The acquisition of electrical equipment provides an opportunity for energy access to impact agriculture (SDG 2). Though the primary occupation in most rural communities, energy intervention rarely have direct positive impact on agriculture. Hence, boasting the capacity of rural communities to perform value addition on their agricultural produce provides an opportunity for electricity access to impact agriculture.

7. **Inclusion of streetlighting in rural energy intervention (SDGs 1, 7, 8, and 16):** While streetlighting is an energy application, it is rarely provided as part of rural energy intervention, yet it holds huge potential in maximising the impact of energy access including those of other complementary actions. Streetlights facilitates optimum location of rural businesses, extension of workhours for productive activities and effective day thus facilitating increased production. Streetlights also facilitates patronage by customers including increasing the demand and consumption of goods and services. It also enables rural dwellers to stay for longer hours outdoor for social networking and entertainment as well as boost security. Hence, the need to include streetlighting in rural energisation projects. Indeed, the question "who pays?" for streetlights and its electricity consumption pose a limitation. Streetlights could be provided and operated with support from the community-based organisations, governments, development organisations, rural development agency or as a corporate social responsibility of energy investors to the host communities.

8. **Access to external market (SDGs 1, 8, 9)**: Productive use of electricity facilitates increased production, however, the conversion of increase in production to increase income, relies on the security of demand. Progressive increase in supply of commodities results in reduction in prices due to market saturation (in accordance with Adam Smith economic law of demand and supply), and may results in crowding out effect. Therefore, maximising the impact of increased production requires access to external market, hence, the need for rural energy investors to work with public, development and non-governmental agencies who are committed to rural development to support rural businesses in accessing external market. This may includes improvement in social networking, access to information, transport facilities including business, communication and marketing skills. The ability to increase income generation through external market also empower rural dwellers to pay for higher tier of electricity and its productive use.

9. **Access to finance and capacity building (SDGs 1, 5, 8, 9, 10 and 16):** A major reason for rural poverty is the over reliance of rural economy on agriculture without capacity for value addition to improve the economic value of agricultural produce. This is largely due to [227][234] inadequate start-up and scale-up capital (SDG 1, SDG 8), limited technical and business skills for development of non-agriculture-based sectors and value addition productive activities for processing of agricultural produce. Therefore, maximising and sustaining the economic impact of energy access require that government and development organisations work with energy companies to complement energy investment with access to finance that would increase the capacities of rural enterprises to acquire new and more efficient electrical equipment. NGOs, CBOs and rural development agencies could help to provide skill acquisition and set up rural dwellers and businesses, especially women into 'self-contained cohesive groups' which leverage on social relations for credibility and collateral for

repayment of credit facilities. The implementation of such support should also prioritise the worse off rural business to reduce inequality (SDG10) as wealthier businesses are able to leverage their capital base and network to increase their capacity in view of maximising the impact of the electricity access. In addition, government and development organisations needs to broker the barriers of rural businesses in accessing formal loans with conditions that captures the peculiarities of rural businesses and livelihood that are beyond the scale of micro-credits that are available to them. Government and development organisations can also set up dedicated credit facilities for rural enterprises. The formation of groups and associations improves social inclusion, and increases the participation of rural dwellers in governance and decision-making (SDG 16) – inclusive governance.

The implementation of the strategies, policy recommendations and complementary actions for rural energy access that maximises its impact on the realisation of the SDGs in rural context of developing countries highlight the need for multistakeholder engagement in rural energy projects. Table 8-1 presents the essential roles of various stakeholders, namely, government, multilateral and development organisations, business organisations, Civil Society Organisations, Community-based Organisations, and Community Stakeholders in implementing the recommendations towards maximising the impact of energy access on SDGs in rural context of developing countries.

Table 8-1: Multistakeholder roles towards maximising the impact of energy access on the SDGs

Policy Caption	**Government**	**Multilateral and Development Organisations**	**Business Organisations (Project Developers)**	**Civil Society Organisations, Community-based Organisations, and Community Stakeholders**
Strategies for rural energy access				
Catalysing rural energy investment	multistakeholder development and implementation of dedicated rural energy access strategies that captures the peculiarities of rural livelihood	multistakeholder development and implementation of dedicated rural energy access strategies that captures the peculiarities of rural livelihood	multistakeholder development and implementation of dedicated rural energy access strategies that captures the peculiarities of rural livelihood	multistakeholder development and implementation of dedicated rural energy access strategies that captures the peculiarities of rural livelihood
	Financial support should be provided to utility companies to offset some of their cost to increase their interest and the profitability of providing electricity access to rural communities	Financial support should be provided to utility companies to offset some of their cost to increase their interest and the profitability of providing electricity access to rural communities		

			development of local technical capacity (training) of residents of target communities for effective operation of rural energy projects	development of local technical capacity (training) of residents of target communities for effective operation of rural energy projects
Profitability and sustainability of rural energy investment	rural energy planning and design should be based on a holistic and multidimensional baseline analysis that adequately captures energy-development dynamics of target rural community to prevent oversizing of energy projects which negatively impact the profitability and sustainability of energy projects	rural energy planning and design should be based on a holistic and multidimensional baseline analysis that adequately captures energy-development dynamics of target rural community to prevent oversizing of energy projects which negatively impact the profitability and sustainability of energy projects	rural energy planning and design should be based on a holistic and multidimensional baseline analysis that adequately captures energy-development dynamics of target rural community to prevent oversizing of energy projects which negatively impact the profitability and sustainability of energy projects	
			integration of electricity-dependent productive activities with rural energy projects by energy companies and/or in partnership with other investors helps to reduce energy wastages while creating jobs and generating income	

			Electricity consumption for productive uses may also be increased by adopting financial models that offers cheaper electricity tariff for productive uses during the day relative to the evening	
High Tier of Electricity Access	support for a share of the investment cost of rural energy investors to enable them supply high tier of electricity	support for a share of the investment cost of rural energy investors to enable them supply high tier of electricity		
			provision and security of high tier of electricity round the rural community to maximise its impact on gender empowerment (SDG 5) and inequality (SDG 10)	
Affordability of Electricity Cost	complimentary actions including access to finance and capacity building for productive use of electricity that would increase the affordability of electricity expenditure. Such support should prioritise the economically worse off so as to reduce the level of inequality (SDG 10) in rural communities	complimentary actions including access to finance and capacity building for productive use of electricity that would increase the affordability of electricity expenditure. Such support should prioritise the economically worse off so as to reduce the level of inequality (SDG 10) in rural communities	complimentary actions including access to finance and capacity building for productive use of electricity that would increase the affordability of electricity expenditure. Such support should prioritise the economically worse off so as to reduce the level of inequality (SDG 10) in rural communities	

Plurality of energy technologies (Energisation, not electrification)	migrate from limiting energy access to electrification to 'energisation' that embraces plurality of energy technologies in rural energy access intervention projects to maximise the dimensions of their impact and the contributions to the 2030 agenda	migrate from limiting energy access to electrification to 'energisation' that embraces plurality of energy technologies in rural energy access intervention projects to maximise the dimensions of their impact and the contributions to the 2030 agenda	migrate from limiting energy access to electrification to 'energisation' that embraces plurality of energy technologies in rural energy access intervention projects to maximise the dimensions of their impact and the contributions to the 2030 agenda	
Policy Constraints				
Leveraging endogenous resources strengthens existing IGAs and jobs while facilitating new ones			biomass projects (from energy crops), being dependent on consistent supply of energy crops (SDG 2 &7) provides and sustain agriculture jobs.	
	Need for policies that ensures a reserved proportion of agricultural land for food production with possible incentives in order to encourage and sustain food security in rural communities where energy is being generated from biomass			
Sustaining hydropower generation and food production	developers of hydropower projects to work with governments to provide new agricultural lands for farmers who may be negatively impacted		developers of hydropower projects to work with governments to provide new agricultural lands for farmers who may be negatively	

	by hydropower projects		impacted by hydropower projects	
			Effective consultation engagement and participation of target communities in energy projects	Effective consultation engagement and participation of target communities in energy projects
Employment	Energy access project should be implemented such that it provides jobs and increased income that at least offset job losses and income reduction that accrue due to the energy intervention project	Energy access project should be implemented such that it provides jobs and increased income that at least offset job losses and income reduction that accrue due to the energy intervention project	Energy access project should be implemented such that it provides jobs and increased income that at least offset job losses and income reduction that accrue due to the energy intervention project	
Community engagement for wind energy generation			need for effective community engagement and participation in deploying wind energy technolgoies	need for effective community engagement and participation in deploying wind energy technolgoies
Use of Electrical Appliances				parental control among other effort to direct the students to beneficial use of electrical appliances
				intensify effort in teaching and dissemination of desirable traditional and

				cultural values (SDG 16)
Complementary Actions				
Boasting Security				Leverage social networking for community policing to improve safety and security in their communities.
Complementary actions to maximise saved time	Realising significant impact on education requires complementary actions such as building of schools, recruitment of teachers, including awareness creation on the benefit of educating the girlchild	Realising significant impact on education requires complementary actions such as building of schools, recruitment of teachers, including awareness creation on the benefit of educating the girlchild		
	complement rural energy investments by creating access to finance to facilitate productive use of saved time by setting up new productive activities or scaling existing ones	complement rural energy investments by creating access to finance to complement energy access project to facilitate productive use of saved time by setting up new productive activities or scaling existing ones		
	support rural businesses by creating access to external market for their produce	support rural businesses by creating access to external market for their produce		support rural businesses by creating access to external market for their produce

	create dedicated funds and capacity development initiatives that increase the capacity of rural businesses to carry out value addition activities on their products to increase their acceptability and increase demand from external market	create dedicated funds and capacity development initiatives that increase the capacity of rural businesses to carry out value addition activities on their products to increase their acceptability and increase demand from external market		
Afforestation Policy	mandate a specified number of tree seedling to be planted for every tree cut down to further enhance nature conservation and the sustainability of the ecosystem			
	awareness and education of the stakeholders who are active in the fuelwood and charcoal business value chain			awareness and education of the stakeholders who are active in the fuelwood and charcoal business value chain

Impact on gender empowerment requires change in technology (SDG 5 and 8)	gender empowerment impact of energy access requires change in technologies and complementary actions which could be achieved in collaborations with government, development organisations and NGOs. Such complementary support includes increasing women education, training and skill sets, access to finance among resources, access to market, and, participation in decision-making	gender empowerment impact of energy access requires change in technologies and complementary actions which could be achieved in collaborations with government, development organisations and NGOs. Such complementary support includes increasing women education, training and skill sets, access to finance among resources, access to market, and, participation in decision-making		gender empowerment impact of energy access requires change in technologies and complementary actions which could be achieved in collaborations with government, development organisations and NGOs. Such complementary support includes increasing women education, training and skill sets, access to finance among resources, access to market, and, participation in decision-making
Boasting rural economy through formal employment	Public recruitment of staff to serve in a rural community should be from those who are resident in those communities to ensure their income contribute to rural economy			
				creation of opportunities, such as possibilities to earn additional income through organisation of evening classes, to increase the willingness of formal employee to live and serve in rural communitis,

				that is, boast rural attractiveness
Acquisition and use of electrical equipment	boasting the capacity of rural communities to perform value addition on their agricultural produce provides an opportunity for electricity access to impact agriculture	boasting the capacity of rural communities to perform value addition on their agricultural produce provides an opportunity for electricity access to impact agriculture		boasting the capacity of rural communities to perform value addition on their agricultural produce provides an opportunity for electricity access to impact agriculture
	facilitate and/or provide financial support for rural businesses to procure electrical equipment to set-up new electricity-driven productive activities and scale-up existing ones to facilitate, catalyse and maximise the impact of energy access on multiple SDGs. Such support should prioritise the economically worse off so as to reduce the level of inequality (SDG 10) in rural communities.	facilitate and/or provide financial support for rural businesses to procure electrical equipment to set-up new electricity-driven productive activities and scale-up existing ones to facilitate, catalyse and maximise the impact of energy access on multiple SDGs. Such support should prioritise the economically worse off so as to reduce the level of inequality (SDG 10) in rural communities.		

Inclusion of streetlighting in rural energy intervention (SDGs 1, 7, 8, 16)	Streetlights could be provided and operated with support from the community-based organisations, governments, development organisations, rural development agency or as a corporate social responsibility of energy investors to the host communities	Streetlights could be provided and operated with support from the community-based organisations, governments, development organisations, rural development agency or as a corporate social responsibility of energy investors to the host communities	Streetlights could be provided and operated with support from the community-based organisations, governments, development organisations, rural development agency or as a corporate social responsibility of energy investors to the host communities	Streetlights could be provided and operated with support from the community-based organisations, governments, development organisations, rural development agency or as a corporate social responsibility of energy investors to the host communities
Access to external market (SDGs 1, 8, 9)	improvement in social networking, access to information, transport facilities including business, communication and marketing skills	improvement in social networking, access to information, transport facilities including business, communication and marketing skills		improvement in social networking, access to information, transport facilities including business, communication and marketing skills
Access to finance and capacity building (SDGs 1, 5, 8, 9)	complement energy investment with access to finance that would increase the capacities of enterprises to acquire new and more efficient electrical equipment	complement energy investment with access to finance that would increase the capacities of enterprises to acquire new and more efficient electrical equipment		
				NGOs, CBOs and rural development agencies could help to provide skill acquisition and set up rural dwellers and IGAs, especially women into '<u>self-contained cohesive groups</u>' which leverage on social relations for credibility and

				collateral for repayment of credit facilities
	broker the barriers of rural businesses in accessing formal loans with conditions that captures the peculiarities of rural businesses and livelihood that are beyond the scale of micro-credits that are available to rural businesses	broker the barriers of rural businesses in accessing formal loans with conditions that captures the peculiarities of rural businesses and livelihood that are beyond the scale of micro-credits that are available to rural businesses		
	set up facilities for dedicated credit facilities for rural enterprises	set up facilities for dedicated credit facilities for rural enterprises		

8.5 Conclusion

Rural communities account for more than half of the populations in developing countries yet suffer a disproportionate share of development challenges, hence, the development of various strategies to improve rural livelihood. "Access to modern energy for all" in rural communities has been identified as a major instrument to catalyse sustainable development in such localities. However the security, sustainability, use and impact of energy access in rural communities is negatively impacted by diverse peculiarities of rural livelihood in developing countries.

Therefore, an effective policy aimed at providing "access to modern energy for all" in rural communities will deploy strategies that capture the peculiarities of rural livelihood to provide high tier of energy access with plurality in energy technologies that addresses the various dimensions of rural development. Such energy technologies needs to be strategically deployed for productive use to boast rural economy with considerations of the affordability of the associated energy cost.

The analysis reveals that energy access for sustainable development in rural context is a multidimensional and multi-stakeholder endeavour that requires plurality in the deployment of energy technologies. While energy-SDGs nexus in rural context encapsulate linkages that facilitate in the achievement of SDGs, and it also have several linkages that limits, weakens and counteract other SDGs, thus constituting policy constraints to policies for energy access. The dynamics of nexus of these linkages explains the reason energy access does not automatically catalyse sustainable development in rural context and the heterogeneity of its impact.

There is a need for in-depth understanding of the diverse linkages within the complex dynamics of energy access-SDGs in the context of target rural communities in order to deploy policies, and strategies that strengthens the linkages that maximise the impact on SDGs and weaken the linkages that could undermine the impact on the realisation of the SDGs. The need to strengthen linkages that maximise impact on SDGs and weaken those that constrains the impact or result in undesirable impact highlight the need for complementary actions.

Moreover, energy access is a necessary but not a sufficient condition for sustainable development. Hardly is there any of the SDGs whose realisation can be significantly achieved by provision of modern energy access without complementary actions. Energy access may not have any positive impact on some of the SDGs whereas it may have undesirable impact on the SDGs without complementary actions. However, each of the complementary actions is a main input in other SDGs. Thus, implementing them as complementary actions without tracking their impact on the SDGs in which they are main inputs does not maximise the investment into such actions which highlight the singleton approach to the implementation of the SDGs is sub-optimal. This demonstrates the cross linkages, interdependence and indivisibility of the United Nations 2030 Agenda, hence, the need for policy coherence for a holistic approach for simultaneous achievement of the SDGs.

CHAPTER NINE

9 Conclusions and Future Works

9.1 Contributions, Relevance and Strengths

The 600 million people without access to electricity across Africa depict the deficiency of the African energy architecture. The availability of huge and diverse renewable energy potential provides alternative energy resources that could be exploited to fast track energy access across the continent. However, electricity generation in Africa has been dominated by fossil fuel, therefore, the integration of renewable energy sources in the African electricity mix requires a new paradigm in its energy sector. Being unconventional energy sources, the exploitation of renewable energy sources comes with multidimensional challenges especially in developing economies.

The study analysis renewable energy exploitation and use in Africa by taking the case of South Africa, Egypt, and Nigeria which are the three largest African economies and all possess abundant renewable energy sources. South Africa and Egypt provide cases of transformational growth in the uptake of renewable energies driven by market-oriented policies and strategies with active support and contributions of the government that cover the various dimensions of renewable energy development. The Nigerian case, on the other hand, exemplifies multidimensional constraints faced by many African countries that limit the optimal exploitation of their renewable energy sources. Based on the significant progress made on renewable energy development recorded in South Africa and Egypt, the study discusses the various policies and programmes including the implementation strategies guiding the renewable energy sector in the two countries. By drawing from the experience, approach and results in the two countries, recommendations were made for other African countries, taking the case of Nigeria, which, if adapted to their local context, could facilitate renewable energy development especially through private sector investment for utility-scale renewable energy projects.

The analysis finds that the varying level of development attained in the uptake of renewable energy for improving the conditions of energy access in the three countries is mainly occasioned by the institutional and policy environment in the three countries.

However, the overall objective of increasing energy access is to facilitate development, and the effectiveness of energy access in facilitating development is dependent on the level of integration of energy access project within the overall economy and development framework.

The development of an integrated system dynamics model developed for investigation, evaluation and analysis of various national energisation policies and their impact on nine other sectors of the national economy, taking the case of Nigeria. The results of the modelling process shows that the model captures the dynamics of the energy sector with nine major sectors of the Nigerian economy. The model results capture the non-linearity, delays and feedbacks within the energy access-development nexus, hence, thus, avoiding "black-box" exogenous relations and approaches in designing energy policies. The model allows helps increase stakeholders' knowledge of the energy-development dynamics in the Nigerian context by serving as a holistic and integrated quantitative tool for understanding how energy variables interact and impact the variables of other sectors of the Nigerian economy.

The results of a modelling process shows that the model captures the dynamics of the energy sector (fossil fuels, renewables, and access to energy) with ten major sectors of the Nigerian economy. The model results capture the non-linearity delays and feedbacks of the system which allows us to link different sectors, thus, avoiding "black-box" exogenous relations and approaches in designing energy policies. The model allows us to increase our knowledge of the energy-development dynamics in the

Nigerian context by serving as a holistic and integrated quantitative tool for understanding how energy variables interact and impact the variables of other sectors of the Nigerian economy.

The endogenous generation of the behaviour of model, and its fitness with historical data, and the error test, disintegration and analysis presented demonstrates the appropriateness of the structure and behaviour of the model. The summary statistics analysed and interpreted above demonstrate the ability of the model to reproduce historical behaviour of the system endogenously, thus, building confidence in the model. In addition, the model has been verified for structural appropriateness to ensure that all equations are dimensionally consistent without the use of parameters without real-world counterpart (dimensional consistency) and structure of the model is consistent with real-life description of the system (structural verification). Indeed, "the true test of a model is its ability to reproduce historical behaviour endogenously, with the structure and parameters that are consistent with descriptive knowledge of the system" [225].

Indeed, energy policies and plans based on country-level aggregated data help to guide national development direction for governments among other stakeholders, yet, they do not reflect the realities within the sub-national contexts especially in developing countries with the wide development margin between urban and rural communities. Therefore, development analysis for intervention based on national averaged data evade stakeholders opportunities to understand the reality of in-country situation and identify the most crucial areas of need. The conditions of livelihood at the sub-national level differ widely between the urban and rural communities in developing countries. Rural communities account for more than half of the populations in developing countries yet suffer a disproportionate share of development challenges, hence, the development of various strategies to improve rural livelihood. The high development deficit in rural developing countries vis-à-vis the high share of their population who reside in them makes rural communities in developing countries form one of the largest group of people affected the global challenges that the United Nations' SDGs seeks to address – 'farthest from behind'. Therefore, the "leaving no one behind" operating principle of the SDGs to catalyse sustainable development 'starting from the farthest behind' makes the case for a new momentum towards rural development in developing countries.

The wide acknowledgement of the pivotal role of "access to modern energy for all" towards realising the SDGs made the security of energy access a major priority in the effort to catalyse sustainable development in rural communities. However the security, sustainability, use and impact of energy access in rural communities is negatively impacted by diverse peculiarities of rural livelihood in developing countries. Hence, making a case for the development of tools that could help to facilitate rural energy access and maximise its impact on the achievement of the SDGs in rural context of developing countries. The development of such planning tools relies on the depth of understanding of the nexus and the interlinkages between energy access and the SDGs in rural context.

In order to identify and establish the impact pathways between the variables of energy access and those of the other SDGs at sub-national (rural) level, the analysis employs a descriptive analysis and causal loop diagrams (CLDs) of the causal relationships between variables of energy access and those of the SDGs in rural contexts of developing countries. Causal Loop Diagrams (CLDs) are conceptual models employed for visual description of the causal relationships, impact pathways and feedback between variables in complex systems which represent the formulation stage in the development of system dynamics models.

The analysis:

i. identified and reviewed the relevant and measurable variables of energy access and those of the SDGs in the rural context of developing countries,

ii. analysed and discuss the causal linkages and impact pathways between the variables of energy access and those of the SDGs,

iii. identified the synergies and trade-offs within the energy access and SDGs dynamics

iv. identified the complementary actions required to leverage on the synergies and trade-offs to maximise the desirable impact of energy access on the SDGs while minimising undesirable impact

v. developed the linkages, causal linkages and impact pathways into Causal loop Diagrams as conceptual models for rural energy access-SDGs and identify the intervening feedback loops

Based on the analysis, the study finds that an effective policy aimed at providing “access to modern energy for all” in rural communities will deploy strategies that capture the peculiarities of rural livelihood to provide high tier of energy access with plurality in energy technologies that addresses the various dimensions of rural development. Such energy technologies needs to be strategically deployed for productive use to boast rural economy with considerations of the affordability of the associated energy cost.

The analysis reveals that energy access for sustainable development in rural context is a multidimensional and multi-stakeholder endeavour that requires plurality in the deployment of energy technologies. While energy-SDGs nexus in rural context encapsulate linkages that facilitate in the achievement of SDGs, and it also have several linkages that limits, weakens and counteract other SDGs, thus constituting policy constraints to policies for energy access. The dynamics of nexus of these linkages explains the reason energy access does not automatically catalyse sustainable development in rural context and the heterogeneity of its impact.

There is a need for in-depth understanding of the diverse linkages within the complex dynamics of energy access-SDGs in the context of target rural communities in order to deploy policies, and strategies that strengthens the linkages that maximise the impact on SDGs and weaken the linkages that could undermine the impact on the realisation of the SDGs. The need to strengthen linkages that maximise impact on SDGs and weaken those that constrains the impact or result in undesirable impact highlight the need for complementary actions.

Moreover, energy access is a necessary but not a sufficient condition for sustainable development. Hardly is there any of the SDGs whose realisation can be significantly achieved by provision of modern energy access without complementary actions. Energy access may not have any positive impact on some of the SDGs whereas it may have undesirable impact on the SDGs without complementary actions. However, each of the complementary actions is a main input in other SDGs. Thus, implementing them as complementary actions without tracking their impact on the SDGs in which they are main inputs does not maximise the investment into such actions which highlight the singleton approach to the implementation of the SDGs is sub-optimal. This demonstrates the cross linkages, interdependence and indivisibility of the United Nations 2030 Agenda, hence, the need for policy coherence for a holistic approach for simultaneous achievement of the SDGs.

9.2 Limitations and Future Work

Building on the integrated system dynamics model developed for investigation, evaluation and analysis of various national energisation policies and their impact on nine other sectors of Nigeria, future work will be focused on policy analysis which will be predicated on extreme and surprise policy test of the model to ensure that the model behave appropriately when subjected to extreme policy. For the policy analysis, an analysis of the annual budget of the government on energy relative to the GDP over time to ascertain inputs for the policy analysis will be required. The extreme and surprise policy test will further build confidence in the model in its ability to evaluate various scenarios of energy policies such as energy investment, resource allocation of energy intervention fund and budgetary allocations vis-à-vis their respective plausible impact on sustainable development. The model will also help in determining, analysing and evaluating optimal energy mix from crude oil and renewables sources and their impact on energy access, GDP, health, education, among other sectors captured by the model. The model will be a tool to evaluate the impact of various scenarios of energy investment, intervention fund and budgetary allocations on household income (SDG 1), education (SDG 3), health (SDG 4), energy access (SDG 7), economic growth (SDG 8) and infrastructure development (SDG 9). The model will also be a tool to identify necessary complementary actions and their effectiveness in maximising the impact of energy interventions to facilitate sustainable development in Nigeria. Users of the model would be able to compare the impact of various resource allocations including ascertaining what level of investment are required in other sectors for effective impact of energy investment.

Moreover, future effort could also build on the causal loop diagrams and the feedback loops developed from the literature analysis on the rural energy access-SDGs nexus. The causal loop diagrams and the feedback loops provide conceptual models for developing an integrated system dynamics model for investigation, evaluation and analysis of various national energisation policies and their impact on SDGs in the rural context of developing countries. The model will aid appropriate policy design towards realising "modern energy access for all" to fast-track sustainable developing in rural context of developing countries.

Publications

Book Chapter (Peer Review)

1. **Adeleke**, F. Inzoli, and E. Colombo, “Renewable Energy Development in Africa: Lessons and Policy Recommendations from South Africa, Egypt, and Nigeria,” in *Renewable Energy for Sustainable Growth Assessment*, Scrivener Publishing LLC, 2022, pp. 259–300. ISBN: 9781119785361

Journal Article (Peer Review)

2. B. Ugwoke, **A. Adeleke**, S. P. Corgnati, J. M. Pearce, and P. Leone, “Decentralized Renewable Hybrid Mini-Grids for Rural Communities: Culmination of the IREP Framework and Scale up to Urban Communities,” Sustainability, vol. 12, no. 18, p. 7411, Sep. 2020.

3. G. Falchetta, A. Adeleke, M. Awais, E. Byers, P. Copinschi, S. Duby, M. Hafner, A. Hughes, G. Ireland, K. Riahi, F. Semeria, D. Shendrikova, S. Rukera-Tabaro, N. Stevanato, A. Troost, M. Tuninetti, A. Vinca, A. Zulu, “A research agenda for planning and financing nexus development objectives in rural sub-Saharan Africa”, Energy Strategy Reviews (Under Review)

Conference Paper (Peer Review)

4. **Adeleke**, F. Riva, F. Tonini, and E. Colombo, “Policy coherence to enable effective energy strategies and promote sustainable development: toward developing an integrated simulation model for Nigeria,” in *Energising the SDGs through appropriate technology and governance*, 2019, no. July, pp. 90–99.

5. F. Tonini, **A. Adeleke,** F. Sanvito, M. Grimoldi, E. Colombo, F. Colombelli, “Towards improving sustainable access to electricity in rural areas of Tanzania: learning from the past preparing for the future” in System Dyanamics Conference., 2019.

Contributions to Global Energy Reports

S/N	**Role**	**Publication**	**Organisation**
5	Lead Country Contributor	REN21, “Renewables **2020**: Global Status Report,” Paris, 2020.	Renewable Energy Network Policy for the 21st Century (REN21), Paris, France
6	Lead Country Contributor	REN21, “Renewables **2019**: Global Status Report,” Paris, 2019.	Renewable Energy Network Policy for the 21st Century (REN21), Paris, France
7	Lead Country Contributor	REN21, “Renewables **2018**: Global Status Report,” Paris, 2018.	Renewable Energy Network Policy for the 21st Century (REN21), Paris, France
8	Lead Country Contributor	REN21, “Renewables **2017**: Global Status Report,” Paris, 2017.	Renewable Energy Network Policy for the 21st Century (REN21), Paris, France

9	Country Contributor	UNEP, “Renewable Energy and Energy Efficiency in Developing Countries: Contributions to Reducing,” Nairobi, **2017**.	United Nations Environnent Programme (UNEP), Nairobi, Kenya

10 Annex

Below are the underlining 250 equations involving 363 variables for the system dynamic model described in Chapter 6.

The model has 363 (363) variables in root model and 10 additional modules with 1 sectors.

Stocks: 23 (23) Flows: 44 (44) Converters: 296 (296)

Constants: 90 (90) Equations: 250 (250) Graphicals: 31 (31)

Education (edu):

literate_elderly_population(t) = literate_elderly_population(t - dt) + (literate_working_age_population_becoming_elderly - literate_elderly_population_deaths_and_migration) * dt {NON-NEGATIVE}

INIT literate_elderly_population = 626804,8722

UNITS: person

INFLOWS:

literate_working_age_population_becoming_elderly = literate_working_age_population/pop.Working_age_duration {UNIFLOW}

UNITS: person/year

OUTFLOWS:

literate_elderly_population_deaths_and_migration = literate_elderly_population* (pop.Elderly_death_rate-pop.Net_migration_rate+pop.elderly_population_death_rate_correction)

UNITS: person/year

literate_working_age_population(t) = literate_working_age_population(t - dt) + (literate_young_population_becoming_adult - literate_working_age_population_becoming_elderly - literate_working_age_population_deaths_and_migration) * dt {NON-NEGATIVE}

UNITS: person

INFLOWS:

literate_young_population_becoming_adult = young_literate_population/time_to_become_adult {UNIFLOW}

UNITS: person/year

OUTFLOWS:

literate_working_age_population_becoming_elderly = literate_working_age_population/pop.Working_age_duration {UNIFLOW}

UNITS: person/year

literate_working_age_population_deaths_and_migration = literate_working_age_population*(pop.Working_age_death_rate-pop.Net_migration_rate)

UNITS: person/year

primary_students(t) = primary_students(t - dt) + (entrance_at_school - graduation - dropouts_and_deaths) * dt {NON-NEGATIVE}

INIT primary_students = pop.School_Age_Population*initial_proportion_of_school_age_population_in_school

UNITS: person

INFLOWS:

entrance_at_school = IF potential_new_student>0 THEN MIN(potential_new_student/time_to_enroll_students; vacant_places_at_school) ELSE 0 {UNIFLOW}

UNITS: person/year

DOCUMENT: IF

potential_new_student>0

THEN

MIN(potential_new_student/time_to_enroll_students, vacant_places_at_school)

ELSE

0

this function can be replaced by

max(0,MIN(potential_new_student/time_to_enroll_students, vacant_places_at_school)

OUTFLOWS:

graduation = primary_students/time_to_complete_primary_school {UNIFLOW}

UNITS: person/year

dropouts_and_deaths = primary_students* (pop.school_age_death_rate+dropout_rate) - MIN(potential_new_student/time_to_enroll_students; 0) {UNIFLOW}

UNITS: person/year

DOCUMENT: IF

potential_new_student>0

THEN

primary_students*

(pop.school_age_death_rate+dropout_rate)

ELSE

primary_students*

(pop.school_age_death_rate+dropout_rate)-potential_new_student/time_to_enroll_students

OR

primary_students*

(pop.school_age_death_rate+dropout_rate)

- min(potential_new_student/time_to_enroll_students, 0)

OR

primary_students*

(pop.school_age_death_rate+dropout_rate)

+ max(-potential_new_student/time_to_enroll_students, 0)

young_literate_population(t) = young_literate_population(t - dt) + (graduation - literate_young_population_becoming_adult - young_literate_population_deaths_and_migration) * dt {NON-NEGATIVE}

INIT young_literate_population = 3125192

UNITS: person

INFLOWS:

graduation = primary_students/time_to_complete_primary_school {UNIFLOW}

UNITS: person/year

OUTFLOWS:

literate_young_population_becoming_adult = young_literate_population/time_to_become_adult {UNIFLOW}

UNITS: person/year

young_literate_population_deaths_and_migration = young_literate_population*(pop.school_age_death_rate-pop.Net_migration_rate)

UNITS: person/year

Average_adult_literacy_rate = (literate_elderly_population+literate_working_age_population)/(pop.Elderly_Population+pop.Working_Age_Population)

UNITS: dmnl

average_cost_per_students = 25000

UNITS: USD2010/person/year

dropout_rate = 0,025

UNITS: dmnl/year

implemented_education_expenditure = DELAYN(real_education_expenditure; time_for_education_expenditure_implementation;1; initial_implemented_education_expenditure)

UNITS: USD2010/year

initial_implemented_education_expenditure = 16015489551

UNITS: USD2010/year

initial_proportion_of_school_age_population_in_school = 0

UNITS: dmnl

potential_new_student = school_age_population_willing_to_go_to_school-primary_students

UNITS: person

primary_school_age_population = pop.School_Age_Population*proportion_of_primary_school_age_population_in_total_school_age_population

UNITS: person

proportion_of_primary_school_age_population_in_total_school_age_population = 0,6

UNITS: Dimensionless

proportion_of_school_age_population_willing_to_go_to_school = GRAPH(hhs.pc_real_disposable_income)

(0, 0,200), (30000, 0,600), (75000, 0,800), (150000, 0,950), (200000, 1,000)

UNITS: Dimensionless

real_education_expenditure = gov.education_expenditure/gdp.gdp_deflator

UNITS: USD2010/year

school_age_population_willing_to_go_to_school = primary_school_age_population*proportion_of_school_age_population_willing_to_go_to_school

UNITS: person

school_system_capacity = implemented_education_expenditure/average_cost_per_students

UNITS: person

time_for_education_expenditure_implementation = 6

UNITS: year

time_to_become_adult = pop.School_age_duration-time_to_complete_primary_school

UNITS: years

time_to_complete_primary_school = 6

UNITS: Years

time_to_enroll_students = 1

UNITS: year

vacant_places_at_school = (school_system_capacity-primary_students)/time_to_enroll_students+dropouts_and_deaths+graduation

UNITS: person/year

Finance (fin):

public_domestic_debt(t) = public_domestic_debt(t - dt) + (net_domestic_financing) * dt

INIT public_domestic_debt = 1,05e10

UNITS: USD

INFLOWS:

net_domestic_financing = net_lending_to_government

UNITS: USD/year

public_foreign_debt(t) = public_foreign_debt(t - dt) + (net_foreign_financing) * dt

INIT public_foreign_debt = 3,3458e10

UNITS: USD

INFLOWS:

net_foreign_financing = (gov.government_total_net_borrowing-net_domestic_financing)

UNITS: USD/year

savings(t) = savings(t - dt) + (household_saving - private_domestic_investment - net_lending_to_government) * dt

INIT savings = 4e10

UNITS: USD

INFLOWS:

household_saving = hhs.private_saving

UNITS: USD/year

OUTFLOWS:

private_domestic_investment = MAX(0; indicated_total_investment*relative_interest_rate^elasticity_of_investment_to_interest_rate-private_capital_and_financial_account-gov.government_investment)

UNITS: USD/year

net_lending_to_government = MIN(gov.government_total_net_borrowing*desired_domestic_financing_share; savings/lending_disbursement_time)

UNITS: USD/year

actual_savings_coverage_ratio = savings/(desired_savings_coverage*gdp.nominal_gdp)

UNITS: dmnl

desired_domestic_financing_share = 0,5

UNITS: dmnl

desired_savings_coverage = 0,125

UNITS: year

domestic_debt_to_gdp_ratio = public_domestic_debt/gdp.nominal_gdp

UNITS: year

elasticity_of_interest_rates_to_saving_coverage = -1

UNITS: dmnl

elasticity_of_investment_to_interest_rate = -1

UNITS: dmnl

foreign_debt_to_gdp_ratio = public_foreign_debt/gdp.nominal_gdp

UNITS: year

indicated_total_investment = (gdp.capital*gdp.real_gdp_growth_rate+gdp.depreciation)*gdp.gdp_deflator

UNITS: USD/year

interest_on_domestic_debt = public_domestic_debt*interest_rate_on_domestic_debt

UNITS: USD/year

interest_on_foreign_debt = interest_rate_on_foreign_debt*public_foreign_debt

UNITS: USD/year

interest_rate_on_domestic_debt = GRAPH(domestic_debt_to_gdp_ratio)

UNITS: dmnl/year

interest_rate_on_foreign_debt = GRAPH(foreign_debt_to_gdp_ratio)

UNITS: dmnl/year

investment = private_domestic_investment+gov.government_investment+private_capital_and_financial_account

UNITS: USD/year

lending_disbursement_time = 2

UNITS: year

private_capital_and_financial_account = gdp.nominal_gdp*private_capital_and_financial_account_as_share_of_gdp

UNITS: USD/year

private_capital_and_financial_account_as_share_of_gdp = GRAPH(TIME)

UNITS: Dimensionless

relative_interest_rate = (actual_savings_coverage_ratio/INIT(actual_savings_coverage_ratio))^elasticity_of_interest_rates_to_saving_coverage

UNITS: dmnl

Gross Domestic Product (gdp):

capital(t) = capital(t - dt) + (real_investment - depreciation) * dt {NON-NEGATIVE}

INIT capital = 18200437932

UNITS: USD2010

INFLOWS:

real_investment = fin.investment/gdp_deflator {UNIFLOW}

UNITS: USD2010/year

OUTFLOWS:

depreciation = capital/avg_depreciation_time {UNIFLOW}

UNITS: USD2010/year

avg_depreciation_time = 2,5

UNITS: years

capital_elasticity = 0,219113

UNITS: dmnl

effect_of_access_to_energy_on_tfp = (nrg.total_population_with_energy_access/INIT(nrg.total_population_with_energy_access))^elasticity_of_tfp_to_access_to_energy

UNITS: dmnl

effect_of_energy_price_on_tfp = SMTHN(indicated_effect_of_energy_price_on_tfp; time_for_effect_to_be_visible; 1; 1)

UNITS: dmnl

effect_of_life_expectancy_on_tfp = (pop.Avg_life_expectancy/INIT(pop.Avg_life_expectancy))^elasticity_of_tfp_to_life_expectancy

UNITS: dmnl

effect_of_literacy_rate_on_tfp = (literate_working_age_population/INIT(literate_working_age_population))^elasticity_of_tfp_to_literacy_rate

UNITS: dmnl

effect_of_roads_density_on_tfp = (ifr.km_of_roads_per_million_ha/INIT(ifr.km_of_roads_per_million_ha))^elasticity_of_tfp_to_road_density

UNITS: dmnl

elasticity_of_tfp_to_access_to_energy = 0,05

UNITS: dmnl

elasticity_of_tfp_to_energy_price = 0,005756

UNITS: dmnl

elasticity_of_tfp_to_life_expectancy = 0,085

UNITS: dmnl

elasticity_of_tfp_to_literacy_rate = 0,125852

UNITS: dmnl

elasticity_of_tfp_to_road_density = 0,07

UNITS: dmnl

gdp_deflator = GRAPH(TIME)

UNITS: USD/USD2010

gdp_growth_rate_time_horizon = 1

UNITS: year

indicated_effect_of_energy_price_on_tfp = (nrg.average_oil_market_price/INIT(nrg.average_oil_market_price))^elasticity_of_tfp_to_energy_price

UNITS: dmnl

initial_gdp = 144248123964,32

UNITS: USD2010/year

labor_elasticity = 0,6

UNITS: dmnl

land_elasticity = (1-labor_elasticity-capital_elasticity)

UNITS: dmnl

literate_working_age_population = edu.literate_working_age_population/pop.Working_Age_Population

UNITS: dmnl

nominal_gdp = real_gdp*gdp_deflator

UNITS: USD/year

real_gdp = initial_gdp*(relative_capital^capital_elasticity)*(relative_working_age_population^labor_elasticity)*(relative_agriculture_land^land_elasticity)*total_factor_productivity

UNITS: USD2010/year

real_gdp_growth_rate = TREND(real_gdp; gdp_growth_rate_time_horizon)

UNITS: dmnl/year

real_pc_gdp = real_gdp/pop.total_population

UNITS: USD2010/person/year

relative_agriculture_land = lnd.agriculture_land/INIT(lnd.agriculture_land)

UNITS: dmnl

relative_capital = capital/INIT(capital)

UNITS: dmnl

relative_working_age_population = pop.Working_Age_Population/INIT(pop.Working_Age_Population)

UNITS: dmnl

time_for_effect_to_be_visible = 1

UNITS: year

total_factor_productivity = effect_of_roads_density_on_tfp*effect_of_life_expectancy_on_tfp*effect_of_literacy_rate_on_tfp*effect_of_energy_price_on_tfp*effect_of_access_to_energy_on_tfp

UNITS: dmnl

Government (gov):

consumption_share_of_government_expenditure = 0,95

UNITS: dmnl

Converter_1 = grants/domestic_revenue

UNITS: Dimensionless

direct_tax_rate = GRAPH(TIME)

UNITS: dmnl

direct_tax_revenue = gdp.nominal_gdp*direct_tax_rate

UNITS: USD/year

domestic_revenue = direct_tax_revenue+oil_product_tax_revenue

UNITS: USD/year

education_expenditure = education_expenditure_as_share_of_gdp*gdp.nominal_gdp

UNITS: USD/year

education_expenditure_as_share_of_gdp = 0,03

UNITS: dmnl

expenditure = education_expenditure+health_expenditure+roads_expenditure+general_administrative_expenditure+subsidies_and_transfers+interest_on_public_debt+nrg.Annual_funding_for_renewable

UNITS: USD/year

general_administrative_expenditure = (real_pc_general_administration_expenditure*pop.total_population)*gdp.gdp_deflator

UNITS: USD/year

government_consumption = (expenditure-subsidies_and_transfers-interest_on_public_debt)*consumption_share_of_government_expenditure

UNITS: USD/year

government_investment = (expenditure-subsidies_and_transfers-interest_on_public_debt)*(1-consumption_share_of_government_expenditure)

UNITS: USD/year

government_surplus_or_deficit = revenue_and_grants-expenditure

UNITS: USD/year

government_total_net_borrowing = -government_surplus_or_deficit

UNITS: USD/year

grants = grants_as_share_of_gdp*gdp.nominal_gdp

UNITS: USD/year

grants_as_share_of_gdp = GRAPH(TIME)

(1980,00, 0,0676478409652), (1981,00, 0,0676478409652), (1982,00, 0,0676478409652), (1983,00, 0,0676478409652), (1984,00, 0,0676478409652), (1985,00, 0,0676478409652), (1986,00, 0,0676478409652), (1987,00, 0,0676478409652), (1988,00, 0,0676478409652), (1989,00, 0,0676478409652), (1990,00, 0,0676478409652), (1991,00, 0,0676478409652), (1992,00, 0,0676478409652), (1993,00, 0,0676478409652), (1994,00, 0,0676478409652), (1995,00, 0,0676478409652), (1996,00, 0,0676478409652), (1997,00, 0,0676478409652), (1998,00, 0,0676478409652), (1999,00, 0,0676478409652), (2000,00, 0,0676478409652), (2001,00, 0,0676478409652), (2002,00, 0,0676478409652), (2003,00, 0,0676478409652), (2004,00, 0,0676393699111), (2005,00, 0,0577245473944), (2006,00, 0,0489379836698), (2007,00, 0,0432836092761), (2008,00, 0,0462279172289), (2009,00, 0,0311448359755), (2010,00, 0,0335254365957), (2011,00, 0,0380757122744), (2012,00, 0,034546645901), (2013,00, 0,0349438493557), (2014,00, 0,0349438493557), (2015,00, 0,0349438493557), (2016,00, 0,0349438493557), (2017,00, 0,0349438493557)

UNITS: dmnl

health_expenditure = gdp.nominal_gdp*heath_expenditure_share_of_gdp

UNITS: USD/year

heath_expenditure_share_of_gdp = 0,03

UNITS: dmnl

interest_on_public_debt = fin.interest_on_domestic_debt+fin.interest_on_foreign_debt

UNITS: USD/year

oil_product_tax_revenue = nrg.Total_energy_demand*oil_products_tax_per_barrel

UNITS: USD/year

oil_products_tax_per_barrel = 2,5

UNITS: USD/barrel

DOCUMENT: assumption based on 23usd/barrel production cost and 12% of royalties

real_pc_general_administration_expenditure = 30

UNITS: USD2010/person/year

real_pc_subsidies_and_transfers = GRAPH(TIME)

UNITS: USD2010/person/year

renewable_energy_as_share_of_gdp = nrg.Annual_funding_for_renewable/gdp.nominal_gdp

UNITS: Dimensionless

revenue_and_grants = domestic_revenue+grants

UNITS: USD/year

roads_expenditure = roads_expenditure_as_share_of_gdp*gdp.nominal_gdp

UNITS: USD/year

roads_expenditure_as_share_of_gdp = 0,03

UNITS: dmnl

subsidies_and_transfers = (real_pc_subsidies_and_transfers*pop.total_population)*gdp.gdp_deflator

UNITS: USD/year

surplus_or_deficit_as_share_of_gdp = government_surplus_or_deficit/gdp.nominal_gdp

UNITS: dmnl

Household (hhs):

elasticity_of_propensity_to_save_to_income = 0,9

UNITS: dmnl

households_disposable_income = households_revenue-gov.domestic_revenue

UNITS: USD/year

households_revenue = gdp.nominal_gdp+fin.interest_on_domestic_debt+gov.subsidies_and_transfers+private_current_transfers

UNITS: USD/year

initial_propensity_to_save = 0,16

UNITS: dmnl

maximum_propensity_to_save = 0,35

UNITS: dmnl

mid_term_average_pc_real_disposable_income = SMTHN(pc_real_disposable_income; time_for_changes_in_income_to_affect_saving_behavior; 1)

UNITS: USD2010/person/year

pc_real_disposable_income = (households_disposable_income/gdp.gdp_deflator)/pop.total_population

UNITS: USD2010/person/year

private_consumption = households_disposable_income-private_saving

UNITS: USD/year

private_current_transfers = GRAPH(TIME)

UNITS: USD/year

private_saving = propensity_to_save*households_disposable_income

UNITS: USD/year

propensity_to_save = MIN(maximum_propensity_to_save; initial_propensity_to_save*((mid_term_average_pc_real_disposable_income/INIT(mid_term_average_pc_real_disposable_income))^elasticity_of_propensity_to_save_to_income))

UNITS: dmnl

time_for_changes_in_income_to_affect_saving_behavior = 11,5

UNITS: year

Health (hlt):

Health_Centers(t) = Health_Centers(t - dt) + (health_centers_construction - health_centers_disruption) * dt

INIT Health_Centers = 10874

UNITS: center

INFLOWS:

health_centers_construction = DELAYN(health_expenditure_for_heath_center_construction/health_centers_unit_construction_cost ; health_centers_average_construction_time; 3)

UNITS: center/year

OUTFLOWS:

health_centers_disruption = Health_Centers/health_center_life_time

UNITS: center/year

access_to_basic_health_care = proportion_of_population_coverage_per_health_centers

UNITS: dmnl

area_covered_by_health_center = working_health_centers*area_covered_per_health_center

UNITS: ha

area_covered_per_health_center = 2827

UNITS: ha/center

health_center_life_time = 50

UNITS: years

health_centers_average_construction_time = 2

UNITS: years

health_centers_running_cost = Health_Centers*relative_population_per_health_center*initial_running_cost_per_health_center

UNITS: USD2010/year

health_centers_unit_construction_cost = 220e6

UNITS: USD2010/center

health_expenditure_for_heath_center_construction = MAX(0; (real_health_expenditure-health_centers_running_cost))

UNITS: USD2010/year

initial_running_cost_per_health_center = 6e06

UNITS: USD2010/center/year

people_covered_per_health_center = pop.total_population*proportion_of_population_coverage_per_health_centers/working_health_centers

UNITS: person/center

proportion_of_population_coverage_per_health_centers = GRAPH(area_covered_by_health_center/lnd.total_land_area)

(0,000, 0,000), (0,030, 0,100), (0,100, 0,225), (0,250, 0,450), (0,500, 0,700), (1,000, 1,000)

UNITS: Dimensionless

proportion_of_running_costs_covered = MIN(1; real_health_expenditure/health_centers_running_cost)

UNITS: dmnl

proportion_of_working_health_centers = SMTHN(proportion_of_running_costs_covered; time_for_expenditure_to_affect_functioning_of_health_centers; 1; 1)

UNITS: dmnl

real_health_expenditure = gov.health_expenditure/gdp.gdp_deflator

UNITS: USD2010/year

relative_population_per_health_center = people_covered_per_health_center/INIT(people_covered_per_health_center)

UNITS: Dimensionless

time_for_expenditure_to_affect_functioning_of_health_centers = 3

UNITS: year

working_health_centers = Health_Centers*proportion_of_working_health_centers

UNITS: center

Infrastructure (ifr):

Functioning_Roads(t) = Functioning_Roads(t - dt) + (roads_completion - roads_disruption) * dt

INIT Functioning_Roads = 108000

UNITS: km

INFLOWS:

roads_completion = Roads_under_construction/time_for_road_construction

UNITS: km/year

OUTFLOWS:

roads_disruption = Functioning_Roads/average_roads_life

UNITS: km/year

Roads_under_construction(t) = Roads_under_construction(t - dt) + (road_construction_start - roads_completion) * dt

INIT Roads_under_construction = 74627,85888

UNITS: km

DOCUMENT: The figure here does not really have a basis, so it can be calibrated parameter.

INFLOWS:

road_construction_start = roads_expenditure_for_construction/average_road_construction_cost_per_km

UNITS: km/year

OUTFLOWS:

roads_completion = Roads_under_construction/time_for_road_construction

UNITS: km/year

average_road_construction_cost_per_km = effects_of_road_density_on_roads_construction_cost*initial_roads_construction_cost_per_km

UNITS: USD2010/km

average_road_life_with_maintenance = 50

UNITS: year

average_road_life_without_maintenance = 25

UNITS: year

average_roads_life = fulfilled_fraction_of_roads_maintenance*average_road_life_with_maintenance+(1-fulfilled_fraction_of_roads_maintenance)*average_road_life_without_maintenance

UNITS: years

effects_of_road_density_on_roads_construction_cost = GRAPH(km_of_roads_per_million_ha/INIT(km_of_roads_per_million_ha))

UNITS: dmnl

fulfilled_fraction_of_roads_maintenance = MIN(1; real_roads_expenditure/roads_maintenance_cost)

UNITS: dmnl

ha_per_million_ha = 1e06

UNITS: ha/Mha

initial_roads_construction_cost_per_km = 150000

UNITS: USD2010/km

km_of_roads_per_million_ha = Functioning_Roads/(lnd.total_land_area/ha_per_million_ha)

UNITS: km/Mha

real_roads_expenditure = gov.roads_expenditure/gdp.gdp_deflator

UNITS: USD2010/year

roads_expenditure_for_construction = MAX(0; real_roads_expenditure-roads_maintenance_cost)

UNITS: USD2010/year

roads_maintenance_cost = Functioning_Roads*roads_maintenance_cost_per_km

UNITS: USD2010/year

roads_maintenance_cost_per_km = 750

UNITS: USD2010/km/year

time_for_road_construction = 3

UNITS: years

Land (lnd):

agriculture_land(t) = agriculture_land(t - dt) + (deforestation_for_agriculture - agriculture_land_degradation) * dt {NON-NEGATIVE}

INIT agriculture_land = 61586000

UNITS: ha

DOCUMENT: UN Data

INFLOWS:

deforestation_for_agriculture = MIN(desired_change_in_agriculture_land+agriculture_land_degradation; maximum_allowed_forest_conversion_rate*forest) {UNIFLOW}

UNITS: ha/year

OUTFLOWS:

agriculture_land_degradation = agriculture_land_degradation_rate*agriculture_land {UNIFLOW}

UNITS: ha/year

degraded_land(t) = degraded_land(t - dt) + (agriculture_land_degradation - degraded_to_settlement - forest_regrowth) * dt {NON-NEGATIVE}

INIT degraded_land = 2670000

UNITS: ha

INFLOWS:

agriculture_land_degradation = agriculture_land_degradation_rate*agriculture_land {UNIFLOW}

UNITS: ha/year

OUTFLOWS:

degraded_to_settlement = desired_change_in_settlement_land {UNIFLOW}

UNITS: ha/year

forest_regrowth = degraded_land/average_forest_regrowth_time

UNITS: ha/year

forest(t) = forest(t - dt) + (forest_regrowth - deforestation_for_agriculture - deforestation_for_settlement) * dt {NON-NEGATIVE}

INIT forest = 17234000

UNITS: ha

DOCUMENT: From UN Data 1990

INFLOWS:

forest_regrowth = degraded_land/average_forest_regrowth_time

UNITS: ha/year

OUTFLOWS:

deforestation_for_agriculture = MIN(desired_change_in_agriculture_land+agriculture_land_degradation; maximum_allowed_forest_conversion_rate*forest) {UNIFLOW}

UNITS: ha/year

deforestation_for_settlement = MIN(desired_change_in_settlement_land-degraded_to_settlement; forest*maximum_allowed_forest_conversion_rate) {UNIFLOW}

UNITS: ha/year

settlement_land(t) = settlement_land(t - dt) + (degraded_to_settlement + deforestation_for_settlement) * dt {NON-NEGATIVE}

INIT settlement_land = 140886

UNITS: ha

INFLOWS:

degraded_to_settlement = desired_change_in_settlement_land {UNIFLOW}

UNITS: ha/year

deforestation_for_settlement = MIN(desired_change_in_settlement_land-degraded_to_settlement; forest*maximum_allowed_forest_conversion_rate) {UNIFLOW}

UNITS: ha/year

agriculture_land_adjustment_time = 0,501757

UNITS: year

agriculture_land_degradation_rate = 0,0000101486

UNITS: dmnl/year

average_forest_regrowth_time = 20

UNITS: year

desert_land = 3700000+4242000

UNITS: ha

desired_change_in_agriculture_land = (total_desired_agriculture_land-agriculture_land)/agriculture_land_adjustment_time

UNITS: ha/year

desired_change_in_settlement_land = (total_desired_settlement_land-settlement_land)/settlement_land_adjustment_time

UNITS: ha/year

desired_pc_agriculture_land = initial_pc_agriculture_land/relative_yield

UNITS: ha/person

desired_pc_settlement_land = 0,00000836477

UNITS: ha/person

elasticity_of_yield_to_total_factor_productivity = 0,999975

UNITS: dmnl

initial_pc_agriculture_land = 0,75

UNITS: ha/person

maximum_allowed_forest_conversion_rate = 0,0421544

UNITS: dmnl/year

relative_yield = gdp.total_factor_productivity^elasticity_of_yield_to_total_factor_productivity

UNITS: dmnl

settlement_land_adjustment_time = 0,999598

UNITS: year

total_desired_agriculture_land = desired_pc_agriculture_land*pop.total_population

UNITS: ha

total_desired_settlement_land = pop.total_population*desired_pc_settlement_land

UNITS: ha

total_land_area = settlement_land+forest+degraded_land+agriculture_land+desert_land

UNITS: ha

total_land_area_test = agriculture_land + degraded_land + desert_land + forest + settlement_land

UNITS: ha

Energy (nrg):

oil_discovered_resources(t) = oil_discovered_resources(t - dt) + (oil_discovery - oil_production) * dt {NON-NEGATIVE}

INIT oil_discovered_resources = 1,71e12

UNITS: barrel

INFLOWS:

oil_discovery = yearly_discovery_fraction*oil_undiscovered_resources {UNIFLOW}

UNITS: barrel/year

OUTFLOWS:

oil_production = MIN(max_yearly_extraction*oil_discovered_resources; actual_oil_demand) {UNIFLOW}

UNITS: barrel/year

oil_undiscovered_resources(t) = oil_undiscovered_resources(t - dt) + (- oil_discovery) * dt {NON-NEGATIVE}

INIT oil_undiscovered_resources = 100e06

UNITS: barrel

OUTFLOWS:

oil_discovery = yearly_discovery_fraction*oil_undiscovered_resources {UNIFLOW}

UNITS: barrel/year

renewable_energy_for_new_energy_access(t) = renewable_energy_for_new_energy_access(t - dt) + (installation_of_renewable_energy_for_new_energy_access - depreciation_of_renewable_energy_for_new_energy_access) * dt {NON-NEGATIVE}

INIT renewable_energy_for_new_energy_access = 0

UNITS: kW

DOCUMENT: unknown

INFLOWS:

installation_of_renewable_energy_for_new_energy_access = Installation_from_public*share_of_funding_for_renewable_for_new_energy_access {UNIFLOW}

UNITS: kW/year

OUTFLOWS:

depreciation_of_renewable_energy_for_new_energy_access = renewable_energy_for_new_energy_access/PV_lifetime {UNIFLOW}

UNITS: kW/year

total_renewable_energy_capacity(t) = total_renewable_energy_capacity(t - dt) + (Installation_from_private + Installation_from_public - Depreciation) * dt {NON-NEGATIVE}

INIT total_renewable_energy_capacity = 1,9384e06

UNITS: kW

INFLOWS:

Installation_from_private = (target_private_investment_in_renewable_energy)/Investment_cost_per_kW {UNIFLOW}

UNITS: kW/year

Installation_from_public = Annual_funding_for_renewable/Investment_cost_per_kW {UNIFLOW}

UNITS: kW/year

DOCUMENT: implentation is fully private sector

OUTFLOWS:

Depreciation = total_renewable_energy_capacity/ Hydropower_lifetime {UNIFLOW}

UNITS: kW/year

actual_oil_demand = Total_energy_demand-(renewable_energy_demand_in_oil_equivalent-solar_energy_demand_for_energy_access_in_oil_equivalent)

UNITS: barrel/year

Annual_funding_for_renewable = external_funding_for_renewables+renewable_energy_expenditure_as_a_share_of_GDP*gdp.real_gdp

UNITS: USD2010/year

annual_funding_for_renewable_for_new_energy_access = Annual_funding_for_renewable*share_of_funding_for_renewable_for_new_energy_access

UNITS: USD/year

annual_operation_hours_for_hydropower = 3000

UNITS: hour/year

annual_operation_hours_for_solar_PV = 3285

UNITS: hour/year

DOCUMENT: 9 hours a day round the year (9*365 =3285 hours)

https://www.degruyter.com/document/doi/10.1515/eng-2019-0009/html

average_oil_market_price = gov.oil_products_tax_per_barrel/gdp.gdp_deflator+domestic_oil_production_cost

UNITS: USD2010/barrel

domestic_oil_production_cost = effect_of_remaining_discovered_resources_on_oil_production_cost*initial_oil_production_cost

UNITS: USD2010/barrel

effect_of_oil_price_on_energy_efficiency = GRAPH(average_oil_market_price/INIT(average_oil_market_price))

(0,000, 0,838), (1,000, 0,903), (2,000, 1,000)

UNITS: Dimensionless

effect_of_oil_price_on_renewable_energy = average_oil_market_price/INIT(average_oil_market_price)

UNITS: dmnl

effect_of_remaining_discovered_resources_on_oil_production_cost = GRAPH(oil_discovered_resources/INIT(oil_discovered_resources))

(0,000, 12,00), (0,050, 6,00), (0,125, 3,00), (0,250, 2,00), (0,500, 1,25), (0,750, 1,10), (1,000, 1,00)

UNITS: dmnl

electricity_generation_for_access_to_energy = renewable_energy_for_new_energy_access*annual_operation_hours_for_solar_PV

UNITS: Hours*kW/Years

electricity_generation_per_year = total_renewable_energy_capacity*annual_operation_hours_for_hydropower

UNITS: Hours*kW/Years

emissions_savings = renewable_energy_demand_in_oil_equivalent*rate_of_ghg_emission_from_oil

UNITS: kgco2/year

energy_demand_for_energy_access = Total_energy_demand*share_of_total_energy_demand_for_energy_access

UNITS: barrel/year

energy_efficiency = DELAYN(target_energy_efficiency; energy_efficiency_adjustment_time; 1; 1)

UNITS: Dimensionless

energy_efficiency_adjustment_time = 8

UNITS: year

external_funding_for_renewables = IF TIME<2017 THEN 1e06 ELSE 1e08

UNITS: USD2010/year

fossil_fuel_ghg_emissions = (Total_energy_demand*ghg_emission_per_barrel_of_oil_in_co2_equivalent)-emissions_savings

UNITS: kgco2/year

gdp_energy_intensity = initial_gdp_energy_intensity/energy_efficiency

UNITS: barrel/USD2010

ghg_emission_per_barrel_of_oil_in_co2_equivalent = 430,7

UNITS: kgco2/barrel

Hydropower_lifetime = 100

UNITS: year

initial_gdp_energy_intensity = 0,0083864143251288*0,207573076

UNITS: barrel/USD2010

initial_oil_production_cost = 12

UNITS: USD2010/barrel

initial_population_with_access_to_energy = 26199246,7

UNITS: person

initial_private_investment_in_renewable_energy = 1e07

UNITS: USD2010/year

Investment_cost_per_kW = 2000

UNITS: USD2010/kW

kWh_to_barrel_converter = 1/1700

UNITS: barrel/(kW*Hours)

max_yearly_extraction = 0,1

UNITS: dmnl/year

new_people_with_energy_access = solar_energy_demand_for_energy_access_in_oil_equivalent/threshold_energy_per_capita

UNITS: person

oil_import = actual_oil_demand-oil_production

UNITS: barrel/year

PV_lifetime = 25

UNITS: Years

rate_of_ghg_emission_from_oil = 52

UNITS: kgco2/barrel

renewable_energy_demand_in_oil_equivalent = electricity_generation_per_year*kWh_to_barrel_converter+pop.total_population*Unaccounted_renewable_energy_per_capita

UNITS: barrel/year

renewable_energy_expenditure_as_a_share_of_GDP = 0,03

UNITS: dmnl

share_of_funding_for_renewable_for_new_energy_access = 0,10

UNITS: dmnl

share_of_population_with_energy_access = total_population_with_energy_access/pop.total_population

UNITS: dmnl

share_of_renewable_energy_in_total_energy_consumption = renewable_energy_demand_in_oil_equivalent/ Total_energy_demand

UNITS: dmnl

share_of_total_energy_demand_for_energy_access = 0,1

UNITS: dmnl

solar_energy_demand_for_energy_access_in_oil_equivalent = electricity_generation_for_access_to_energy*kWh_to_barrel_converter

UNITS: barrel/year

state_of_the_art_energy_efficiency = 1,25

UNITS: dmnl

target_energy_efficiency = state_of_the_art_energy_efficiency* effect_of_oil_price_on_energy_efficiency

UNITS: Dimensionless

target_private_investment_in_renewable_energy = initial_private_investment_in_renewable_energy* effect_of_oil_price_on_renewable_energy

UNITS: USD2010/year

threshold_energy_per_capita = 3000

UNITS: barrel/year/person

Total_energy_demand = gdp.real_gdp*gdp_energy_intensity

UNITS: barrel/year

total_population_with_energy_access = initial_population_with_access_to_energy+new_people_with_energy_access

UNITS: person

Unaccounted_renewable_energy_per_capita = 3,4

UNITS: barrel/person/year

yearly_discovery_fraction = 0,01

UNITS: dmnl/year

Population (pop):

Elderly_Population(t) = Elderly_Population(t - dt) + (Becoming_elderly + Elderly_population_net_migration - Elderly_deaths) * dt {NON-NEGATIVE}

INIT Elderly_Population = 2742870

UNITS: person

INFLOWS:

Becoming_elderly = Working_Age_Population/Working_age_duration {UNIFLOW}

UNITS: person/year

Elderly_population_net_migration = Elderly_Population* Net_migration_rate

UNITS: person/year

OUTFLOWS:

Elderly_deaths = Elderly_Population* (Elderly_death_rate+elderly_population_death_rate_correction) {UNIFLOW}

UNITS: person/year

Infant_Population(t) = Infant_Population(t - dt) + (Births + Infant_net_migration - Becoming_School_Age - Infant_Deaths) * dt {NON-NEGATIVE}

INIT Infant_Population = 16808706,18

UNITS: person

INFLOWS:

Births = (Women_in_fertile_age* Total_fertility_rate)/ Duration_of_fertile_period {UNIFLOW}

UNITS: person/year

Infant_net_migration = Infant_Population* Net_migration_rate

UNITS: person/year

OUTFLOWS:

Becoming_School_Age = Infant_Population/Infant_stage_duration {UNIFLOW}

UNITS: person/year

Infant_Deaths = Infant_Population* Infant_death_rate {UNIFLOW}

UNITS: person/year

School_Age_Population(t) = School_Age_Population(t - dt) + (Becoming_School_Age + School_age_population_net_migration - Becoming_working_Age - School_age_population_deaths) * dt {NON-NEGATIVE}

INIT School_Age_Population = 26036938

UNITS: person

INFLOWS:

Becoming_School_Age = Infant_Population/Infant_stage_duration {UNIFLOW}

UNITS: person/year

School_age_population_net_migration = School_Age_Population* Net_migration_rate

UNITS: person/year

OUTFLOWS:

Becoming_working_Age = School_Age_Population/School_age_duration {UNIFLOW}

UNITS: person/year

School_age_population_deaths = School_Age_Population* school_age_death_rate {UNIFLOW}

UNITS: person/year

Working_Age_Population(t) = Working_Age_Population(t - dt) + (Becoming_working_Age + Working_age_population_net_migration - Becoming_elderly - Working_age_population_deaths) * dt {NON-NEGATIVE}

INIT Working_Age_Population = 49681474

UNITS: person

INFLOWS:

Becoming_working_Age = School_Age_Population/School_age_duration {UNIFLOW}

UNITS: person/year

Working_age_population_net_migration = Working_Age_Population* Net_migration_rate

UNITS: person/year

OUTFLOWS:

Becoming_elderly = Working_Age_Population/Working_age_duration {UNIFLOW}

UNITS: person/year

Working_age_population_deaths = Working_Age_Population* Working_age_death_rate {UNIFLOW}

UNITS: person/year

Avg_life_expectancy = GRAPH(Well_being_Index)

UNITS: year

Contraceptive_Prevalence = Initial_contraceptive_prevalence*(edu.Average_adult_literacy_rate/INIT(edu.Average_adult_literacy_rate))^ Elasticity_of_contraceptive_prevalence_to_adult_literacy_rate

UNITS: dmnl

Desired_fertility_rate = Initial_desired_fertility_rate*(Perceived_PC_real_disposable_income/INIT(Perceived_PC_real_disposable_income))^ Elasticity_of_desired_fertility_rate_to_PC_disposable_income

UNITS: dmnl

Duration_of_fertile_period = 30

UNITS: years

Elasticity_of_contraceptive_prevalence_to_adult_literacy_rate = 0,1005

UNITS: dmnl

Elasticity_of_desired_fertility_rate_to_PC_disposable_income = 0,532633

UNITS: dmnl

Elderly_death_rate = GRAPH(Avg_life_expectancy)

UNITS: dmnl/year

elderly_population_death_rate_correction = 0,036852

UNITS: dmnl/year

Income_weight = 0,770908

UNITS: dmnl

Infant_death_rate = GRAPH(Avg_life_expectancy)

UNITS: dmnl/year

Infant_stage_duration = 4

UNITS: years

Initial_contraceptive_prevalence = 0

UNITS: dmnl

Initial_desired_fertility_rate = 4

UNITS: dmnl

Natural_fertility_rate = 7,07

UNITS: dmnl

Net_migration_rate = GRAPH(TIME)

UNITS: dmnl/year

Perceived_PC_real_disposable_income = SMTHN(hhs.pc_real_disposable_income; Time_for_Income_to_affect_fertility; 1; 94000)

UNITS: USD2010/person/year

school_age_death_rate = GRAPH(Avg_life_expectancy)

UNITS: dmnl/year

DOCUMENT: Great leverage for school age population

School_age_duration = 10

UNITS: year

Share_of_women_in_fertile_age_in_working_age_population = 0,426386081

UNITS: dmnl

Time_for_Income_to_affect_fertility = 10

UNITS: Years

Total_fertility_rate = Desired_fertility_rate*Contraceptive_Prevalence+ Natural_fertility_rate*(1-Contraceptive_Prevalence)

UNITS: dmnl

total_population = Infant_Population+Working_Age_Population+Elderly_Population+School_Age_Population

UNITS: person

Well_being_Index = MIN(1; Perceived_PC_real_disposable_income/Well_being_saturation_income)*Income_weight+ hlt.access_to_basic_health_care*(1-Income_weight)

UNITS: dmnl

Well_being_saturation_income = 1705000

UNITS: USD2010/person/year

Women_in_fertile_age = Working_Age_Population* Share_of_women_in_fertile_age_in_working_age_population

UNITS: person

DOCUMENT: 15-49years

Working_age_death_rate = GRAPH(Avg_life_expectancy)

UNITS: dmnl/year

Working_age_duration = 50

UNITS: year

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